The Economic and Social Review, Vol. 56, No. 4 Winter 2025, pp.389-419

A Scenario Analysis of Financing Options for Energy Retrofits Among Irish Mortgage Holders

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Abstract: This paper examines household costs and benefits of investing in building energy efficiency. Using a large sample of mortgaged households, we compare long-run benefits (energy and mortgage savings) and costs (loan instalments) across several loan types and scenarios. Our results show that retrofitting generally leads to net lifetime savings for most households. However, these savings are highly dependent on a number of key factors, including energy price assumptions, rebound effects (where

Acknowledgements: All views expressed are those of the authors alone and do not represent the views of the Central Bank of Ireland, SEAI, Ofgem, LSE or ATU. The authors are solely responsible for the content and the views expressed. The authors are grateful for comments from Michael Mahony, Cian O' Neill and attendees at the 2024 Dublin Economics Workshop.

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energy use increases post-retrofit) and interest rates. In particular, the financial viability of retrofitting improves under scenarios with higher fossil fuel prices and lower electricity prices. Retrofitting through loan financing can create short-term cash flow pressures, where loan repayments exceed energy and mortgage savings, posing a significant barrier for many households. Longer loan terms and, in particular, mortgage top-ups, are the most effective means to smooth costs over time. These findings highlight the importance of tailored financing options and supportive policies to encourage retrofitting at scale, helping Ireland achieve its national climate targets. We note that these results are likely to be at the lower bound of household net benefits, as they do not account for increased wealth (higher property value) or improved comfort and health, all of which can be substantial.

I INTRODUCTION

Climate change and the transition to net zero are among the biggest challenges facing society, governments and the global economy. The actions taken in the coming decades will be pivotal in reducing long-term damages, with earlier interventions yielding the greatest benefits. Retrofitting homes is a critical step toward environmental sustainability, while also enhancing household financial stability. Accessible financing options – such as loans, mortgage top-ups, grants, and incentives – can boost adoption by reducing upfront costs, mitigating energy expenses, and stimulating local economies. Ensuring the availability of suitable financial mechanisms is essential for scaling retrofitting efforts, meeting national climate targets, and safeguarding household financial resilience.

Ireland's Climate Action Plan sets out the roadmap for Ireland on climate action – committing to achieve a 51 per cent reduction in emissions by 2030, and net-zero emissions by 2050, aligned with the European Green Deal. As part of this plan, Ireland has committed to retrofitting 500,000 homes to a Building Energy Rating[1] (BER) of B2 or better, and to the installation of 680,000 heat pumps. Achieving retrofit at scale can prove challenging due to the presence of large, tangible and immediate costs. These are paired with long-term, uncertain benefits that are often difficult to quantify. These considerations and information gaps on the net benefits can lead to collective inaction. As such, achieving national targets requires significant societal, technological and economic change.

This analysis quantifies the household costs and benefits of retrofitting to a BER rating of B2 or higher across a range of future scenarios. Recognising the significant upfront costs of retrofitting, the study evaluates various financing models. To our knowledge this is the first paper to combine administrative loan-level data with administrative data on energy efficiency investment costs and estimated savings for a wide portfolio of dwellings. The analysis uses a novel dataset that merges Central Bank of Ireland loan-level data with data from the

[1] Building Energy Ratings are the Irish implementation of the Energy Performance Certificate scheme as required by the EU Energy Performance of Buildings Directive.

Sustainable Energy Authority of Ireland's (SEAI) flagship National Home Energy Upgrade Scheme and the National Building Energy Rating Database. Combining these datasets creates a unique dataset on financing costs, retrofit costs and potential savings for a representative sample of Irish dwellings. Ultimately, this study provides policymakers with important insights into the financial implications of retrofitting, and presents policy options which could steer national residential investments towards national decarbonisation targets.

Our results show the conditions which increase the viability of private household energy efficiency investments. Retrofitting to a BER of B2 or higher leads to net lifetime savings for most households. However, financing these upgrades with a standard term loan can create significant short-term financial pressures. For instance, with a five-year loan at 7 per cent interest, monthly repayments can exceed combined energy and green mortgage savings by as much as €700 per month in certain scenarios. Lower interest rates and longer loan terms can effectively mitigate these short-term cash flow challenges by spreading investment costs over time. Notably, mortgage top-ups prove to be the most effective option, virtually eliminating negative short-term cash flow impacts.

Net savings vary significantly across the mortgage sample, largely due to differences in individual property characteristics, such as size, location, and initial BER rating. For example, net lifetime savings are considerably higher for deeper retrofits (households with very low starting BER levels), despite the higher upfront cost of upgrading. The results are also influenced by the specific scenarios considered, such as energy price trajectories and rebound effects. For example, higher rebound effects (increased household energy demand post-retrofit) have clear implications for long-run energy saving forecasts. We also show that retrofitting becomes more financially viable when fossil fuel prices are higher and electricity prices are lower.

II LITERATURE REVIEW

In light of the aims of this study, this section details the effectiveness of programmes designed to improve energy efficiency, evidence on differences between predicted and actual energy savings and recent trends in how energy efficiency is financed.

While the primary policy objective of retrofitting is to advance national decarbonisation goals, retrofits also enhance household resilience to energy price inflation. Previous research has shown that retrofitting is an important tool for mitigating transition risks in the mortgage market associated with climate change. Specifically, occupants in less efficient dwellings are likely to be disproportionately vulnerable to shocks in energy prices which can strain debt servicing ratios – the proportion of monthly income used to meet mortgage payments (Adhikari *et al*., 2023; Bank of England, 2022).

2.1 Energy Efficiency Programme Effectiveness

The results from energy efficiency programme evaluations, while generally delivering net benefits, show significant variation in energy savings. A systematic review of 39 evaluations across 23 different residential retrofit programmes, based on ex-post billing or consumption data (Giandomenico *et al*., 2022), found that energy savings ranged from 0 per cent to 27 per cent of pre-upgrade consumption, with an average reduction of 7.2 per cent. These findings are broadly consistent with other large-scale reviews, such as Gillingham *et al*. (2018), which reported savings in the range of 0 per cent to 25 per cent. Related research in Ireland aligns with these results, with Scheer *et al*. (2013) estimating a reduction in gas demand of approximately 21 per cent following retrofits.

Energy efficiency upgrades are generally cost-effective,[2] but, in some cases, long payback periods can challenge the notion of cost-effectiveness from a financial perspective. Most relevant to our study, the payback periods for new heating systems can be 12 to 23 years, and attic and wall insulation pays back in 12 to 46 years (Giandomenico *et al*., 2022). However, some very credible and widely-cited examples show that NPVs can be negative (e.g. Fowlie *et al*., 2018), and as much as –7.8 per cent. This result is due to significant up-front investment costs and realised savings being significantly lower than ex-ante engineering models predicted. Cost-effectiveness can also depend heavily on a number of other factors, such as the choice of economic parameters, energy prices and discount rates used in the evaluation (Belaïd *et al*., 2021).

Beyond energy and cost savings, retrofitting delivers a range of “multiple benefits” including improved health, wellbeing, energy affordability and increased disposable income (Ryan and Campbell, 2012). Milner *et al*. (2024) examined the health and comfort outcomes associated with the “Warmth and Wellbeing” pilot scheme, which targeted homes of persons with chronic respiratory conditions in the Dublin area. The study found that the energy efficiency measures were linked to numerous positive outcomes, including fewer GP and hospital visits, improved comfort and satisfaction, and enhanced physical and mental health. Other work has shown that programmes targeting low-income households often result in lower than expected energy savings, as households tend to “take-back” some of the savings through increased comfort post-retrofit (McCoy and Kotsch, 2021). In such schemes, policymakers are often trading off emission reduction with other welfare enhancing objectives such as alleviating energy poverty.

2.2 Energy Performance Gap and Rebound

Estimates of the direct benefits of retrofitting can be complicated by a lack of measured energy usage before and after a retrofit. Research has identified an Energy Performance Gap where actual energy use differs significantly from the level

[2] We define cost-effectiveness as those interventions which have a positive Net Present Value (NPV).

expected by the Energy Performance Certificate without undergoing a retrofit (Coyne and Denny, 2021b; Cozza *et al*., 2020; Majcen *et al*., 2013; Sunikka-Blank and Galvin, 2012). Consideration of this issue is essential as it will inform how we adjust the energy savings estimates in our modelling.

Rebound is the term used where occupants begin to consume more energy after receiving a retrofit (Sorrell, 2007). This so-called direct rebound effect offsets the energy savings that may otherwise be achieved. For example, if a homeowner installs more energy efficient windows, they might feel more comfortable and decide to increase their thermostat setting in colder weather or spend more time at home, thereby using more energy than anticipated. Rebound can serve to undermine the intent and effectiveness of policies that encourage retrofit (Gerarden *et al*., 2015), while uncertainty regarding the actual size of rebound makes it difficult to formulate policy (Aydin *et al*., 2017).

A review of empirical estimates of the direct rebound effect identifies a long-run mean direct rebound effect of 20 per cent, with estimates ranging from 1.4 per cent to 60 per cent (Sorrell *et al*., 2009). Research from the Netherlands finds that average rebound varies for homeowners (26.7 per cent) and tenants (42.1 per cent), perhaps reflecting different income and energy use intensity (Aydin *et al*., 2017). Research from the UK suggests that only half of the expected savings are realised, with rebound (via higher temperatures) accounting for 15 per cent of the shortfall (Sanders and Phillipson, 2008). Other evidence from the UK suggests that actual savings from retrofit can be half of what is expected due to poor installation, monitoring and rebound (Dowson *et al*., 2012). A recent review (Giandomenico *et al*., 2022) found that energy efficiency interventions using ex-post billing data had an average "realisation rate" – the proportion of actual savings versus what was expected (from engineering-based estimates) – ranging from 25 per cent to 86 per cent, with a mean of 55 per cent (equivalent to a 45 per cent rebound).

For Ireland, research studying household heating and electricity consumption – of which some received a retrofit – found evidence of significant deviation between actual energy use and the level expected by the BER (Coyne and Denny, 2021a). The results show that actual energy use is about 17 per cent less than the BER would predict across the full sample, and an additional average rebound of 10 per cent is observed.

2.3 Financing Energy Efficiency

Given the uncertainties and difficulties in estimating the financial benefits from retrofit, it is not surprising that lenders have found it difficult to price financial instruments supporting residential energy efficiency. Research from projects such as the LENDERS initiative in the UK has shown that incorporating household energy costs into mortgage affordability calculations could allow households to borrow more capital or borrow at a lower interest rate (UK GBC, 2017). Lower interest rates for energy efficient properties (and retrofit loans) may also be justified through increased borrower resilience to climate risks and high/variable energy prices. This is not always the case.

Previous research in France (Giraudet *et al*., 2021) and the UK (Bell *et al*., 2023) suggested that initially banks were not pricing energy efficiency into their lending rates. Giraudet *et al*. (2021) created a dataset of posted lending rates from 15 credit institutions across France and compared green home loans with other home renovation projects. They found that green home loans were not priced lower than other renovation projects. Similarly, in a dataset of 1.8 million mortgages, Bell *et al.* (2023) found no evidence of lenders charging higher rates for more energy-inefficient properties.

In contrast, some evidence suggests that energy efficiency projects backed by green bonds receive lower interest rates and lower debt service coverage ratios than their brown alternatives (e.g. Devine *et al*., 2022). Lambert *et al*. (2023) documented the recent history of Green Mortgages (GM) in Ireland, identifying five lenders offering green rates explicitly linked to the Irish Energy Performance Certificate (EPC) scheme – the Building Energy Rating (BER). That work developed a methodology to identify GMs in the lending data reported by banks to the Central Bank of Ireland and found a typical discount of about 30 basis points for a green mortgage.

III METHODS AND DATA

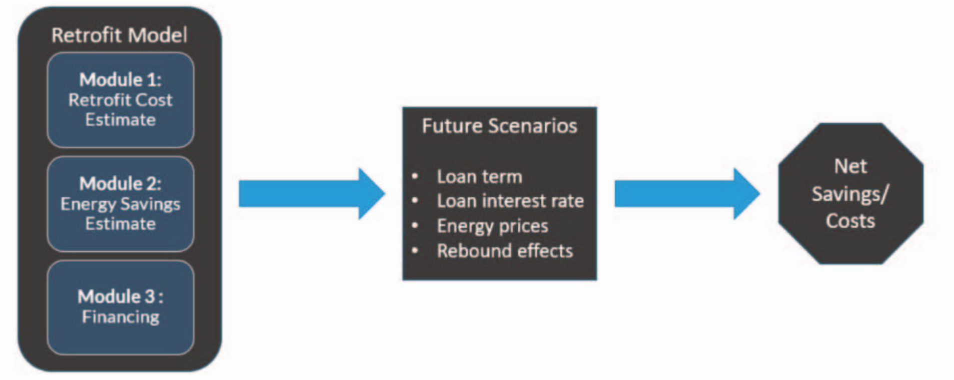
This study develops a property-level retrofitting model that simulates investment costs, energy savings and green mortgage savings. The analysis focuses on all properties with energy efficiency levels below B2 BER – the minimum efficiency threshold within government retrofitting targets for 2030. The sensitivity of costs and savings are explored using a range of alternative scenarios for loan types, energy prices and rebound effects. The remainder of this section describes the key methodological steps in more detail.

3.1 Loan-level Data Adaptations

Our core dataset is the Central Bank of Ireland's "Monitoring Template Data" (MTD), which records information on all new mortgage originations in Ireland. The dataset includes all loan information as well as borrower and building characteristics, such as property type and size.[3] For the purpose of this analysis, we focus on first-time buyers, second and subsequent buyers, and mortgage switchers. We exclude buy-to-let properties and apartments due to the small sample size in the matched energy information dataset.

[3] MTD submission is mandatory for financial institutions that advance at least €50 million of new mortgage lending over a six month period (H1: January to June, or H2: July to December).

Figure 1: Property-level Retrofit Model



Source: Authors' design.

Although the Central Bank began collecting BER data in 2022, significant data gaps remain, with BER ratings unavailable for most of the sample. To address this gap, we classify energy-efficient properties using the approach outlined in Lambert *et al*. (2023), who identify "green mortgages" (typically provided for B3 BER or higher) based on observable loan characteristics in the MTD, such as interest rate and loan-to-value ratios. Specifically, we match institution-specific green mortgage interest rate discounts to loan terms and loan-to-value ratios to identify green mortgage originations. As green mortgage loans already meet national retrofit targets, they are excluded from the sample. Similarly, new properties are excluded as all new builds require a BER rating of A2 or higher.[4] The final sample, covering the period from 2019 to June 2023 includes approximately 70,000 properties with BER levels below B3.

Retrofit cost and energy saving calculations require both pre- and post-retrofit efficiency estimates. Where pre-retrofit BER is not provided in our mortgage dataset (89 per cent of properties), we apply a stratified random assignment matched to county BER shares obtained from the Central Statistics Office ("Start BER" in Table 1).[5] Similarly, post-retrofit BER is assigned using retrofit data provided by the SEAI ("End BER" in Table 1).

3.2 Module 1: Retrofit Cost Estimation

To allocate retrofit costs to each property in the MTD, we use a combination of data extracted from the National Building Energy Rating Register (BER database), and data accumulated through the SEAI home energy upgrade grant schemes

[4] See New Energy Efficiency Standards for New Dwellings, 2019 (https://www.gov.ie/en/department-of-housing-local-government-and-heritage/publications/new-energy-efficiency-standards-for-new-dwellings/)
[5] CSO Domestic Energy Ratings Quarter 4 2022 – Table 4 (https://www.gov.ie/en/department-of-housing-local-government-and-heritage/publications/new-energy-efficiency-standards-for-new-dwellings/)

Table 1: Sample Shares by Pre- and Post-retrofit BER

	A1	*A2*	*A3*	*B1*	*B2*	*Start BER*
C1	0.2%	0.4%	2.6%	3.9%	8.4%	**15.4%**
C2	0.1%	0.6%	3.7%	4.4%	7.9%	**16.7%**
C3	0.1%	0.6%	3.6%	4.3%	6.9%	**15.3%**
D1	0.2%	0.9%	3.7%	3.6%	6.0%	**14.4%**
D2	0.1%	0.9%	2.9%	3.3%	5.1%	**12.3%**
E1	0.1%	0.6%	1.8%	1.7%	2.9%	**7.0%**
E2	0.1%	0.5%	1.3%	1.4%	2.3%	**5.6%**
F	0.1%	0.6%	1.5%	1.2%	2.3%	**5.8%**
G	0.1%	0.8%	2.8%	1.4%	2.5%	**7.6%**
End BER	**1.1%**	**5.8%**	**23.7%**	**25.1%**	**44.2%**	**100%**

Source: Own calculations using Central Bank of Ireland Monitoring Templates Data and SEAI National Home Energy Upgrade scheme (known commonly as the One-Stop Shop (OSS) scheme) and associated BER data for 2019-2023.
Notes: Assumes uplift to B2 or higher.

(grants database).[6] While cost data on home energy upgrades are available for several SEAI upgrade schemes, this study only uses data from the SEAI National Home Energy Upgrade scheme (known commonly as the One-Stop Shop (OSS) scheme) for two key reasons: firstly, homes participating in this scheme consistently have both pre- and post-works BER assessments carried out; secondly, the data can be reliably filtered to only include private applicants and exclude applications from approved housing body applicants, where costs differ considerably compared to private individuals. Costs are expressed as net of SEAI grants and in terms of euro spent per square metre of the upgraded dwelling (€/m2).

BER data and OSS programme data are merged using anonymised identification keys for the purposes of this study. To align with the MTD dataset, homes with a pre-retrofit BER of B2 or better were removed, as were apartments. Only dwellings that had a heat pump installed were included in the study to align with the National Retrofit Plan. Outlier removal was implemented by identifying and excluding data points that fall within the upper/lower 1 per cent quantiles for retrofit cost, floor area, and retrofit efficiency uplift, to reduce potential bias from extreme values. The relevant dataset for dwelling characteristics and retrofit costs for analysis consisted of 657 dwellings (see Table 2 for descriptive statistics).

[6] The BER database retains the accumulated results of all Energy Performance Certificates issued in residential buildings across Ireland, although in this study we focus on the period 2021 to 2023 to align with the MTD sample. Energy ratings in Ireland are determined using the Dwelling Energy Assessment Procedure (DEAP), which uses the physical characteristics of the building – its location, dimensions, placement, and insulation, as well as its heating/cooling, ventilation and lighting systems – to estimate the annual primary energy requirements under nominal occupancy.

Table 2: Upgrade Cost Dataset – Descriptive Statistics

	Min.	*Max.*	*Mean*	*Std. Dev.*	*Units*
Retrofit Cost	69.8	1,683.8	472.0	284.2	€/m^2
Retrofit Grant	67.3	758.5	270.9	125.5	€/m^2
Floor Area	33.8	243.7	102.0	46.1	m2
Pre-Retrofit Energy Value	131.7	1,776.5	315.0	165.1	kWh/m^2/annum
Dwelling Energy Efficiency Uplift	44.1	1,080.0	242.2	133.0	kWh/m^2/annum

Source: SEAI One Stop Shop programme data and associated BER data for 2021-2023.
Notes: Data comprised of 693 dwellings: Detached (393); Semi-Detached (199); Terraced (101).

Retrofit cost estimates in the MTD are generated using coefficients from an auxiliary regression applied to the OSS data. In this regard, we estimate the following model (OLS) on the OSS data to measure the relationship between BER uplift and upfront cost, controlling for property size and type interactions:

$$\begin{aligned} \ln(I) = \beta_0 + \beta_1 S + \beta_2 U + \beta_3 (E_{Pre}) + \beta_{4SD}(T_{SD}) \\ + \beta_{5T}(T_T) + \beta_{6SD}(ST_{SD}) + \beta_{7T}(ST_T) + \varepsilon \end{aligned} \quad (1)$$

Where:

- ln (I): natural logarithm of retrofit investment costs (net of grants) in euro/m^2;
- S: size of the property (floor area, m^2);
- U: uplift – difference between pre- and post-BER energy value (kWh/m^2/year);
- E: dwelling rated energy value in (kWh/m^2/year) from BER;
- T_{SD} and T_T: dummy variables for semi-detached and terraced (detached as the omitted category);
- ST_{SD} and ST_T: interaction terms between property type (semi-detached and terraced) ;and floor area, m^2. The interaction terms between detached and floor area is the omitted base category;
- ε: error term.

The selected best-fit model's coefficients are included in Table A.1 in the Appendix, where the residuals are shown in Figures A.1 and A.2. This model was selected as it showed the best combination of explanatory power and homoscedasticity, as well as showing coefficient signs that were consistent with expectations about economies of scale associated with larger homes and deeper retrofits.

The coefficient values for size (β_1), uplift (β_2), dwelling rated energy value (β_3), and type (β_{4SD} and β_{5T}) are multiplied by their respective variable values in the MTD to provide individual estimates of retrofit costs for each property. The retrofit cost model was fitted using the natural logarithm of net retrofit cost as the dependent variable, and predicted log-costs were exponentiated to return to the original cost scale. This back-transformation can introduce bias, typically resulting in underestimated cost predictions due to the non-linear nature of the exponential function. To correct for this, a post-estimation adjustment was applied: a secondary regression was performed, regressing observed costs on the exponentiated predicted costs in order to generate an estimate of prediction error.[7] The resulting slope coefficient (1.0987) from this regression served as a correction factor, which was then applied to the predicted costs in the MTD dataset to produce bias-adjusted estimates. This estimation process leads to a median investment of €41,746 net of grants, although median costs show a high level of variation by initial BER rating (see Figure A.3 in Appendix).

Our retrofit estimates are broadly in line with prior analysis.[8] For example, previous research by SEAI from a deep retrofit pilot study found an average cost to upgrade from F to A3 is €60,814 with significant variation due to house type, size, age and the extent of works performed (SEAI, 2018). More recent evidence from the recent OSS model for a sample of 672 households finds a median cost to homeowner of €37,489 (comprised of median cost of works (€59,734) less median grant (€22,150)) to rise from an average pre-works BER of E1 to an average post-works BER of A2 (SEAI, 2024a). By contrast, a sample of homes belonging to Approved Housing Bodies (n = 672) rise from an average BER C3 to BER A3 with a median cost to homeowner of €14,699 (SEAI, 2024a). This difference is indicative of the greater financial hurdle required for low-efficiency dwellings to climb the "ladder" of energy efficiency and the important role of third party providers in helping to facilitate upgrades and alleviate non-monetary barriers to upgrade.

3.3 Module 2: Energy Savings Estimation

The BER database is also used to estimate the energy savings associated with a retrofit, in this instance to produce average estimates of the "delivered energy" required for heating according to the BER assessments for all homes within a given BER level.[9] All retrofits in this exercise switch from fossil fuel heating (weighted by national heating fuel shares) to a heat pump, consistent with Ireland's longer-

[7] Observed-Predicted comparison as suggested by Piñeiro *et al.* (2008). Similar methods are applied in regulatory cost-assessment models.

[8] The average cost of an Electric Ireland Superhomes retrofit is circa €30,000 net of grants (https://electricirelandsuperhomes.ie/costs-fees/).
BuildTech typical range between €30,000 and €70,000 depending on size of retrofit excluding grants https://buildtech.ie/blog/how-much-deep-retrofit-cost-ireland#:~:text=Ready%20to%20Invest%20in%20a,%E2%82%AC70%2C000%20(excluding%20grants).

[9] Delivered energy is the amount of energy that enters the home (as measured by the electricity or gas meter, for example), and includes the energy requirements for primary and secondary (if present) space and water heating systems, as well as for pumps and fans which are often associated with the operation of the heating system, but excludes any energy consumption by lighting and appliances. In contrast, "primary energy" [9]

Continued over

term heating goals (for example, target of 680,000 heat pump installations by 2030). To allow us to separately apply electricity costs versus other heating fuel costs, we differentiate between average delivered energy between electricity and other heating fuels (Table 3).

Table 3: Average Delivered Energy for Heating by BER Level

Retrofit State	*BER Level*	*Energy Value Range, kWh/m2/year*	*Average Delivered Energy for Heating, kWh/m2/year*			
			Without Heat Pump		*With Heat Pump*	
			Electricity	*Other Fuels*	*Electricity*	*Other Fuels*
Post-Retrofit BER Levels	A1	≤25			23.8	4.3
	A2	(25—50]			24.6	4.4
	A3	(50—57]			27.6	4.6
	B1	(75—100]			35.7	6.7
	B2	(100—125]			44.8	10.0
	B3	(125—150]				
Pre-Retrofit BER Levels	C1	(150—175]	9.7	120		
	C2	(175—200]	13.5	131		
	C3	(200—225]	18.2	142		
	D1	(225—260]	24.3	156		
	D2	(260—300]	32.0	176		
	E1	(300—340]	38.8	202		
	E2	(340—380]	43.4	229		
	F	(380—450]	48.0	267		
	G	>450	106.0	360		

Source: SEAI Building Energy Ratings data as computed using the Dwelling Energy Assessment Procedure.

Equations 3 and 4 present our estimation method for annual energy costs before ("pre") and after ("post") the retrofit, respectively. While pre-retrofit boiler types are unknown, we use a weighted average for national heating energy prices (kerosene, gas and electricity, weighted by national boiler type shares).[10] Post-retrofit, we assign each property an electric heat pump, based on post-retrofit data provided by the SEAI which suggests the majority (95 per cent) of retrofits had switched to an electric heat pump in line with the National Retrofit Plan. For long-run analysis, we extend this process forward, with future energy prices discounted based on NGFS (Network for Greening the Financial System) long-run energy price forecasts.

continued: (the units employed on a BER certificate) considers the total energy required to supply households from source, and also accounts for any energy losses associated from generation, transmission and distribution. As a consequence, primary energy is typically higher than delivered. However, for properties with both solar photovoltaics (SPV), which are more prevalent at B1 or higher, and heat pumps, delivered energy can be higher than primary energy, as the SPV system can deliver energy for in-home consumption that requires no primary energy from the grid.

[10] National boiler shares as provided by the SEAI.

$$C_{Pre} = [A_{Heat} * E_{Pre} * S * P_{Heat}] = [A_{Elec} * E_{Pre} * S * P_{Elec}] \quad (3)$$
$$C_{Post} = [A_{Heat} * E_{Post} * S * P_{Elec}] = [A_{Elec} * E_{Post} * S * P_{Elec}] \quad (4)$$
$$R = (C_{Post} - C_{Pre}) * (1 - r) \quad (5)$$

Where:
- *C*: annual energy costs before (“Pre”) and after (“Post”) retrofit;
- *E*: expected energy use (kWh) per metre squared per annum;
- *A*: share of energy assigned to heating (“Heat”) and electricity (“Elec”);
- *P*: price of energy;
- *S*: Size of the property in metre squared;
- *R*: annual energy cost savings from retrofit;
- *r*: rebound factor.

Total energy savings (Equation 5) also allow for behavioural aspects (“rebound effects” (*r*)), which implies that realised energy reductions are lower than theoretical. For year one post-retrofit, our energy cost estimates use average electricity, gas and kerosene prices from 2022 through 2023 (inclusive of VAT) from the SEAI Domestic Fuel Cost Comparison.[11] This averaged approach was followed due to the current exceptionally high energy price environment following the war in Ukraine, which may represent an outlier in the long-run trajectory. For later years, we also employ alternative energy price indices (discussed in Section 3.5).

The initial post-retrofit median annual energy savings per household is estimated at €1,200 (approximately €100 per month) and can range significantly depending on the initial starting BER, from €315 for a C1 to €2,500 for an E2 (see Figure A.4). As expected, there are significantly higher savings for F- and G-rated properties, €3,100 and €5,900 respectively.

3.4 Module 3: Financing

The sole cost of the home retrofit in our model is the monthly loan repayments each household will incur to pay off a green retrofit loan. The green retrofit loan in our model has baseline parameters set at 7 per cent interest over a five-year loan term. Retrofit loan repayments are calculated using the standard amortisation formula (Equation 6), given our loan parameters: loan term, interest rate and principal amount (as defined in Section 3.2).

[11] Data available from SEAI (https://www.seai.ie/data-and-insights/energy-data-portal). Average prices (2022/2023) are 29.6 cent/kWh (electricity: Band DC), 13.7 cent/kWh (gas: Band D2) and 11.2 cent/kWh (kerosene: typical discounted price). Note that the analysis excludes annual standing charges; in the particular case of an upgrade from mains gas to a heat pump, it is possible that a household can forego gas supply entirely and save €120-150 annually, but these savings are not included here.

$$A = P\frac{i(1+i)^n}{(1+i)^n - 1} \tag{6}$$

Where:

- A: periodic payment amount;
- P: principal – retrofit investment amount net of grants;
- i: periodic interest rate;
- n: total number of payments.

Mortgage holders can also avail of lower "green mortgage" rates following the retrofit. Initially, lenders which introduced green mortgage rates offered a 30 basis points saving over the standard rate, although this has fluctuated and even greater savings are possible in some cases.[12] The amortisation formula is again utilised to calculate the expected mortgage savings from switching from the regular mortgage rate to the green rate (typically a saving of 30 basis points). The median mortgage saving is about €30 per month, but can be as high as €100 per month for some households. Our analysis assumes instant switching by households to quantify the upper bound of potential savings. These results are therefore subject to households actively switching to a lower green mortgage rate upon retrofit completion. However, we acknowledge it may not be possible for many households to switch immediately.

3.5 Scenario Analysis

Given the significant uncertainty in long-run monetary flows and heterogeneity in behavioural response (rebound effects), we test the sensitivity of our findings to a range of alternative scenarios (Table 4).

Table 4: Scenario Attributes and Alternative Levels

Attribute	*Scenario 1*	*Scenario 2*	*Scenario 3*
Rebound Rate	27%	45%	–
Energy Prices	Current Policies	Fragmented World	Net Zero
Interest Rate	7%	3.5%	–
Loan Term	5 years	10 years	–
Loan Type	Term Loan	Mortgage Top-Up	–

Source: Designed by the authors using prior literature and current market offerings.

Based on previous research, we apply two alternative rebound rate scenarios. Scenario 1 uses an Irish-based estimate of rebound and the energy performance gap (Coyne and Denny, 2021a). This acknowledges that actual energy use differs from the BER before and after a retrofit – and often to different extents. This is a

[12] AIB's five year Green fixed rate mortgage rate is 1.15 per cent lower than their equivalent non-green mortgage rate (https://aib.ie/content/dam/aib/group/Docs/Press%20Releases/2023/interest-rates-increase-press-release.pdf)

combination of an average deficit between actual energy use and the BER of 17 per cent, and average rebound (10 per cent) identified in Coyne and Denny (2021a) for an Irish sample. The aggregated nature of this study means that more granular differences are not explored. The second scenario is a literature-informed lower bound estimate case where actual energy use deviates substantially from what is expected. There is merit in each scenario, with more conservative scenarios featuring a larger factor applied.

For energy price forecasts, we use three scenarios from the Network for Greening the Financial System (NGFS), each reflecting higher fossil fuel prices due to stronger carbon pricing: "Current Policies" (no increase in global climate policy ambition), "Fragmented World" (a period of delayed transition, followed by divergent global policies) and "Net Zero" (net zero 2050 targets are achieved through strong coordinated international climate policies.[13] Importantly, electricity prices experience relative declines in the latter scenarios due to higher renewable generation (which is not affected by carbon taxes). We also consider a range of alternative loan options that differ on pricing and term, but also the implications of a mortgage "top-up" instead of a new term loan, where the mortgaged household adds the retrofit cost to their current mortgage balance, but spreads the retrofit costs over significantly longer durations.

3.6 Data Limitations

To our knowledge, our dataset is the first to supplement a loan-level dataset with energy efficiency characteristics, property-level retrofit cost estimates and forecasted energy savings using behaviourally-informed consumption corrections (rebound effects). We note that the matched dataset primarily serves as a platform to explore the aggregate effects of scenario level changes, rather than for estimating individual costs and benefits (individual property-level estimates will be clearly biased in this setting).

While the ideal dataset for this analysis would contain actual energy efficiency levels pre/post-retrofit, investment costs experienced by the householder, metered energy consumption data and final energy costs, we have used multiple representative sources to provide estimates for each according to our observable household characteristics (location, property size and property type). As a consequence, while individual values will be inaccurate, given that missing data are estimated using the most complete and representative datasets available, we expect that aggregate results will be representative. Future research could address these gaps, such as by incorporating metered energy consumption data.

[13] We use final energy prices for residential and commercial (oil, gas and electricity) in Ireland from the NGFS REMIND-MAgPIE 3.2-4.6 model (Phase 4) with integrated physical damages (median) (https://www.ngfs.net/en/publications-and-statistics/publications/ngfs-climate-scenarios-central-banks-and-supervisors-phase-iv). These price forecasts are provided in USD per gigajoule at 2010 purchasing price parity. We use these data to create an index with 2023 (our retrofit year).

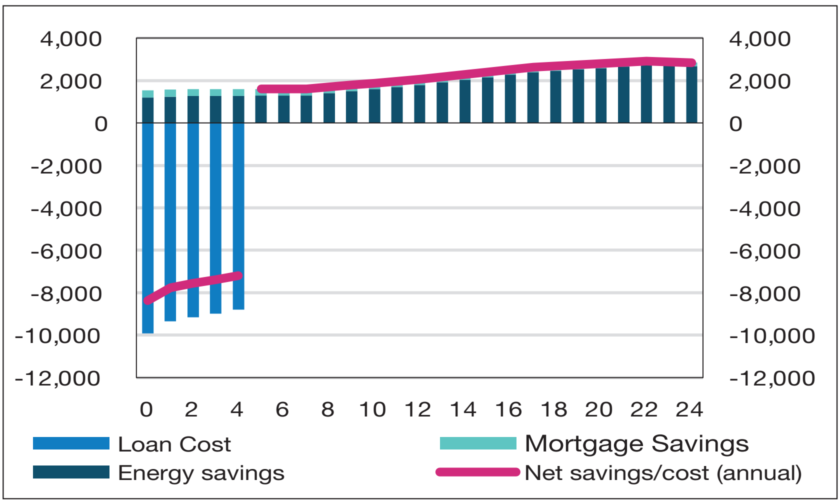
It is also possible that our net savings estimates are conservative. For example, we note that the retrofit cost data come from the SEAI National Home Energy Upgrade scheme, which may not be representative of the population of homes receiving home energy upgrades, so could lead to an overstating of costs.[14] Furthermore, our baseline estimates of energy savings are significantly below BER estimates due to rebound effects. It is also important to highlight that monetary savings are a narrow view of welfare changes in this setting – retrofits also lead to improved comfort, health and property value. Similarly, it is also challenging to account for the non-monetary costs of retrofitting a home (hassle and disruption).

IV RESULTS

4.1 Reference Results

To illustrate our reference results, in Figure 2 we present a breakdown of the components of our net costs/savings for the retrofit where the household finances the upgrade via a five-year loan at 7 per cent interest under a scenario where climate policy globally is delayed and divergent ("Fragmented World" scenario). During the loan term (first five years), loan instalments considerably exceed energy and mortgage savings. However, following loan repayment, the homeowner begins to

Figure 2: Annual Costs/Savings Over Time Under Standard Loan Term (Median) €

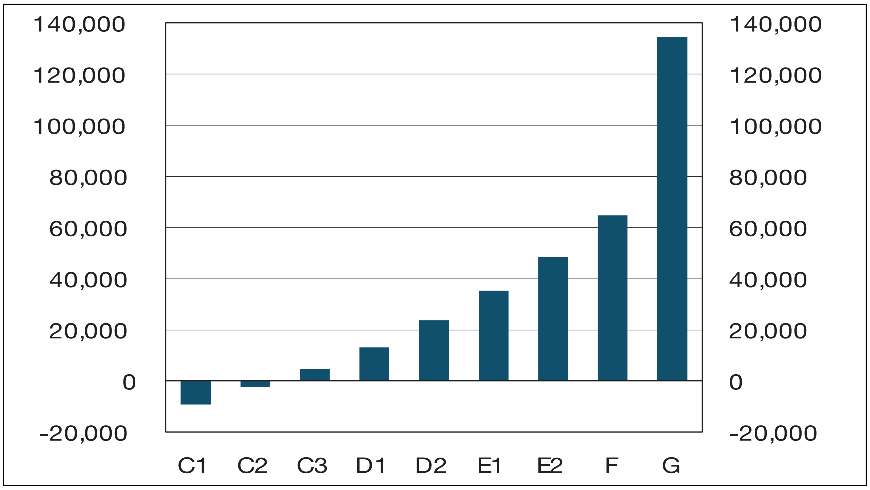


Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to B2 or higher, rebound 0.27 and "Fragmented World". Five-year standard loan with 7 per cent interest rate.

[14] See, for example, select committee on environment and climate discussion (25 June 2024) on (https://www.oireachtas.ie/en/debates/debate/select_committee_on_environment_and_climate_action/2024-06-25/3/).

achieve net annual savings as energy savings and mortgage savings accrue. In fact, once the initial loan has cleared, net benefits persist for the remainder of the investment horizon. Indeed, over the lifetime of a mortgage in our sample, the median household saving under a "Fragmented World" energy price scenario would be approximately €1,700 per year once the initial term loan has been repaid. Depending on a household's starting BER, lifetime net savings can range from –€9,000 for a C1 BER rated property (i.e. a loss) to over €65,000 for an F rated property (Figure 3).

Figure 3: Lifetime Net Savings Per Initial BER Rating (Median) €



Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to B2 or higher, rebound 0.27 and 'Fragmented World'. Five-year standard loan with 7 per cent interest rate.

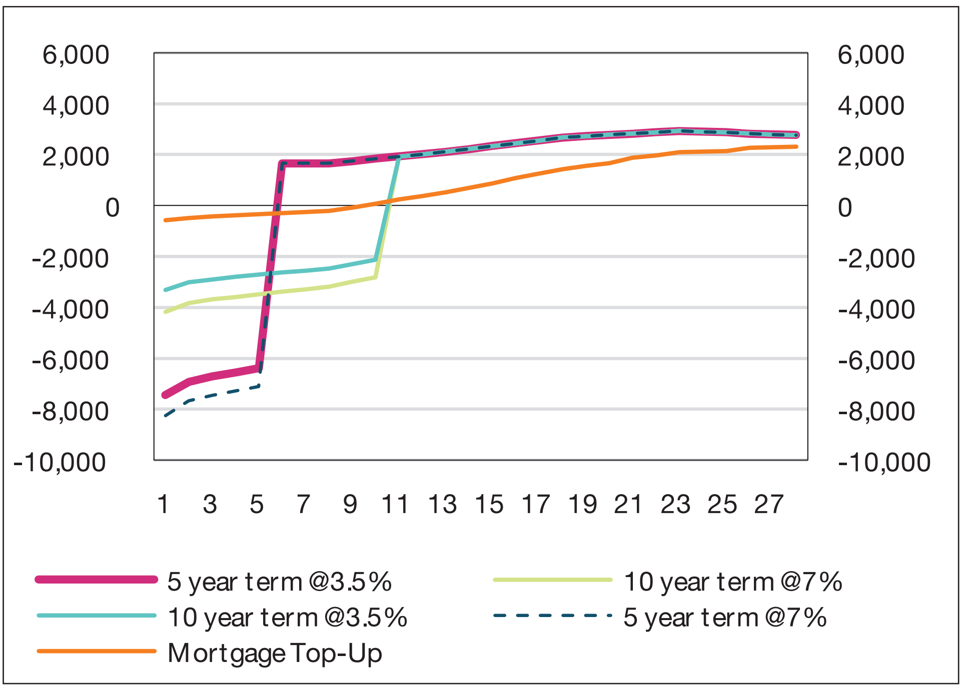
4.2 Scenario 1: Loan Characteristics

In Figure 4 we explore net costs/savings by alternative loan terms and interest rates. Lower interest rates (such as those featured in the government's home energy upgrade loan scheme) and longer loan terms reduce initial negative cash flow implications. In addition, if borrowers use a mortgage top-up for the retrofit, households can smooth investment costs over the lifetime of their mortgage to alleviate the initial negative cash flow implications associated with term loans. In relation to lifetime returns (Figure 5), the largest net benefits would accrue where the homeowner finances the upgrade with a five-year loan at the lower 3.5 per cent interest rate. However, when compared to a 10-year loan at a similar interest rate, the five-year term loan option would occur higher initial costs.

The benefits and costs can vary substantially based on factors such as starting BER rating or choice of heating upgrade, energy prices, and the real use of heating compared to the nominal heating demand given in BER ratings. Our models predict that certain households will experience a net cost when financing a retrofit with either a term loan or a mortgage top-up. This cohort of households are generally concentrated in homes that had good energy efficiency prior to the retrofit, typically C1 to D1 on the BER scale (over 85 per cent of net loss households), and tend to require high retrofit costs for relatively little energy efficiency gains. In contrast, those with lower BER ratings reap the greatest benefits from undergoing a retrofit. However, because underheating is highest for poorly-performing homes (Coyne and Denny 2021b), not all of these benefits may be realised.

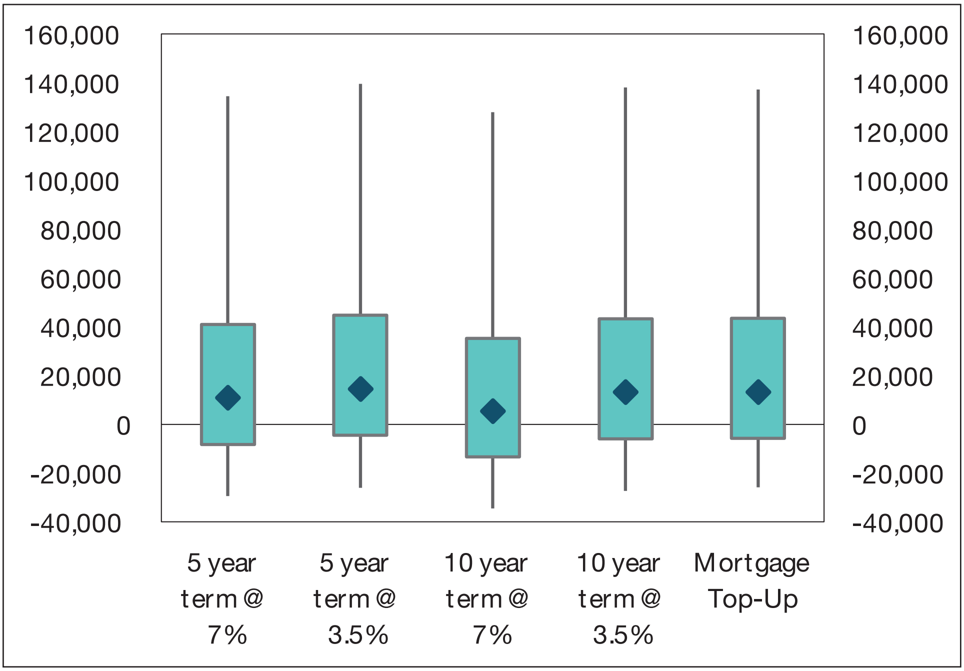
For homeowners contemplating retrofitting their properties, there is a trade-off between incurring more costs upfront and achieving greater lifetime net benefits versus incurring lower costs upfront at the expense of less lifetime net benefits. The choice of option will necessarily depend on a borrower's preference and repayment capacity.

Figure 4: Annual Net Costs/Savings Over Time Under Different Loan Terms (Median) €



Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to B2 or higher, rebound 0.27 and "Fragmented World".

Figure 5: Distribution of Net Benefits Over Lifetime of Mortgage Under Different Loan Terms €

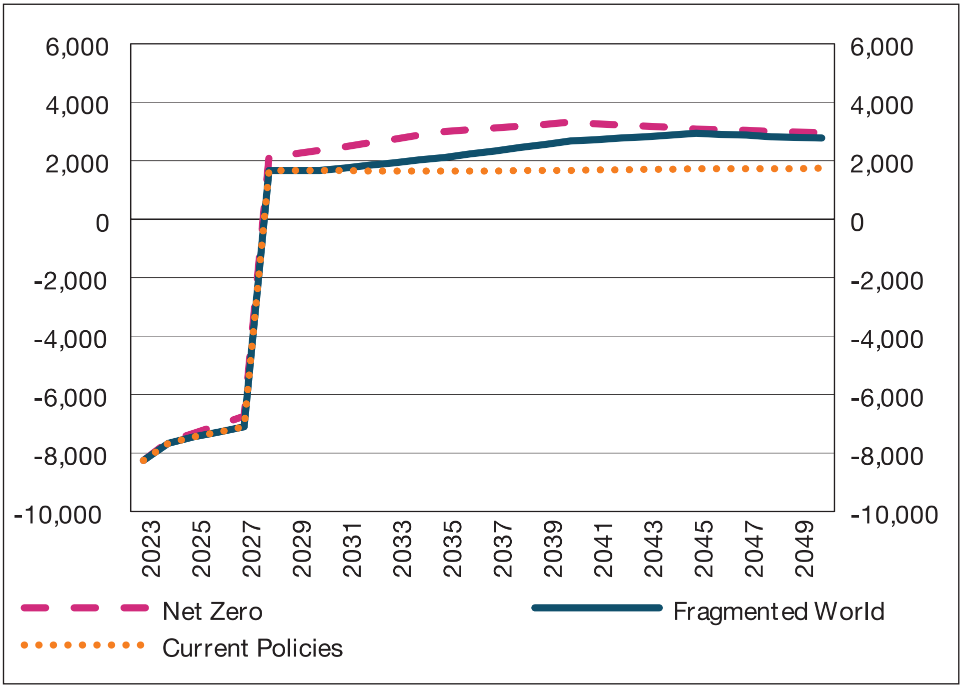


Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to B2 or higher, rebound 0.27 and "Fragmented World".

4.3 Scenario 2: Energy Price Trajectories

In this section, we compare the net costs/savings under alternative NGFS climate scenarios, which is illustrated using the five-year term loan with an interest rate of 7 per cent. The NGFS consider at least three distinct paths for climate change. The "Net Zero" scenario aims to limit global warming to 1.5°C by implementing stringent climate policies and innovations, achieving global net zero CO_2 emissions around 2050. The "Fragmented World" scenario assumes delayed and divergent climate policy ambitions globally, leading to high physical and transition risks due to inconsistent efforts across countries. The "Current Policies" scenario assumes that only currently implemented policies are maintained, resulting in high physical risks and potentially significant global warming, as no additional measures are introduced to mitigate climate. Unsurprisingly, the greatest net benefits to retrofitting will accrue if the climate transition path turns out to be closer to the NGFS "Net Zero" path (Figure 6 and Figure 7). In such a situation, the highest carbon taxes would be needed and the most stringent climate policies would be implemented.

Figure 6: Annual Net Costs/Savings Over Time Under Different Future Energy Price Scenarios (Median) €

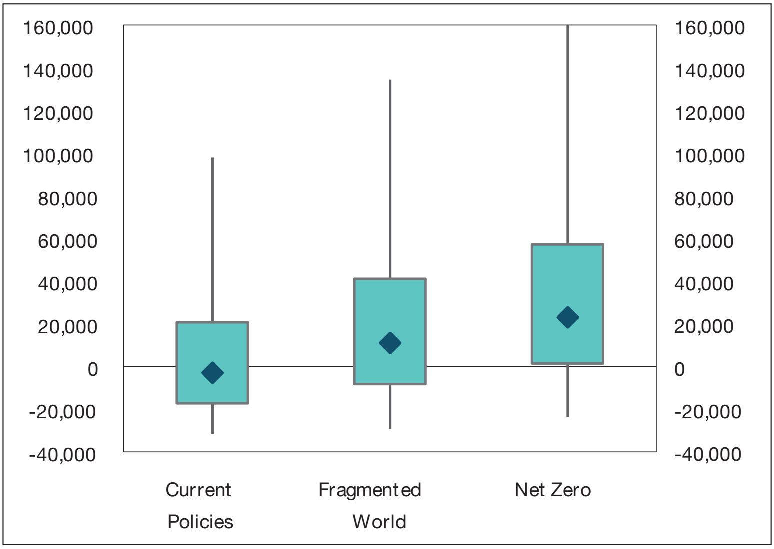


Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to minimum B2, rebound 0.27. Five-year standard loan with 7 per cent interest rate.

4.4 Scenario 3: Rebound Effects

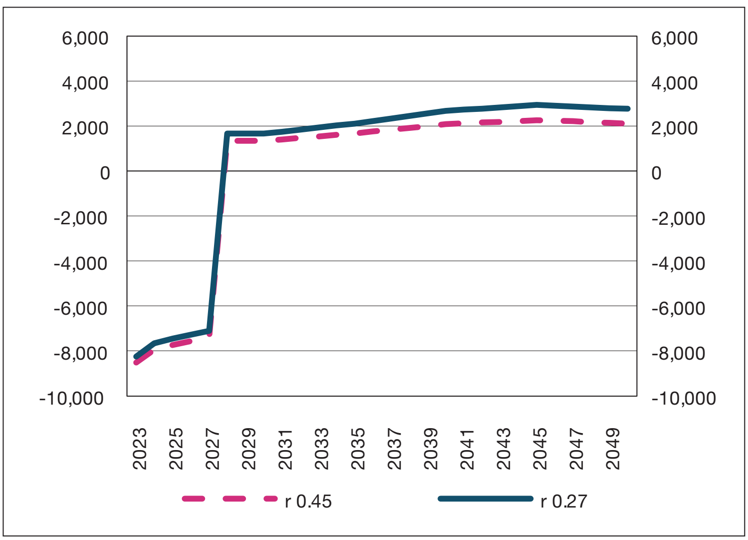
We next consider how the net costs/savings of retrofitting depends on the choice of "rebound" assumption. Rebound is the term used where occupants begin to consume more energy after receiving a retrofit (Sorrell, 2007). This so-called direct rebound effect offsets the energy savings that may otherwise be achieved. For example, if a homeowner installs more energy efficient windows, they might feel more comfortable and decide to increase their thermostat setting in colder weather or spend more time at home, thereby using more energy than anticipated. Rebound can serve to undermine the intent and effectiveness of policies that encourage retrofit (Gerarden *et al.*, 2015), while uncertainty regarding the actual size of rebound makes it difficult to formulate policy (Aydin *et al.*, 2017). In the absence of pre-and post-metered energy consumption data, an assumed rebound factor must be applied. All else equal, the lower the rebound factor, the greater the annual savings that will accrue to the homeowner once the term loan is repaid (Figure 8) and the greater the lifetime net benefits achieved (Figure 9).

Figure 7: Distribution of Net Benefits Over Lifetime of Mortgage Under Different Future Energy Price Scenarios €



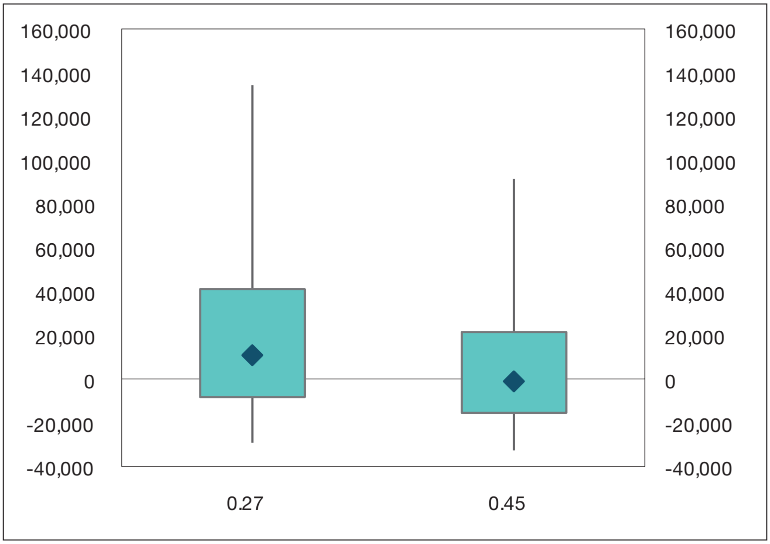
Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to minimum B2, rebound 0.27. Five-year standard loan with 7 per cent interest rate.

Figure 8: Annual Net Costs/Savings Over Time Under Different Rebound Scenarios (Median) €



Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to B2 or higher and "Fragmented World". Five-year standard loan with 7 per cent interest rate.

Figure 9: Distribution of Net Benefits Over Lifetime of Mortgage Under Different Rebound Scenarios €



Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to B2 or higher and "Fragmented World". Five-year standard loan with 7 per cent interest rate.

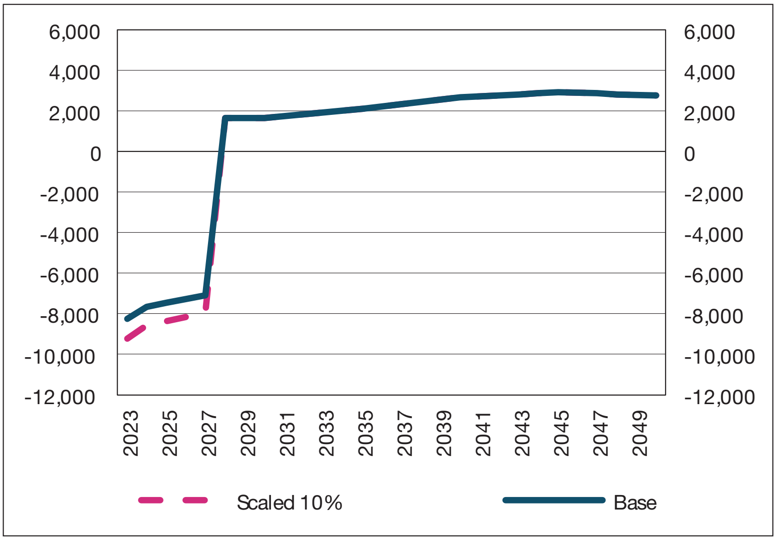
4.5 Sensitivity Analysis

In our analysis, investment costs of retrofitting are estimated using an SEAI National Home Energy Upgrade scheme dataset of completed retrofits. We recognise that households that have undertaken a retrofit may differ systemically from those that have not, i.e. households may have chosen to retrofit partially due to the cost. This could lead to an underestimation of upfront investment costs for households that have yet to undertake a retrofit. By contrast, as the sample is focussed on large scale retrofits, there may also exist bias in the opposite direction.

In this section, to address this potential underestimation of costs, we introduce a sensitivity analysis that scales investment costs upward. Specifically, we create a scenario where retrofit costs are increased by a fixed percentage (e.g. 10 per cent) to account for the possibility that future retrofits may involve more complex or expensive upgrades. This allows us to assess the robustness of our findings under higher cost assumptions.

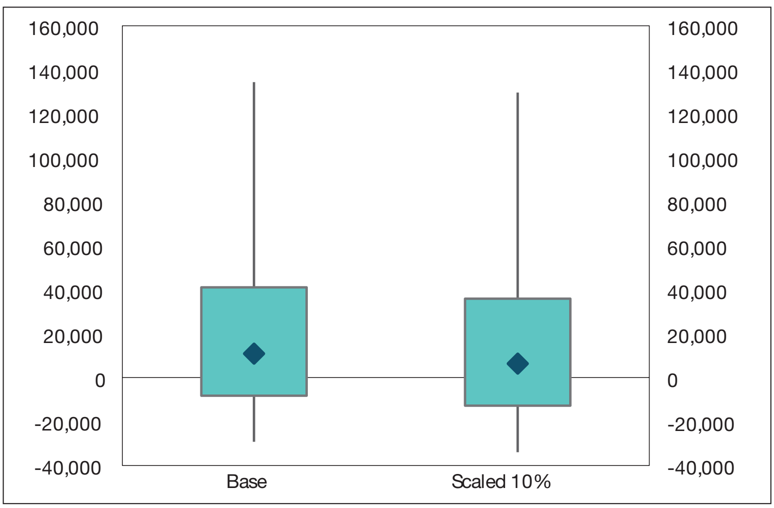
In Figure 10, we show that over the first five years, net cost is approximately €1,000 per year higher (€70-80 per month) if the initial investment cost is scaled upwards by 10 per cent. This results in household net benefit over the lifetime of the mortgage falling by approximately €4,000 (Figure 11). This may necessitate greater financial support, i.e. higher grant support or low-interest loans, to ensure retrofitting remains accessible to households, particularly those in lower income brackets.

Figure 10: Annual Net Costs/Savings Over Time Under Different Rebound Scenarios (Median) €



Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to B2 or higher, rebound 0.27 and "Fragmented World". Five-year standard loan with 7 per cent interest rate.

Figure 11: Distribution of Net Benefits Over Lifetime of Mortgage Under Different Rebound Scenarios €



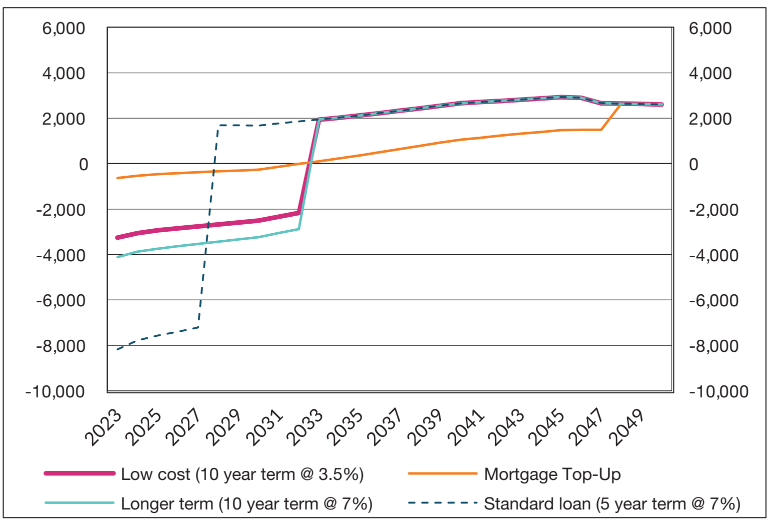
Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to B2 or higher, rebound 0.27 and "Fragmented World". Five-year standard loan with 7 per cent interest rate.

4.6 Illustrative Example

In this section, we take a "typical" (median) mortgaged household and simulate multiple outcomes dependent on loan term, interest rate, and loan type. In this regard, we use the median loan, borrower and property characteristics in the loan-level mortgage data between 2019 and 2023: outstanding balance of €200,000, mortgage interest rate of 3 per cent, mortgage term of 25 years, pre-retrofit BER D1 and post-retrofit BER B1 with a heat pump installed, and property size of 120 square metres.

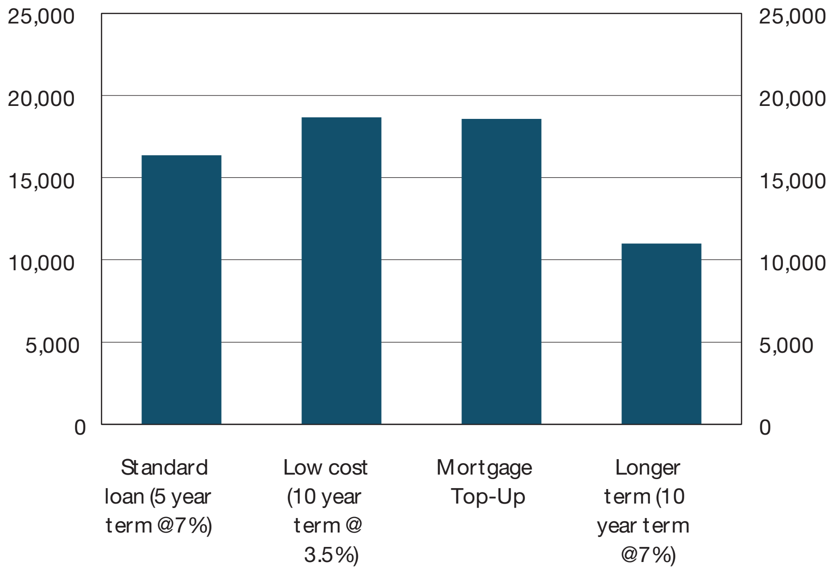
In Figure 12, we compare the trade-offs between the different financing approaches. Consistent with the above, it is clear that longer-term financing options (top-ups in particular) significantly reduce the initial negative cash flow impacts for households. Mortgage top-ups and longer-term loans at reduced rates also provide significantly higher long-term net returns compared to a standard loan or long-term loan with standard rates (Figure 13). Mortgage top-ups also exhibit the quickest payback period, with the "typical" household realising a net saving after 16 years. Payback periods are higher for other financing options, 21 years for the low cost option and up to 23 years for a long-term high interest loan. Although not shown explicitly in Figure 12 and 13 (due to lack of household savings data), the use of savings for the retrofit investment would also reduce interest payments. For example, if the median household paid half of the retrofit from savings, the cumulative net retrofit savings up to 2050 would increase from €10,950 to €13,050 (for ten-year loan with 7 per cent interest).

Figure 12: Illustrative Example for "Typical" Borrower – Annual Net Costs/Savings under Alternative Scenarios €



Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to B2 or higher, rebound 0.27 and "Fragmented World".

Figure 13: Illustrative Example for "Typical" Borrower – Cumulative Net Savings up to 2050 €



Source: Own calculations using Central Bank of Ireland Monitoring Templates Data.
Note: Assumes uplift to B2 or higher, rebound 0.27 and "Fragmented World".

V DISCUSSION AND CONCLUSIONS

This study is among the first to provide a cost-benefit analysis of the household retrofit decision that explicitly accounts for the choice of financial instrument, the overarching policy goal to achieve retrofits to a certain energy efficiency standard and the expected financial costs to achieve the required upgrade. It uses a novel dataset of loan-level data merged with the most appropriate energy efficiency upgrade costs to estimate both short-run and long-run implications.

Our model allows us to test the financial implications of retrofitting under a range of alternative financing, behavioural and pricing scenarios. We note that this framework, while an appropriate setting to explore the scenarios under investigation, is not a complete assessment of individual household net benefits, as we are unable to consider the wider costs and benefits of retrofit, and the non-financial benefits that accrue to the homeowner, such as improved comfort and air quality. Although this study provides several insights into potential pathways, some phenomena are beyond the scope of the data and our analysis. We exclude some ancillary financial benefits – such as increased property value of a retrofitted home – which cannot be distinguished from overall property price rises within the data available. The latter, while beyond our scope, is clearly an important determinant of retrofit "viability" for adopters, with prior research showing large and statistically significant energy efficiency premiums in property sales data in Ireland (Carroll *et al*., 2024). Beyond this, the analysis is unable to address the other adoption/transaction costs of retrofits including time, inconvenience, and in some cases the real cost of temporary alternative accommodation during works. We also acknowledge that a wider nationwide retrofit scheme might adversely affect grant approval times, consumer interest in undertaking a retrofit and boost the demand (and price) of specialised labour. Skills shortages in this sector are known barriers to achieving the low-carbon transition (CCAC, 2023) and are an important area for future research.

Within our framework, we find that retrofitting leads to net savings for most households. However, the costs and savings accrue differently depending on the financing instrument chosen. For example, if the household finances their retrofit via a five-year "green" term loan (7 per cent interest), the householder experiences a net cost of €685 per month prior to loan clearance. However, once this loan is repaid, the householder can realise savings of €140 per month, on average. Longer loan terms and, in particular, financing through a mortgage top-up, alleviate such cash flow pressures considerably. Currently established retrofit loan schemes such as the SEAI Home Energy Upgrade Loan Scheme could encourage greater use of longer loan terms. We also show that households with lower starting BERs have the highest net savings, despite the higher upfront cost of deeper retrofits.

While not explicitly explored within our analysis, we acknowledge that there is likely significant heterogeneity in costs, benefits and access to retrofit finance. For example, prior research (Lambert *et al*., 2023) shows that those availing of green mortgages to date tend to have higher incomes (for higher value energy efficient properties). This suggests the potential for distributional inequalities over time, with wealthier households receiving a greater share of the financial benefit of retrofit. Our results demonstrate the long-term financial and environmental benefits of retrofitting, including increased property value, reduced energy costs, and progress toward decarbonisation goals. These findings underscore the importance of exploring tailored policy mechanisms to extend financing options to households that may otherwise be excluded. National retrofit schemes should seek to achieve a low carbon transition while providing benefits to all households, including those experiencing fuel poverty who may stand to benefit even more from retrofit (Coyne *et al*., 2018).

Savings also depend on behavioural factors, with higher rebound effects (increased household energy demand post-retrofit) leading to lower long-run energy-saving forecasts. Furthermore, we show that the benefits of retrofitting increase with higher fossil fuel prices and lower electricity prices. This result emphasises the importance of consistent complementary policies, such as carbon pricing to lock-in the long-term financial benefits of retrofits to homeowners. The current high and variable residential electricity price environment likely has negative implications for the rate of household switching to electrical heat (and transport).

To conclude, knowledge of the costs and benefits of retrofitting helps homeowners to assess their options when deciding to retrofit their homes. It also helps policymakers in devising incentives and loan schemes to effectively incentivise retrofit take-up, particularly among lower BER rated homes and among lower income households. To achieve Ireland's commitment to retrofitting 500,000 homes to a Building Energy Rating (BER) of B2, there is both a need for greater transparency on the upfront and lifetime savings of retrofitting, and for policy incentives to create the investment environment which facilitates private adoption. This study helps shed new light on these two key areas and serves as an important reference point for any policymaker grappling with decarbonising the built environment sector.

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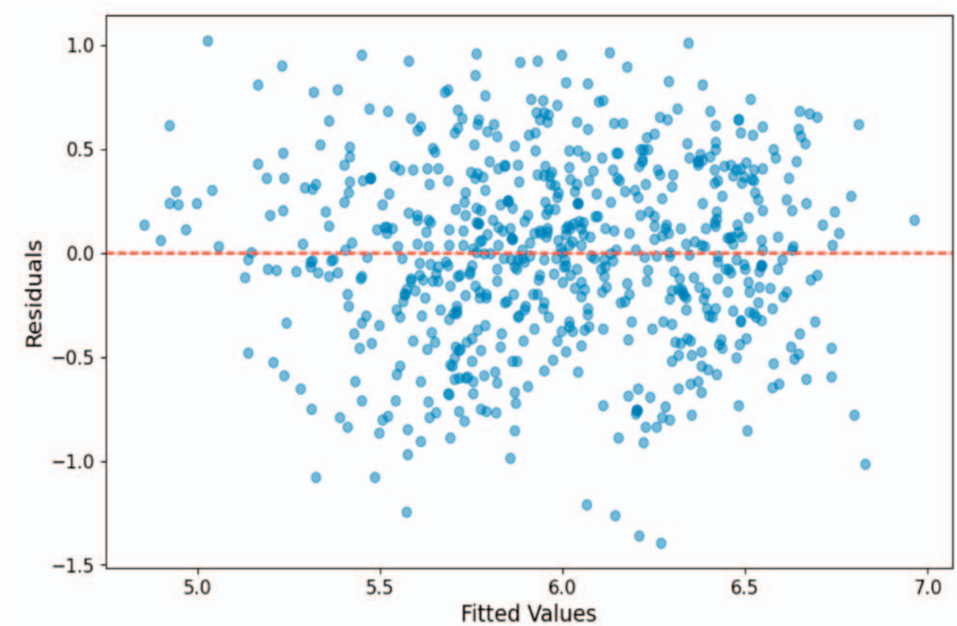
APPENDIX

Table A.1: Cost Model Results (OLS)

	Model Linear		*Model Log Cost with Interactions*		*Model Linear Cost with Interactions*	
	β	s.e.	*β*	s.e.	*β*	s.e.
Constant	927.3	63.9 **	6.353	0.085 **	585.1	42.7 **
S (Total Floor Area)	–9.241	0.860 **	–0.0057	0.001 **	–2.828	0.240 **
S^2	0.025	0.003 **				
E (Starting BER)	–0.796	0.200 **	–0.001	0.000 *	–0.128	0.121
E^2	0.000	0.000 **				
U (Uplift)	2.119	0.297 **	0.002	0.000 **	1.017	0.142 **
U^2	–0.002	0.000 **				
E*U					–0.001	0.000 **
Type: Detached (base)	—	—	—	—	—	—
Type: T_{SD}, Semi-Detached	40.542	22.079 †	0.470	0.119 **	83.07	22.37 **
Type: T_T, Terraced	–1.109	29.887	0.285	0.170 †	98.91	28.89 **
Type: Detached (base)*S						
Type: T_{SD}, Semi-Detached*S		–0.003	0.001 *			
Type: T_T, Terraced*S		–0.001	0.003			
R^2	0.495	0.460	0.437			
Adj. R^2	0.489	0.454	0.432			
F	83.873 **		78.913 **		88.73 **	
AIC	9336		808.35		9408	
BIC	9377		844.247		9440	
Log-Likelihood	–4659		–396		–4697	

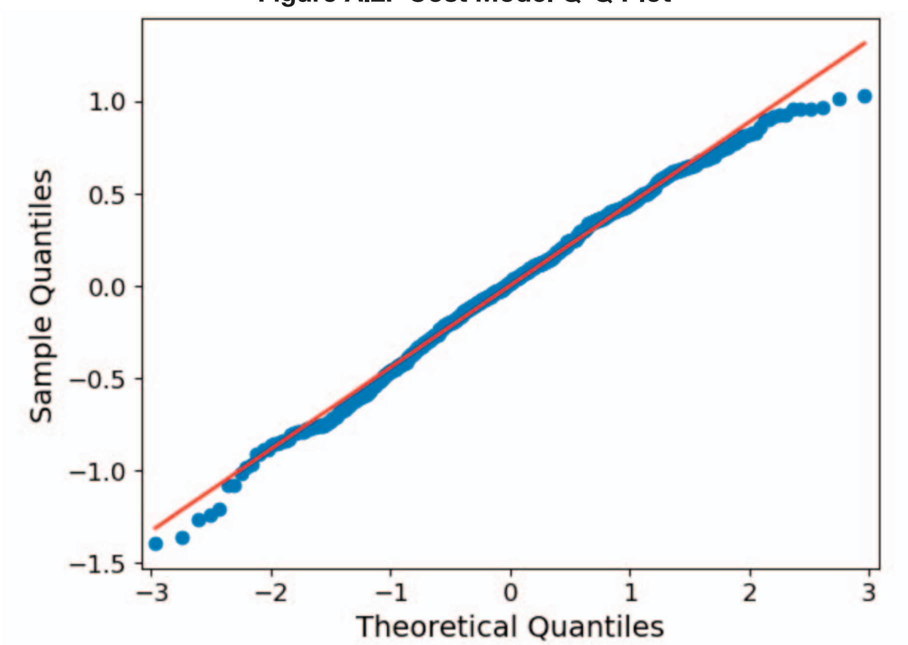
Source: Authors' analysis.
Note: ** $p < 0.01$, * $p < 0.05$, † $p < 0.1$.

Figure A.1: Cost Model Residuals Compared to Fitted Values



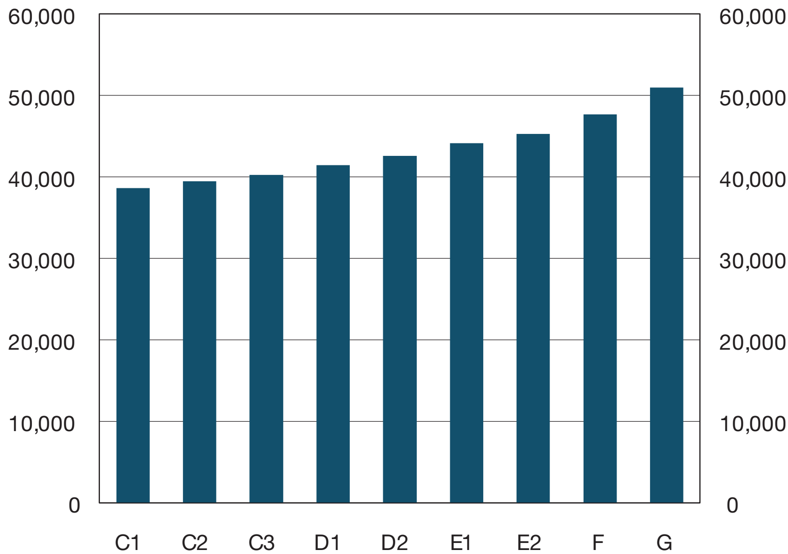
Source: Own estimates using SEAI One-Stop-Shop data.

Figure A.2: Cost Model Q-Q Plot



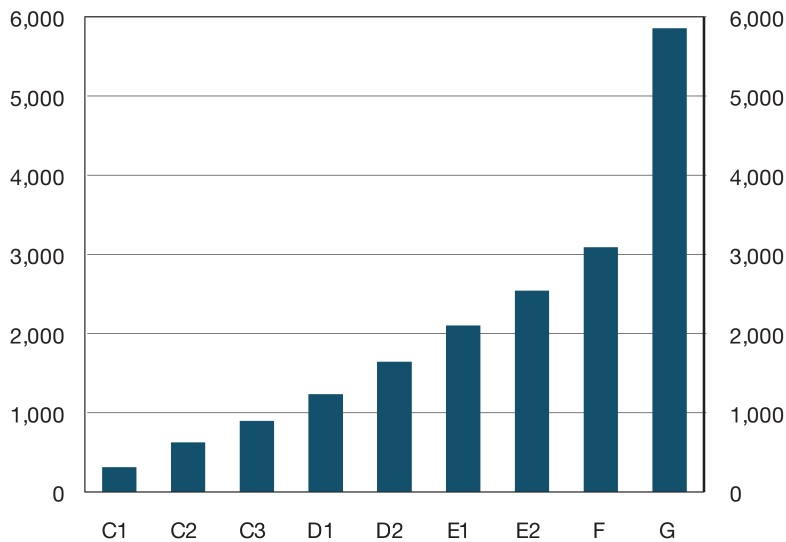
Source: Own estimates using SEAI One-Stop-Shop data.

Figure A.3: Total Investment Cost by BER Rating (Sample Median) €



Source: Own calculations using Central Bank of Ireland Monitoring Templates Data and SEAI data.
Note: Assumes uplift to B2 or higher.

Figure A.4: Annual Energy Savings Per Initial BER Rating (Median) €



Source: Own calculations using Central Bank of Ireland Monitoring Templates Data and SEAI data.
Note: Assumes uplift to B2 or higher.