Value for money in energy efficiency retrofits in Ireland: Grant provider and grant recipients

Matthew Collins[a,b,*], John Curtis[a,c]

[a] *Economic and Social Research Institute, Sir John Rogerson's Quay, Dublin, Ireland*
[b] *Sustainable Energy Authority of Ireland, Wilton Park House, Wilton Place, Dublin, Ireland*
[c] *Trinity College Dublin, Dublin, Ireland*

Abstract

The Sustainable Energy Authority of Ireland (SEAI) administers the Better Energy Homes scheme to provide a financial incentive for home owners to engage in energy efficiency retrofits. This study analyses data from the scheme and Building Energy Rating data for participant to the scheme to examine the value for money achieved by households. In addition, this research identifies which retrofit combinations provide greatest value for money, in terms of energy efficiency gains, for the grant provider. We utilise an error-in-variables approach to model the variation in benefits accruing to households of varying characteristics. We find that household and grant provider surplus can be maximised in the short term by retrofitting less energy efficient and larger homes, timber or steel frame homes and houses rather and apartments. The types of retrofits leading to the greatest surplus for both household and grant provider include cavity wall insulation paired with either a boiler with heating controls or heating controls only retrofit.

Keywords: residential energy efficiency retrofit; energy efficiency investment; error-in-variables regression

1. Introduction

As of December 2015, over 50% of Irish homes possess Building Energy Ratings of between D1 and G, on a 15-point scale ranging from A1 to G, with A1 being the most efficient[1]. To provide context, a B1-rated home would be expected to use, for heating and lighting, less than half of the energy required by a C2-rated home on a per-metre squared basis, based on a standardised occupancy. Consequently there is scope for improvements in residential energy efficiency as a means of reducing Ireland's overall energy consumption by 20% by 2020, a target set by the European Union (European Parliament and the Council of the European Union 2012). To that end, the Sustainable Energy Authority of Ireland (SEAI) operates the Better Energy Homes (BEH) scheme, which provides grant aid for home owners to engage in energy efficiency retrofits of their homes. At present, grant aid is available for up to four energy efficiency retrofit measures, which are roof insulation upgrades, wall insulation upgrades, one of a high efficiency boiler with heating control upgrade or heating controls only upgrades and solar collector installation.

Engaging in an energy efficiency retrofit can require a significant financial outlay, often with uncertain benefits as home owners may not be fully aware of the energy efficiency improvements that can be gained by engaging in retrofitting activity. It is also possible that the grant scheme may be incentivising specific measures, rather than those which can provide the greatest benefit for a home owner. It is therefore

*Corresponding author
Email addresses: matthew.collins@esri.ie (Matthew Collins), john.curtis@esri.ie (John Curtis)

[1] Based on CSO weightings of BER database to national level. Central Statistics Office (2015) Domestic Building Energy Ratings Release, December 2015, Table 15, available: http://www.cso.ie/en/releasesandpublications/er/dber/domesticbuildingenergyratingsquarter42015/

important to gain an understanding of the potential improvement households can extract by making an investment in energy efficiency retrofit measures. This research aims to gain a greater understanding of value for money in energy efficiency retrofitting from two perspectives, in the context of the BEH scheme. The first of these is the value for money attained in retrofitting on the household side, in terms of the net benefit accruing over the lifetime of investment and in terms of capital costs per unit technical energy saving. The second perspective is the cost to the grant provider, in this case the Sustainable Energy Authority of Ireland (SEAI). By investigating these outcomes, we hope to identify characteristics of households that possess greater investment payoffs and we identify whether certain combinations are providing more or less value for money and, in turn, if certain measures may require greater subsidisation in order to provide necessary returns to investment to home owners. From the grant provider point of view we identify whether combinations of retrofit measures exist which can provide equal energy efficiency improvements in the building stock in a less costly manner to the state.

Residential retrofits provide many benefits to households. The most-often referred to benefits, and those used in SEAI's promotional literature with regard to the BEH scheme, are comfort gains, cost savings and environmental benefits. These are discussed as the main drivers of retrofitting activity from the perspective of private households (Aravena, Riquelme, and Denny 2016; Clinch and Healy 2001; Gillingham, Newell, and Palmer 2009). Other benefits include increased home values and individual health benefits. Building Energy Ratings (BER) are an energy performance certificate used to rate a home's energy requirements for space and water heating. Hyland, Lyons, and Lyons (2013) found that, in Ireland, improved BERs were associated with a price premium in both house purchase prices and rental prices. With regard to health benefits, different trials in New Zealand in insulating homes and installing heating systems in homes have been found to lead to improved self-reported health and fewer self-reported GP visits, alongside reduced sick days from work and school for adults and children, respectively (Howden-Chapman et al. 2012).

The option of engaging in an energy efficiency retrofit can be seen as occurring in a choice set of investment opportunities for a household. The decision is therefore compared to other options using a range of criteria and household considerations. Lee et al. (2004) provides a review of the literature with regard to household investment decision making. The literature on investment decision making refers to the choice between immediate and deferred consumption, i.e. the benefits of consuming now relative to the benefits derived from investing now (Nagy and Obenberger 1994; Neumann and Morgenstern 1947). The benefits to be gained from investing, however, are uncertain and households may not possess full information of the benefits available. Potential investors are therefore required to form their own expectations with regard to unknown future outcomes. Investors often use information on the past performance of a good to inform their expectations of future performance (Moore et al. 1999; Sirri and Tufano 1998). Energy efficiency retrofits are not common goods, however, and as such, information on past performance of retrofits may not be freely available or may only be available anecdotally from social connections, advertising material, etc.

Households also associate investments with risk. Kaplan, Szybillo, and Jacoby (1974) outline components of this risk, detailing the physical, psychological, social, financial and performance risks associated with household investment. Due to these risks, household discount rates may be quite high. Decision making is also affected by household structure in terms of which family members are involved in the decision making process, the nature of the process and the structure of the household (Davis 1976). This is particularly important in retrofitting investment decisions as not all members of a household will necessarily see environmental benefits as a priority in assessing the costs and benefits of such an investment. Similarly, even when all members of households agree, there likely exists significant heterogeneity across households with regard to environmental concerns. Given this heterogeneity, based on the impossibility paradox (Arrow 1950), there is no specific type of retrofit which can efficiently satisfy the preferences of all households.

Energy costs to home owners have been shown to be the main driver of energy efficiency retrofit investments in Switzerland (Amstalden et al. 2007). In Ireland, money and comfort gains were found to be drivers of retrofit activity, while environmental concerns were not found to be a factor in driving retrofits (Aravena, Riquelme, and Denny 2016). With regard to risk, Sadler (2003) concludes that households possess a discount rate of 20.79% when trading off the capital cost of renovations with annual heating cost savings. In terms of policy, the size and structure of financial aid has been found to be a factor in driving retrofit investments. Neuhoff et al. (2011) found, in analysing financial aid schemes in Italy, the Netherlands, Germany and the United States, that tax incentives as well as loans and grant aid had a high take-up. Neuhoff et al. (2011) also found that countries which offered increasing levels of financial support per retrofit measure for retrofits comprising greater numbers of measures had a higher take-up of comprehensive retrofits than those who offered a constant level of support for each measure, regardless of how many measures were undertaken. Collins and Curtis (2016), however, found that bonus payments for retrofits comprising a greater number of measures did not lead to a higher take-up of such retrofits under the Better Energy Homes scheme. Michelsen, Neuhoff, and Schopp (2015) suggest providing equity capital to cover the initial cost of investment, with repayments made based on energy cost savings over time as a means of reducing investment risk for households.

Dowson et al. (2012) examine the incentive to engage in an energy efficiency retrofit in the UK, calculating lifetime savings, returns on investment and payback periods for varying energy efficiency retrofit measures. The return on investment is found to vary from an average of -€3,184 for double glazing of windows to and average of €2,880 for cavity wall insulation in pre-1976 dwellings. Ahern, Griffiths, and O'Flaherty (2013) examine the benefits of thermal retrofits to detached homes of varying characteristics in Ireland. In estimating the returns to improving the glazing, walls, roof and air tightness of these dwellings, an average payback period of 12 years is found across all homes built prior to 1977, although this rises incrementally when moving to newer cohorts of buildings, with a payback period of 45 years expected for dwellings built between 2005 and 2006. This is due to rising energy efficiency standards in Irish residential buildings, particularly those built from 2006 onward. As these buildings are more efficient prior to retrofitting, the gains accrued from retrofitting are lower and hence investments in those dwellings possess longer payback periods.

In evaluating the provision of grant aid, all-encompassing cost-benefit analyses tend to dominate the literature. For example, Chapman et al. (2009) employ a cost-benefit analysis to evaluate the success of a retrofit grant aid scheme aimed at low-income households in New Zealand where a family member suffers from a respiratory disease. This study examined the total health, energy and CO2 improvements as a result of the scheme as a whole. Similarly, CEEEP (2012) examined a range of retrofit grant aid schemes on offer in New Jersey, comparing energy and CO2 reductions to the costs involved in retrofitting. In the Irish context, Clinch and Healy (2001) provide a cost-benefit methodology to analyse retrofit schemes ex-ante, using a case study of designing a scheme for Irish households, while SEAI (2012) analysed observed billing data of participants to the BEH scheme to estimate the energy cost and comfort improvements gained by households across the scheme as a whole.

With regard to identifying packages of retrofit measures which provide greatest value for money, Friedman, Becker, and Erell (2014) provide an ex-ante cost-benefit analysis of a suite of measures in different areas of Israel, which accrue heterogeneous benefits due to differences in climate. This cost-benefit analysis is based on engineering estimates of the improvements to be gained from retrofitting in each region, using building types that are typical in Israeli architecture. As part of this analysis, costs and benefits were estimated for two types of roof insulation, two types of wall insulation, window shading and various combinations thereof.

While households must decide, under uncertainty, whether to invest in an energy efficiency retrofit, we examine the returns to investment of those that have made the choice to engage in residential retrofitting works. Rather than using expected returns based on estimated characteristics of the housing stock, we examine observed improvements that have been made via energy efficiency retrofit works. We examine, using an econometric approach, the net present value of investment for participant homes, taking into account the costs of investment, grant aid, technical energy savings over the lifetime of the investment and direct rebound effects in energy use. We also analyse value for money exhibited by capital costs to the household, measured as the Euro spend for every unit ($kWh/m^2/yr$) improvement in a homes BER. We use this capital cost methodology to examine value for money on the part of the grant provider.

The remainder of the paper is organised as follows. Section 2 provides a description of the data and section 3 contains a discussion of modelling and estimation issues. This is then followed by the presentation and discussion of the estimation results in section 4, while section 5 concludes.

2. Data and Descriptive Analysis

2.1. 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). We use an administrative dataset of all applications made to the BEH scheme and a technical dataset of Building Energy Rating (BER) assessments of homes following completion of retrofit works. This comprises the period June 2010, when BER assessments became compulsory, to October 2015. 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 heating system 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 heating system 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. We describe the period following introduction as “scheme 1”, and each period following an amendment to levels of aid or the structure of the grant as “scheme 2”, “scheme 3”, etc. It may be noted that bonus payments for deeper retrofits, in this case retrofits comprised of three or four measures, were introduced as part of scheme 5.

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

To October 2015, the BEH scheme has helped over 169,000 homes improve their energy efficiency and, since June 2010, has mandated an ex-ante pre-works and post-works Building Energy Rating (BER) assessment. A BER takes account of primary energy requirements for space heating, ventilation, water heating and lighting, less savings from energy generation technologies, measured in kilowatt hours ($kWh/m^2/year$). This is based on a standardised occupancy, with living areas heated to 21°C and other rooms to 18°C (SEAI 2013). This calculation requires assessment of a home's dimensions, orientation, insulation and space and water heating system efficiencies. When assessing a property's post-works BER, an independent assessor will assess the property's building energy rating, which is registered for that property. The assessor then uses information provided by the relevant contractor(s) to discount the relevant parameters to their pre-works values, providing an estimate of the pre-works BER. The pre-works BER is not quality-checked and is not registered and the values of the adjusted parameters are not provided. We must therefore assume the presence of an element of error in this pre-works BER value. This is because, without quality-checking, assessors may see this pre-works BER estimate as an unimportant part of the process and complete the assessment inaccurately. In the BEH data, 2,673 households completed multiple retrofits which included a post-works BER assessment. This allows us to examine the accuracy of the pre-works BER for these properties by comparing the estimated pre-works BER to the most recent previously assessed BER. By comparing a dwellings estimated pre-works BER to the assessed post-works BER from that dwellings prior grant application, a measure of the 'BER Error' inherent to the estimated pre-works BER is calculated. This error possesses a mean of 21.8 $kWh/m^2/yr$ and standard deviation of 48.8. As we will discuss in section 2.2, we use the pre-works and post-works assessments to calculate the change in a building's BER and, as such, we must account for this error. SEAI classifies technical errors into grades of severity on a scale of 1 to 3, with 1 being the most severe[2]. With regard to the gross change in a BER caused by assessor error, errors of less than 10% of the BER value are classified as compliant, with larger errors categorised by severity. By this measure 72.34% of pre-works BERs examined could be deemed compliant. It may be noted that prior to June 2010, ex-ante BER assessments were not mandatory and had close to zero uptake of this assessment. As such, the data is comprised of only homes participating in the scheme from June 2010 onward.

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 and submits a declaration of works form to SEAI, 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 home owner's 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.[3] Of the 11 obligated parties, six have engaged customers via the BEH scheme. Obligated parties and counter parties have unique, anonymous identifiers within the dataset.

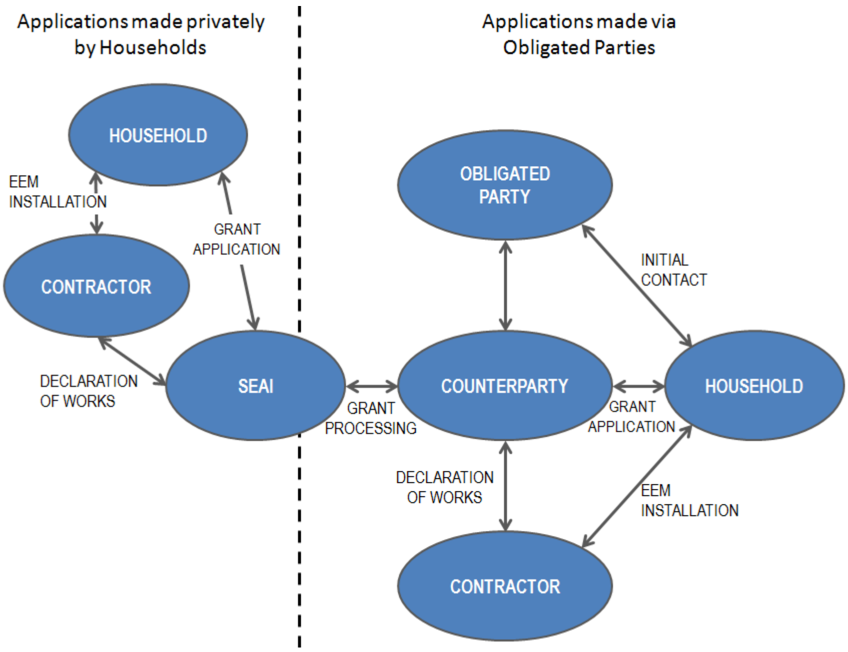
The relationship between obligated parties and other agents involved in the grant process is described in figure 1. As shown on the right of the figure, obligated parties make initial contact with households to consider investment in EEMs for their property. If a household is interested in EEM adoption, the obligated party will then engage a counterparty to contact the household with regard to EEM installation. The counterparty will then assign a contractor to complete the works and process the grant application and declaration of works form on behalf of the SEAI, with SEAI then awarding the relevant grant aid, subject to satisfying technical standards. Private applications for grant aid are more common and the process is

[2]More information on the classification of technical errors is available at `http://www.seai.ie/Your_Building/BER/Code-and-QADP-communication-of-key-changes/DBER-Technical-Error-Classification-New.pdf`

[3]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/`

outlined on the left of Figure 1, where households engage contractors to install EEMs, before applying for the BEH grant, and the grant application is finally processed once the works are completed. We control for obligated party and counterparty activity as obligated parties receive credits toward their energy savings targets based on the measures they facilitate. This provides a different incentive scheme than households who apply privately and obligated parties may therefore have different strategies in terms of the homes and energy savings they target. Our value for money analysis does not, however, take into account any monies or discounts provided to the household by the obligated party.

Figure 1: Obligated parties and their relationships



We also examine various characteristics of the applicant properties. The combination of retrofit measures undertaken is perhaps the most important predictor of the benefits accruing to households, alongside the characteristics of the property itself. Specifically, the characteristics of the property included in the data comprise the dwelling type, year of construction, floor area, number of chimneys, number of open flues and the structure type. We combine the number of chimneys and open flues for our analysis. The benefits of retrofitting are also affected by the costs involved, which are reduced at the time of investment by the grant aid awarded via the BEH scheme. We therefore control for the scheme rule changes described in table 1. Summary statistics for the variables used in our analysis, along with those to be discussed in section 2.2, are presented in table 2.

Table 2: Descriptive Statistics

	Observations	Proportion		Observations	Proportion
Retrofit Combination			*Obligated Party ID*		
External Wall Insulation	5,963	6.70	Private	76,454	85.84
Dry Lining	712	0.80	OP 1	1,300	1.46
Boiler w/ HC	16,061	18.03	OP 2	529	0.59
HC Only	1,444	1.62	OP 3	8,767	9.84
Solar	4,574	5.14	OP 4	1,477	1.66
Other 1	767	0.86	OP 5	273	0.31
Attic + Cavity	47,068	52.85	OP 6	263	0.30
Attic + External	1,619	1.82		89,063	
Attic + Dry-Lining	1,429	1.60			
Attic + Boiler	1,419	1.59	*Property type*		
Boiler + Solar	584	0.66	Detached House	42,058	47.22
Other 2	2,082	2.34	Semi-Detahced House	30,816	34.60
Attic + Cavity + Boiler	2,170	2.44	End of Terrace House	5,054	5.67
Attic + Cavity + HC Only	1,041	1.17	Mid-Terrace House	10,157	11.40
Attic + Dry-Lining + Boiler	668	0.75	Apartment	978	1.10
Other 3	980	1.10		89,063	
4 Measures	482	0.54			
	89,063		*Structure Type*		
Scheme Rule Changes			Masonry/Insulated Concrete	87,749	98.52
Scheme 2	28,725	32.25	Timber or Steel Frame	1,314	1.48
Scheme 3	19,661	22.08		89,063	
Scheme 4	37,174	41.74			
Scheme 5	3,503	3.93	*Chimneys and Open Flues*		
	89,063		0	4,320	4.85
			1	52,562	59.02
			2	26,360	29.60
			3+	5,821	6.54
				89,063	

	Observations	Mean	Std. Dev.	Min	Max
Pre-Works BER ($kWh/m^2/yr$)	89,063	288.13	93.03	77.26	891.64
Floor Area (m^2)	89,063	87.29	41.89	30	504.02
Net Benefit (€)	89,063	888.18	3,208.29	-16,048.41	13,656.50
Household Cost/BER improvement (€$/kWh/m^2/yr$)	89,063	51.64	99.44	0.03	10,222.20
Grant Aid/BER Improvement (€$/kWh/m^2/yr$)	89,063	20.96	37.28	0.62	4,545.49

2.2. Net benefit of retrofit adoption

Using the available data, we calculate the net present value of the retrofit investment. The initial cost of investment is calculated as the total cost of the retrofit measures installed, less the grant aid awarded to the household. Yearly total energy savings are based on technical energy savings, as per the ex-ante pre- and post-works BER assessment. SEAI provide expected energy costs for homes of varying types and sizes at each BER grade based on heating the home to a suitable level of comfort. The associated costs according to a home's pre- and post-works BER are compared to estimate annual energy cost savings. The expected annual costs and cost per square metre calculations are presented in Table 3. This provides a general guide to annual energy costs but fails to take into account variations in prices due to differing fuel sources. We note that it is unlikely that comfort is maintained at an adequate level in very large and inefficient homes, which may lead to an overestimation of savings in some cases. Given that the BEH scheme is designed such that home owners provide ca. 65% of the upfront cost and given the presence of another scheme, the Better energy Warmer Homes scheme, which provides aid for homes suffering from fuel poverty, the population of BEH-participants is likely to be of a higher socio-economic profile than the national population (Scheer, Clancy, and Hógáin 2013). These homes are therefore more likely to maintain adequate levels of comfort in heating and as such we have not made any adjustments to pre-works energy costs.

In calculating energy cost savings, we account for rebound effects in energy use as a result of improvements in energy efficiency. Rooted in the concept of Jevon's paradox, whereby consumption of a resource rises as the efficiency with which that resource can be used improves (Jevons 1906), the rebound effect, or temperature take-back as a result of improved energy efficiency represents the additional energy used to heat a home as energy efficiency improves. Essentially, as homes who participate in the BEH scheme can more efficiently heat their home, they may decide to heat it for longer or to a higher temperature. Scheer, Clancy, and Hógáin (2013) examined the magnitude of the rebound effect in gas consumption of participants

Table 3: Indicative annual running costs for different properties and BERs

Rating	2 Bed Apartment 75 m^2 Total Cost (€)	Cost per m^2 (€)	3 Bed Semi-Detached 100 m^2 Total Cost (€)	Cost per m^2 (€)	4 Bed Semi-Detached 150 m^2 Total Cost (€)	Cost per m^2 (€)	Detached House 200 m^2 Total Cost (€)	Cost per m^2 (€)	Large House 300 m^2 Total Cost (€)	Cost per m^2 (€)	Avg. Cost per m^2 (€)
A1	140	1.87	190	1.90	280	1.87	400	2.00	600	2.00	1.93
A2	280	3.73	380	3.80	560	3.73	800	4.00	1,100	3.67	3.79
A3	350	4.67	470	4.70	700	4.67	900	4.50	1,400	4.67	4.64
B1	440	5.87	590	5.90	900	6.00	1,200	6.00	1,800	6.00	5.95
B2	570	7.6	800	8.00	1,100	7.33	1,500	7.50	2,300	7.67	7.62
B3	700	9.33	900	9.00	1,400	9.33	1,900	9.50	2,800	9.33	9.30
C1	800	10.67	1,100	11.00	1,600	10.67	2,200	11.00	3,300	11.00	10.87
C2	1,000	13.33	1,300	13.00	1,900	12.67	2,600	13.00	3,900	13.00	13.00
C3	1,100	14.67	1,500	15.00	2,200	14.67	2,900	14.50	4,400	14.67	14.70
D1	1,300	17.33	1,700	17.00	2,600	17.33	3,500	17.50	5,200	17.33	17.30
D2	1,500	20.00	2,000	20.00	3,100	20.67	4,100	20.50	6,100	20.33	20.30
E1	1,800	24.00	2,300	23.00	3,500	23.33	4,700	23.50	7,000	23.33	23.43
E2	2,000	26.67	2,600	26.00	4,000	26.67	5,300	26.50	7,900	26.33	26.43
F	2,400	32.00	3,200	32.00	4,700	31.33	6,300	31.50	9,500	31.67	31.70
G	3,000	40.00	4,000	40.00	5,900	39.33	7,900	39.50	11,900	39.67	39.70

Adapted from SEAI's 'A guide to Building Energy Rating for Homeowners', available at `http://www.seai.ie/Your_Building/BER/Your_Guide_to_Building_Energy_Rating.pdf`.
Costs based on typical occupancy and heating the entire dwelling to a comfortable level.
Costs are based on fuel and electricity factors from February 2014.

to the Better Energy Homes scheme, finding a direct rebound effect of 36±8%. As this is based only on gas consumption, we use the lower bound of 28% as rebound effects are found to be lower for other energy users, such as lighting and water heating, and reduce annual energy savings to 72% of the cost reduction estimated based on technical energy consumption. Without possessing information on wealth or income levels of the participant households, some bias may be introduced as rebound effects are found to be greater among lower income households as they are less likely to heat their homes to a standard level of comfort when living in energy inefficient properties (Sorrell, Dimitropoulos, and Sommerville 2009).

A maximum time horizon of investment of 20 years is used. This horizon is reduced to 10 years for solar panels[4] and 15 years for oil or gas boilers[5]. The present value of these savings are calculated using a discount factor of 7.5%. With regard to retrofitting investment, Clinch and Healy (2001) recommend a discount factor for Irish households of 9%. As we do not account for inflation in our analysis, we revise this downward by 1.5%, which represents the inflation forecast for Ireland at the time of writing (OECD 2017). This allows for discounting at the real discount rate of households. This net benefit calculation is likely to understate the true net benefit of retrofit adoption as we do not account for the value to the home owner of improved comfort and warmth, health benefits, improved environmental conscience, etc. Similarly, hidden costs such as search costs, disruption, etc. are not included.

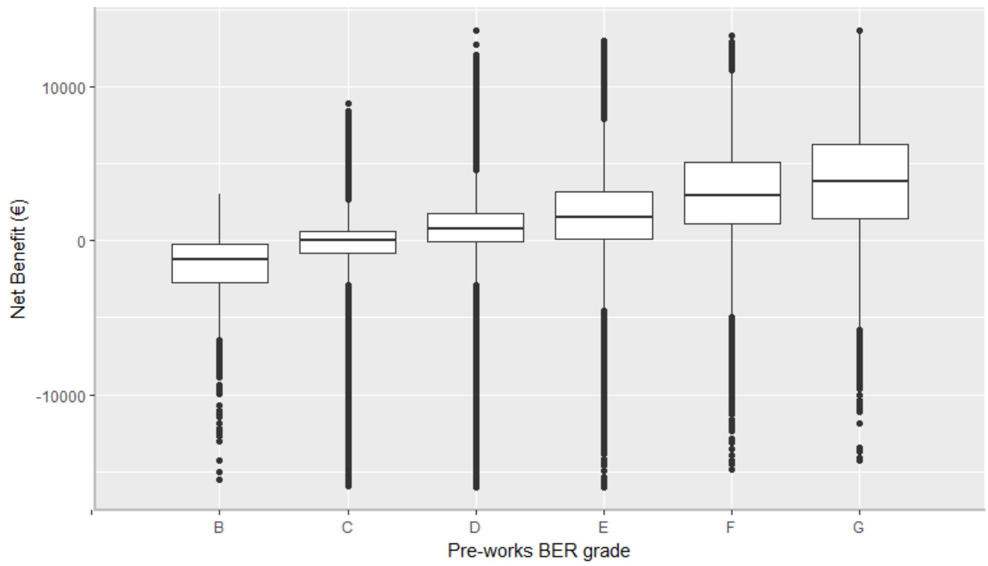
Descriptive statistics of the dependent and explanatory variables used for modelling are presented in table 2, while figure 2 shows the distribution of the net benefit across pre-works BER letter grades. As we move from the most efficient to the least efficient grades, the median benefit and variation in benefits rise. B-rated homes, for example, possess a negative median net benefit, although the distributions at each pre-works grade possess quite long tails. We also see, in figure 3, some variation in benefit, depending on the number of measures that are installed. The largest mean net benefit and lowest level of variance exists in the distribution of net benefits accrued via retrofits comprising two measures. This is likely due to the

[4] The National Renewable Energy Laboratory of the U.S. Department of Energy advises the useful life to solar water heating technology to be between 10-25 years. We have conservatively chosen the lower bound. More information is available at: `http://www.nrel.gov/analysis/tech_footprint.html`

[5] The Chartered Institution of Building Services Engineers Guide M 2014 advises the the expected lifetime of a domestic gas or oil boiler to be 15 years. More information is available at: `http://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7oZAAS`

prevalence of attic and cavity insulation retrofits, which provide a very cost effective opportunity to improve energy efficiency. Following two-measure retrofits, those comprising three measures possess the next largest mean net benefit, at €992, relative to the mean of €1,454 of two-measure retrofits. These are followed by four-measure retrofits with a mean net benefit of €428, although the distribution of net benefit among these retrofits possesses the largest variance.

Figure 2: Boxplot of net benefits accrued by homes of varying pre-works BER



While decision-makers are generally considered to be boundedly rational, it is not unexpected that some households may accrue negative levels of net benefits as some may not possess fully accurate expectations of costs and benefits prior to engaging in retrofit works. Alternatively, one may view these negative levels of net benefit as the amount home owners are willing to pay for other benefits of retrofitting discussed in section 1, or a combination of both interpretations.

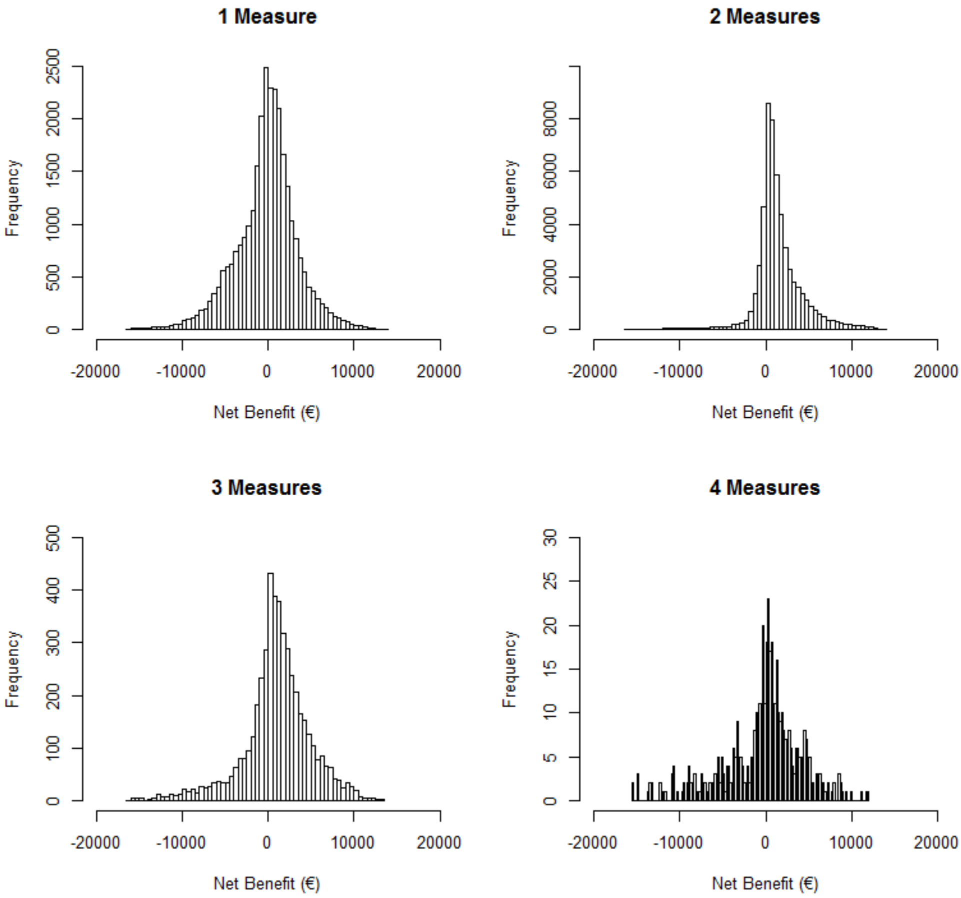
3. Methodology

This section specifies three separate analyses of value for money in the Better Energy Homes scheme. Section 3.1 outlines the household net benefit model of retrofit adoption, while section 3.2 outlines the household capital costs model and section 3.3 outlines the grant provider capital costs model.

3.1. Household net benefit model of retrofit adoption

We take a similar approach to Gamtessa (2013) in defining the decision to engage in an energy efficiency retrofit. In the context of the Better Energy Homes scheme, we consider a situation in which a household may invest in a combination of between one and four retrofit measures to improve the energy efficiency of their home. These measures are available to households at a cost equal to the total cost of investment K_0 minus the grant aid awarded, G_0, with benefits, B_t accruing over time to year n based on energy cost savings each year, increased comfort in the home, etc. Households make the decision to invest at the optimal time, i.e. on the basis that the net present value of investment is maximised at the time of retrofitting, having taken into account expected future changes in the capital costs involved, assumptions as to the level of grant aid that will be offered during various periods in the future and expected changes to energy costs over

Figure 3: Distribution of net benefit accrued via retrofits of varying numbers of measures



time and their variability. The decision to invest in a combination of energy efficiency measures is therefore described by the following net present value (NPV) equation:

$$NPV = \Sigma_{t=0}^{n} \frac{B_t}{(1+r)^t} - (K_0 - G_0) \tag{1}$$

As it is difficult to quantify the non-monetary benefits of investment, we focus on the annual energy savings gained as a measure of the annual benefit of investment. These savings are made each year following EEM adoption, for the lifetime of the energy efficiency measures installed. Due to the savings made on energy costs, this money can be be spent elsewhere by households. For this reason, we treat energy savings as an annuity. Expected improvements by measure are calculated by taking the average improvement gained by households undertaking each individual measure only, i.e. as part of a one-measure retrofit. Net benefits are therefore apportioned to retrofit measures based on their proportion of the sum of these expected benefits for the chosen retrofit combination. The net present value of investment is therefore expressed as:

$$NPV = \Sigma_{m=1}^{M} \frac{E[\Delta BER_m]}{E[\Delta BER]} \Sigma_{t=0}^{n_m} \frac{B_t}{(1+r)^t} - (K_0 - G_0) \tag{2}$$

where the net benefit of retrofitting is calculated as the sum of the present values of the yearly benefit accruing from installing measure m, which is an element of the overall retrofit combination chosen, M, over the lifetime of that measure, n_m, with benefits assigned based on the expected energy savings accruing from that measure, ΔBER_m, as a proportion of the total energy savings accruing from all chosen measures, ΔBER. As a degree of information asymmetry is likely to exist with regard to home owners not possessing for information on the benefits accruing until after retrofit works are completed, some uncertainty will prevail. Households therefore make the decision to invest in a combination of energy efficiency measures such that the expected net present value of investment is greater than zero.

The net benefit is calculated for each completed retrofit i in the data and modelled as a function of the characteristics of the household, including dwelling characteristics, denoted as Z, the combination of retrofit measures, M and the regulatory environment, R, which includes the level of grant aid awarded. The costs are dependent on the contractor and relationship therewith, K. The expected net present value is thus presented as a function of X, which is a matrix of independent variables made up of those discussed:

$$NPV_i = \beta_0 + \Sigma\beta_i X_i + u_i \tag{3}$$

$$(Z_i, M_i, R_i, K_i) \in X_i \tag{4}$$

where u_i is assumed to be normally distributed with mean zero. As discussed in section 2, an element of measurement error is present in both our explanatory and dependent variables. As the annual energy savings gained is imputed based on the improvement in a home's BER, both sides of our modelling equation are influenced by the pre-works BER, which is measured with error. When utilising the pre-works BER as a regressor, in order to account for this measurement error on the right hand side of our equation, we use a linear error–in–variables regression model with a known reliability ratio to estimate the expected net present value of an investment taking into account measurement error as follows:

$$X_{BER,i} = X^*_{BER,i} + v_{BER,i} \tag{5}$$

where $X_{BER} \in Z$ and in turn $X_{BER} \in X$ and is equal to the true value of the pre-works BER, X^*_{BER} and measurement error v_{BER}, which is assumed to be independent of both X^*_{BER} and the regression error, u, with mean zero. This implies that measurement error is due to the process of measurement and is not related to the magnitude of the latent variable. While it is difficult to quantify the non-monetary costs, such as disruption and noise pollution, we posit that at least some of this variation is internalised by controlling for the retrofit combination chosen and the monetary cost. This is because disruption is likely correlated with the type of property, which helps to determine the type of retrofit available, for example solid wall insulation, as opposed to cavity wall insulation. Similarly, the non-monetary benefits are difficult to quantify due to the subjectiveness of comfort, health benefits and environmental gains. It should also be noted that net benefit does not represent actual energy cost savings to the household but is based on SEAI estimates of annual energy costs by house type and size.

3.2. Household capital costs model of retrofit adoption

For a household deciding whether to engage in retrofitting activity, capital costs are a large contributor to the decision making process (Aravena, Riquelme, and Denny 2016). As the personal discount rate of households is subject to heterogeneity, we remove the time element and analyse only the capital cost to the household of investment. Households must make an initial investment in retrofit works, paying the total cost of retrofitting up-front before receiving grant aid, which reduces the private cost to the household. While more expensive retrofits would generally be associated with greater energy efficiency gains, we model value for money as the net expenditure per unit BER improvement. Household value for money, VFM_{HH}, is thus calculated as follows:

$$VFM_{HH} = \frac{K_0 - G_0}{\Delta BER} \tag{6}$$

where K_0 and G_0 again represent the costs and grant aid awarded, respectively, at time zero, i.e. the time of investment. This net cost to the household is divided by the energy efficiency improvement, measured as the change to the property's Building Energy Rating to provide a measure of value for money, measured in $€/kWh/m^2/yr$. As the dependent variable, i.e. the cost to the household per unit BER improvement, is non-negative and continuous, the distribution of the dependent variable is right-skewed and, as such, the Euro expenditure per unit improvement is log-transformed.

This focusses solely on the monetary cost of investment with respect to the final energy efficiency improvement, and therefore fails to consider other costs to the household, such as noise pollution and disruption during installation, or benefits, such as an improved environmental conscience. When using the pre-works BER of a property, we again utilise an error–in–variables regression model to take into account the reliability of this variable.

3.3. Grant provider capital costs model of retrofit implementation

For the grant provider, in this case SEAI, it would be prudent to aim to incentivise retrofits that provide greater value for money on their part, i.e. providing greater energy efficiency improvements at a lower cost to the state. In order to analyse which households or types of retrofit provide the greatest value for money, we calculate this value for money to the grant provider, VFM_{GP}, as follows:

$$VFM_{GP} = \frac{G_0}{\Delta BER} \tag{7}$$

where G_0 again represents the grant aid awarded at time zero, i.e. the time of investment. This cost to the grant provider is divided by the energy efficiency improvement, measured as the change to the property's Building Energy Rating to provide a measure of value for money, measured in $€/kWh/m^2/yr$. This likely understates the cost to the grant provider as it does not take into account transaction costs, such as the costs of grant processing, BER auditing, advertising, etc. although some of these can potentially be seen as sunk costs with regard to providing grant aid to households. As before, when using the pre-works BER of a property, we utilise an error–in–variables regression model to take into account the reliability of this variable. As the dependent variable is non-negative and continuous and the distribution of the dependent variable is right-skewed and, as such, the Euro expenditure per unit improvement is log-transformed.

4. Results and Discussion

Table 4 presents the estimated results of our value for money models. The sensitivity of these results is examined in section 4.4. We examine first in section 4.1 the net benefit accruing to households who participate in the BEH scheme, which is followed by a discussion of household capital costs in section 4.2 and value for money in grant provision in section 4.3.

Table 4: Estimation Results

Model	1		2		3	
Dependent Variable	Household Net Benefit		Log Household Capital Cost		Log Cost to Grant Provider	
Constant	-7,346***	(65.95)	5.061***	(0.0192)	5.287***	(0.0100)
Scheme (ref = Scheme 2)						
Scheme 3	-28.90	(20.62)	0.105***	(0.00599)	-0.206***	(0.00313)
Scheme 4	-446.0***	(18.93)	0.298***	(0.00550)	-0.389***	(0.00288)
Scheme 5	-539.3***	(42.53)	0.302***	(0.0124)	-0.0697***	(0.00647)
Pre-Works BER ($kWh/m^2/yr$)	23.51***	(0.128)	-0.00832***	(3.73e-05)	-0.00829***	(1.95e-05)
Floor Area (m^2)	29.36***	(0.274)	0.00141***	(7.95e-05)	-0.00223***	(4.16e-05)
Chimneys and Open Flues (ref= 0)						
1	19.59	(35.87)	0.0583***	(0.0104)	0.0235***	(0.00545)
2	-231.5***	(38.07)	0.177***	(0.0111)	0.0844***	(0.00579)
3+	-714.7***	(46.35)	0.374***	(0.0135)	0.192***	(0.00705)
Structure Type (ref = Masonry/Insulated Concrete)						
Timer or Steel Frame	939.8***	(62.01)	-0.343***	(0.0180)	-0.126***	(0.00943)
Dwelling Type (ref = Detached House)						
Semi-Detached House	252.8***	(21.48)	-0.291***	(0.00624)	-0.128***	(0.00327)
End of Terrace House	27.70	(36.69)	-0.351***	(0.0107)	-0.0755***	(0.00558)
Mid-Terrace House	1,054***	(30.21)	-0.812***	(0.00878)	-0.171***	(0.00459)
Apartment	-354.4***	(76.37)	-0.518***	(0.0222)	0.369***	(0.0116)
Combination(ref = Attic + Cavity)						
External Wall Insulation	-4,971***	(31.55)	1.580***	(0.00917)	1.731***	(0.00480)
Internal Dry-Lining	-1,287***	(86.20)	0.527***	(0.0251)	1.268***	(0.0131)
Boiler w/ Heating Controls	-639.7***	(21.07)	0.770***	(0.00612)	-0.334***	(0.00320)
Heating Controls Only	270.5***	(58.73)	-0.276***	(0.0171)	-0.400***	(0.00893)
Solar	-4,649***	(35.65)	1.861***	(0.0104)	0.893***	(0.00542)
Other 1 Measure	378.8***	(82.83)	-0.298***	(0.0241)	-0.356***	(0.0126)
Attic + External Wall Insulation	-4,871***	(56.27)	1.551***	(0.0164)	1.548***	(0.00855)
Attic + Internal Dry-Lining	-994.7***	(59.74)	0.458***	(0.0174)	1.120***	(0.00908)
Attic + Boiler w/ Heating Controls	-1,042***	(59.60)	0.989***	(0.0173)	-0.205***	(0.00906)
Boiler w/ Heating Controls + Solar	-2,835***	(91.61)	0.968***	(0.0266)	0.0105	(0.0139)
Other 2 Measures	-2,570***	(49.31)	0.893***	(0.0143)	0.269***	(0.00750)
Attic + Cavity + Boiler w/ HC	71.40	(48.13)	0.429***	(0.0140)	-0.224***	(0.00732)
Attic + Cavity + HC Only	563.8***	(68.77)	0.00410	(0.0200)	-0.174***	(0.0105)
Attic + Dry-Lining + Boiler w/ HC	-2,881***	(85.94)	1.366***	(0.0250)	0.616***	(0.0131)
Other 3 Measure	-3,880***	(70.93)	1.265***	(0.0206)	0.606***	(0.0108)
4 Measures	-2,165***	(100.4)	0.746***	(0.0292)	0.0452***	(0.0153)
Obligated Party (ref = private)						
OP 1	-1,093***	(62.37)	0.520***	(0.0181)	-0.0624***	(0.00948)
OP 2	-214.2**	(97.90)	-0.249***	(0.0285)	-0.0726***	(0.0149)
OP 3	-300.1***	(27.28)	0.113***	(0.00793)	-0.00790*	(0.00415)
OP 4	-37.10	(58.93)	0.156***	(0.0171)	0.0155*	(0.00896)
OP 5	247.7*	(133.3)	0.174***	(0.0387)	0.0201	(0.0203)
OP 6	-696.4***	(135.7)	0.305***	(0.0395)	0.0777***	(0.0206)
Observations	89,063		89,063		89,063	
R-squared	0.535		0.691		0.847	

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

4.1. Household net benefit

4.1.1. Dwelling characteristics

Semi-detached houses are found to accrue a net benefit of €252 less than detached houses, which make up 47% of homes in our data. Apartments accrue a benefit €354 less than detached houses, while mid-terrace houses are found to accrue a benefit of €1,054 greater than detached houses, all else equal. This is quite an interesting finding from a policy perspective, as scheme 4 introduced categorised grant levels for solid wall insulation. These categories grouped mid-terrace houses and apartments together, offering the lowest level of grant aid for solid wall insulation of all categories. It may therefore be prudent to re-consider these groupings given the large difference in net benefit between mid-terrace houses and apartments.

The pre-works BER is a significant determinant of the expected net benefit, with an linear expected increase in net benefit of €23.51 for every kWh of a home's BER, all else equal. All grades from A1 to C3 are comprised of bands of 25 kWh, which means that a home with a pre-works BER one grade less than an equivalent home could be expected to accrue an additional net benefit of €587.75, all else equal. Larger houses are also found to gain a greater net benefit, with an expected increase in benefit of €29 for every square metre of floor area. We also find that timber- or steel-frame buildings can expect to accrue a benefit just over €939 more than a masonry or insulated concrete home, other things equal. We find no difference in benefit for homes with one chimney or open flue, relative to none, while a home with two chimneys/open flues or three or more can expect a drop of €231 and €714, respectively.

4.1.2. Retrofit measures chosen

A large variation in net benefit is associated with the combination of retrofit measures installed. We examine retrofit combinations relative to attic and cavity retrofits, as this is the most commonly completed retrofit. We look at all retrofit combinations occurring in at least 400 homes. Other retrofits are categorised by the number of measures installed. Three retrofit combinations provide a greater net benefit than attic and cavity retrofits with the greatest net benefit provided by attic, cavity and heating controls retrofits. These are followed by those combinations included in 'other 1 measure', i.e. attic or cavity insulation individually, followed in turn by heating controls only retrofits. These are relatively small improvements over to attic and cavity retrofits, with improvements varying between €270 and €563. On the other end of the scale, external wall insulation retrofits provide the lowest net benefit, providing a benefit €4,971 less than an attic and cavity retrofit. One must take into account that differences in building types determine the type of wall insulation that can be installed as homes possessing solid walls are precluded from the option of cavity wall insulation and must choose between external wall insulation or, alternatively, internal dry-lining, which may not be desirable to home owners as it requires a reduction in floor and room space on the inside of the home. Comparing this to the alternative, internal dry-lining provides a benefit €1,287 less than an attic and cavity retrofit, falling to €994 less for an attic and dry-lining retrofit.

There is a large variation in net benefit across combinations of retrofit measures, with an expected difference of €5,534.8 between the combinations providing the greatest and least benefit. What is particularly apparent here is that this variation occurs even among the retrofits of greater numbers of measures for which the models control. Four-measure retrofits, for example, provide a benefit of €2,165 less than an attic and cavity insulation retrofit. While the true benefits are understated without allowing for comfort and environmental benefits, this result suggests that it is in households' financial interest to engage in shallower rather than deeper retrofits. Consequently, greater incentives may need to be provided to drive home owners to engage in deeper retrofits.

4.1.3. Scheme rule changes and obligated parties

Controlling for scheme rule changes, i.e. schemes 2–5, we note that as the BEH scheme has progressed, the net benefit accruing to households has fallen progressively. This result was anticipated as scheme 3 saw a slight reduction in grant aid awarded for most measures, with further falls occurring as part of scheme 4 for attic and wall insulation, alongside the categorisation of dwelling types to reduce even further the aid awarded to dwellings of differing types. Scheme 5, however, saw an increase in aid relative to scheme 4. It is therefore surprising that the expected level of net benefit fell further with this rule change. It is possible that moving from earlier to later, participating households might have lesser potential for energy efficiency improvements. Most households expecting to extract greater net benefit from retrofitting were likely among the early adopters of the scheme. As a result, homes retrofitting during later stages of the scheme may have possessed lesser potential to gain from retrofitting.

Variation is found across obligated parties, with OP 5 engaging homes in retrofits with a net benefit €247 greater than private retrofits. While OP 4 was not found to be significantly different to private retrofits, the remaining four parties were found to engage homes in retrofits of lower net benefit. Without greater information on the characteristics and strategies of obligated parties or the relationship between the obligated parties and participant households, however, it is difficult to comment on what is driving this variation.

4.2. Household capital costs

4.2.1. Dwelling characteristics

Similar patterns are found in household capital costs to those regarding net benefits, the estimated results for which are presented by model 2. As our dependent variable is the natural log of the cost to the household per unit BER improvement, our estimated coefficients can be interpreted as the percentage change in the cost of retrofitting brought about by a unit change in the explanatory variables. Less efficient homes face a lower cost per unit BER improvement, with a 0.8% decrease in costs for every kWh rise (i.e. worsening energy efficiency) in a dwelling's pre-works BER. Larger homes, on the other hand, can expect to pay more, with every square metre increase in floor space leading to a 0.14% increase in costs per unit energy efficiency improvement. Detached houses are found to be the most costly to retrofit for each unit energy efficiency improvement. Mid-terrace houses are found to be the cheapest, with private costs of 81.2% less than a detached house. Semi-detached and end of terrace houses are found to be 29% and 35% less expensive, respectively. Apartments then are also less expensive than detached houses, being found to be 51% less costly than detached house. This provides retrospective justification for the reduction in grant levels for certain categories of dwelling types introduced as part of scheme 4.

4.2.2. Retrofit measures chosen

In addition to providing the weakest net benefit, external wall retrofits, solar panel retrofits and the combination of attic and external wall retrofits are found to be the most expensive options. Deeper retrofits are again found to be more expensive, although four measures retrofits are found to be less expensive than the three-measure retrofits for which we have controlled, excluding the combinations of attic and cavity insulation and boiler with heating controls or heating controls only retrofits.

4.2.3. Scheme rule changes and obligated parties

Scheme rule changes have led to progressive increases in capital costs for households in the BEH scheme. This can be seen as the expected outcome, as the level of grant aid on offer was reduced from scheme 2 to scheme 3 and again from scheme 3 to scheme 4, as discussed in section 4.1.3. Again variation is found across obligated parties, with OP 2 engaging in retrofits that are 24% less expensive per unit improvement than private retrofits. The remaining five obligated parties are found to engage homes in more costly retrofits than private retrofits.

4.3. Grant provider capital costs

4.3.1. Dwelling characteristics

As the grant provider is an independent government agency, the main goal of the grant aid scheme is not to optimise support for, and in turn votes for the incumbent government, but to optimise the improvement in the energy efficiency of residential buildings on a per capita basis as a means of meeting energy efficiency targets. As such, optimising energy efficiency improvements across dwelling characteristics can be seen as an important aspect of the scheme. Model 3 provides the estimated coefficients of our model with regard to the cost to the grant provider, i.e. SEAI, per $kWh/m^2/yr$ improvement in a homes BER. It can be argued that a more efficient grant scheme would be such that maximises the improvement in the residential building stock at the lowest cost to the state. Again, as the dependent variable has been log-transformed, the estimated coefficients can be interpreted as the percentage change in costs to the grant provider for a unit increase in our explanatory variables. Relative to detached houses, apartments are found to require 36% more grant aid per unit BER improvement, while other dwelling types are found to require less grant aid than detached houses. Relative to detached houses, apartments are found to have cost the grant provider more, while costing the home owner less, although the home owner is also provided with a lesser net benefit over a twenty year time horizon. It can therefore be argued that grant aid for apartments should be increased or decreased. In one sense, it would be even more costly for SEAI to improve the energy efficiency of apartments, although an increase would bring the expected net benefit for apartments closer in line to that of detached houses.

4.3.2. Retrofit measures chosen

As with household costs, combinations including external wall insulation require the highest levels of grant aid. This is followed by combinations including internal dry-lining and by solar panel retrofits. The least costly retrofit combinations from the grant provider's perspective are some of the more simple retrofits, such as boiler with heating controls retrofits or heating controls only retrofits, and some of the more complicated combinations. Some other more complicated retrofits prove more costly, with three-measure retrofits not including attic and cavity insulation coming in over 60% more costly than attic and cavity insulation retrofits.

4.3.3. Scheme rule changes and obligated parties

When moving across scheme rule changes, scheme 3 and scheme 4 provided progressive reductions in the costs to the grant provider per unit BER improvement. This is followed by a relative increase from scheme 4 to scheme 5, with scheme 5 grant aid costs remaining lower than those of scheme 2. This is due to the fall in grant aid between schemes 2 and 3, and 3 and 4, respectively, followed by an increase in aid in scheme 5. With categorised aid levels for solid wall insulation, overall grant aid is lower in scheme 5 than scheme 2, thus this scheme possesses a negative coefficient.

4.4. Sensitivity of Results

Due to the presence of measurement error in our regressors, sensitivity analysis is performed to examine the robustness of our results to a more reliable vector of regressors. As discussed in section 2.1, we deem 72.34% of pre-works assessments to be compliant with BER assessment procedures. We re-estimate our baseline model with higher reliability estimates of the pre-works BER. This is because, for our estimations, the pre-works BER likely possesses a higher reliability than 0.7234. This is due to the selection of observations to remove outliers, which are the most likely unreliable pre-works BER assessments, such as those leading to negative or excessively large energy efficiency improvements. The proportion of pre-works assessments which could be classed as compliant with auditing procedures is therefore likely to be higher than that of the population. We also estimate our model including only observations with a pre-works BER of C or D, as these are the most common BERs and we estimate our model using only observations possessing a BER improvement within one standard deviation of the mean BER improvement as very large of very small improvements could be caused by unreliable pre-works BER values. Table 5 shows the estimated coefficient on the pre-works BER of a dwelling for each of our models 1 − 3 and each specification of same.

Table 5: Estimated coefficients of PRE-Works BER value across models

	Model	Baseline (Reliability = 0.7234)	Reliability = 0.8	Reliability = 0.9	Reliability = 1	Pre-Works BER = C/D	Pre-Works BER = mean ± σ
Net Benefit	1	23.51***	20.69***	17.89***	15.76***	23.49***	19.90***
		(0.128)	(0.117)	(0.104)	(0.0937)	(0.320)	(0.161)
Household C.C.	4	-0.00832***	-0.00733***	-0.00633***	-0.00558***	-0.0113***	-0.00782***
		(3.73e-05)	(3.45e-05)	(3.11e-05)	(2.83e-05)	(0.000108)	(5.26e-05)
Grant Provider C.C.	7	-0.00829***	-0.00729***	-0.00630***	-0.00555***	-0.0117***	-0.00691***
		(1.95e-05)	(2.01e-05)	(1.95e-05)	(1.85e-05)	(6.28e-05)	(2.83e-05)

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

[1] Full estimated results of sensitivity analysis are presented in Appendix A

The lowest estimated coefficients for each of our three models are found using a linear regression, i.e. where we assume that the pre-works BER is wholly reliable. These also possess the smallest standard errors. This is expected as the downside of using a linear regression to estimate a model with measurement error in an independent variable is the understatement of the effects of those independent variables possessing measurement errors (Chesher 1991). Some variation does exist when estimating the models for only a subset of the population. We find a sizeable reduction in the magnitude of the coefficient on net benefit when using only observations with a BER improvement within a standard deviation of the sample but similar decreases are much smaller when looking at household capital costs and costs to the grant provider. On the other hand, when estimating the models using only buildings with a pre-works BER of C or D, we find a noticeable increase in the magnitude of our coefficients on household capital costs and costs to the grant provider, while the coefficient on net benefit is not found to change significantly. Overall, results in table 4 are broadly similar and largely possess the same order of magnitude as the results of the sensitivity analysis.

5. Conclusion and Policy Implications

It is a stated policy aim in Ireland to reduce residential energy consumption (DCENR 2014) and residential retrofitting can help to meet this targeted reduction by improving the energy efficiency of the residential building stock and thus reducing residential energy demand. By examining the value for money extracted by households via the Better Energy Homes scheme, we identify households and combinations of retrofit measures that may require greater or lesser subsidisation in order to incentivise household investment. In examining value for money in terms of the cost to the grant provider we also identify which combinations of measures and which types of homes can be retrofitted with greater cost-efficiency from a grant administration point of view, providing evidence for policy makers on achieving energy efficiency targets in the least costly manner. In examining observed benefits of retrofits, an error-in-variables regression model is used to estimate the effect of various household and application characteristics on the net benefit of home energy efficiency retrofit investments over a twenty-year time horizon. The error-in-variables specification is also used to examine value for money to the household of the capital cost required per unit energy efficiency improvement and the grant aid provided per unit energy efficiency improvement.

We find that retrofitting less energy efficiency homes, larger homes and homes with fewer chimneys and open flues provides a greater net benefit to the home owner and is less costly for the grant provider. Timber or steel frame homes are found to provide greater benefits than masonry or insulated concrete form buildings, while apartments produce a lower surplus than houses for both the household and grant provider. While variation exists across combinations of retrofit measures undertaken, the greatest benefit is found in retrofits including attic and cavity wall insulation and boiler and/or heating controls upgrades, while the opposite is true of retrofits involving solid wall insulation, particularly external wall insulation.

This research adds to the literature on the benefits of retrofitting at an individual household level and by using observed costs and benefits of energy efficiency retrofits, as opposed to estimated benefits based on uniform building types. In the Irish context, a number of policy implications may be considered. A significant policy adjustment during the scheme was to categorise homes and provide varying levels of grant aid by home type. These divisions are as follows: detached houses; semi-detached houses and end of terrace houses; mid-terrace houses and apartments. We find in our analysis a large variation, in each of our three measures of value for money, between mid-terrace houses and apartments. For this reason, to provide equal incentive to all property types, it may be worthwhile to consider whether these categories should remain as they currently are. Looking at value for money across different combinations of retrofit measures, retrofits including solid wall insulation or solar collection units provide a much lower net benefit and are more costly to the grant provider. In attempting to efficiently reduce the energy consumption attributed to the residential building stock, homes with cavity walls should be prioritised relative to those with solid walls. In a distributional sense, however, this may not be equitable due to the urban-rural divide in building types. Urban dwellings are more likely to have been built with solid walls than those in rural areas. Urban dwelling also have a lesser incentive to retrofit due to ownership structures, with landlords less likely to engage in a residential retrofit than an owner-occupier. For these reasons, a focus on homes with cavity walls would have a knock-on effect of prioritising rural dwellings over urban dwellings. It is worth noting, however, that many of the most energy inefficient homes in Ireland are built with solid walls and, as a result, prioritising cavity walls could limit the energy savings that could be made. Extending grant aid toward these solid wall measures may also lead to beneficial knock-on effects, such the development of a greater market for these measures, improving skills and in turn reducing prices and improving the benefits available. The findings of this research may therefore be seen as identifying retrofit measures that provide benefits to households and value for money to the grant provider in the shorter term.

In examining the level of grant aid available and the level of grant aid awarded per unit energy efficiency improvement, a large variation exists across retrofit combinations. While grant levels are currently designed to cover a percentage of the total cost of retrofitting, this leads to significant variation in the level of grant aid provided relative to the energy efficiency improvement gained. It may therefore be of interest to examine the potential to award grant aid based on the energy efficiency improvement gained. This would guarantee constant returns to the grant provider but may lead to higher transaction costs and lead to perverse incentive. The most notable transaction cost would be the requirement for households to undertake a pre-works BER assessment. While a pre-works BER is currently estimated as part of the post-works assessment, this system would require a quality-assured pre-works assessment, increasing costs to homeowners at the point of implementing retrofit works. This might increase transaction costs to both the home owner and the state for homes that have not been previously assessed a BER, although currently existing BER assessments could be used to provide home owners with automatically generated starting points. Perverse incentive may also be introduced in assessing a building's pre-works and post-works BER. This is because the energy efficiency of a home prior to retrofitting could be manipulated to appear less efficient than it is, and the post-works energy efficiency manipulated to be appear more efficient than reality in order to maximise the stated energy efficiency improvement and thus maximise the grant award to the homeowner. In terms of equity, this would also incentivise smaller homes to retrofit as awarding grant aid based on $kWh/m^2/yr$ would mean rewarding homes of varying sizes equally, despite likely higher costs for many retrofit measures for larger homes, particularly insulation retrofits. A possible alternative may be to award grant aid based on expected energy savings for the home rather than energy savings per square metre, although this would fail to account for variation in lifetimes of retrofit measures.

Acknowledgement(s)

We acknowledge the Sustainable Energy Authority of Ireland for access to the anonymous dataset of Better Energy Homes scheme applications and thank Kieran McQuinn, contributors at SEAI and others for helpful comments and suggestions.

Funding

This research has been financially supported by Sustainable Energy Authority of Ireland and the Energy Policy Research Centre.

Ahern, Ciara, Philip Griffiths, and Micheál O'Flaherty. 2013. "State of the Irish housing stock - Modelling the heat losses of Ireland's existing detached rural housing stock & estimating the benefit of thermal retrofit measures on this stock." *Energy Policy* 55: 139–151.

Amstalden, Roger W, Michael Kost, Carsten Nathani, and Dieter M Imboden. 2007. "Economic potential of energy-efficient retrofitting in the Swiss residential building sector: the effects of policy instruments and energy price expectations." *Energy Policy* 35 (3): 1819–1829.

Aravena, Claudia, Andrés Riquelme, and Eleanor Denny. 2016. "Money, comfort or environment? Priorities and determinants of energy efficiency investments in Irish households." *Journal of Consumer Policy* 1–28.

Arrow, Kenneth. 1950. "A difficulty in the concept of social welfare." *Journal of Political Economy* .

CEEEP. 2012. *Cost-Benefit analysis of the New Jersey clean energy program.* Center for Energy, Economics and Environmental Policy.

Chapman, Ralph, Philippa Howden-Chapman, H Viggers, D Odea, and Martin Kennedy. 2009. "Retrofitting houses with insulation: a cost–benefit analysis of a randomised community trial." *Journal of Epidemiology and Community Health* 63 (4): 271–277.

Chesher, Andrew. 1991. "The effect of measurement error." *Biometrika* 78 (3): 451–462.

Clinch, J Peter, and John D Healy. 2001. "Cost-benefit analysis of domestic energy efficiency." *Energy Policy* 29 (2): 113–124.

Collins, Matthew, and John Curtis. 2016. "An examination of energy efficiency retrofit depth in Ireland." *Energy and Buildings* 127: 170–182.

Davis, Harry L. 1976. "Decision making within the household." *Journal of Consumer Research* 2 (4): 241–260.

DCENR. 2014. *A National Renovation Strategy for Ireland.* Department of Communications, Energy and Natural Resources. Available online `https://ec.europa.eu/energy/sites/ener/files/documents/2014_article4_en_ireland.pdf`.

Dowson, Mark, Adam Poole, David Harrison, and Gideon Susman. 2012. "Domestic UK retrofit challenge: Barriers, incentives and current performance leading into the Green Deal." *Energy Policy* 50: 294–305.

European Parliament and the Council of the European Union. 2012. *Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending directives 2009/125/EC and 2010/30/EU and repealing directives 2004/8/EC and 2006/32/EC.* European Union.

Friedman, Chanoch, Nir Becker, and Evyatar Erell. 2014. "Energy retrofit of residential building envelopes in Israel: A cost-benefit analysis." *Energy* 77: 183–193.

Gamtessa, Samuel Faye. 2013. "An explanation of residential energy-efficiency retrofit behavior in Canada." *Energy and Buildings* 57: 155–164.

Gillingham, Kenneth, Richard G Newell, and Karen Palmer. 2009. *Energy efficiency economics and policy.* National Bureau of Economic Research.

Howden-Chapman, Philippa, Helen Viggers, Ralph Chapman, Kimberley OSullivan, Lucy Telfar Barnard, and Bob Lloyd. 2012. "Tackling cold housing and fuel poverty in New Zealand: a review of policies, research, and health impacts." *Energy Policy* 49: 134–142.

Hyland, Marie, Ronan C Lyons, and Sean Lyons. 2013. "The value of domestic building energy efficiencyevidence from Ireland." *Energy Economics* 40: 943–952.

Jevons, William Stanley. 1906. *The coal question.* Macmillan and Co.

Kaplan, Leon B, George J Szybillo, and Jacob Jacoby. 1974. "Components of perceived risk in product purchase: A cross-validation." *Journal of Applied Psychology* 59 (3): 287.

Lee, Jinkook, et al. 2004. "Consumer information search when making investment decisions." *Financial Services Review* 13 (4): 319.

Michelsen, Claus, Karsten Neuhoff, and Anne Schopp. 2015. "Using equity capital to unlock investment in building energy efficiency?" *DIW Economic Bulletin* 5 (19): 259–265.

Moore, Don A, Terri R Kurtzberg, Craig R Fox, and Max H Bazerman. 1999. "Positive illusions and forecasting errors in mutual fund investment decisions." *Organizational Behavior and Human Decision Processes* 79 (2): 95–114.

Nagy, Robert A, and Robert W Obenberger. 1994. "Factors influencing individual investor behavior." *Financial Analysts Journal* 50 (4): 63–68.

Neuhoff, Karsten, Kateryna Stelmakh, H Amecke, A Novikova, J Deason, and A Hobbs. 2011. "Financial incentives for energy efficiency retrofits in buildings." *German Institute for Economic research and Climate Policy Initiative* .

Neumann, Ludwig Johann, and Oskar Morgenstern. 1947. *Theory of Games and Economic Behavior*. Vol. 60. Princeton University Press.

OECD. 2017. "Inflation forecast." *OECD Data* Organisation for Economic Co-operation and Development.

Sadler, Margo. 2003. "Home energy preferences & policy: Applying stated choice modeling to a hybrid energy economy model." PhD diss., Simon Fraser University.

Scheer, Jim, Matthew Clancy, and Sadhbh Ní Hógáin. 2013. "Quantification of energy savings from Irelands Home Energy Saving scheme: an ex post billing analysis." *Energy Efficiency* 6 (1): 35–48.

SEAI. 2012. *Better Energy Homes Scheme Impact Report–Billing Analysis*. Sustainable Energy Authority of Ireland.

SEAI. 2013. *Dwelling Energy Assessment Procedure: Introduction to DEAP for Professionals*. Sustainable Energy Authority of Ireland. Available online: `http://www.seai.ie/Your_Building/BER/BER_Assessors/Technical/DEAP/Introduction_to_DEAP_for_Professionals.pdf`.

Sirri, Erik R, and Peter Tufano. 1998. "Costly search and mutual fund flows." *The Journal of Finance* 53 (5): 1589–1622.

Sorrell, Steve, John Dimitropoulos, and Matt Sommerville. 2009. "Empirical estimates of the direct rebound effect: A review." *Energy Policy* 37 (4): 1356–1371.

Appendix A. Full Results of Sensitivity Analysis

Table A.6: Sensitivity of Model 1 (Net Benefit)

Model 1	Reliability = 0.8		Reliability = 0.9		Reliability ==1		Pre-Works BER = C/D		BER Improvement ∈ mean ±σ	
Constant	-6,344***	(64.36)	-5,349***	(62.77)	-4,592***	(61.62)	-6,426***	(95.74)	-6,115***	(69.80)
Scheme (ref = Scheme 2)										
Scheme 3	-54.28**	(21.29)	-79.48***	(21.94)	-98.68***	(22.43)	-45.41**	(22.72)	-30.20	(20.42)
Scheme 4	-487.9***	(19.54)	-529.5***	(20.12)	-561.2***	(20.56)	-454.6***	(20.89)	-451.2***	(18.98)
Scheme 5	-573.8***	(43.93)	-608.1***	(45.28)	-634.2***	(46.29)	-524.7***	(46.54)	-560.2***	(42.71)
Pre-Works BER ($kWh/m^2/yr$)	20.69***	(0.117)	17.89***	(0.104)	15.76***	(0.0937)	23.49***	(0.320)	19.90***	(0.161)
Floor Area (m^2)	27.14***	(0.278)	24.94***	(0.283)	23.27***	(0.287)	19.91***	(0.273)	25.62***	(0.263)
Chimneys and Open Flues (ref = 0)										
1	14.69	(37.06)	9.816	(38.21)	6.108	(39.06)	75.77*	(42.31)	39.36	(37.12)
2	-165.4***	(39.30)	-99.79**	(40.49)	-49.82	(41.37)	-1.559	(44.82)	-131.3***	(39.29)
3+	-579.2***	(47.79)	-444.7***	(49.18)	-342.2***	(50.22)	-257.4***	(54.99)	-487.9***	(47.77)
Structure Type (ref = Masonry/Insulated Concrete)										
Timer or Steel Frame	782.7***	(63.97)	626.6***	(65.86)	507.8***	(67.27)	536.4***	(60.12)	731.5***	(60.91)
Dwelling Type (ref = Detached House)										
Semi-Detached House	188.1***	(22.15)	123.9***	(22.79)	75.00***	(23.26)	179.2***	(23.22)	180.9***	(21.37)
End of Terrace House	60.90	(37.90)	93.87**	(39.06)	119.0***	(39.93)	326.8***	(47.57)	177.2***	(38.74)
Mid-Terrace House	994.5***	(31.19)	935.5***	(32.13)	890.6***	(32.82)	1,019***	(35.46)	1,054***	(30.91)
Apartment	-283.3***	(78.89)	-212.8***	(81.31)	-159.0*	(83.11)	232.6**	(100.2)	-346.2***	(79.84)
Combination(ref = Attic + Cavity)										
External Wall Insulation	-4,834***	(32.46)	-4,698***	(33.33)	-4,595***	(33.98)	-4,554***	(41.15)	-4,555***	(32.23)
Internal Dry-Lining	-1,163***	(89.01)	-1,040***	(91.72)	-946.6***	(93.73)	-989.8***	(119.5)	-1,179***	(93.37)
Boiler w/ Heating Controls	-573.6***	(21.72)	-508.0***	(22.34)	-458.0***	(22.81)	-300.2***	(23.75)	-480.0***	(20.91)
Heating Controls Only	215.0***	(60.66)	159.9**	(62.53)	118.0*	(63.91)	489.6***	(58.15)	274.2***	(54.70)
Solar	-4,661***	(36.84)	-4,673***	(37.97)	-4,682***	(38.82)	-4,177***	(37.22)	-4,624***	(35.70)
Other 1 Measure	346.0***	(85.58)	313.4***	(88.22)	288.6***	(90.17)	379.7***	(88.67)	468.8***	(92.84)
Attic + External Wall Insulation	-4,687***	(57.98)	-4,503***	(59.64)	-4,364***	(60.88)	-4,813***	(85.28)	-4,494***	(65.40)
Attic + Internal Dry-Lining	-794.9***	(61.55)	-596.4***	(63.31)	-445.2***	(64.62)	-772.4***	(87.75)	-917.2***	(73.14)
Attic + Boiler w/ Heating Controls	-925.8***	(61.52)	-810.0***	(63.37)	-721.9***	(64.75)	-838.1***	(73.83)	-983.6***	(66.38)
Boiler w/ Heating Controls + Solar	-2,830***	(94.65)	-2,824***	(97.57)	-2,820***	(99.74)	-2,808***	(92.26)	-2,916***	(90.69)
Other 2 Measures	-2,548***	(50.94)	-2,527***	(52.51)	-2,511***	(53.67)	-2,301***	(52.89)	-2,334***	(51.58)
Attic + Cavity + Boiler w/ HC	69.32	(49.72)	67.26	(51.26)	65.69	(52.40)	-91.98*	(49.92)	-145.2***	(50.81)
Attic + Cavity + HC Only	497.2***	(71.04)	431.0***	(73.22)	380.6***	(74.83)	495.7***	(66.66)	510.1***	(65.11)
Attic + Dry-Lining + Boiler w/ HC	-2,693***	(88.69)	-2,506***	(91.34)	-2,363***	(93.31)	-3,347***	(131.9)	-3,234***	(153.6)
Other 3 Measure	-3,778***	(73.24)	-3,676***	(75.47)	-3,598***	(77.13)	-4,002***	(88.30)	-3,437***	(89.67)
4 Measures	-2,160***	(103.7)	-2,155***	(106.9)	-2,151***	(109.3)	-1,698***	(104.8)	-1,473***	(110.8)
Obligated Party (ref = private)										
OP 1	-1,070***	(64.44)	-1,048***	(66.42)	-1,031***	(67.90)	-1,014***	(72.17)	-997.4***	(62.89)
OP 2	-189.8*	(101.1)	-165.5	(104.3)	-147.1	(106.6)	-400.4***	(110.0)	-186.0*	(96.66)
OP 3	-286.4***	(28.19)	-272.8***	(29.06)	-262.5***	(29.70)	-218.3***	(29.58)	-265.7***	(26.99)
OP 4	-59.54	(60.88)	-81.84	(62.76)	-98.81	(64.15)	14.29	(59.99)	-18.35	(58.03)
OP 5	240.0*	(137.7)	232.4	(141.9)	226.6	(145.1)	19.76	(136.7)	140.5	(131.3)
OP 6	-648.0***	(140.2)	-599.9***	(144.6)	-563.3***	(147.8)	-547.9***	(161.4)	-813.4***	(139.5)
Observations	89,063		89,063		89,063		55,667		72,005	
R-squared	0.504		0.473		0.449		0.449		0.501	

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

Table A.7: Sensitivity of Model 2 (Log Household Capital Costs)

Model 1	Reliability = 0.8		Reliability = 0.9		Reliability ==1		Pre-Works BER = C/D		BER Improvement $\in$ mean $\pm\sigma$	
Constant	4.706***	(0.0190)	4.354***	(0.0188)	4.086***	(0.0186)	5.664***	(0.0324)	4.823***	(0.0228)
Scheme (ref = Scheme 2)										
Scheme 3	0.114***	(0.00628)	0.123***	(0.00656)	0.129***	(0.00676)	0.0980***	(0.00770)	0.0947***	(0.00666)
Scheme 4	0.313***	(0.00577)	0.328***	(0.00601)	0.339***	(0.00620)	0.287***	(0.00708)	0.290***	(0.00619)
Scheme 5	0.314***	(0.0130)	0.326***	(0.0135)	0.335***	(0.0140)	0.303***	(0.0158)	0.323***	(0.0139)
Pre-Works BER ($kWh/m^2/yr$)	-0.00733***	(3.45e-05)	-0.00633***	(3.11e-05)	-0.00558***	(2.83e-05)	-0.0113***	(0.000108)	-0.00782***	(5.26e-05)
Floor Area (m^2)	0.00220***	(8.21e-05)	0.00298***	(8.46e-05)	0.00357***	(8.64e-05)	0.00258***	(9.26e-05)	0.00223***	(8.56e-05)
Chimneys and Open Flues (ref = 0)										
1	0.0601***	(0.0109)	0.0618***	(0.0114)	0.0631***	(0.0118)	0.0236	(0.0143)	0.0661***	(0.0121)
2	0.153***	(0.0116)	0.130***	(0.0121)	0.113***	(0.0125)	0.0636***	(0.0152)	0.156***	(0.0128)
3+	0.326***	(0.0141)	0.278***	(0.0147)	0.242***	(0.0151)	0.147***	(0.0186)	0.309***	(0.0156)
Structure Type (ref = Masonry/Insulated Concrete)										
Timer or Steel Frame	-0.288***	(0.0189)	-0.232***	(0.0197)	-0.190***	(0.0203)	-0.244***	(0.0204)	-0.290***	(0.0199)
Dwelling Type (ref = Detached House)										
Semi-Detached House	-0.268***	(0.00653)	-0.245***	(0.00681)	-0.228***	(0.00701)	-0.256***	(0.00787)	-0.270***	(0.00697)
End of Terrace House	-0.363***	(0.0112)	-0.374***	(0.0117)	-0.383***	(0.0120)	-0.384***	(0.0161)	-0.384***	(0.0126)
Mid-Terrace House	-0.791***	(0.00920)	-0.770***	(0.00960)	-0.754***	(0.00989)	-0.761***	(0.0120)	-0.801***	(0.0101)
Apartment	-0.543***	(0.0233)	-0.568***	(0.0243)	-0.587***	(0.0251)	-0.463***	(0.0340)	-0.585***	(0.0260)
Combination(ref = Attic + Cavity)										
External Wall Insulation	1.531***	(0.00958)	1.483***	(0.00996)	1.446***	(0.0102)	1.372***	(0.0139)	1.473***	(0.0105)
Internal Dry-Lining	0.483***	(0.0263)	0.439***	(0.0274)	0.406***	(0.0283)	0.499***	(0.0405)	0.449***	(0.0305)
Boiler w/ Heating Controls	0.747***	(0.00641)	0.724***	(0.00668)	0.706***	(0.00688)	0.502***	(0.00805)	0.663***	(0.00682)
Heating Controls Only	-0.257***	(0.0179)	-0.237***	(0.0187)	-0.222***	(0.0193)	-0.454***	(0.0197)	-0.291***	(0.0178)
Solar	1.865***	(0.0109)	1.870***	(0.0113)	1.873***	(0.0117)	1.678***	(0.0126)	1.826***	(0.0116)
Other 1 Measure	-0.286***	(0.0253)	-0.275***	(0.0264)	-0.266***	(0.0272)	-0.311***	(0.0301)	-0.584***	(0.0303)
Attic + External Wall Insulation	1.486***	(0.0171)	1.421***	(0.0178)	1.371***	(0.0184)	1.347***	(0.0289)	1.404***	(0.0213)
Attic + Internal Dry-Lining	0.387***	(0.0182)	0.317***	(0.0189)	0.263***	(0.0195)	0.213***	(0.0297)	0.306***	(0.0239)
Attic + Boiler w/ Heating Controls	0.947***	(0.0182)	0.906***	(0.0189)	0.875***	(0.0195)	0.718***	(0.0250)	0.835***	(0.0216)
Boiler w/ Heating Controls + Solar	0.966***	(0.0279)	0.964***	(0.0292)	0.963***	(0.0301)	0.853***	(0.0313)	0.915***	(0.0296)
Other 2 Measures	0.885***	(0.0150)	0.878***	(0.0157)	0.872***	(0.0162)	0.702***	(0.0179)	0.755***	(0.0168)
Attic + Cavity + Boiler w/ HC	0.429***	(0.0147)	0.430***	(0.0153)	0.431***	(0.0158)	0.373***	(0.0169)	0.348***	(0.0166)
Attic + Cavity + HC Only	0.0277	(0.0210)	0.0511**	(0.0219)	0.0690***	(0.0226)	-0.0207	(0.0226)	0.0113	(0.0212)
Attic + Dry-Lining + Boiler w/ HC	1.299***	(0.0262)	1.233***	(0.0273)	1.182***	(0.0281)	1.122***	(0.0447)	1.073***	(0.0501)
Other 3 Measure	1.229***	(0.0216)	1.193***	(0.0226)	1.165***	(0.0233)	1.055***	(0.0299)	1.039***	(0.0292)
4 Measures	0.744***	(0.0306)	0.743***	(0.0320)	0.741***	(0.0330)	0.549***	(0.0355)	0.524***	(0.0361)
Obligated Party (ref = private)										
OP 1	0.512***	(0.0190)	0.504***	(0.0199)	0.498***	(0.0205)	0.512***	(0.0245)	0.532***	(0.0205)
OP 2	-0.257***	(0.0298)	-0.266***	(0.0312)	-0.272***	(0.0321)	-0.139***	(0.0373)	-0.199***	(0.0315)
OP 3	0.108***	(0.00832)	0.103***	(0.00868)	0.0996***	(0.00895)	0.0922***	(0.0100)	0.131***	(0.00880)
OP 4	0.164***	(0.0180)	0.172***	(0.0188)	0.178***	(0.0193)	0.115***	(0.0203)	0.128***	(0.0189)
OP 5	0.177***	(0.0406)	0.179***	(0.0424)	0.181***	(0.0437)	0.184***	(0.0463)	0.168***	(0.0428)
OP 6	0.288***	(0.0414)	0.271***	(0.0432)	0.258***	(0.0445)	0.177***	(0.0547)	0.325***	(0.0455)
Observations	89,063		89,063		89,063		55,667		72,005	
R-squared	0.660		0.629		0.606		0.562		0.619	

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

Table A.8: Sensitivity of Model 3 (Log Cost to Grant Provider)

Model 1	Reliability = 0.8		Reliability = 0.9		Reliability ==1		Pre-Works BER = C/D		BER Improvement $\in$ mean $\pm\sigma$	
Constant	4.934***	(0.0111)	4.584***	(0.0118)	4.317***	(0.0122)	5.822***	(0.0188)	4.812***	(0.0122)
Scheme (ref = Scheme 2)										
Scheme 3	-0.197***	(0.00366)	-0.188***	(0.00411)	-0.182***	(0.00442)	-0.216***	(0.00446)	-0.198***	(0.00358)
Scheme 4	-0.374***	(0.00336)	-0.359***	(0.00377)	-0.348***	(0.00405)	-0.376***	(0.00410)	-0.369***	(0.00333)
Scheme 5	-0.0576***	(0.00755)	-0.0455***	(0.00848)	-0.0363***	(0.00913)	-0.0776***	(0.00915)	-0.0458***	(0.00749)
Pre-Works BER ($kWh/m^2/yr$)	-0.00729***	(2.01e-05)	-0.00630***	(1.95e-05)	-0.00555***	(1.85e-05)	-0.0117***	(6.28e-05)	-0.00691***	(2.83e-05)
Floor Area (m^2)	-0.00145***	(4.78e-05)	-0.000675***	(5.30e-05)	-8.45e-05	(5.65e-05)	-0.000847***	(5.37e-05)	-0.00135***	(4.60e-05)
Chimneys and Open Flues (ref = 0)										
1	0.0252***	(0.00636)	0.0269***	(0.00716)	0.0282***	(0.00770)	0.0688***	(0.00831)	0.00882	(0.00651)
2	0.0612***	(0.00675)	0.0380***	(0.00758)	0.0204**	(0.00816)	0.0746***	(0.00881)	0.0343***	(0.00689)
3+	0.144***	(0.00821)	0.0968***	(0.00921)	0.0607***	(0.00991)	0.0928***	(0.0108)	0.0911***	(0.00838)
Structure Type (ref = Masonry/Insulated Concrete)										
Timer or Steel Frame	-0.0711***	(0.0110)	-0.0161	(0.0123)	0.0258*	(0.0133)	-0.0866***	(0.0118)	-0.0650***	(0.0107)
Dwelling Type (ref = Detached House)										
Semi-Detached House	-0.105***	(0.00380)	-0.0822***	(0.00427)	-0.0650***	(0.00459)	-0.0397***	(0.00456)	-0.0842***	(0.00375)
End of Terrace House	-0.0872***	(0.00651)	-0.0988***	(0.00732)	-0.108***	(0.00788)	-0.0408***	(0.00935)	-0.0887***	(0.00679)
Mid-Terrace House	-0.150***	(0.00536)	-0.129***	(0.00602)	-0.114***	(0.00647)	-0.0998***	(0.00697)	-0.129***	(0.00542)
Apartment	0.344***	(0.0135)	0.319***	(0.0152)	0.300***	(0.0164)	0.130***	(0.0197)	0.356***	(0.0140)
Combination(ref = Attic + Cavity)										
External Wall Insulation	1.683***	(0.00557)	1.635***	(0.00624)	1.598***	(0.00670)	1.610***	(0.00809)	1.632***	(0.00565)
Internal Dry-Lining	1.225***	(0.0153)	1.181***	(0.0172)	1.148***	(0.0185)	1.129***	(0.0235)	1.190***	(0.0164)
Boiler w/ Heating Controls	-0.357***	(0.00373)	-0.381***	(0.00418)	-0.398***	(0.00450)	-0.449***	(0.00467)	-0.396***	(0.00367)
Heating Controls Only	-0.381***	(0.0104)	-0.361***	(0.0117)	-0.347***	(0.0126)	-0.475***	(0.0114)	-0.400***	(0.00959)
Solar	0.898***	(0.00633)	0.902***	(0.00711)	0.905***	(0.00766)	0.732***	(0.00731)	0.822***	(0.00626)
Other 1 Measure	-0.344***	(0.0147)	-0.333***	(0.0165)	-0.324***	(0.0178)	-0.338***	(0.0174)	-0.618***	(0.0163)
Attic + External Wall Insulation	1.483***	(0.00996)	1.418***	(0.0112)	1.369***	(0.0120)	1.469***	(0.0168)	1.472***	(0.0115)
Attic + Internal Dry-Lining	1.049***	(0.0106)	0.979***	(0.0119)	0.926***	(0.0127)	0.975***	(0.0172)	1.027***	(0.0128)
Attic + Boiler w/ Heating Controls	-0.246***	(0.0106)	-0.287***	(0.0119)	-0.318***	(0.0128)	-0.309***	(0.0145)	-0.293***	(0.0116)
Boiler w/ Heating Controls + Solar	0.00866	(0.0163)	0.00681	(0.0183)	0.00541	(0.0197)	-0.0417**	(0.0181)	0.00973	(0.0159)
Other 2 Measures	0.261***	(0.00875)	0.254***	(0.00983)	0.248***	(0.0106)	0.129***	(0.0104)	0.211***	(0.00904)
Attic + Cavity + Boiler w/ HC	-0.224***	(0.00854)	-0.223***	(0.00960)	-0.222***	(0.0103)	-0.223***	(0.00981)	-0.183***	(0.00891)
Attic + Cavity + HC Only	-0.150***	(0.0122)	-0.127***	(0.0137)	-0.109***	(0.0148)	-0.171***	(0.0131)	-0.140***	(0.0114)
Attic + Dry-Lining + Boiler w/ HC	0.549***	(0.0152)	0.483***	(0.0171)	0.433***	(0.0184)	0.493***	(0.0259)	0.548***	(0.0269)
Other 3 Measure	0.570***	(0.0126)	0.534***	(0.0141)	0.507***	(0.0152)	0.357***	(0.0174)	0.387***	(0.0157)
4 Measures	0.0434**	(0.0178)	0.0416**	(0.0200)	0.0403*	(0.0216)	-0.0868***	(0.0206)	-0.0211	(0.0194)
Obligated Party (ref = private)										
OP 1	-0.0704***	(0.0111)	-0.0784***	(0.0124)	-0.0845***	(0.0134)	-0.0415***	(0.0142)	-0.0758***	(0.0110)
OP 2	-0.0812***	(0.0174)	-0.0897***	(0.0195)	-0.0962***	(0.0210)	-0.0252	(0.0216)	-0.0568***	(0.0169)
OP 3	-0.0127***	(0.00484)	-0.0175***	(0.00544)	-0.0211***	(0.00586)	-0.0216***	(0.00581)	0.00251	(0.00473)
OP 4	0.0234**	(0.0105)	0.0312***	(0.0118)	0.0372***	(0.0127)	0.0107	(0.0118)	-0.00225	(0.0102)
OP 5	0.0228	(0.0236)	0.0255	(0.0266)	0.0275	(0.0286)	0.00378	(0.0269)	0.00212	(0.0230)
OP 6	0.0606**	(0.0241)	0.0437	(0.0271)	0.0308	(0.0291)	0.0496	(0.0317)	0.0897***	(0.0245)
Observations	89,063		89,063		89,063		55,667		72,005	
R-squared	0.792		0.737		0.695		0.711		0.759	

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