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Empowering Homes? Unravelling the Connection Between Energy Efficiency and Well-being

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Abstract

We study how residential energy efficiency impacts well-being. We propose an innovative framework to assess the effects of investments in energy efficiency through the lens of energy poverty experiences. Leveraging a novel micro-level dataset of Irish households' and buildings' characteristics, we find that improvements in energy efficiency lead to modest im-provements in households capacity to afford adequate warmth. These effects are concentrated at the lower end of the energy efficiency and income distributions. Income emerges as the key determinant of energy poverty, while other household characteristics like home ownership also influence risk. Overall, the relationship between energy efficiency and energy affordability ap-pears to be weak. Our results suggest that energy efficiency investments are unlikely to deliver the large welfare and environmental benefits widely expected from them, raising questions about their role in achieving a just energy transition.

JEL classification: D74, L25, O15, O17
Keywords: Energy efficiency, energy poverty, well-being.

1 Introduction

Considered as one of the central pillars of modern energy policy, energy efficiency improvements often feature in national governments' climate and development strategies.[1] Investments in energy efficiency are considered to have the potential to simultaneously contribute as a solution to a range of pressing issues, including access to affordable energy, decarbonization of the economy, and poverty alleviation. In the building sector, energy efficiency improvements reduce the amount of energy services required to reach and maintain adequate indoor temperatures. Although a reduction in the relative price of heating services encourages more consumption, overall energy savings are anticipated as a result of increased efficiency. This should translate into a higher capacity for households to keep and afford adequate warmth. At a social level, lower energy consumption implies reduced greenhouse gas (GHG) emissions. This perspective often elevates energy efficiency to a "silver bullet" status, a view bolstered by various engineering studies that praise the cost-effectiveness of these investments (IEA, 2023; Laitner, 2013; McKinsey, 2010).

Vast amounts of resources are expected to be devoted to increasing energy efficiency across Europe. The European Green Deal recognizes the need for structural renovation of public and private buildings - during the next 10 years, the Social Climate Fund (SCF) is expected to provide up to €72 billion to support citizens to finance investments in energy efficiency and cleaner mobility.[2] At a national level, residential energy efficiency programmes have become essential to the governments' climate and development strategies due to their theoretical potential to support households' disposable incomes, reduce energy demand and meet emissions reduction targets.

Empirical evidence on the extent to which energy efficiency can achieve these outcomes is limited and less than encouraging. While engineering projections consistently estimate positive private returns as a product of large energy savings, mounting evidence suggests the contrary. Researchers have noted the inconsistency between large expected benefits and low observed levels of energy investments. Early studies provide explanations for the apparent inconsistency, mostly pointing towards behavioral issues (Allcott and Greenstone, 2012; Gillingham and Palmer, 2014), or market failures (Gerarden et al., 2017). Others identify issues limiting the potential energy efficiency investments including: the rebound effect (Aydin et al., 2017; Sorrell et al., 2009) and additionality

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[1] Ireland's Climate Action Plan key targets for the residential sector include retrofitting 120,000 dwellings to BER B2 or cost-optimal equivalent by 2025 and 500,000 dwellings by 2030 (Climate Action Plan, 2024).

[2] On 14 July 2021 the European Commission adopted the 'fit for 55' package, a set of legislative proposals to meet the new EU objective of a minimum 55% reduction in GHG emissions by 2030. The fit for 55 package is part of the Commission's European Green Deal, which aims to set the EU firmly on the path towards net zero GHG emissions (climate neutrality) by 2050. Together with a mandatory 25% contribution of the Member States to their Social Climate Plans, the SCF should mobilize at least €86.7 billion over the 2026-2032 period.

(Boomhower and Davis, 2020; Houde and Aldy, 2017). Nevertheless, this debate rests on the assumption that energy efficiency investments are indeed cost-beneficial. Recent empirical evidence challenges the commonly held assumption that investments in energy efficiency generate private returns through increased energy savings. The most robust evidence in the literature finds that the costs of energy investments far outweigh the benefits, even after accounting for positive environmental externalities (Allcott and Greenstone, 2017; Fowlie et al., 2018). Studies using a wide range of methodologies arrive at similar conclusions, engineering projects consistently overestimate energy savings (Chuang et al., 2022; Davis et al., 2020; Hancevic and Sandoval, 2022). So far, the literature has focused on monetary returns, leaving the relationship between energy efficiency and well-being largely understudied. The significance of this knowledge gap is underscored by the widespread implementation of energy efficiency interventions; the large public resources required to attain the goals set out by national governments; and the urgent imperative to decarbonise the economy.

This paper delves into three questions central to the energy efficiency debate. Firstly, it investigates whether there is empirical support for the notion that energy efficiency investments lead to substantial energy savings and reductions in emissions. Secondly, the analysis explores how the impacts of these investments vary across different socio-economic groups. Lastly, the paper examines the effects of these investments on overall well-being, with a specific focus on their role in mitigating experiences of energy poverty.

This paper focuses on the impacts of residential energy efficiency improvements. We propose a simple utility-maximization model to motivate our analysis. In our empirical framework, we model investments needed for obtaining higher energy performance ratings (EPCs) as a reduction in the relative cost of heating services. We introduce a theoretical minimum heating requirement into our model, which facilitates the exploration of the potential welfare effects associated with energy efficiency investments. Next, our empirical analysis considers Ireland's Building Energy Ratings (BERs) as a proxy for energy efficiency investments, and increases in households' self-reported capacity to keep and afford adequate warmth as improvements in well-being.

Leveraging on a novel and comprehensive micro-level dataset of Irish households', we exploit variation in homes' BERs to estimate the effects of energy efficiency investments on households' capacity to keep and afford adequate warmth - which are indicators of energy poverty experiences. Additionally, we investigate income and other household and dwelling characteristics as potential drivers of energy poverty. Our analysis pays particular attention to the interaction of these effects, uncovering the crucial role of income.

Our empirical strategy examines the link between energy efficiency and well-being. We argue that experiences of energy poverty are equivalent to tangible losses in well-being. If investments required to achieve a higher Building Energy Rating (BER) do not improve households' ability to maintain adequate warmth, it raises questions about the benefits of such investments on well-being. Results suggest that living in energy-efficient dwellings modestly increases the likelihood of maintaining and affording a warm home. Within the scope of our empirical framework, investments in energy efficiency have the potential to enhance welfare – consumption of alternative basic goods and thermal comfort increases, energy consumption and associated greenhouse gas emissions are reduced. However, the estimated effects are relatively small, and the correlation appears weak. Consequently, the energy savings may not realize the substantial benefits often projected by engineering models. Despite the uptick in welfare, the returns on investment may not be positive.

This paper makes three contributions to the energy efficiency literature. First, we propose an innovative framework to assess the impact of energy efficiency on welfare and well-being. Our methodology places a new emphasis on analyzing households' subjective perceptions regarding their capacity for adequate warmth. Our research sits at the forefront of the literature, analyzing the link between Energy Performance Certificates (EPCs) and the affordability of adequate thermal comfort, and exploring its implications on well-being.

Second, we are the first to exploit a micro-level dataset that integrates households' socioeconomic characteristics, dwellings' energy efficiency ratings, and both objective and subjective measures of thermal comfort affordability. This level of granularity surpasses previous research, allowing us to better control for alternative confounding factors. While recent studies have estimated the broader societal benefits of energy efficiency derived from such things as emissions reductions, little attention has been put to those from improvements in health, productivity, and overall well-being.

Third, our research adds valuable insights to the body of work studying residential energy efficiency programs. We find a notable inconsistency between projected energy savings and their real impact on enhancing households' ability to afford and sustain adequate warmth, questioning the programs' purported cost-effectiveness. Our analysis reveals how the impacts of energy efficiency are influenced by varying socio-economic factors and vulnerabilities. The evidence contributes to the debate on the energy efficiency gap, reinforcing the arguments that the limited adoption of energy efficiency programs stems from their relatively low objective - or perceived - returns. Moreover, our analysis suggests that the rebound effect is higher among low-income and energy-poor households. Investments that reduce the price of heating services should facilitate the consumption of a minimum level of thermal comfort. Therefore, improvements in well-being and energy poverty are considered to be a condition for meaningful reductions in energy consumption and

GHG emissions.

This study also makes special contributions to the literature on energy poverty. Our empirical analysis of the effects of energy efficiency investments on well-being is based on indicators commonly used to measure energy poverty. This dual-focus approach provides a novel perspective on the impacts of such investments on the real-world experience of energy poverty. This analysis is increasingly valuable as Europe embarks on costly transitions to a net-zero economy, with substantial investments in energy-efficient technologies that are not just expected to deliver large energy savings and GHG emissions reduction but also enable a socially just green transition. These large investments are expected to prioritize vulnerable groups. Therefore, analysis and monitoring indicators of well-being and energy poverty are crucial in evaluating the effectiveness and benefits of energy efficiency investments.

In addition to analyzing the effects of energy efficiency investments, our study identifies key drivers of energy poverty. Income emerges as the crucial factor, with home ownership and the absence of health issues significantly influencing energy poverty risks. Our findings offer insights into effective approaches for tackling energy poverty. Raising incomes is shown to mitigate the disparity in energy poverty between low and high-efficiency rated homes; and between owners and tenants. Additionally, direct subsidies for energy expenses appear to be a progressive and efficient short-term measure, offering greater benefits to occupants of lower energy-efficient homes.

2 Background

The global push towards sustainability and a low-carbon economy has brought energy efficiency to the forefront of the policy discourse.

Governments around the world are setting ambitious targets. The EU has recently updated its legislation. Changes made to the Energy Efficiency Directive entered into force in October 2023, including a new stronger binding target.[3]

Attaining these objectives will require massive investments in energy efficiency and technology adoption. Some of the purported benefits of energy efficiency investments include lower energy bills, environmental protection, climate change mitigation, quality of life improvements, energy security, and sustainable growth (EU, 2023).[4] It's anticipated that the benefits, derived from sub-

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[3] The Directive set a target of reducing EU final energy consumption by 11.7% by 2030, compared to the projected energy use for 2030. It recognized the particular change faced in the building sector, 75% of building stock in Europe has a poor energy performance.

[4] As a result of the Russian invasion of Ukraine, reducing the EU's reliance on external suppliers of oil and gas has become increasingly important.

stantial energy savings and associated positive externalities, will outweigh the considerable costs.

These positive expectations are mainly supported by engineering models' projections, developed by private consultancies or government agencies themselves (McKinsey, 2010). Advanced building energy simulation programs like EnergyPlus, developed by the U.S. Department of Energy, are used to estimate the energy and environmental performance of a building by considering the interaction of all the building components and systems. In Ireland, the cornerstone of the Sustainable Energy Authority's (SEAI) modelling is the BER system, which assesses the energy performance of buildings. This system assigns an energy label to the building, similar to the labels found on household appliances, ranging from A (most efficient) to G (least efficient). The rating is based on the characteristics of major components of the building such as walls, roof, windows, heating system, lighting, and ventilation. For residential buildings, SEAI uses DEAP, a software tool used for BER assessments and to demonstrate compliance, it calculates the energy performance and CO2 emissions of a dwelling based on its design and specifications above.[5]

Energy Performance Certificates (EPCs) and inspections, e.g. the BER system, are designed to inform consumers and policy-makers about the energy efficiency of buildings. Certificates include energy performance ratings, which allow for better selling and buying decisions; and recommendations for cost-effective improvements that inform parties in a transaction about potential energy savings and carbon emissions reductions (EU, 2023) [6]. EPCs have become widely used as policy metrics. They are used to identify and monitor energy poverty, e.g. the Low-Income Low-Energy Efficiency indicator (LILEE). In the building sector, they are used as indicators of the progress made towards achieving carbon reduction goals (Economidou et al., 2020). Furthermore, residential energy efficiency programmes commonly set their targets based on EPCs ratings. These programs' strategies rely on supporting home retrofitting and energy efficiency upgrades. They require substantial public investment, Ireland's plan to retrofit half a million dwellings is expected to amount €8 billion (DECC, 2021).

For the expected benefits to come to fruition, investments and technology adoption must translate into meaningful energy efficiency gains. This implies that individuals and businesses must able to effectively consume less energy whilst achieving similar outcomes, such as adequate temperatures. Current modeling methodologies are quite sophisticated. Yet, there's still limited empirical evidence on the actual energy savings, broader welfare effects, and impacts on well-being from investing in energy-efficient technologies. The road towards sustainable and just energy transition is fraught with challenges, recent evidence cast doubts on the potential of energy efficiency

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[5] BER assessments are carried out by independent registered assessors.

[6] Following the Energy Performance of Buildings Directive (2010/31/EU), all EU countries have established independent control systems for energy performance certificates and inspection reports for heating and cooling systems.

investments to yield the anticipated results.

While engineering projections consistently estimate positive private returns as a product of large energy savings, evidence from empirical studies evaluating residential energy efficiency programmes suggests the contrary. The most credible evidence on residential retrofit programmes finds returns on investment are negative. In the U.S., Fowlie et al. (2018) studied the Federal Weatherization Assistance Program (WAP) by conducting a randomized control trial with a sample of more than 30,000 households in Michigan. They estimate that actual energy savings cover only half of the upfront investment costs. Notably, they find no significant indoor temperature difference post-weatherization, bringing into question the energy efficiency gains of subsidized energy upgrades. Their results hold even after accounting for environmental externalities from reduced emissions - energy efficiency investments do not pass private or social cost-benefit tests. Although data limitations prevent us from making a comparison between actual energy savings estimates with investment costs, our empirical framework provides a simple and straightforward way to assess whether the effects of energy efficiency improvements have a meaningful effect on households' thermal comfort and their capacity to afford necessary energy services.

Allcott and Greenstone (2017) use a randomized experiment subsidizing energy audits and administrative data together with a structural model to analyze two home energy retrofit programs in Wisconsin. Once again, the evidence points to low realized energy savings - less than 60 percent of projections. Furthermore, subsidies seem to fail at targeting investments with the highest environmental benefits. As a consequence, they estimate negative effects on welfare - the marginal value of public funds (MVPF) suggests that for each dollar subsidized, the consumer, producer, and environmental benefits increased by only \$0.93. Why do agents choose to make investments with negative private and social returns? Their evidence suggests households make decisions considering non-monetary factors like hassle costs, aesthetics, comfort, and satisfaction from pro-environmental behavior. Our study contributes to this literature by evaluating non-monetary investment benefits through households' self-assessments of their ability to keep and afford adequate warmth.

Studies using a wide range of methodologies arrive at similar conclusions. Chuang et al. (2022) use billing data of more than 11 million households adopting residential energy efficiency upgrades through subsidy programmes and find that most of them have small energy-saving effects. For example, heat pumps and other HVAC retrofits reduce electricity consumption by less than one percent. Evidence from a field experiment in Mexico shows that energy-efficiency upgrades did not have any effect on thermal comfort. Electricity was projected to decrease by 26 percent, but no effect was identified. The authors speculate that behavioral factors compromise the potential impacts of insulation and other energy upgrades, making costs outweigh the benefits (Davis et al., 2020). Local residential energy efficiency programmes are popular because of their closer contact with the communities and potential to better target vulnerable groups. Hancevic and Sandoval (2022) analyze the Low Income Energy Efficiency Program Plus (LEEP Plus), energy efficiency upgrades appear to have zero effect on gas consumption but reduce electricity consumption by seven percent, proving insufficient to offset investment costs.

It is important to bear in mind that investments that improve homes' energy efficiency reduce prices of energy services, which incentives demand. The associated increase in energy consumption is referred to as the rebound effect. The potential for this effect to limit the expected climate and environmental benefits of investments has captured the attention of researchers and policy makers. Aydin et al. (2017) show that the effects are influenced by household characteristics. While among homeowners the rebound effect is estimated at approximately 27 percent, tenancy status could further increase it by 17 percent. Overall, estimates for household heating suggest that most engineering models largely overestimate energy savings — the identified average effect is close to 50 percent of projected savings. Importantly, the effect is likely to be larger among low-income households (Sorrell et al., 2009). Residential programs that subsidize energy efficiency investments must also deal with issues of additionality - investments that would have occurred within the market, or at lower levels of subsidy. Empirical estimates suggest that up to 50 percent of program participants would invest in energy-efficient technologies, even without a subsidy. This limits the impact of programs on long term energy demand, and suggests that large amounts of subsidies are unlikely to be cost-effective (Boomhower and Davis, 2020; Houde and Aldy, 2017).

Another strand of the literature analyses the effects of energy efficiency regulation — legislative mandates that introduce building codes with standards aimed at reducing energy consumption and associated carbon emissions.[7] Evidence from California shows mixed results. Levinson (2016) compares the energy use of households built under different standards within California and between states. His results suggest that changes in energy performance associated with the implementation of building standards do not yield the projected results. By contrast, Novan et al. (2022) use hourly household smart-meter data to reexamine California's minimum efficiency standards. Their pre-post analysis estimates that houses built just after 1978 use between 8 percent and 13 percent less energy, making the policy pass their cost-benefit test. Using high-frequency data of Irish households, Meles et al. (2023) provide evidence suggesting that the differences in energy efficiency ratings have negligible effects on indoor temperatures and the rate of heat loss

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[7] In Ireland, new building standards require residential dwellings constructed after November 2019 to have an A2 BER.

- an approximation of actual energy performance of dwellings. Arguably, these results raise two potential hypotheses. One, investments made to meet energy efficiency standards might not realize the expected efficiency gains — achieving adequate heating using less energy. Second, EPCs do not accurately capture buildings' actual energy performance. We contribute to this strand of the literature by assessing whether higher energy efficiency ratings improve households' capacity to keep or afford a warm home. Our results support evidence questioning the cost-effectiveness of minimum performance standards.

Beyond energy savings and GHG emissions reductions, the primary purpose of energy investment packages like the SCF is to facilitate a socially fair transition to a green economy. This implies protecting the most vulnerable from the effects of a costly energy transition. In this context, the SCF aims to contribute to a reduction in energy poverty. Energy poverty is recognized as a major challenge in Europe. Structural measures, in particular building renovations and access to energy from renewable sources, are considered to be crucial long-term and lasting solutions to energy poverty. Will these investments manage to reduce energy poverty while reducing energy consumption and emissions? Our study provides valuable insights to answer this empirical question.

The connection between energy efficiency and well-being receives a lot of attention in regulatory documents and policy discussions, yet it remains understudied in the academic literature.[8] There's a growing interest in how energy efficiency improvements impact energy poverty, but few studies have delved into this area. Our study addresses this gap, focusing on the impact of energy efficiency investments on various well-being and energy poverty indicators. We examine how energy efficiency, along with other factors related to households' socioeconomic and dwellings' characteristics, influences aspects like the ability to heat homes affordably, the occurrence of unpaid energy bills, and a combined well-being measure. Analyzing this relationship provides a simple but effective method to evaluate the benefits of energy efficiency investments and their contribution towards a sustainable and equitable energy transition.

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[8] Energy Efficiency and Energy Efficiency of Buildings Directives require efforts to improve energy efficiency alongside alleviation of energy poverty.

3 Data

We leverage a novel micro-level dataset that combines the European Union Survey Income and Living Conditions (EU-SILC) for Ireland with the Domestic Building Energy Ratings Register from the SEAI (BER dataset).[9] The EU-SILC collects comprehensive data on households' economic characteristics and aspects of social exclusion throughout Europe. The EU-SILC data offers two main advantages: it includes information suitable for well-being assessment, and it is updated annually, providing consistent and timely data. For these reasons, it has become a popular resource to monitor energy poverty.[10] The BER dataset comprises data on dwellings' with an Irish EPC, including information on energy performance ratings —ranging from A to G — among other characteristics.[11]

The novel SILC-BER dataset offers a unique opportunity to analyze the effects of buildings' energy efficiency on well-being, specifically through the lens of energy poverty. It provides a rich set of household-level controls, including socio-economic characteristics, electricity demand, and main heating sources, thereby facilitating robust analysis. Additionally, we enhance our analysis by incorporating domestic energy prices from SEAI to assess the impact of energy costs. [12]

Our empirical analysis focuses on data spanning the period 2016 to 2022. The full sample size of the BER-SILC dataset consists of 11,103 household-level observations, representative of the Irish population. For purposes of the econometric analysis, we use a sub-sample of 7,283 households. The reduction in the number of observations responds to our data cleaning and validation process - we keep only those observations for which we are certain that the dwellings' energy performance rating at the time of the survey is correctly identified. [13] These data are used to study the relationship between buildings' energy efficiency and the probability of households falling into energy poverty. Summary statistics of relevant variables used in the econometric analysis are presented in Table 1. [14]

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[9] We provide a summary of the dataset construction process and outline some important particularities inherent to the merged data in the Appendix.

[10] The European Commission's initiative, Energy Poverty Advisory Hub (EPAH) research work on indicators for effective energy poverty measurement provides important information on the sources, and technical details associated with them (Gouveia et al., 2023, 2022)

[11] Access to these data was made possible by the collaboration between Ireland's Central Statistics Office (CSO) and the Economic and Social Research Institute (ESRI) in the framework of the Research Program on Energy Poverty (RPEP). Further information on the BER-SILC database is provided in the Appendix - construction, variable description, special considerations and limitations.

[12] For broader context on Ireland's economic and demographic trends, we use the full yearly EU-SILC microdata in some of our descriptive statistics, these span the period from 2004 to 2022.

[13] A full explanation of the sub-sample construction process is presented in Appendix.

[14] Table 3 presents summary statistics for the full set of relevant variables available in the dataset.

Table 1: Descriptive Statistics

	n	mean	sd	min	max
Incapable to keep adequate warmth (IKAW) $\in (0,1)$	7,558	0.0597	0.237	0	1
Incapable to afford adequate warmth (IAAW) $\in (0,1)$	7,558	0.0992	0.299	0	1
Arrears on utility bills (AEB)$\in (0,1)$	7,431	0.0907	0.287	0	1
Composite indicator (CI)$\in (0,1)$	7,558	0.160	0.367	0	1
At risk of poverty $\in (0,1)$	7,558	0.174	0.379	0	1
Consistent poverty $\in (0,1)$	7,558	0.0744	0.262	0	1
Total HH gross income (€/month)	7,558	5,174	3,929	0	19,966
Total HH net income (€/month)	7,558	4,033	2,502	2.271	17,278
Current rent of dwelling (€/month)	2,523	552.2	504.1	3	4,000
Tenant status$\in (0,1)$	7,470	0.338	0.473	0	1
Total housing costs (€/month)	7,555	549.2	397.9	0	4,380
Energy expenditure estimation (€/month)	7,555	271.1	139.5	0	2,898
At least 1 65+ in HH $\in (0,1)$	7,558	0.254	0.435	0	1
Single adult with children $\in (0,1)$	7,558	0.0581	0.234	0	1
Poor health $\in (0,1)$	7,554	0.0585	0.235	0	1
Chronic illness $\in (0,1)$	7,548	0.356	0.479	0	1
Household size (number of individuals)	7,558	1.861	0.751	1	5.620
Total habitable floor area (m^2)	7,558	108.5	47.91	11	603

Note.- The table shows national-level averages of our variables of interest. Differences in observations are explained by the characteristics of the specific variable. For example, only households with tenant status pay rent. *Source:* own calculations using BER-SILC sample observations for econometric analysis.[a]

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[a] "Results are based on analysis of strictly controlled Research Microdata Files provided by the Central Statistics Office (CSO). The CSO does not take any responsibility for the views expressed or the outputs generated from this research."

To assess changes in households' well-being, we employ two questions that provide us with households' assessments of their experienced thermal comfort and financial ability to afford essential heating services. The first question, *"Does the household keep the home adequately warm?"* probes into the residents' perceived level of thermal comfort, offering insights into their living conditions and the adequacy of their heating solutions.[15] The second question, *"Have you ever had to go without heating during the last 12 months due to lack of money?"* specifically targets the economic aspect, exploring whether financial constraints have impacted the ability to maintain a warm living environment. Additionally, we rely on another question that provides a direct measure of energy services affordability, "*In the last 12 months, did it happen that this household was unable to pay utility bills such as electricity, and heating, due to financial difficulties?"* We use these questions to build four well-being indicators: inability to keep adequate warmth (IKAW), inability to afford adequate warmth (IAAW), arrears on energy bills (AEB), and a composite in-

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[15] The CSO codes the associated deprivation variable for this questions as one when a respondents report not being able to keep adequate warmth due to financial reasons.

dicator (CI) that identifies when households report experiencing any of the above. Together, these indicators provide a comprehensive view of how well-being is influenced by both physical comfort and economic capability.

The IKAW and IAAW are referred to as subjective indicators because they are based on a consensual approach where individuals self-report their assessment of indoor housing comfort and conditions to meet specific energy necessities. By contrast AEB, while also self-reported, falls into the category of objective indicators because it measures specific financial outcomes—namely, situations involving overdue energy bills. In this context, we argue that changes in well-being can be effectively approximated by these indicators. Furthermore, these indicators have been extensively used to study and monitor energy poverty. Energy poverty is experienced in different ways and depends on individuals' choices. For example, a household might decide to save energy and suffer from lower temperatures while another might decide not to, even if that means becoming indebted. Our analysis aims to capture variation in well-being while accounting for the different mechanisms that influence energy poverty experiences. Henceforth, we use these indicators in their capacity as energy poverty indicators. Moving forward, we will employ these indicators specifically in their capacity as measures of energy poverty.

Descriptive statistics in Table 1 show the average energy poverty rates during our period of analysis. Six percent of Irish households were not able to keep a warm home; ten percent report being incapable of affording adequate warmth: and nine percent have arrears on their energy bills. Meanwhile, the composite indicator suggests approximately 16 percent of households experienced energy poverty. The differences between our indicators reveal that, while highly correlated, these energy poverty indicators do not necessarily capture the same individual experiences of energy poverty. For example, 56 percent of those reporting not being able to afford adequate warmth did not report not being able to keep adequate warmth. This provides suggestive evidence that individuals engage in "energy poverty mitigation behaviors"; and shows that focusing on a single indicator could underestimate the real number of households experiencing energy poverty difficulties. Alternatively, 55 percent of households with arrears do not report being incapable of affording adequate warmth. This suggests that some households might face arrears on their energy bills for reasons other than energy poverty.

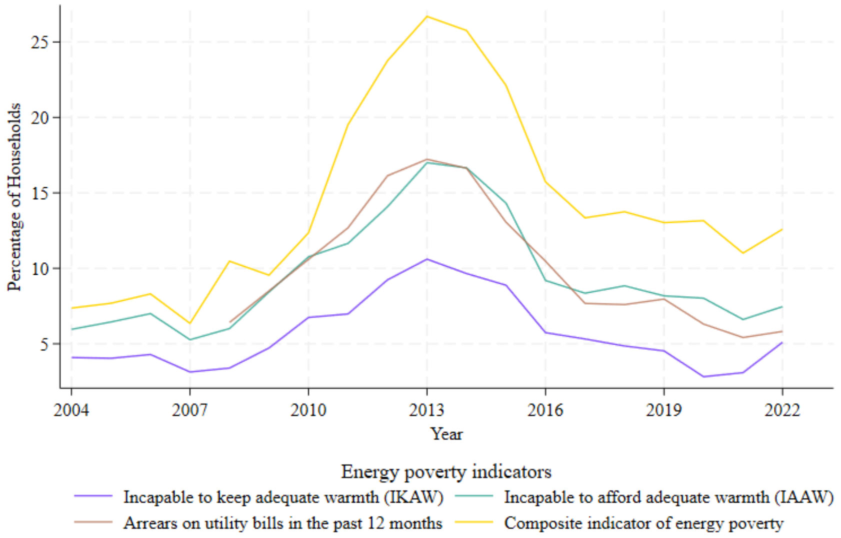

Figure 1: Energy poverty in Ireland

Note.— The Figure shows the trends of our indicators for all available years. *Source:* full SILC micro-level database.

Figure 1 presents trends in our indicators from 2003 to 2022. Notably, during this period, six percent of households reported issues with maintaining adequate warmth at home, while ten percent struggled with affording it. This difference suggests that there are diverse mechanisms through which energy poverty experiences arise, such as inadequate home insulation and overall energy performance or budget constraints. It highlights the interconnections of well-being with dimensions of poverty, as well as the potential substitution patterns between consumption of essential goods like heating, food, and transportation. A point to consider is that these differences might be influenced by what behavioral economics refers to as "social desirability bias."[16]

The descriptive statistics and trends of our indicators closely align with those of general poverty and deprivation indicators, showing a clear relationship. Table 1 shows that 7.5 percent of the population suffer from consistent poverty, and 17 percent are identified to be at risk. [17] In our sample, about 40 percent of households facing energy poverty also fall into the at-risk category for poverty. This data underscores the significant intersection between energy poverty and other

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[16] This occurs when respondents in surveys give answers that they believe are more socially acceptable or desirable, rather than providing truthful or accurate responses.

[17] In Ireland, the CSO uses the following definitions of poverty An individual is defined as being at risk of poverty if their nominal equivalised disposable income is under the at risk of poverty threshold, i.e. 60% of the median nominal equivalised disposable income. The consistent poverty measure is defined as people who are both at risk of poverty and experiencing enforced deprivation.

forms of deprivation, particularly income poverty. This comparison highlights the overlap between energy poverty and other types of deprivation, particularly income poverty.

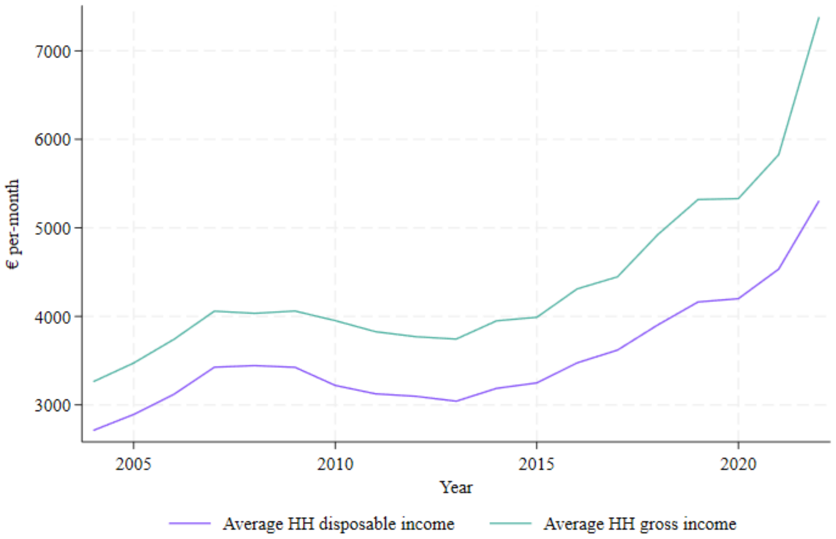

Figure 2: Income trends in Ireland

Note.— The Figure presents average national income trends in Ireland. *Source:* full SILC micro-level database.

Energy poverty and income are strongly intertwined. In some standard definitions, energy poverty is defined as a function of income. For example, an individual or household can be considered energy-poor if more than ten percent of their disposable income is devoted to energy services (>10% indicator). Definitions also rely on a combination of factors, e.g. if they are considered to have low income and also experience high-energy costs (LIHC) or low energy efficiency (LILEE).[18] Our approach in this paper is not to analyze those measures themselves but to identify the impact that income has on self-reported measures and experiences of energy poverty. Figure 2 shows income trends in Ireland. Their fluctuation and overall positive trajectories are consistent changes and the decrease in self-reported energy poverty. Between 2016 and 2022, average incomes in Ireland have increased by 34 percent, while energy poverty has decreased by eleven percent. In our econometric analysis, we explore how differences in income affect the probability of experiencing energy poverty.

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[18] In Ireland, the definition of low income is often linked to the concept of being "at risk of poverty." The SILC uses the threshold of 60% of the median equivalised disposable income to determine this risk. Low energy efficiency relies on energy performance ratings, e.g. in the UK a category D or lower.

Figure 3: Energy Efficiency of Irish Homes

Note.— The Figure presents an approximation of the average dwelling energy efficiency of Ireland's housing stock. Columns display the distribution of dwellings' energy efficiency over time. Calculations made using . *Source:* own calculations using BER-SILC sample observations.^{a}

To study the effects that improvements in energy efficiency have on well-being, we analyze the variation in buildings' energy performance ratings. Figure 3 shows that the energy efficiency of the Irish housing stock has improved during the past seven years. We observe the proportion of A- and B-rated homes increasing, while the proportion of D-rated and other less energy-efficient homes decreases. For example, the share of B-rated homes increased 26 percent - from 14.8 to 18.08. Meanwhile, E-rated homes were reduced by a similar amount - from 11 to 8.8 percent. In this paper, we will estimate the probability of experiencing energy poverty depending on dwellings' energy performance. Additionally, we use and alternative strategy to estimate the effect of an average increase in the share of high-efficiency homes on Irish county-level energy poverty rates.

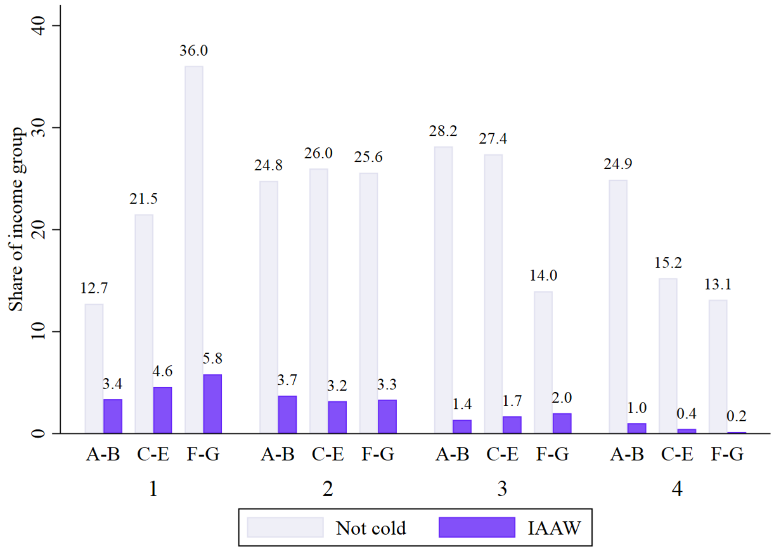

Figure 4: Energy Efficiency, Incomes, and Energy Poverty

Note: The Figure displays the share of households across energy efficiency categories $\in (A - G)$, over income quartiles $\in (1-4)$. Observe the negative trend of income, and the higher share of energy-poor among the low-energy-efficiency rated households. *Source:* Own calculations using BER-SILC sample observations.^{a}

Households' income and the quality of the dwelling they live in are arguably two of the most important determinants of their capacity to afford adequate energy services. Interesting insights on their role are provided by Figure 4. It displays the share of households unable to afford adequate warmth across energy efficiency groups, over income quartiles. First, we observe that higher energy efficiency homes (A-B) are inhabited mostly by households in the top-half of the income distribution (3 and 4) , while lower-efficient homes (F-G) are inhabited by low-income households (1). Second, there is a slightly negative relationship between energy efficiency and affordability — 11.3 percent of households in low-efficiency homes (F-G), compared with 9.9 percent of households in (A-B) report being IAAW.[19] Third, there is a clear negative relationship between energy affordability and income - for every efficiency category group, much larger shares of households report being unable to afford adequate warmth in the bottom quartiles of the income distribution (1 and 2). These patterns provide preliminary evidence supporting our priori expectations - higher incomes and energy performance are negatively correlated with energy poverty experiences.

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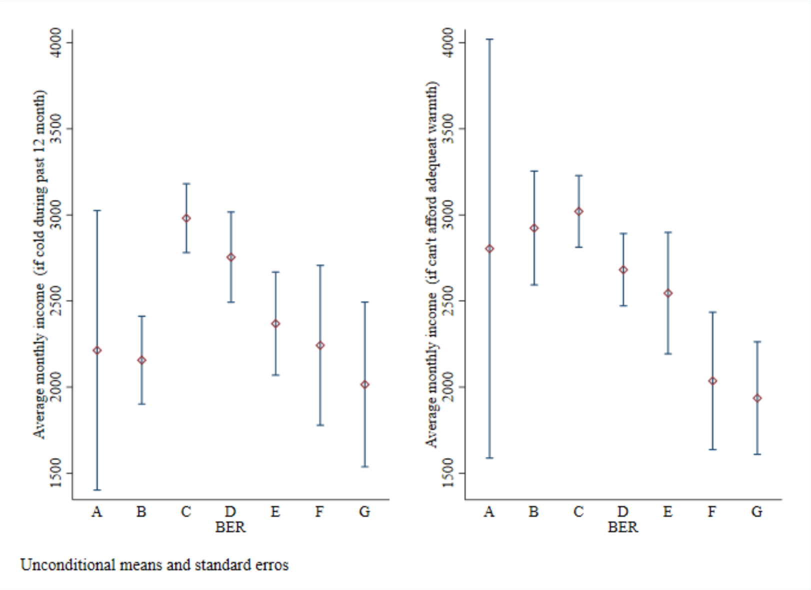
[19] Calculate by summing the shares of IAAW of an energy efficiency group across income quartiles.



Unconditional means and standard erros

Figure 5: Disposable income of the energy-poor across BER

Note: The Figure plots average households' disposable income and standard deviations of energy-poor households across energy rating groups. *Source:* Own calculations full BER-SILC data observations.[a]

High-income households are generally more capable of affording high-quality housing, either as owners or renters. Hence, we expect a positively correlation between these two variables. Figure 5 presents the average disposable incomes across energy efficiency groups for our group of interest, the energy-poor according to two subjective indicators. Surprisingly, we observe that beyond the positive correlation between energy performance ratings and income, households living in high-efficiency buildings (A and B) exhibit substantial variation in disposable income. This indicates that residing in a highly-rated dwelling does not equate to having a high income.

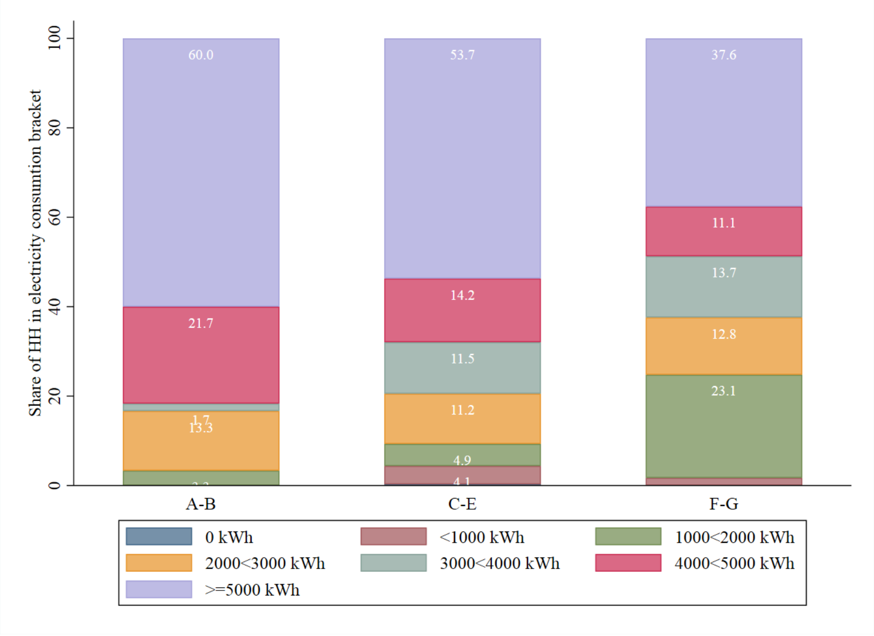


Figure 6: Energy efficiency and electricity consumption

Note: The Figure displays the share of electricity consumption brackets across energy efficiency categories for households reporting electricity as the main heating source. Observe that high-energy-efficient homes consume the most. *Source:* Own calculations using BER-SILC sample observations. ^{a}

While it's tempting to jump to the conclusion that households living in high-energy efficiency buildings will consume less electricity, there are reasons to believe otherwise. For instance, wealthy households living in high-energy efficiency buildings could consume more energy because they own an electric vehicle or other appliances. By contrast, low-income households living in F-rated buildings might ration the hours that the heating is turned on. Figure 6 suggests that this is the case. Among households who's main heating fuel is electricity, almost 50 percent of those living in A- and B-rated buildings consume more than 4000 kWh, compared to only 30 percent of F- and G-rated households. These consumption patterns reflect income differences and suggest that energy is a normal good. Households living in A-rated homes have average disposable incomes of 5,300 euros per month, approximately 40 percent larger than that of G-rated households.

These combinations of income, energy efficiency, and electricity consumption patterns deserve further examination. They are in line with the intuition that household consumption behavior changes according to their perception of how much they can afford to spend on electricity, perceptions which are informed by the energy efficiency of their dwelling. Alternatively, it is also possible that regardless of their income, households with a preference for comfort self-select into high-energy efficient dwellings. These patterns are consistent with the well-documented "rebound effect" (Sorrell et al., 2009).

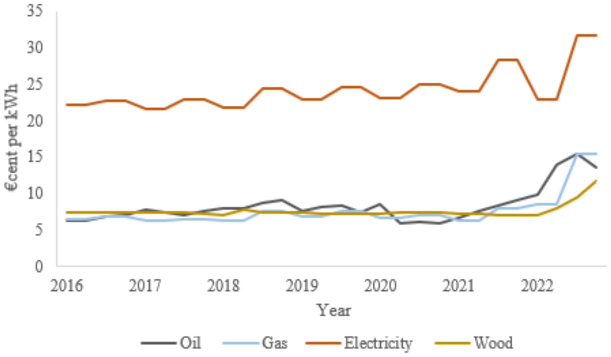


Figure 7: Domestic energy prices in Ireland

Note: The Figure presents the price time series for our period of analysis of domestic rates of kerosene oil, bagged wood pellets, and average domestic rates for gas and electricity. *Source:* SEAI.

Households' disposable income are sensitive to energy prices. In Europe, the dependence on energy imports leaves many low-income households vulnerable to price shocks that might leave them unable to pay their energy bills or force them to reduce consumption to the point of falling into energy poverty.[20] We account for energy prices in our econometric by including the price of fuels used in households' main heating systems. Figure 7 shows stable domestic energy prices until 2021 when they started to rise as a consequence of the COVID-19 pandemic and the Russian invasion of Ukraine. The average price of electricity during the period of the analysis is 24 €/kWh, three times larger than the price of the remaining fuels which average approximately 7.95 €/kWh. [21] At the moment, it is difficult to asses the impacts of these recent price spikes on energy poverty. And, as a consequence of overall low variation in energy prices, we do not expect to identify a significant effect of energy prices on energy poverty.

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[20] Note that energy prices are implicitly accounted for in alternative definitions of energy poverty. For example, expenditure-based indicators: energy poor if disposable income after energy expenditures > 10 percent.

[21] Domestic electricity customers received two account credits of €200 between January and June 2023. Due to its popularity, a similar intervention is programmed for 2024.

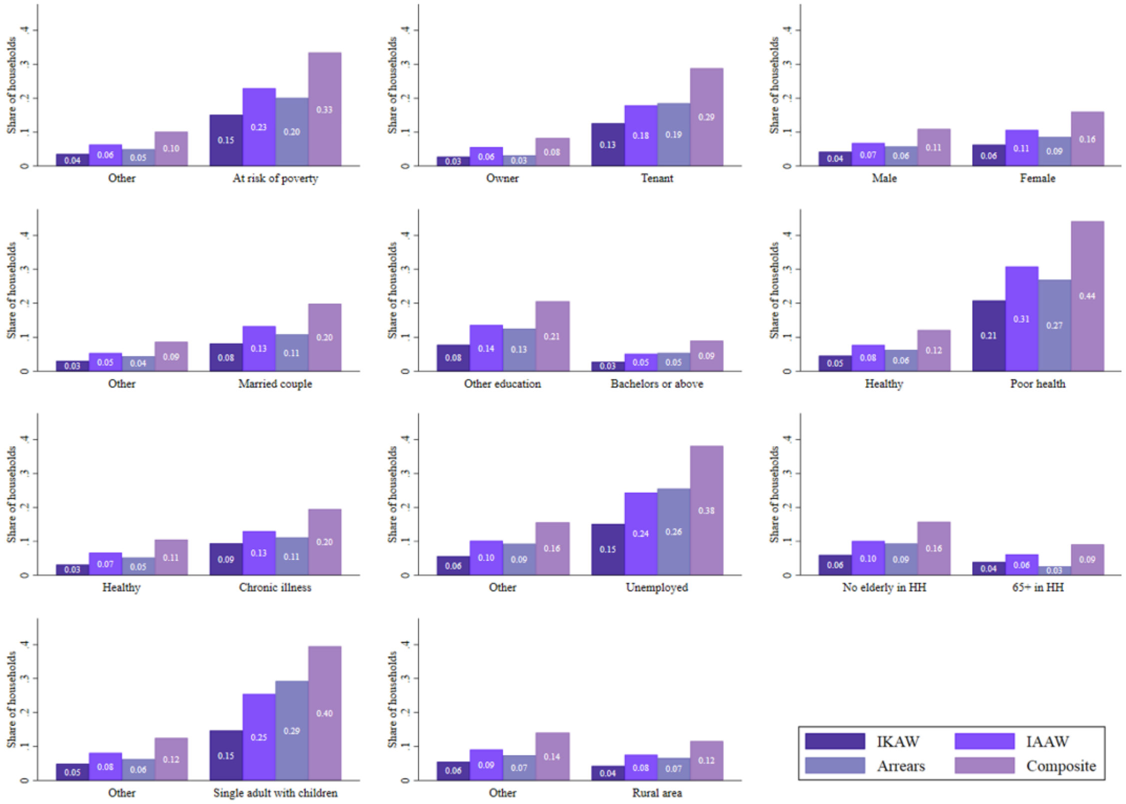

Figure 8: Energy poverty across vulnerable groups

Note.— The Figure presents the share of energy-poor across vulnerable groups and other socioeconomic characteristics. Averages for the period 2016 - 2022 are calculated using BER-SILC sample observations. *Source:* Own calculations full BER-SILC data observations.[a] [a]

In an effort to make the best use of limited resources, governments aim at improving the targeting of policies. This is true for policies designed to tackle energy poverty, such as direct cash transfers, or retrofitting subsidies. Therefore, this paper pays special attention to demographic and socioeconomic groups that are potentially vulnerable to energy poverty. Summary statistics of our sample data, presented in Table 1, suggest that 25 percent of Irish households have at least one elderly person; almost 6 percent consist of a single parent with children. Regarding health issues, we observe that 35 percent of households have a member suffering from chronic illness; and approximately 6 percent suffer from poor health or disability. Figure 8 presents an overview of energy poverty experiences across vulnerable groups. The unconditional group means provide preliminary evidence on the differences in energy affordability risks — tenants, unemployed, women, and poor health appear to be more likely to self-report energy poverty experiences.

4 Empirical Framework

This section presents the empirical framework that guides and motivates our study. We use basic consumer theory to introduce energy efficiency investments as welfare-enhancing tools in a utility maximization model. With this conceptual framework in mind, we empirically evaluate the effects of energy efficiency investments on well-being.

A simple model of energy efficiency. Assume a utility maximization framework where agents (representative households) choose quantities from a basic basket of goods - e.g. food, housing, energy services, and health services. Rational households seek to maximize their benefits given the price of goods, subject to their incomes (budget constraint) and preferences. Households respond to changes in incomes and prices by re-optimizing their consumption. Two effects are associated with a price change: income and substitution. For example, consider a reduction in the price of a good (H). The income effect allows households to consume more goods overall, while the substitution effect alters the relative combination of chosen quantities based on their preferences. Overall, welfare is enhanced by increased or optimized consumption.

Inspired by the previous literature on energy efficiency, we conceptualize the relationship between the consumption of heating services and energy expenditure within this optimal choice problem. Fowlie et al. (2015) present a conceptual framework to estimate willingness to pay (WTP) for weatherization programmes — a measure of the private value of energy efficiency investments. We adapt two main features of this framework. First, we model energy efficiency improvements as reduction in the price of heating services, enabling consumers to achieve any level of thermal comfort at lower costs. Second, we also introduce a building-specific relationship between heating services and the energy required (E) to achieve a given indoor temperature.

Additionally, we introduce the notion of "minimum heating services" (H_{min}) into this framework. We conceptualize H_{min} as a threshold that reflects the minimum level of heating services required to produce adequate temperatures.[22] Generally, recommended indoor temperatures range from 20 to 26 degrees Celsius.[23] When the optimal bundle of goods (H, Y) lies to the left of the threshold, a household is assumed to be incapable of affording adequate warmth. Conversely, when the optimal bundle lies to right of H_{min}, a household is assumed to be able to afford adequate warmth. This conceptual device serves as a key element in interpreting our empirical results, as it

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[22] The "minimum heating services" threshold is a function of building characteristics - the higher the BER, the lower the heating services required to achieve adequate temperatures. However, our interpretation of the results is only reinforced since identifying an effect is more easily achievable than when assuming a static threshold. Alternatively, one can consider the average "minimum heating services" with no changes in the interpretation of the results.

[23] Energy Star, a U.S. Department of Energy (DOE) program on energy efficiency suggests values between 68 to 78 degrees Fahrenheit, depending on the season of the year.

allows us to link the basic utility maximization framework to the identification strategy presented in the next section.

We assume that households in our data are optimizing their consumption. Consequently, we can use our data to locate them in reference to the H_{min} threshold. When households self-report as incapable of affording adequate warmth, going without heating, or having arrears on their energy bills, they can be assumed to be consuming to the left H_{min}. By contrast, households that do not self-report any of these issues are assumed to be consuming above their minimum heating service needs, to the right of H_{min}.

Under these assumptions, our empirical framework and identification strategy offer a transparent and straightforward way to assess the effects energy efficiency investments. In Figure 9 we plot two hypothetical scenarios to illustrate the logic behind our empirical assessment of the effects of energy efficiency investments on well-being. In short, if having a higher energy efficiency rating has no effect on our set of indicators, it implies that the change in the budget constraint is insufficient to make a bundle of goods with adequate heating services affordable. Conversely, if a significant effect is identified, it implies that improving energy efficiency rating allows households to move from inadequate to adequate consumption of heating services.

The conceptual framework used for our analysis is depicted in Figure 9. The top quadrants plot the familiar utility maximization problem, adapted to our empirical setting. A representative household's consumption of home heating services (H) is plotted on the horizontal axis, while consumption of a bundle of all other basic goods (Y) is plotted on the vertical axis. We assume households' preferences for both goods display a certain degree of substitutability, indicating that they are willing to give up some thermal comfort to consume alternative basic goods. [24] This is captured by the family of indifference curves that track households' utility. Each figure in the panel plots two budget constraints. Efficiency levels of the building envelope (e.g., attic insulation, window sealing, and other types of retrofitting) are modeled by pivoting the budget constraint. The B_G line represents low-efficiency buildings, while the $B_{A(+)}$ lines correspond to higher-efficiency buildings. The slope decreases as the dwelling's energy performance increases. This change is analogous to a decrease in prices that allows agents to afford more heating services. Consequently, households living in higher energy efficiency buildings face lower costs for any given level of thermal comfort. The bottom quadrants associate heating services with the energy demand required to achieve a given temperature. Higher efficiency buildings require less energy to produce the same level of heating services and temperatures. Energy efficiency gains associated with a higher

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[24] This implies $0 < \alpha < 1$, in a standard Cobb-Douglas function. Assuming perfect complements would result in similar conclusions. However, both perfect complements or substitutes seem an unrealistic assumption, so we ignore this scenario.

energy performance rating are reflected by the slopes of the curves. The relationship assumes constant outdoor temperatures and building characteristics.[25] Energy consumption is a function of individuals preferences, building's efficiency and consumed heating services $E(H; Z = G, A_{(+)})$. This framework shows that energy savings, and the associated GHG emissions depend on the change in the distance between the optimal consumption bundle and H_{min} value.

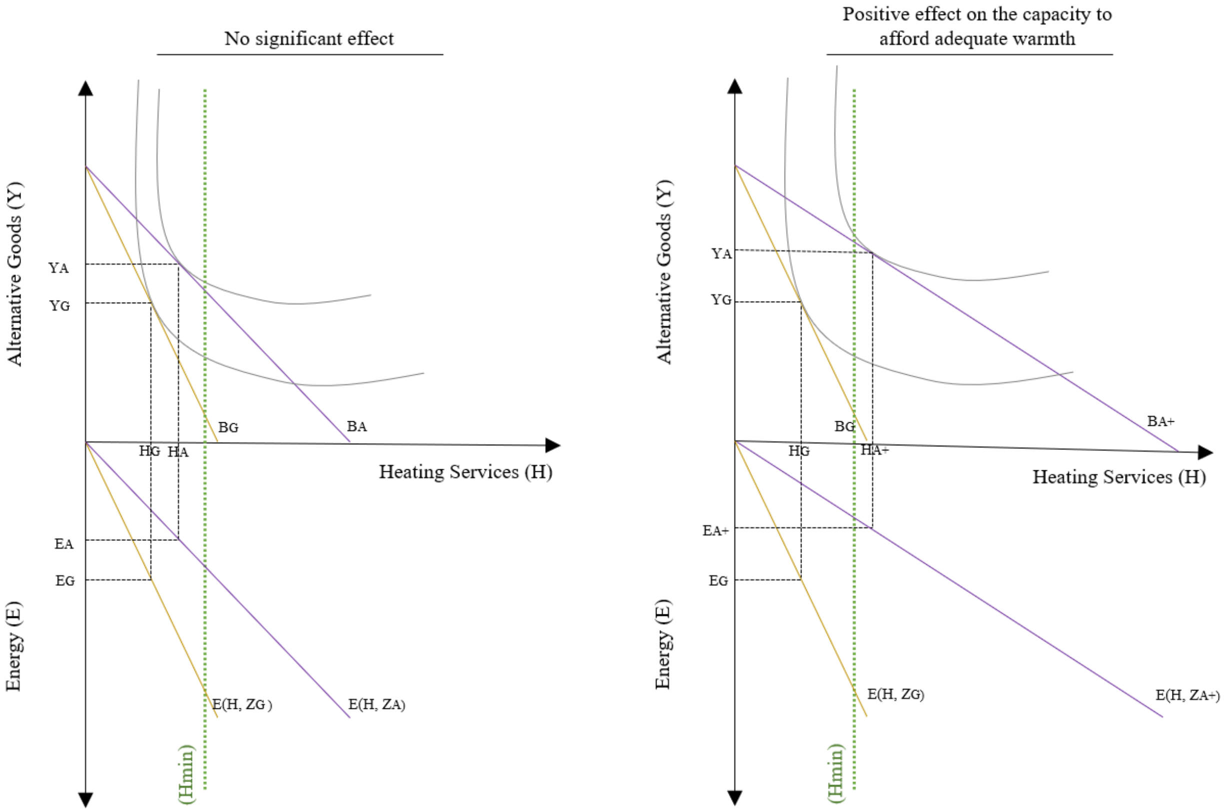

Figure 9: Effects of increased energy efficiency

Note.— The Figure presents a simple utility-maximization model. In both panels, the top quadrant plots budget constraints and indifference curves of a representative consumer optimizing a combination of heating services and alternative basic goods. The bottom quadrant plots the relationship between heating services and energy demand. The lines identify dwellings with high and low energy efficiency performance ratings, the slope reflects their energy efficiency. The vertical line *Hmin* indicates the minimum consumption of heating services required to keep adequate thermal comfort levels. The left panel plots a situation where the improvement in energy efficiency is not large enough for the agent to consume adequate levels of warmth while the right plots one that does.

The optimal consumption of the representative household living in a low energy performance building is (H_G, Y_G). Similarly, households living in a high efficiency home maximize their util-

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[25] See Fowlie et al. (2015) for further details on this assumption.

ity by consuming $(H_{A(+)}, Y_{A(+)})$. The minimum heating services value H_{min} is displayed by a vertical green line. As mentioned before, it is used to identify whether households are consuming the minimum required energy services to produce adequate warmth. Therefore, the magnitude of the effects of energy efficiency investments - or the differences between dwellings' efficiency characteristics - can be assessed by comparing these optimal consumption bundles.

Figure 9 illustrates two potential outcomes from energy efficiency upgrades. Energy efficiency gains imply less energy consumption for the same amount of output — in our setting, heating services and indoor temperature. The left-hand plot illustrates a scenario of low energy efficiency gains. In it, households living in low energy performance buildings consume (H_G, Y_G), while those living in high energy performance buildings consume (H_A, Y_A). Both representative households maximize consumption below the theoretical minimum heating services value H_{min}. This scenario also illustrates a situation in which investments required to achieve a high energy efficiency rating do not yield the expected returns - a meaningful increase in the capacity to afford adequate warmth. Conversely, the right-hand plot describes a situation where the efficiency gains from living in higher efficiency a rated home, or the investments required to achieve it, decreases the cost of heating services enough to make adequate warmth affordable, $H_{A(+)}$ is above the H_{min}. Using H_{min} as a reference, our empirical strategy allows us to identify whether energy efficiency effects are large enough to a minimum level of heating services affordable. The hypothetical scenarios plotted in Figure 9 illustrate how empirically identifying a significant effect is equivalent to observing the optimal consumption bundle increasing from (H_G, Y_G) to (H_{A+}, Y_{A+}).

Implications for the empirical analysis. Our identification strategy estimates the effects of living in buildings with varying energy performance ratings on the probability of households' self-reported capacity to maintain and afford adequate warmth. The two scenarios described above serve as the basis for interpreting the estimated coefficients.

First, identifying a zero effect suggests that improving buildings' energy performance ratings does not enhance households' self-reported capacity to afford adequate warmth. In other words, energy efficiency gains are insufficient to trigger the required cost reductions that enable households to consume adequate levels of heating services. The absence of an effect is only compatible with changes in consumption that occur to the left of H_{min} threshold, a situation described in the left-hand plot.[26] Second, identifying a positive effect suggests investments improve the probability of households' capacity to afford adequate levels of heating services. In our conceptual frame-

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[26] A zero effect might also be compatible with changes in consumption that occur exclusively to the right of the H_{min} threshold if households could afford adequate levels of thermal comfort both before and after the investment, which is not the case in hour data. Our identification strategy uses G-rated homes as a base group, which has a substantial share of energy-poor households.

work, a positive effect is only compatible with consumption changes that bring the optimal basket of goods from the left-hand to the right-hand side of the H_{min} threshold.[27]

Evaluating private returns of energy efficiency. Our empirical framework presents a straightforward approach to assess efficiency improvements. We argue that improving households' capacity to keep and afford adequate warmth can be regarded as a condition to consider that investments have meaningfully positive private returns. If this premise is accepted, failing to find an effect represents enough evidence to question the large projected energy savings made by engineering models and investments' financial profitability.

Advantages and limitations. Due to the lack of access to empirical measurements of energy savings and data on upfront investment costs, we are unable to perform a cost-benefit analysis or provide estimates on the return on investment (ROI). However, our analysis presents several advantages. By relying on households' lived experiences and their subjective assessments of the benefits derived from living in energy-efficient dwellings, we can interpret these benefits in terms of well-being — an approach that is novel in the literature. Furthermore, our empirical framework allows us to address previously neglected nuances in the mechanisms through which investments have their effects. For example, consider the relevance of substitution effects and their relationship to low income. It is unlikely that the costs and energy savings resulting from increased efficiency are primarily used to consume more heating services. Consumption patterns depend on agents' preferences and budget constraints. Low-income households are likely limited in their capacity to consume adequate amounts of both basic goods and heating services. Our model accounts for households that might prioritize the consumption of alternative goods before substantially increasing their heating services consumption. This indicates that energy efficiency investments might not affect households' capacity to maintain adequate warmth until cost reductions and higher incomes enable them to meet other basic needs.

The effects of energy efficiency on energy poverty. Households' self-reported assessments of their capacity to maintain and afford adequate warmth are commonly used as indicators of energy poverty. Therefore, our empirical analysis simultaneously estimates the effects of energy efficiency improvements on the probability of experiencing energy poverty. Access to rich data on households' socioeconomic and dwelling characteristics allows us to identify the main factors driving energy poverty.

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[27] In the unlike scenario where higher energy efficiency is found to have a negative effect on the probability of affording adequate warmth. The situation would correspond to a movement from $H_{A(+)}$ to H_G in the right-hand panel. As a consequence, our empirical framework would suggest that households' welfare would decrease, and energy consumption would increase.

5 Empirical Strategy

5.1 Identification strategy

Our main specification serves a dual purpose. Firstly, estimated coefficients provide the empirical evidence needed to evaluate the effects of energy efficiency improvements within our empirical framework. Secondly, it serves to identify and analyze the drivers of energy poverty. Equation 1 presents the fixed effects logistical model.

$$Y_{it} = \alpha + \sum_{j=1}^{7} \beta_j \mathit{Dwelling\ Efficiency}_i + \beta_8 \mathit{Income}_i + \chi_i + \delta_c + \lambda_t + \varepsilon_{im}, \tag{1}$$

where Y_{it} represents our set of indicators - households being incapable of keeping or affording adequate warmth, or having arrears on energy bills. *Dwelling efficiency* dummies designate the building's energy performance ratings (BERs A to F), low energy efficiency homes (G-rated) are our baseline. Our coefficients of interest β_j estimate the log-odds of energy efficiency categories. *Income* is the household's disposable income. Additionally, we investigate and control for the effects of an array of variables. Socio-economic characteristics include households' *tenure status* and the *fuel and other government support* they receive. Health and other conditions of potential vulnerability include the presence of e*lderly individuals* (*65+ in HH*), *chronic illness* status, and *single parent* status. Additionally, we include dwelling characteristics like their *main space heating* system, and *total habitable floor area*. We control for energy demand through a set of dummy variables that indicate the electricity consumption bracket for each household; and examine the role of energy prices faced by consumers by including an interaction term between *main heating source and fuel price*. [28]

We estimate three different specifications with varying combinations of fixed effects. Our preferred and most stringent specification includes county-level δ_c and time fixed effects λ_t to exploit the variation of our data while accounting for unobserved heterogeneity and differences between counties and years that may affect the outcome. Coefficients obtained with this specification are estimated using the remaining within-group variation. Hence, we estimate how changes in our variables of interest are associated with changes in the log-odds of our indicators within each county over time.

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[28] These variables correspond to our preferred specification. Results from specifications with the full set of controls are presented in the Appendix.

Energy efficiency and well-being. We estimate the effects of energy performance ratings (BER) and use them to evaluate whether improvements in buildings' energy efficiency have a significant effect on households' capacity to afford adequate warmth. Under our conceptual framework, evidence of increased well-being and meaningful energy efficiency gains requires us to find a lower probability of self- reporting issues in keeping and affording adequate warmth among highly-rated buildings.

The drivers of energy poverty. Because our indicators of energy affordability are commonly used as energy poverty measures, we can estimate the effects on predicted probabilities across variables and characteristics of interest and interpret them as their effect on the probability of falling into energy poverty. We analyze how these effects interact to gain further insights into the mechanisms that drive energy poverty.

6 Results

Table 2 presents the estimated coefficients from Equation 1, for each of the four energy poverty indicators using our most stringent specification. These coefficients represent the change in the log-odds of experiencing energy affordability issues for each building energy rating compared to the reference category (G). The remaining variation exploited by this specification is within county-year, which means that we are comparing the outcomes of households in the same county during the same year. The combination of county and time fixed effects controls for unobserved characteristics that do not change over time in each county, and the average unobserved differences that are common across countries as well as year-specific shocks like the COVID-19 pandemic and the ensuing rise in both household energy demand and energy prices.

Energy efficiency. The effects of energy efficiency improvements are captured by the coefficients that identify buildings' BERs. Their negative signs suggest that, compared to the base energy efficiency group (G-rated buildings), households living in higher efficiency dwellings are less likely to report being unable to afford adequate warmth. To facilitate the interpretation of our results, we present Figures that plot estimated predicted probabilities across different values of our variables of interests. Our findings reveal that the relationship between energy efficiency and households capacities to afford adequate warmth is weak. Outside the lower extreme of the distribution, households appear to face the same probability of experiencing energy affordability issues regardless of the efficiency of their homes. Under the conceptual framework presented in Section 4, our results suggest that the gains associated with energy efficiency investments are unlikely to generate the cost reductions that grant energy deprived households the capacity to afford minimum levels of heating services.

Our theoretical model shows that efficiency gains imply energy savings and reduced GHG emissions because a similar indoor temperature can be achieved with lower consumption. Our results show that households are not able to substantially increase their heating service consumption. Therefore, we infer that energy savings and emissions reductions from these investments are unlikely to be meaningful. Similarly, failing to find significant differences in households' capacity to afford adequate warmth suggests that the well-being benefits from living in higher energy efficiency buildings are small. Overall, our evidence questions the large purported benefits of energy efficiency investments.

Table 2: Energy efficiency and the drivers of energy poverty

	Energy affordability Indicators			
	(IKAW)	(IAAW)	(ABE)	(CI)
Building Energy Rating (B)	-0.8764*	-0.5925	-0.4229	-0.4646
	(0.485)	(0.361)	(0.455)	(0.359)
Building Energy Rating (C)	-0.8580**	-0.7300**	-0.2977	-0.4305*
	(0.335)	(0.284)	(0.356)	(0.243)
Building Energy Rating (D)	-0.9420**	-0.6966**	-0.3225	-0.4429
	(0.473)	(0.331)	(0.379)	(0.297)
Building Energy Rating (E)	-0.7904**	-0.7121**	-0.3368	-0.2118
	(0.363)	(0.320)	(0.304)	(0.209)
Building Energy Rating (F)	-0.6582	-0.9800**	-0.4099	-0.5429
	(0.469)	(0.422)	(0.525)	(0.355)
Total HH net income	-0.0003***	-0.0002***	-0.0003***	-0.0003***
	(0.000)	(0.000)	(0.000)	(0.000)
Fuel Allowance	0.3897	0.7765***	1.0589***	0.6249***
	(0.254)	(0.137)	(0.256)	(0.131)
Other Supports	1.0140***	0.9115***	1.3374***	0.8389***
	(0.282)	(0.141)	(0.205)	(0.104)
Fuel and Other Supports	1.3203***	1.3355***	1.5982***	1.3716***
	(0.209)	(0.206)	(0.226)	(0.142)
Tenant status	0.9849***	0.5524***	0.8402***	0.7613***
	(0.133)	(0.130)	(0.179)	(0.081)
Total habitable floor area	0.0017	0.0016	-0.0021	0.0018
	(0.002)	(0.002)	(0.002)	(0.001)
Main space heating source - Electricity	-0.4382	-0.4446	-0.5196	-0.4122
	(0.680)	(0.516)	(0.508)	(0.317)
Main space heating source - Heating Oil	0.2726	0.2488	-0.0241	0.2352
	(0.261)	(0.312)	(0.237)	(0.170)
Main space heating source - LPG	0.6064	0.7508**	-0.5470	0.5610**
	(0.625)	(0.359)	(0.623)	(0.239)
Main space heating source - Mains Gas	0.0588	0.1861	0.3067	0.1254
	(0.270)	(0.323)	(0.338)	(0.212)
Main heating source x Fuel price	0.0145	0.0234	0.0118	0.0078
	(0.035)	(0.027)	(0.030)	(0.014)
Electricity consumption <1000 kWh	0.2850	0.9904	-0.3473	0.9851
	(0.435)	(0.912)	(0.477)	(0.758)
Electricity consumption 1000<2000 kWh	-0.2265	0.7233	-0.9340***	0.8613
	(0.301)	(0.813)	(0.244)	(0.666)
Electricity consumption 2000<3000 kWh	-0.0925	0.9027	-0.5147***	1.0837
	(0.241)	(0.755)	(0.184)	(0.682)
Electricity consumption 3000<4000 kWh	-0.0525	0.9243	-0.3029*	1.2234*
	(0.248)	(0.762)	(0.168)	(0.677)
Electricity consumption 4000<5000 kWh	-0.1236	0.7256	-0.2730	1.1706*
	(0.208)	(0.788)	(0.182)	(0.711)
Electricity consumption >=5000		0.9957		1.3758*
		(0.788)		(0.716)
At least 1 65+ in HH	-0.6690***	-0.8804***	-1.6204***	-0.9820***
	(0.207)	(0.166)	(0.215)	(0.112)
Chronic illness	1.0411***	0.5876***	0.6807***	0.5891***
	(0.213)	(0.184)	(0.160)	(0.126)
Rural area	0.0172	0.0547	0.5838*	0.0301
	(0.292)	(0.237)	(0.328)	(0.166)
Constant	-3.5665***	-3.6262***	-1.9920***	-2.4130***
	(0.473)	(0.936)	(0.428)	(0.794)
Observations	7,125	7,287	7,161	7,337
Fixed Effects - county	YES	YES	YES	YES
Fixed Effects - time	YES	YES	YES	YES

Note.— Columns estimate Equation 1 for each indicator. The table presents coefficients of interest in log-odds. The base groups are defined by households living G-rated energy-efficient dwellings, privately owned, heated by solid fuels, in an urban area. Observations come from a representative sample of Irish households during the period 2016 to 2022. Results for all indicators including coefficients for controls are presented in the Appendix 4. *Source:* Estimations using BER-SILC sample data observations.[a]

Robust standard errors, clustered at regional or county level, in parentheses.

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

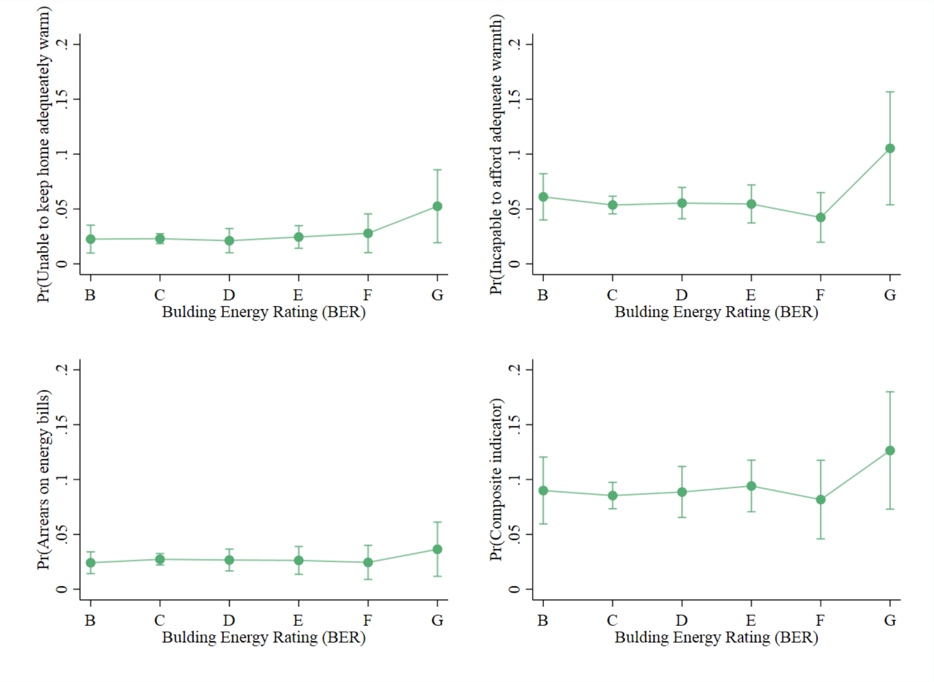

Figure 10: Estimated effects of energy efficiency

Note.— The Figure presents predicted probabilities across BER categories, adjusted predictions with 95 percent confidence intervals. [a]

The drivers of energy poverty. As expected, households' capacity to afford adequate levels of heating services improves as disposable incomes increase. Results suggest that income is the key determinant of energy poverty experiences. We observe a strong and consistently negative relationship across all four indicators. Similarly, home ownership appears to be an important factor driving energy poverty. Results from across the different specifications show that tenants are more likely to struggle to afford adequate warmth. The chronically ill and disabled populations, requiring support equipment, tend to have higher energy consumption needs. Consistently, our results suggest households with individuals suffering from chronic illness due to health issues have a higher likelihood of experiencing energy poverty.

By contrast, results suggest that some of the factors one would initially expect would influence energy poverty do not appear to have a substantial impact. This is the case of the type of fuel used in the main home heating system.[29] Furthermore, households do not seem affected by changes in the prices of these fuels. When interpreting these results, one must remember that fixed effects capture the effect of average fuel prices in each county during our period of analysis. Therefore,

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[29] When examining the influence that the type of fuels used to heat homes, the base group is defined as homes heated using solid fuels.

we may be unable to identify an effect because of the relatively small variation in fuel prices during our period of analysis. Households with one or more elderly individuals appear less likely to report being unable to met their heating service needs. This result is unexpected given the conventional wisdom that elderly individuals are particularly vulnerable to energy poverty. Although, this result is consistent throughout our analysis, it does not necessarily imply that the elderly are exempted of energy poverty. Differences in generational values and assessments of discomfort, or the possibility of individuals to engage in mitigating behavior such as wearing warm clothes might explain this result. Careful interpretation is required and should consider the self-reported nature of our indicators.

The graphs panel in Figure 10 display - for each indicator - the estimated predicted probabilities for each BER energy performance rating. [30] Results plotted in the different quadrants consistently show that, at the low extreme of the energy efficiency distribution, households living in G-rated buildings have the highest probability of reporting being incapable of affording adequate warmth. Notably, differences in probabilities across most of the energy efficiency distribution are small. The relationship between a building's energy performance ratings and the probability of being able to afford the necessary heating services to feel adequately warm appears to be weak. Overall, results suggest that beyond improvements at the extreme of the energy efficiency rating distribution, the effects of improvements are negligible. This evidence is consistent with previous results in the literature that find that energy efficiency investments do not yield the expected outcomes in terms of private and social returns, energy savings, or improvements in indoor temperatures (Allcott and Greenstone, 2017; Fowlie et al., 2018).

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[30] By default, all estimations of predicted probabilities hold other explanatory variables at their mean or baseline values.

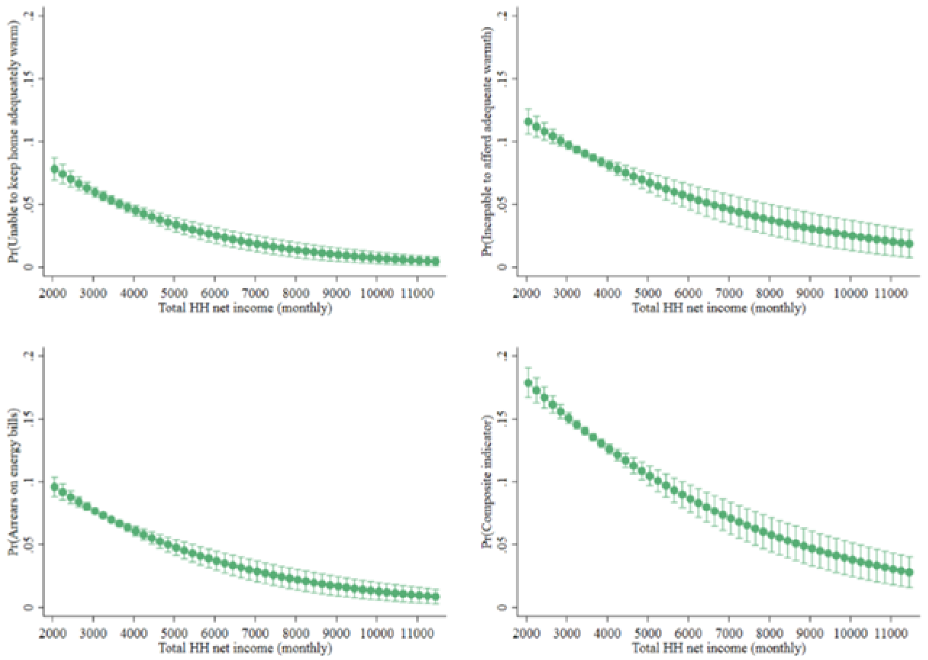

Figure 11: Estimated effects of income

Note: The Figure presents predicted probabilities across income distribution values, adjusted predictions with 95 percent confidence intervals.[a]

In Figure 11, we explore the influence that income has on households' capacities to achieve adequate indoor temperatures. Predicted probabilities are plotted across the entire disposable income distribution. Results show that increases in income can substantially reduce the risk of experiencing energy poverty. Effects are larger among low-income households, as shown by the change in the curves' slopes. We observe that when households earning 2000€per month double their income, the probability of being unable to afford adequate warmth almost halves. Income emerges as the single most important predictor of energy poverty indicators.

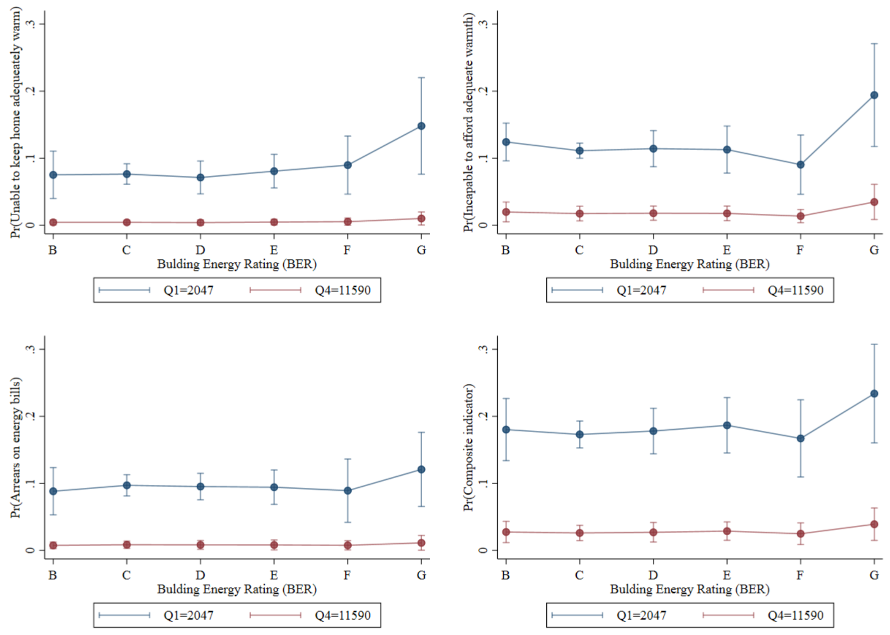

Figure 12: Estimated interaction effects of energy efficiency and income

Note: The Figure presents predicted probabilities across energy efficiency categories effects for the first and last income quartiles of the income distribution. Adjusted predictions are estimated using average disposable income of each quartile, indicated in the graphs. [a]

Our analysis reveals that the interactions between energy efficiency, income, and other household characteristics determine their capacity to afford adequate warmth. Vulnerabilities appear to compound, increasing the risk of exposure to energy poverty. Figure 12 compares low- and high-income households estimated probabilities across energy efficiency categories. The red lines plot the results for households in the last quartile of the income distribution; estimated probabilities are close to zero, and the difference between B-rated and G-rated households is small. The blue lines present results for low-income households belonging to the first quartile of the income distribution. A comparison of these two groups shows that the probability of lower income households living in a B-rated buildings is seven times larger, and up to 15o times larger for individuals those living in G-rated buildings. These results are consistent with previous evidence on the effects of income and energy efficiency. Furthermore, they reveal that vulnerabilities are exacerbated for those experiencing multiple types of deprivations.

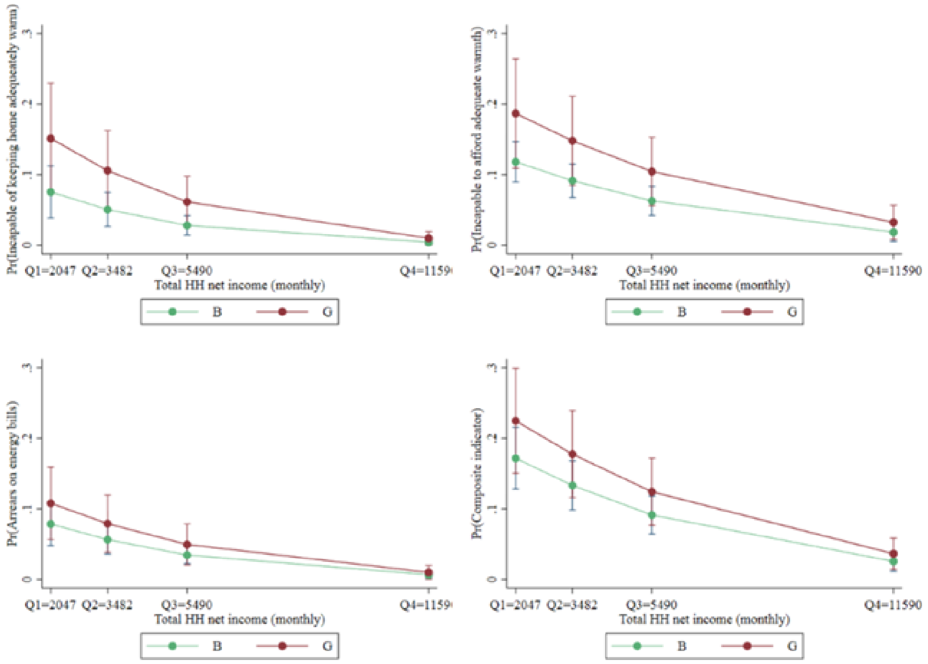

Figure 13: Estimated interaction effects of energy efficiency and income

Note: The Figure presents predicted probabilities across quartiles of the income distribution for low- and high- energy efficiency categories (B and G). Adjusted predictions are estimated using average disposable income of each quartile, as indicated in the graphs' horizontal axis.

Figure 13 displays the interaction in a slightly different way, plotting the estimated predicted probabilities for energy efficiency categories B and G across quartiles of the income distribution. These results show that higher energy efficiency reduces low-incomes households' estimated probabilities of being incapable of affording adequate warmth. However, the overlap of confidence intervals confirms that the relationship between buildings' efficiency and energy affordability is weak.[31] More importantly, the results suggest that the effects of increasing household income are more pronounced among households living in low-energy efficiency dwellings — going from the first to the last quantile of the income distribution reduces the estimated probabilities substantially more for households in G rated dwellings.[32]

So far, our analysis supports policy interventions that target low-income and low-energy efficiency groups. Residential retrofitting subsidies benefit households with low energy efficiency the most, while they might make little difference for those in the middle of the distribution. Our

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[31] Holding income and other household characteristics constant, energy efficiency effects often lack statistical significance.

[32] Similar results are observed for other energy efficiency categories.

findings endorse the use of unconditional and well targeted cash transfers to help consumers pay for energy bills. Income supports appear to be an effective and progressive short term measure to mitigate energy poverty.[33] Additionally, our evidence suggests that interventions aimed at tackling income poverty and inequality will simultaneously help alleviate energy poverty.

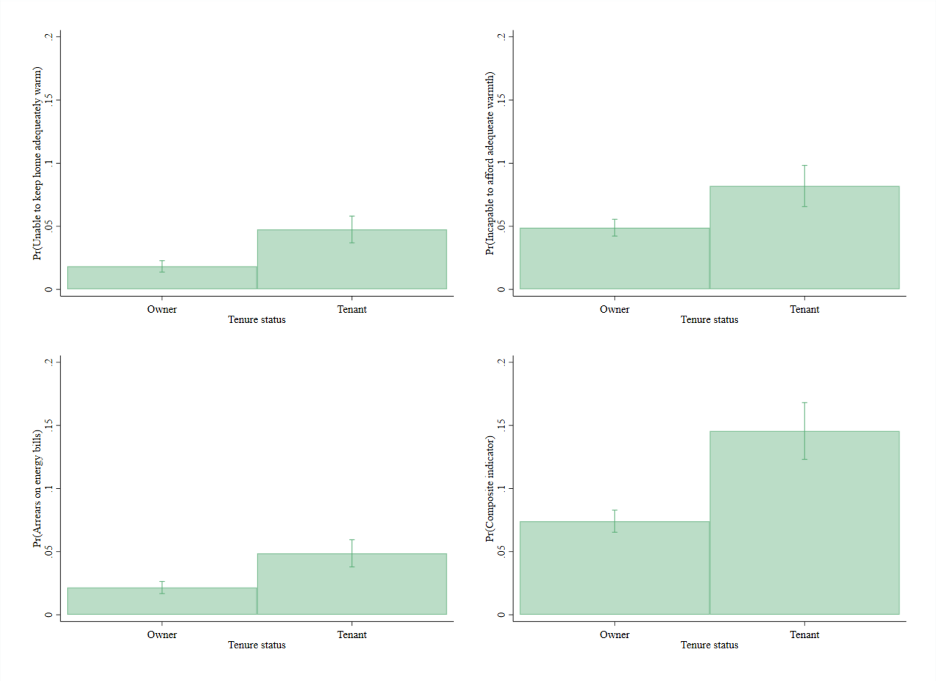

Figure 14: Estimated by home ownership status .

Note.— The Figure presents the predicted probabilities for home owners and tenants, adjusted predictions with 95 percent confidence intervals.[a]

Next, we explore the effects of alternative drivers of energy affordability. We focus the analysis on the interactions between energy efficiency and income with factors such as home ownership, health status, energy consumption, heating systems and fuel use, and social transfers.

Results suggest that home ownership significantly reduces the probability of being able to afford adequate warmth. Figure 14 shows that tenants can be more than three times as likely to experience affordability issues. Figure 18 in the Appendix explores the heterogeneity of this result. Among homeowners, the probabilities are higher when having a mortgage. Conversely, tenants with subsidized accommodation are for likely to report affordability issues, but the difference does not appear to be statistically significant. Figure 15 compares homeowners and renters across energy efficiency ratings. Across most them, homeowners face a lower risk. However, the statistical

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[33] In Ireland, energy credits — unconditional cash transfers — have been granted to all electricity users since 2022. (Department of Public Expenditure, NDP Delivery and Reform; Department of Finance, 2022, 2023)

significance of this gap is questionable at among low energy efficiency buildings. Notably, homeowners of G-rated properties and tenants living in B-rated dwellings have a similar probabilities of being unable to afford adequate warmth. Additionally, Figure 16 illustrates the interaction between ownership status and income. Tenants at the lower end of the income distribution are more are more than twice as likely to experience energy affordability issues as homeowners with similar incomes. Nevertheless, this gap diminishes as income increases, ownership status ceases to be relevant once household disposable income approaches €8,000 per-month. These results reveal a significant energy poverty gap associated with ownership status.

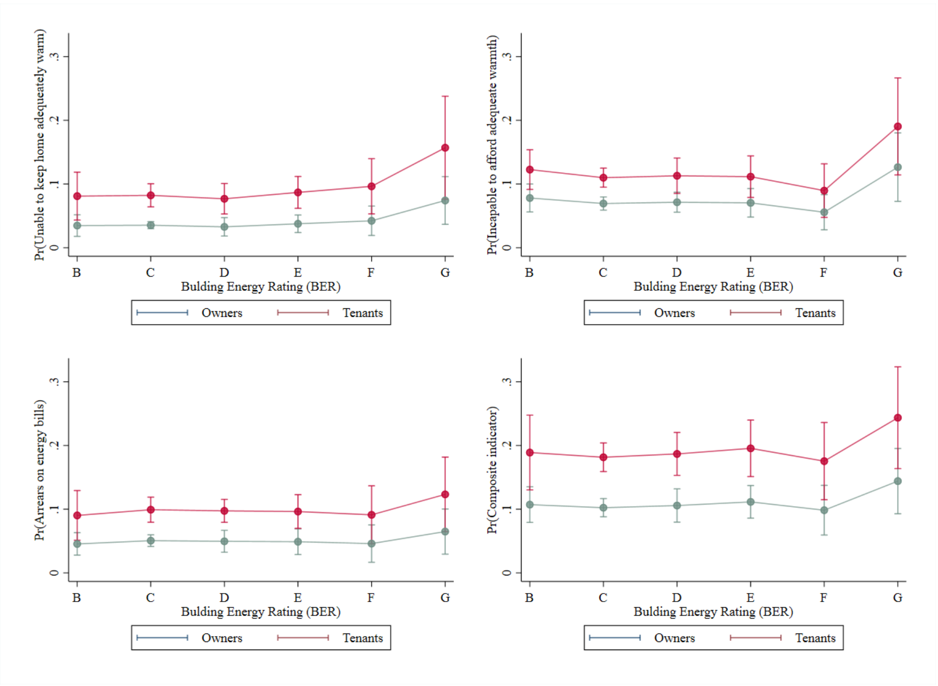

Figure 15: Estimated interaction effects of energy efficiency and tenure status.

Note.— The Figure presents predicted probabilities across energy efficiency categories effects for home owners and tenants, adjusted predictions with 95 percent confidence intervals. [a]

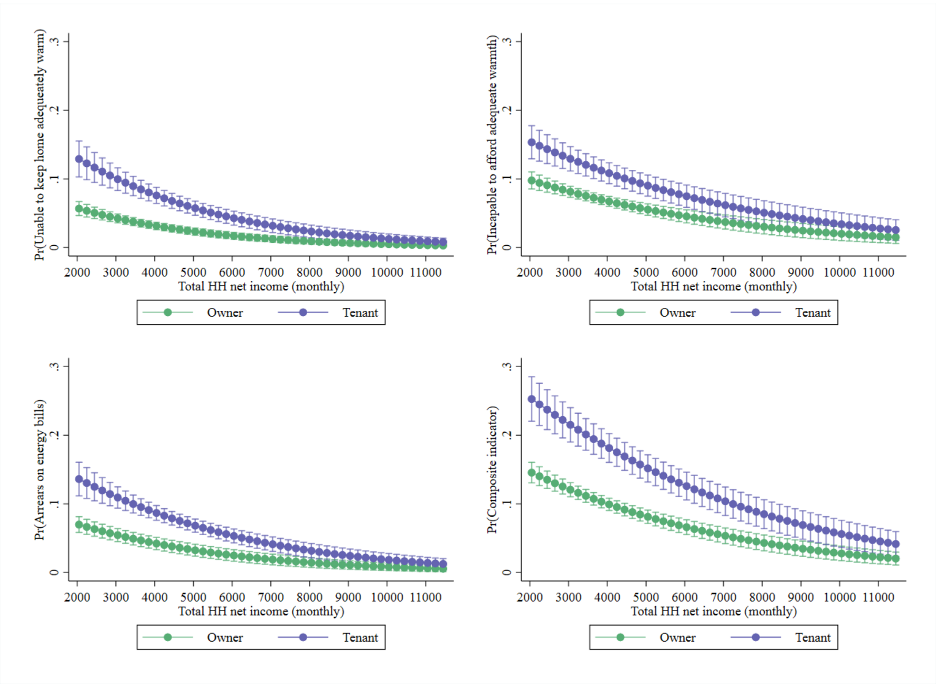

Figure 16: Estimated interaction effects of income and tenure status

Note.— The Figure presents predicted probabilities across income distribution values for homeowners and tenants, adjusted predictions with 95 percent confidence intervals.[a]

Similar results and tendencies are observed among other household characteristics. Individuals with chronic health issues tend to have higher energy needs, making them particularly vulnerable to energy poverty issues. Figure 19 compares households having at least one individual with a diagnosed chronic illness with households that report no health issues. Results suggest that having chronic illness more than doubles the probability of experiencing energy affordability issues. As before, analysis of the interaction effects shows that risks of affordability are higher among certain energy efficiency categories and low income households. In the Appendix, Figure 20 shows that probabilities converge as income increases, once households' income nears €6,500 per month the health gap ceases to be significant. Similarly, Figure 21 shows that single parent households face higher probabilities of experiencing energy affordability issues.

Other household characteristics seem to have less or no impact on energy affordability. Switching the type of fuel and upgrading to more efficient heating systems is considered a key method for improving energy efficiency and cutting down on greenhouse gas emissions. Figure 22 examines how the main heating system fuel influences a household's ability to afford their energy needs. Although differences are not statistically significant, homes with electricity powered heating systems have the lowest probabilities of experiencing affordability issues. Conversely, those using LPG boilers have the highest. Overall, the data suggest that the fuel type used as the main heating source has a small impact on the likelihood of a household experiencing energy poverty. Figure 23 shows that differences in electricity consumption do not appear to influence energy affordability. Similarly, Figure 24 shows that having the gender of the head of household has no effect. Although a urban-rural gap might be expected, Figure 25 shows there is no statistically significant difference.

7 Policy Implications and Discussion

This paper provides valuable contributions and insights for academics and policymakers alike. Regarding its scientific contribution, it adds empirical evidence to the emerging literature that challenges the cost-effectiveness of investments in energy efficiency in the residential sector (Chuang et al., 2022; Davis et al., 2020; Fowlie et al., 2018; Hancevic and Sandoval, 2022). Our results suggest that after retrofitting, the energy services cost required to maintain adequate comfort in the dwelling does not drop significantly. This work also has substantial practical policy implications. It underscores that, from a public finance standpoint, directing public resources towards improving the energy efficiency of energy-poor households may not yield the expected results. It also draws attention to significant technical challenges, such as the complexity and cost of upgrading energy-inefficient dwellings like G-rated ones. Even if these challenges are overcome, it remains uncertain whether the results will meet the expectations of providing a minimum comfort level that is affordable for the residents.

In recent years, various European governments have implemented transfers to alleviate the pressure caused by high energy prices in the region. These measures have faced criticism due to their limited target design (Arregui et al., 2022). The main issue with this design is that universal transfers impose a larger burden than targeted ones on public finances and are not aligned with the environmental purposes of reducing energy demand. The European Union recently published recommendations to tackle energy poverty in the region (European Commision, 2023). The strategy distinguishes short- and long-run strategies. Income transfers are often viewed as a short-term policy tool to address energy poverty. In this view, income supports households during short term shocks while energy efficiency improvements aim to address the issue in the long-run. It is essential to recognise the interconnection between energy poverty and income poverty. In light of this, it is imperative to align anti-poverty policies with addressing energy poverty by enhancing the efficiency of public resource allocation to protect vulnerable households.

The Renovation Wave, the Energy Performance of Buildings Directive (EPBD) and the Energy

Efficiency Directive (EED) foresee improvements in energy efficiency as a primary strategy to tackle fuel poverty in the long run. Our results show that households with decent energy efficiency still struggle to afford proper heating levels, which highlights two potential issues. On the one hand, our results indicate that income poverty is more prevalent in energy poverty than we thought. Consequently, envisioning that high levels of energy efficiency will immediately lead us to win our battle against energy poverty could be a fallacy.

Energy efficiency can enhance well-being through channels other improving energy affordability. Improving energy efficiency in the residential sector has health and other well-being implications, research has documented improvements in the health of the children after retrofitting (Somerville et al., 2000). Reducing investment costs, increasing household engagement in the decision-making process, and properly using technology are critical to increasing the adoption of energy efficiency measures. One interesting proposal is the community-led retrofit approach (Putnam and Brown, 2021). According to the author, this approach can affect both the retrofit cost and behavioural aspects. Community sharing knowledge can affect attitudes and engagement. In addition, this develops the local supply chain and delivers economies of scale that can reduce the financial burden of the investment. It is worth noting that energy efficiency measurement has room for improvement (Meles et al., 2023). Inadequate diagnosis of the issue could undermine efforts towards a green energy transition. Recent EU directives encourage the improvement of energy poverty measurements that inform efficient policy design and allow for comparison across member states (European Commision, 2024).

8 Conclusions

In this study propose an innovative empirical framework to assess the impact of energy efficiency improvements on well-being.

Energy efficiency investments are expected to yield large welfare benefits through improved access to affordable energy, decarbonization of the economy, and poverty alleviation. To assess their benefits, we consider the enhancement of households' capacity to afford adequate warmth as a minimum requirement for investments to have meaningfully positive returns.

We leverage on a novel micro-level dataset that integrates households' socioeconomic characteristics, dwellings' energy efficiency ratings, and both objective and subjective measures of thermal comfort affordability. We interpret the estimated probabilities of reporting energy poverty experiences across energy performance ratings as indicators of the effects of energy efficiency improvements. Our conceptual framework offers a straightforward approach to assess their implications on well-being, and allows us to simultaneously study the drivers of energy poverty.

Our findings suggest that improvements in buildings' energy efficiency have modest to negligible effects — the probability of being incapable to afford adequate warmth is similar across most of the energy efficiency distribution. Effects are concentrated at the lower extreme, between the least efficient (G-rated) homes and the rest. Therefore, investments required to make such improvements are unlikely to yield the expected efficiency gains, the associated energy savings, or the reductions in GHG emissions.

Income emerges as the critical determinant of energy poverty. The probability of energy poverty more than doubles when households move from the first to the third quantile of the income distribution. Similarly, home ownership and health status are found to significantly influence households' ability to afford adequate warmth.

This study demonstrates the importance of considering the interactions between households' socioeconomic characteristics and buildings' energy efficiency. We find that households living in low-efficient homes see the greatest benefits from income increases, highlighting the opportunities of well-targeted policies. Our results indicate that improvements in energy efficiency alone cannot completely offset the disparities created by ownership status. For instance, tenants in B-rated buildings and homeowners of G-rated buildings display similar abilities to meet their heating needs. By contrast, ownership status ceases to be relevant when household incomes are sufficiently high. To fully understand the potential of energy efficiency in alleviating energy poverty, further research with even more comprehensive data is essential.

The policy implications of our study are profound. Energy efficiency is no silver bullet. Initiatives to improve building energy efficiency must be part of a broader strategy to reduce inequality, improve household incomes, foster home ownership, support vulnerable groups, and promote behavioral change.

In summary, our research contributes to the literature on the effects of energy efficiency on social well-being; in particular, exploring its potential to reduce energy poverty. It challenges some prevailing assumptions and highlights the complex interplay of factors that influence it. As we move forward, a more integrated and holistic approach is essential in designing and implementing policies to effectively combat energy poverty, ensuring that the benefits of energy efficiency reach those most in need.

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9 Appendix

A The BER-SILC microdata

This paper was developed as part of the Research Programme in Energy Poverty (RPEP), a multi-stakeholder effort lead by the Economic and Social Research Institute (ESRI). The Central Statistics Office (CSO) of Ireland, one of the partner institutions, constructed the BER-SILC database for this research programme.

A.1 Database construction

The construction methodology can be summarized in three steps. First, the CSO linked observations from the 2016 to 2022 Irish SILC microdata files with the 2016 Population Census data using unique identifiers. As a result, SILC observations were assigned their corresponding Eircode. Second, the Building Energy Rating (BER) microdata contains the electricity meter point reference number or MPRN. This was used to match with the electricity meter customer file to add more Eircodes into the BER dataset. Unique addresses in the BER file and in the ESB meter file were given Eircodes in 2015 before the launch of the Eircode. Eircode was not a mandatory variable in the BER audit until around 2021 so energy audits conducted during that period did not need to have their Eircode recorded.Third, the Eircode was used to match SILC and BER microdata files. The energy rating and a small number of other variables from the BER dataset were added to the SILC to create the BER-SILC micro-data files.[34]

A.2 Special considerations and data limitations

The resulting BER-SILC dataset has certain limitations. One, households in SILC lacking BER information were dropped. Two, only the latest BER audits for each household were included. Therefore, we can not identify those which upgraded their BER recently. Furthermore, we are forced to make certain assumptions to assign a BER at the time of the survey. Three, other BER observations were not matched. Records in the ESB Networks enhanced BER file that did not have an Eircode, year of construction, main space heating fuel, or other variable, were excluded.

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[34] Eircode is the national postcode system in Ireland. An Eircode is a unique 7-character code consisting of letters and numbers. It is necessary to highlight that this exercise can only be performed by the CSO to ensure strict compliance with data protection regulations. We have access to a research file that is fully anonymised for our research porpoises.

These decisions reduced variation in the data. We address these issues through the sample selection process discussed in the next sub-section.

It is also important to acknowledge certain particularities inherent in the SEAI's National BER Register.[35] The BER assessments are conducted by independent, registered assessors and are guided by the Dwelling Energy Assessment Procedure (DEAP). [36] A critical aspect of these assessments is their reliance on existing documentation pertaining to the dwelling. In instances where homeowners lack comprehensive documentation, assessors resort to using default values. This reliance on available documentation might significantly influence the accuracy of the energy efficiency evaluations of the dwellings. Additionally, our analysis of the distribution of energy ratings. Table 3 shows the distribution of dwellings' energy ratings, revealing a surprisingly low number of A-rated homes in the entire sample. This observation suggests potential anomalies or vague elements in the assessment process. [37] A final note on construction of BER dataset. If a home does not have a main heating system, electricity is assigned as the main heating source. The assumption is that electric appliances are used to warm the dwelling. While our data represent what is probably the most accurate approximation of dwellings' energy efficiency available, their particularities should be considered when interpreting the results.

The BER data will be added on an ongoing basis as more energy audits are conducted. The latest BER data might be updated, changing the energy efficiency value of some observations. This poses concerns around the future reproducibility of results. Similarly, dwellings that completed a SILC interview during 2016 to 2022 that subsequently have a BER audit will be added to the BER-SILC RMF file for the year that the SILC interview was conducted. Hence, the number of records in each annual RMF file may increase over time.

A.3 Sub-sample construction and validation

This sub-section presents a detailed explanation of the data cleaning and validation process of the BER-SILC database version made available as a Research Microdata File (RMF) in Dember 2023 by the Ireland's Central Statistics Office (CSO).

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[35] SEAI maintains a BER register in accordance with S.I. NO. 243/2012. The BER register provides an extract of the BER data file for an individual building.

[36] DEAP consists of a software tool and guidance manuals. BER Assessors use DEAP to publish Building Energy Rating (BER) certificates and advisory reports for homes. DEAP is also the compliance tool specified in Part L of the Irish Building Regulations. The DEAP software is web-based and used to calculate the annual delivered energy consumption, primary energy consumption (kWh/m2/year) and carbon dioxide emissions (kgCO2/m2/y) for standardised occupancy.

[37] For new buildings these include wall, roof and floor specifications and copies of certificates of performance for construction products and appliances installed in the property. For existing buildings documentation of any upgrade works done to your property, and any available documentation regarding the original construction.

The BER-SILC data spans the period 2016 to 2022. The full database consists of 11,597 household-level observations, see Table 3. Due to the construction methodology of the BER-SILC database, we cleaned for observations that would force us to make strong assumptions regarding household dwelling's actual energy efficiency rating at time of survey. The BER data merged into the BER-SILC database has a single year of energy efficiency values for each household - their latest BER audit information in 2023. Therefore, there is a number of observations in the SILC database that were assigned BER ratings obtained through audits that occurred after the survey was collected. To avoid making the assumption that households BERs did not change between the time of SILC survey and the time of households latest BER audit we drop all observations that meet the following condition: *BER audit year > SILC survey year.* As a result 3,820 observations, equivalent to 32% of the original sample, were dropped. When analyzing the income distribution of the SILC data we identified extreme values and implausible values - . We drop observations that meet the following condition: *Household Disposable Income > 50,000 euros per month.* As a result 297 observations, equivalent to 2.56% of the original sample, were dropped. The cleaning and validation process leaves us with a sample of 7,558 observations for the econometric analysis, see Table 1.

B Supplementary descriptive statistics

Table 3: Summary Statistics

	n	mean	sd	min	max
Incapable to afford adequate warmth (IAAW) $\in (0, 1)$	11,103	0.100	0.300	0	1
Incapable to keep adequate warmth (IKAW) $\in (0, 1)$	11,103	0.0604	0.238	0	1
Arrears on utility bills (AEB)$\in (0, 1)$	10,892	2.894	0.359	1	3
At risk of poverty	11,103	0.169	0.374	0	1
Consistent poverty	11,103	0.0749	0.263	0	1
Deprivation indicator	9,477	0.200	0.400	0	1
Number of rooms in the HH	10,922	5.505	1.565	1	10
Total HH gross income (€/month)	11,103	5,158	3,949	0	19,978
Total HH net income (€/month)	11,103	4,029	2,537	2.271	17,406
Total housing costs (€/month)	11,103	546.4	396.0	0	6,831
Family/children related allowances (€/year)	11,103	3,039	5,710	0	59,450
Social exclusion income support (€/year)	11,103	55.20	685.6	0	45,497
Housing allowances (€/year)	11,103	681.9	1,968	0	44,119
Social exclusion income support (net€/year)	11,103	55.20	685.6	0	45,497
Old-age benefits (net€/month)	11,103	5,734	11,476	0	133,436
Disability benefits (net€/month)	11,103	992.3	3,360	0	44,845
Survivor's benefits (net€/month)	11,103	195.6	1,505	0	29,753
Sickness benefits (net€/month)	11,103	57.29	585.9	0	22,949
HH size (number of people)	11,103	1.872	0.760	1	6.280
Energy expenditure estimation (€/month)	11,103	272.2	127.2	0	2,898
Gender $\in (0, 1)$	11,103	0.567	0.496	0	1
Age of respondent	11,103	53.23	15.56	17	97
Bachelors equivalent or above $\in (0, 1)$	7,722	0.316	0.465	0	1
Unemployed $\in (0, 1)$	7,788	0.0713	0.257	0	1
At least 1 65+ in HH $\in (0, 1)$	11,103	0.265	0.441	0	1
Single adult with children $\in (0, 1)$	11,103	0.0565	0.231	0	1
Not married $\in (0, 1)$	11,103	0.489	0.500	0	1
Tenure status $\in (0, 1)$	11,103	0.322	0.467	0	1
Current rent of dwelling	3,569	564.6	498.8	3	4,000
Disabled - no work $\in (0, 1)$	7,788	0.0758	0.265	0	1
Chronic illness because health problems $\in (0, 1)$	11,103	0.357	0.479	0	1
Poor health $\in (0, 1)$	11,101	0.0583	0.234	0	1
Apartment $\in (0, 1)$	11,103	0.0892	0.285	0	1
Detached house $\in (0, 1)$	11,103	0.288	0.453	0	1
Semi-detached house $\in (0, 1)$	11,103	0.351	0.477	0	1
Terraced house $\in (0, 1)$	11,103	0.273	0.445	0	1
Heating - Electricity $\in (0, 1)$	11,103	0.0916	0.288	0	1
Heating - Oil $\in (0, 1)$	11,103	0.381	0.486	0	1
Heating - LPG $\in (0, 1)$	11,103	0.00937	0.0963	0	1
Heating - Mains Gas $\in (0, 1)$	11,103	0.468	0.499	0	1
Heating - Solid Fuel $\in (0, 1)$	11,103	0.0503	0.219	0	1
BER (A) $\in (0, 1)$	11,103	0.0207	0.142	0	1
BER (B) $\in (0, 1)$	11,103	0.157	0.363	0	1
BER (C) $\in (0, 1)$	11,103	0.407	0.491	0	1
BER (D) $\in (0, 1)$	11,103	0.232	0.422	0	1
BER (E) $\in (0, 1)$	11,103	0.104	0.306	0	1
BER (F) $\in (0, 1)$	11,103	0.0398	0.196	0	1
BER (G) $\in (0, 1)$	11,103	0.0395	0.195	0	1
Rural area $\in (0, 1)$	11,103	0.149	0.356	0	1

Note.- The table shows national-level averages of our variables of interest. Differences in observations are explained by the characteristics of the specific variable. For example, only households with tenant status pay rent. [a]

C Additional Results and Robustness checks

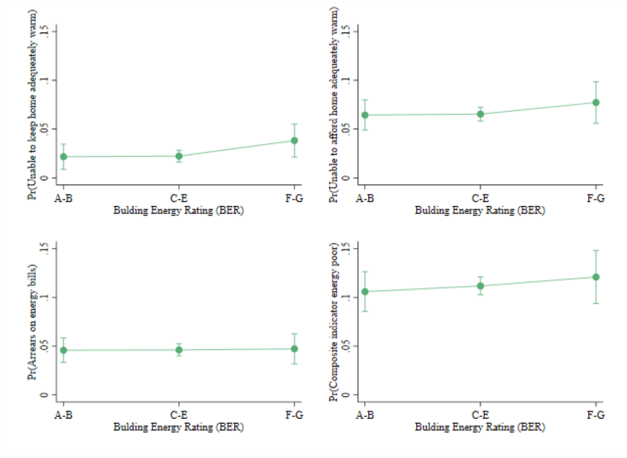

Figure 17: Estimated effects of energy efficiency

Note.— The Figure presents the adjusted predictions of BER categories with 95 percent confidence intervals. [a]

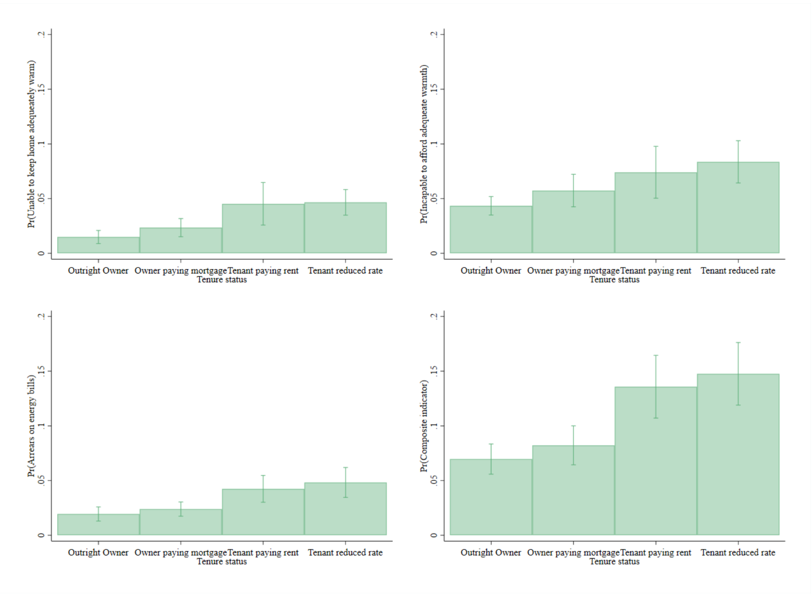

Figure 18: Estimated by disaggregated tenure status .

Note.— The Figure presents the adjusted predictions of energy efficiency categories effects for home owners and tenants. [a]

Table 4: Energy efficiency and the drivers of energy poverty

	Energy affordability Indicators											
	(IKAW)	(IKAW)	(IKAW)	(IAAW)	(IAAW)	(IAAW)	(AEB)	(AEB)	(AEB)	(CI)	(CI)	(CI)
Building Energy Rating (B)	-0.8437*	-1.0092**	-1.0653**	-0.5289	-0.5499	-0.5743	-0.5198	-0.6335	-0.5925	-0.3630	-0.4237	-0.4379
	(0.437)	(0.512)	(0.486)	(0.339)	(0.392)	(0.391)	(0.355)	(0.505)	(0.498)	(0.303)	(0.380)	(0.373)
Building Energy Rating (C)	-0.8366***	-1.0165***	-1.0304***	-0.7031**	-0.7386**	-0.7560**	-0.3641	-0.4712	-0.4475	-0.4711*	-0.5083*	-0.5074*
	(0.321)	(0.371)	(0.349)	(0.273)	(0.306)	(0.306)	(0.318)	(0.396)	(0.392)	(0.242)	(0.289)	(0.281)
Building Energy Rating (D)	-0.9727***	-1.1125**	-1.1141**	-0.7238***	-0.7585**	-0.7742**	-0.3010	-0.4054	-0.3898	-0.4183*	-0.4704	-0.4686
	(0.308)	(0.493)	(0.479)	(0.262)	(0.358)	(0.356)	(0.306)	(0.391)	(0.390)	(0.234)	(0.335)	(0.328)
Building Energy Rating (E)	-0.7509**	-0.8840**	-0.8800**	-0.6303**	-0.6551**	-0.6756**	-0.1718	-0.2500	-0.2391	-0.2617	-0.2982	-0.2892
	(0.325)	(0.381)	(0.373)	(0.284)	(0.325)	(0.333)	(0.322)	(0.304)	(0.302)	(0.245)	(0.255)	(0.252)
Building Energy Rating (F)	-0.5112	-0.6735	-0.6635	-0.8581**	-0.9040**	-0.9135**	-0.2701	-0.3218	-0.3136	-0.4112	-0.4337	-0.4230
	(0.376)	(0.470)	(0.467)	(0.352)	(0.400)	(0.400)	(0.380)	(0.479)	(0.473)	(0.283)	(0.371)	(0.370)
Total HH net income	-0.0003***	-0.0003***	-0.0003***	-0.0002***	-0.0002***	-0.0002***	-0.0003***	-0.0003***	-0.0003***	-0.0002***	-0.0002***	-0.0002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Fuel Allowance	0.2065	0.3039	0.3137	0.7266***	0.7413***	0.7538***	0.9651***	1.0489***	1.0539***	0.6942***	0.7119***	0.7185***
	(0.224)	(0.260)	(0.264)	(0.194)	(0.160)	(0.163)	(0.210)	(0.305)	(0.300)	(0.162)	(0.179)	(0.182)
Other Supports	0.9309***	1.0026***	1.0380***	0.8480***	0.8785***	0.8780***	1.2480***	1.3214***	1.3034***	0.8813***	0.9356***	0.9529***
	(0.195)	(0.262)	(0.262)	(0.156)	(0.135)	(0.133)	(0.172)	(0.182)	(0.181)	(0.127)	(0.135)	(0.131)
Fuel and Other Supports	1.1646***	1.3287***	1.3434***	1.2294***	1.2835***	1.2867***	1.3775***	1.5178***	1.5411***	1.3445***	1.4317***	1.4420***
	(0.204)	(0.195)	(0.197)	(0.171)	(0.225)	(0.222)	(0.198)	(0.226)	(0.224)	(0.147)	(0.176)	(0.180)
Tenant status	0.8334***	0.8605***	0.8972***	0.4337***	0.4460***	0.4416***	0.6565***	0.6828***	0.6521***	0.5722***	0.6176***	0.6258***
	(0.186)	(0.152)	(0.155)	(0.134)	(0.147)	(0.146)	(0.154)	(0.215)	(0.205)	(0.112)	(0.130)	(0.128)
Detached house	-0.0396	-0.2251	-0.2698	0.3643	0.3708	0.3626	0.3220	0.3414	0.3299	0.1926	0.1912	0.1822
	(0.370)	(0.369)	(0.378)	(0.282)	(0.277)	(0.276)	(0.339)	(0.417)	(0.420)	(0.233)	(0.248)	(0.249)
Semi-detached house	0.3940	0.2658	0.2412	0.3174	0.3631*	0.3547*	0.3277	0.4531	0.4353	0.1584	0.2050	0.1958
	(0.289)	(0.409)	(0.413)	(0.229)	(0.204)	(0.208)	(0.245)	(0.288)	(0.299)	(0.186)	(0.206)	(0.210)
Terraced house	0.2164	0.0593	0.0198	0.1775	0.1460	0.1328	0.4439*	0.4714*	0.4622*	0.0715	0.0439	0.0336
	(0.275)	(0.356)	(0.352)	(0.220)	(0.159)	(0.158)	(0.227)	(0.253)	(0.253)	(0.179)	(0.191)	(0.189)
Total habitable floor area	0.0035*	0.0029	0.0027	0.0006	0.0008	0.0007	-0.0034	-0.0028	-0.0028	-0.0003	-0.0002	-0.0003
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.001)	(0.001)	(0.002)
Main space heating source - Electricity	-0.8473	-1.2213	-0.3343	-0.1856	-0.3218	-0.3560	-0.0709	-0.2181	-0.6089	-0.3990	-0.5447	-0.3253
	(0.708)	(0.835)	(0.682)	(0.476)	(0.601)	(0.575)	(0.433)	(0.572)	(0.527)	(0.402)	(0.494)	(0.452)
Main space heating source - Heating Oil	0.3579	0.2545	0.3611	0.4334*	0.2922	0.2807	0.2089	0.0257	-0.0165	0.2969	0.1772	0.2044
	(0.279)	(0.254)	(0.265)	(0.229)	(0.326)	(0.333)	(0.248)	(0.242)	(0.254)	(0.187)	(0.204)	(0.211)
Main space heating source - LPG	0.8148*	0.9395	0.9420	1.0764***	1.0608***	1.0790***	0.1200	-0.1449	-0.1630	0.5638*	0.4608	0.4594
	(0.494)	(0.660)	(0.667)	(0.378)	(0.378)	(0.369)	(0.492)	(0.668)	(0.687)	(0.335)	(0.331)	(0.329)
Main space heating source - Mains Gas	0.3531	0.1128	0.1120	0.4826**	0.2115	0.1977	0.4940**	0.2522	0.2589	0.4126**	0.1547	0.1545
	(0.274)	(0.267)	(0.264)	(0.227)	(0.329)	(0.331)	(0.239)	(0.320)	(0.324)	(0.187)	(0.254)	(0.257)
Main heating source x Fuel price	0.0693*	0.0770	0.0130	0.0246	0.0212	0.0227	-0.0003	-0.0094	0.0181	0.0266	0.0210	0.0044
	(0.037)	(0.048)	(0.036)	(0.025)	(0.034)	(0.031)	(0.024)	(0.027)	(0.030)	(0.021)	(0.026)	(0.023)
Electricity consumption <1000 kWh	0.4095	0.4908	0.3756	0.8938	0.9632	1.0114	-0.3055	-0.3377	-0.3067	1.0956	1.0864	1.1415
	(0.376)	(0.390)	(0.411)	(0.817)	(0.891)	(0.877)	(0.337)	(0.387)	(0.405)	(0.789)	(0.809)	(0.802)
Electricity consumption 1000<2000 kWh	-0.2002	-0.1305	-0.2051	0.5399	0.6166	0.6753	-0.8475***	-0.8957***	-0.9042***	0.8990	0.9233	0.9771
	(0.265)	(0.273)	(0.302)	(0.783)	(0.792)	(0.789)	(0.227)	(0.197)	(0.218)	(0.766)	(0.707)	(0.712)
Electricity consumption 2000<3000 kWh	-0.1314	-0.0475	-0.1037	0.6581	0.7196	0.7781	-0.5248***	-0.5528***	-0.5463***	1.0294	1.0533	1.1194
	(0.237)	(0.249)	(0.247)	(0.769)	(0.750)	(0.745)	(0.199)	(0.197)	(0.199)	(0.758)	(0.687)	(0.694)
Electricity consumption 3000<4000 kWh	-0.1404	-0.0305	-0.0520	0.6646	0.7233	0.7908	-0.3401*	-0.3688**	-0.3665**	1.1200	1.1341*	1.2102*
	(0.241)	(0.248)	(0.251)	(0.768)	(0.750)	(0.745)	(0.193)	(0.167)	(0.171)	(0.757)	(0.680)	(0.683)
Electricity consumption 4000<5000 kWh	-0.0700	-0.1003	-0.1268	0.5168	0.5341	0.6031	-0.2298	-0.2650	-0.2775	1.0810	1.0850	1.1602
	(0.225)	(0.210)	(0.206)	(0.767)	(0.780)	(0.773)	(0.206)	(0.186)	(0.193)	(0.756)	(0.711)	(0.720)
Period of construction 1978-1999	-0.0371	0.0788	0.0926	0.1234	0.1242	0.1233	-0.0186	0.0513	0.0438	0.1203	0.1318	0.1341
	(0.185)	(0.155)	(0.155)	(0.151)	(0.136)	(0.136)	(0.163)	(0.176)	(0.177)	(0.128)	(0.118)	(0.119)
Period of construction 2000-2004	-0.0180	0.0893	0.1007	0.0546	0.1372	0.1388	0.2708	0.3604	0.3564	0.1261	0.1834	0.1877
	(0.285)	(0.239)	(0.230)	(0.211)	(0.214)	(0.212)	(0.202)	(0.252)	(0.251)	(0.174)	(0.182)	(0.178)
Period of construction 2005-2009	0.0161	0.2166	0.2306	-0.0632	0.0421	0.0395	0.4423**	0.5591	0.5527	0.1315	0.2111	0.2162
	(0.259)	(0.295)	(0.292)	(0.219)	(0.324)	(0.318)	(0.223)	(0.362)	(0.358)	(0.183)	(0.271)	(0.268)
Period of construction 2010-2014	-0.8742	-1.0359	-0.9930	0.0022	-0.1013	-0.0899	-0.7489	-1.0412	-1.0427	-0.3593	-0.6054	-0.5946
	(0.723)	(1.158)	(1.165)	(0.592)	(0.622)	(0.613)	(0.765)	(1.195)	(1.220)	(0.564)	(0.545)	(0.536)
At least 1 65+ in HH	-0.4193	-0.4860*	-0.5080**	-0.5208***	-0.5719***	-0.5859***	-1.0384***	-1.0938***	-1.1026***	-0.5094***	-0.5404***	-0.5488***
	(0.279)	(0.253)	(0.254)	(0.180)	(0.197)	(0.200)	(0.228)	(0.249)	(0.246)	(0.164)	(0.204)	(0.202)
Age - head of household	-0.0052	-0.0050	-0.0050	-0.0099*	-0.0114**	-0.0113**	-0.0186***	-0.0211***	-0.0201***	-0.0122**	-0.0135***	-0.0133***
	(0.008)	(0.006)	(0.007)	(0.006)	(0.005)	(0.006)	(0.006)	(0.008)	(0.007)	(0.005)	(0.005)	(0.005)
Gender - head of household	0.1595	0.1846	0.1842	0.2652**	0.2821**	0.2810**	0.0042	-0.0165	-0.0169	0.1812*	0.1886*	0.1889*
	(0.155)	(0.153)	(0.150)	(0.120)	(0.114)	(0.115)	(0.131)	(0.155)	(0.156)	(0.100)	(0.110)	(0.110)
Single adult with children	0.0411	-0.1246	-0.1357	0.2707	0.2169	0.2175	0.4455**	0.3922*	0.4160**	0.3308*	0.2922	0.2857
	(0.253)	(0.297)	(0.314)	(0.203)	(0.255)	(0.253)	(0.204)	(0.212)	(0.206)	(0.177)	(0.186)	(0.183)
Poor health status	0.8353***	0.8812***	0.8993***	1.0161***	1.0336***	1.0450***	0.9903***	0.9642***	0.9707***	1.1319***	1.1400***	1.1434***
	(0.226)	(0.201)	(0.198)	(0.164)	(0.138)	(0.137)	(0.185)	(0.204)	(0.206)	(0.162)	(0.144)	(0.145)
Chronic illness	0.9547***	0.9355***	0.9308***	0.4353***	0.4579**	0.4638**	0.6075***	0.6441***	0.6275***	0.4338***	0.4460**	0.4446**
	(0.167)	(0.244)	(0.241)	(0.133)	(0.195)	(0.192)	(0.139)	(0.210)	(0.214)	(0.107)	(0.177)	(0.177)
Rural area	0.1739	0.2677	0.2591	-0.0536	0.0504	0.0471	0.7249***	0.7786**	0.7826**	0.0963	0.1397	0.1397
	(0.280)	(0.336)	(0.327)	(0.224)	(0.285)	(0.286)	(0.249)	(0.319)	(0.322)	(0.188)	(0.250)	(0.249)
Constant	-3.5211***	-4.2547***	-3.8007***	-3.0308***	-3.6915***	-3.7039***	-1.6230***	-1.5531**	-1.7544***	-2.7852***	-3.0613***	-2.9665***
	(0.734)	(0.766)	(0.875)	(0.970)	(1.003)	(1.060)	(0.591)	(0.679)	(0.666)	(0.904)	(0.764)	(0.797)
Observations	7,281	7,123	7,123	7,335	7,285	7,285	7,159	7,159	7,159	7,335	7,335	7,335
Fixed Effects - county	NO	YES	YES	NO	YES	YES	NO	YES	YES	NO	YES	YES
Fixed Effects - time	NO	NO	YES	NO	NO	YES	NO	NO	YES	NO	NO	YES

Note.— Columns estimate Equation 1 for each indicators under a set of different fixed effects. The table presents coefficients of interest in log-odds. The base groups are defined by households living G-rated energy-efficient dwellings, privately owned, heated by solid fuels, in an urban area. Observations come from a representative sample of Irish households during the period 2016 to 2022. [a]
Robust standard errors, clustered at regional or county level, in parentheses.
***p<0.01, **p<0.05, *p<0.1

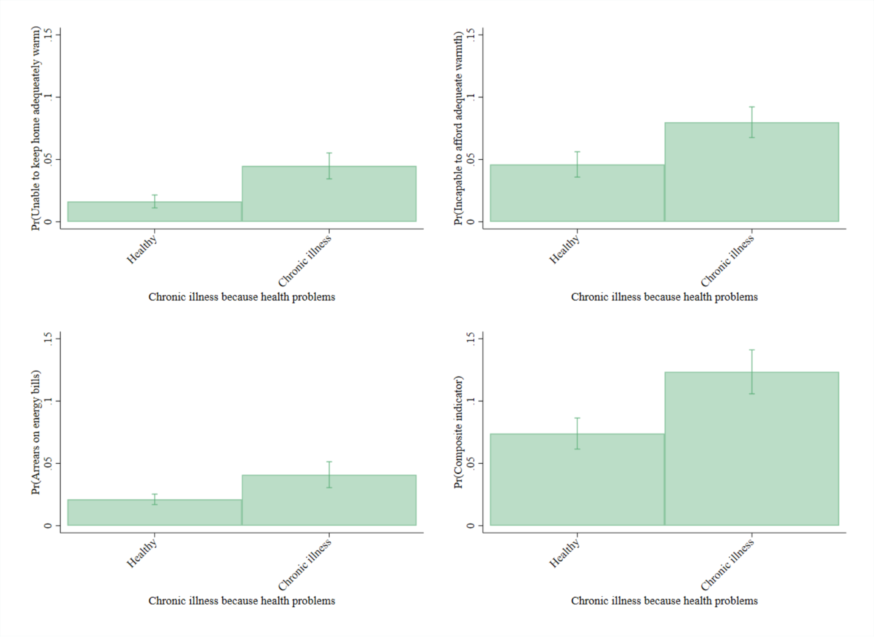

Figure 19: Estimated of effects health status

Note: The Figure presents the adjusted predictions of chronic illness effects with 95 percent confidence intervals. [a]

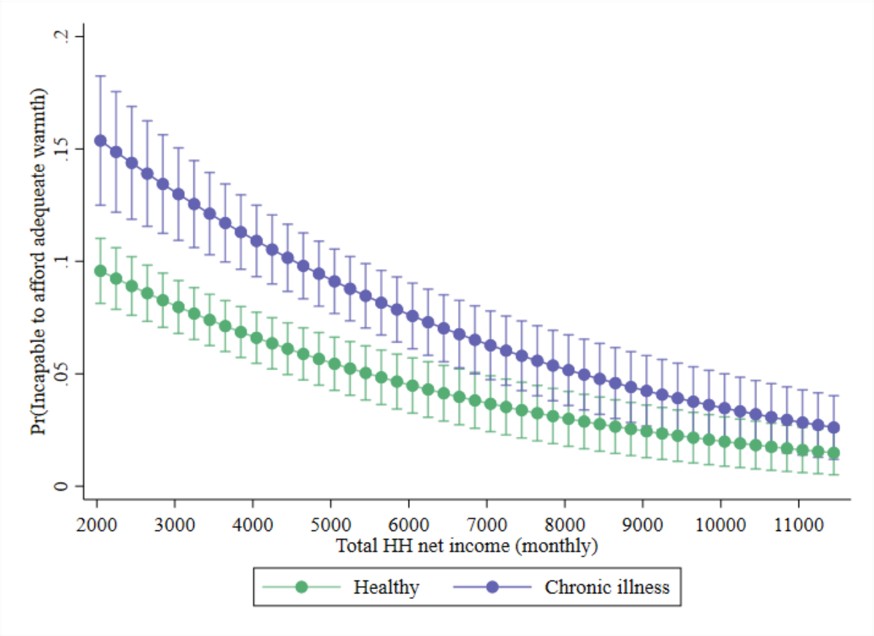

Figure 20: Estimated interaction effects of income and chronic illness status

Note: The Figure presents the adjusted predictions of income effects over chronic illness status with 95 percent confidence intervals. [a]

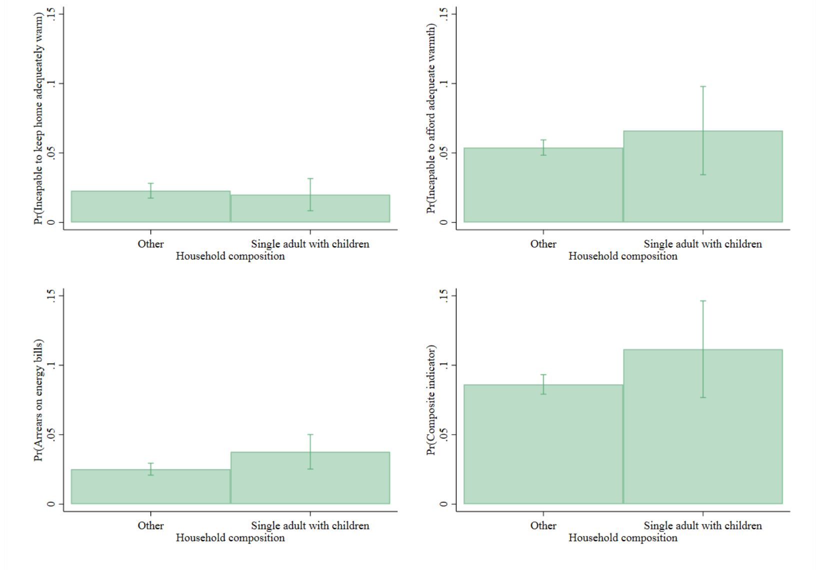

Figure 21: Household composition — single parents

Note: The Figure presents the adjusted predictions of the effects of household composition - single parent households - with 95 percent confidence intervals. [a]

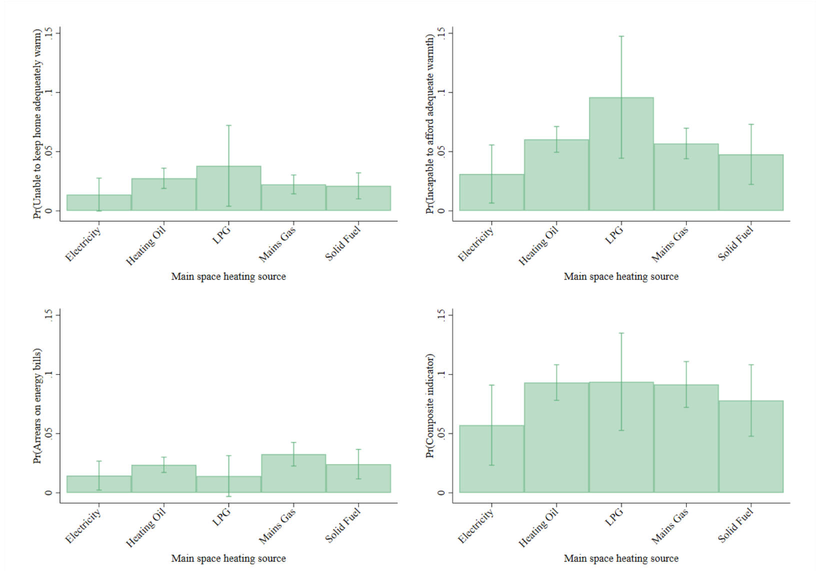

Figure 22: Estimated effects heating fuel type

Note: The Figure presents the adjusted predictions of the effects of main heating system fuel type with 95 percent confidence intervals. [a]

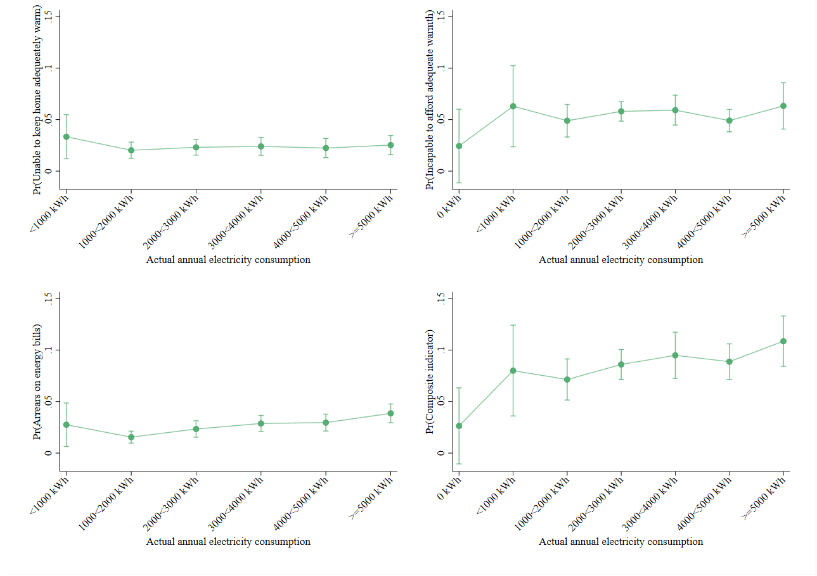

Figure 23: Estimated effects electricity demand

Note: The Figure presents the adjusted predictions of the effects of electricity demand with 95 percent confidence intervals. [a]

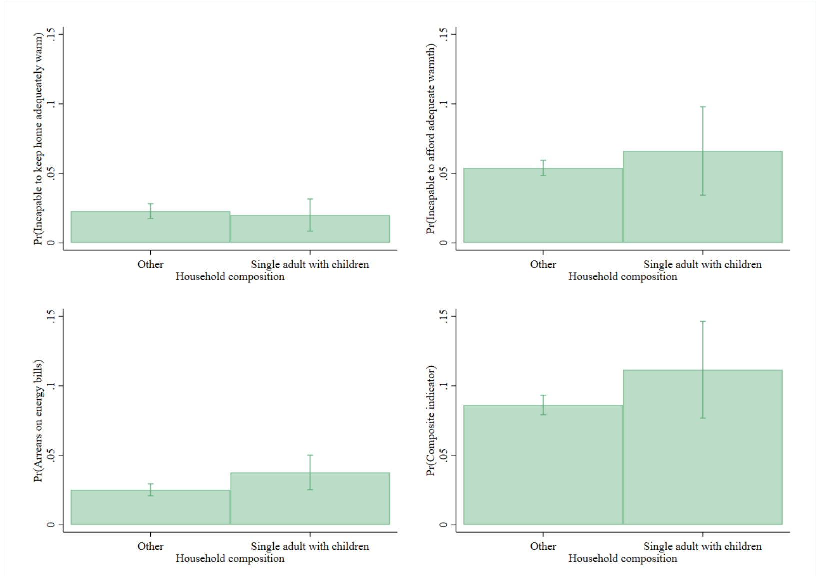

Figure 24: Household composition — Gender

Note: The Figure presents the adjusted predictions of the effects of household composition - head of household - with 95 percent confidence intervals. [a]

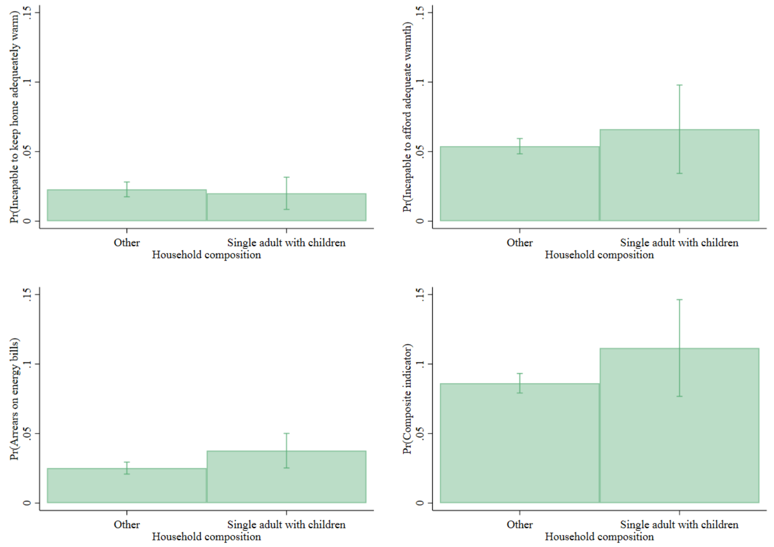

Figure 25: Household composition — Urban

Note: The Figure presents the adjusted predictions of the effects of household composition fuel type with 95 percent confidence intervals. [a]