Welfare trade-offs of energy-efficient homes: poverty, environment and comfort*

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Abstract

Energy efficiency improvements in low-income housing are increasingly used as a policy instrument to tackle poverty. Our paper shows that targeting the poor comes at the expense of lower environmental benefits. We perform a quasi-experimental evaluation of a large Dutch nationwide residential heating efficiency program. Unlike earlier literature, we examine the income heterogeneity in program effects and derive formally the behavioral mechanisms behind this heterogeneity. Our empirical work follows a sample of 125,000 households during eight years, exploiting a unique conditionally random treatment assignment; the results are then combined with a computable microeconomic choice model. Our findings suggest that the poorest realize one third lower than average energy and environmental savings. This is only partly compensated by the significant comfort gains they realize. We show further that, under the high gas prices that have been

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observed since 2022, the heating efficiency home upgrades likely generate positive private returns, also for the poor.

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1 Introduction

Many countries subsidize energy-efficient home upgrades in low-income housing (e.g. insulation to diminish heat losses, solar panels and heat pumps for renewable energy generation). These policies often hinge on two interconnected goals. One is carbon emission reduction and environmental quality improvement, see as example the 2012 Energy efficiency covenant in the Dutch social housing sector (Ministry of the Interior and Kingdom Relations, 2012). The other goal involves energy cost reduction and living comfort improvement for poor households in need.[1] This is explicit in e.g. the Weatherization Assistance Program in the US, or the UK's Warm Front Home Energy Efficiency Scheme (Fowlie et al., 2018; Sovacool, 2015). Our paper shows that the two goals are competing: prioritizing energy efficiency upgrades for the poor comes at the expense of lower environmental benefits. We conclude this based on a large quasi-experimental evaluation of the Dutch nationwide residential heating efficiency program, conducted on a sample of 125,000 households during eight years and combined with a computable microeconomic choice model. More specifically, we evaluate the (welfare) effects of the program on energy expenditures, comfort and environment, for different income groups.

Existing economic evaluations tend to report negative private and social returns to low-income energy efficiency upgrades, and document hardly any improvements in comfort. A well-known example is the seminal article by Fowlie et al. (2018) that performs a randomized experiment on a sample of 30,000 households eligible for the US Weatherization program and finds, on average, that the benefits of Weatherization fall short of the costs. More recent literature argues that the average conceals a significant variation in both positive and negative returns (Christensen et al., 2024, 2023). The behavioral mechanisms behind this heterogeneity have not been sufficiently studied yet. This is unfortunate as being able to predict the behavioral responses and the welfare gains for different population groups will help better target the energy efficiency policies but also

[1] The underlying assumption is that poor households, due to severe credit constraints, may bring down their energy use to a level harmful for their health and well-being (European Commission, 2023).

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to optimally adjust these policies to exogenous shocks, such as e.g. the peaking energy prices observed since 2022.

Our paper aims to fill the gap by explicitly modeling how heterogeneity in the size and composition of the benefits of heating efficiency upgrades arises from income and energy price differentials. For this, unlike earlier literature, we combine a computable microeconomic consumer choice model and a quasi-experimental evaluation of a large countrywide heating efficiency program in the Netherlands. The consumer model formally describes how people optimize between the home thermal comfort, which is produced from natural gas, and other consumption goods, and how this is affected by the home heating efficiency. It analytically derives testable hypotheses about the income heterogeneity in behavioral responses to home upgrades. Further, the model allows to compute the welfare effects of the upgrades, including the difficult to value comfort benefits. We use the low-income heating efficiency program to test the predictions of and provide the parameters for the consumer choice model. The unique features of the program are a conditional random assignment to treatment and no possibility of opting-out.

The program started in 2012 when all Dutch housing associations – non-commercial entities owning low-income social houses – agreed in a covenant to upgrade the heating efficiency in more than one million old dwellings they own.[2] The home improvements took place in the subsequent years through insulation upgrades, i.e. adding extra material to the walls and the roof. Since a large number of houses qualified for the upgrade, only a small share could be tackled on a yearly basis. As we will show, housing associations based the decision which of the qualifying dwellings should be treated in which year, on organizational and cost efficiency considerations rather than on the house and tenant characteristics.[3] This made the treatment assignment random, conditional on housing

[2]The social housing sector in the Netherlands is large and includes 2.2 million dwellings (30% of the Dutch housing stock) and around 400 housing associations. It offers housing to people below the median income, at regulated rent levels. In 2020 the income threshold to be eligible for social housing was around 40.000 euro gross yearly income.

[3]For example, upgrades were synchronized with the timing of regular painting works in buildings, which is a cyclical event planned many years in advance.

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observables.[4] Further, self-selection was prevented because people could not opt out of the program.[5] As a consequence, we can make use of a clean identification of program effects and a large longitudinal sample of 125,000 qualifying houses of which somewhat more than 10% got treated. The sample has a large variation in household income, which we exploit.[6]

We evaluate the effects of the program on natural gas consumption by income using a two-way fixed effect panel regression (Angrist and Pischke, 2008), as well as the recent advances in staggered treatment effect estimation (Callaway and Sant'Anna, 2021; Sun and Abraham, 2021). To enable welfare effect calculation and decomposition, we estimate the consumer choice model parameters to match the observed pre-retrofit gas use distribution by income and the estimated quasi-experimental gas savings distribution by income. The model is then run to predict how different population groups re-optimize thermal comfort and other consumption after a home upgrade. Subsequently, compensating variation allows to value the comfort increases and the natural gas savings. In the welfare analysis, we use two scenarios: (i) low gas prices (level 2016) and (ii) high gas prices (level 2022), the latter being twice as high as the former.

There are three primary findings. First, we predict theoretically and document empirically a significant income heterogeneity in the effects of home upgrades on natural gas use. Our consumer choice model shows that: (i) the poor choose for lower than average thermal comfort and gas use for heating, more so in houses with bad heating efficiency; (ii) they increase the comfort relatively more after a home upgrade, with lower gas savings as a result (i.e. the poor experience a larger rebound effect). Empirical tests suggest that households at the very left tail of the income distribution have 20% lower than average heating demand before the upgrade. After the upgrade, we find a reduction in natural gas use of 22% on average and a much smaller reduction of 16% for the poor.

[4]In Section 3 we discuss the selection process at length and also provide a formal test of conditional randomness as well as balancing tests.

[5]Self-selection is a common problem in effect evaluations. We will show that tenants did not adjust behavior in anticipation either.

[6]Although social housing is meant for low-income people, the income check is only done once, when the renter signs a contract for a new dwelling. The actual income distribution of social renters thus also includes a sufficient number of households with higher incomes.

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These estimates are robust to a host of different specifications and modeling assumptions. From the policy perspective, the results suggest that tackling the poor with heating efficiency upgrades leads to lower than average environmental benefits.[7]

Second, the paper provides a variety of novel insights into the driving factors behind the returns from heating efficiency programs. We start by decomposing the private benefits into monetary savings and increased comfort. The latter accounts for up to 20% of the total private gain, the share falls however sharply with income. Then we show that the distribution of the private benefits across income groups is not equal: a poor household receives up to 15% smaller gain than a higher income peer. Finally, while negative private and social returns prevail in the reference scenario with low gas prices, a positive private (and social) return becomes feasible in the counterfactual with high gas prices. Given that currently in Europe some 20% and in the Netherlands almost 50% of the consumer price for natural gas consists of taxes and charges (Eurostat, 2024), the governments seem to have effective instruments at hand to affect the private payback of the heating efficiency investments and thus reduce the energy efficiency gap.

Third, the computable consumer choice model allows to derive an analytic expression for the rebound effect from microeconomic premises and to document significant income heterogeneity in this rebound.[8] For example, for poor households and high gas prices, we find a rebound of 20%, while for the entire sample and low gas prices, we find 5%.

Our paper makes three primary contributions to the literature on energy efficiency. First, it provides a causal evidence on the income heterogeneity in the benefits of heating efficiency, based on a large field test with clean identification. There exists a small quasi-experimental and non-experimental literature that

[7]We also provide additional insight into other possible behavioral adjustments of the poor people in response to the home upgrade, such as e.g. substitution between different heating sources, but do not find evidence of this.

[8]The analytic expression follows the definition by Gillingham et al. (2016): the difference between the actual energy savings and those forecast without any consumer and market responses to the energy efficiency improvement.

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looks into how the returns vary by income and other household characteristics, see Davis et al. (2014); Aydin et al. (2017); Liang et al. (2018); McCoy and Kotsch (2021); Hammerle and Burke (2022). These studies face various identification issues, most frequent of which is self-selection due to the voluntary character of the program. Our paper, on the contrary, uses a large representative sample and identification based on a conditional random assignment to treatment.

Second, our paper is one of the first efforts to understand the driving factors and behavioral mechanisms behind the returns to energy efficiency investments in homes. There have been numerous attempts to quantify the monetary savings from energy efficiency programs, based on quasi-experimental and experimental evidence, see Gillingham et al. (2018) and Saunders et al. (2021) for reviews. Large-scale evaluations include Fowlie et al. (2018) and Allcott and Greenstone (2017) for the US; Webber et al. (2015), Peñasco and Anadón (2023), McCoy and Kotsch (2021) and Adan and Fuerst (2016) for the UK, Davis et al. (2014) for Mexico. These existing studies use a reduced form econometrics and are therefore not able to predict benefits under different scenarios. Neither are they able to value the comfort improvements. Our paper combines econometrics with a computable consumer choice model and fills these two gaps.

Third, we provide a welfare-based formula that allows to compute the rebound effect for different income groups. Many studies measure rebound as the gap between the ex-ante engineering forecasts and the actual savings from energy efficiency upgrades, see Sorrell and Dimitropoulos (2008); Gerarden et al. (2015); Allcott and Greenstone (2017); Aydin et al. (2017) and also a review in Peñasco and Anadón (2023). Christensen et al. (2023) uses a method based on machine learning. Our approach explicitly builds upon a simple microeconomic model. Further, while income heterogeneity in the rebound was pinpointed as early as 2000 by Milne and Boardman (2000), to our knowledge, this paper is the first to perform a large-scale empirical measurement of this heterogeneity.

The rest of the article is organized as follows. Section 2 introduces the consumer choice model explaining why the poor have lower responses to energy efficiency upgrades. Section 3 describes the institutional background, the sample and the data. Section 4 discusses the empirical methodology and identi-

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fication and reports the main results. Section 5 derives the parameters for the computable consumer choice model and calculates welfare effects under different scenarios. Section 6 concludes.

2 Theoretical Framework

In this section, we develop a simple consumer choice model in which a household spends its income on consumption and heating. We solve the model and derive the optimal household consumption and gas use levels. Using the resulting indirect utility function, we compute a monetary measure of the energy efficiency upgrade, the compensating variation. To decompose this welfare gain of the household to a thermal comfort component and a consumption component, we use the Slutsky compensation.

2.1 Model

Household utility is given by the following constant elasticity of substitution, CES, specification:

$$u(x,\theta) \stackrel{\text{def}}{=} \left((f_1(x))^{\frac{\sigma-1}{\sigma}} + (f_2(\theta))^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}},$$

where $x \geq 0$ is the consumption of a composite good and $f_1(x)$ is the consumption utility component, θ is the thermal comfort measured by the indoor winter temperature and $f_2(\theta)$ is the thermal comfort utility component. Parameter σ is the elasticity of substitution between the consumption utility and the thermal utility components.

We assume that the thermal comfort utility component $f_2(\theta)$ is increasing and concave and reaches its maximum at some temperature $\bar{\theta}$. The idea behind this assumption is that not only too low but also too high indoor temperatures negatively affect the individual well-being. As a result, the household never chooses a value of θ beyond $\bar{\theta}$. We operationalize $f_2(\theta)$ as the second degree concave polynomial as follows:

$$f_2(\theta) \stackrel{\text{def}}{=} (2\bar{\theta} - \theta)\theta.$$

For the consumption utility component $f_1(x)$, we assume

$$f_1(x) \stackrel{\text{def}}{=} x.$$

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Thus, the household utility is defined for $x \geq 0$ and θ by

$$u(x,\theta) = \left(x^{\frac{\sigma-1}{\sigma}} + \left((2\bar{\theta}-\theta)\theta\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}. \tag{1}$$

Thermal comfort θ is produced from natural gas according to the production function:

$$\theta = \theta_0 + qg,$$

where $g > 0$ is the gas use for heating, θ_0 is the natural indoor winter temperature when $g = 0$, and $q \geq 0$ is the home heating efficiency parameter. The higher is q, the less gas is needed to increase the indoor temperature by one degree. We use an increase in q from $q = q_L$ to $q = q_H > q_L$ for modeling home heating efficiency upgrades.

The household earns income w and spends it on (x, g). We normalize the price for consumption to unity, $p_x = 1$, and the natural gas price is $p_g > 0$. The household budget constraint is, therefore:

$$x + \frac{p_q}{q}(\theta - \theta_0) = w. \tag{2}$$

where $\frac{1}{q}(\theta - \theta_0)$ is the annual gas use. All households face the same gas price p_g, and each household is characterized by parameters $(q, w, \theta_0, \bar{\theta}, \sigma)$ and chooses $x \geq 0$ and $\theta \in [\theta_0, \bar{\theta}]$ to maximize utility (1) subject to the budget constraint (2). Since we are only interested in the effects of home heating efficiency q and income w on household behavior, we omit all other exogenous variables $(p_g, \theta_0, \bar{\theta})$ from the argument lists in what follows.

2.2 Household Optimal Behavior

The following proposition provides the solution (x^*, θ^*) to the utility maximization problem, UMP, of a household.

Proposition 1 *Let the critical income level $\underline{w}(q)$ be defined by:*

$$\underline{w}(q) \stackrel{\text{def}}{=} (2\bar{\theta} - \theta_0)\theta_0 \left(\frac{p_g}{2q(\bar{\theta} - \theta_0)}\right)^{\sigma}. \tag{3}$$

Then:

1. *If $w \leq \underline{w}(q)$, then $x^*(q,w) = w$ and $\theta^*(q,w)) = \theta_0$.*

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2. *If* $w > \underline{w}(q)$, *then* $\theta^*(q, w)$ *is uniquely defined by:*

$$0 = w - (2\bar{\theta} - \theta^*)\theta^* \left(\frac{p_g}{2q(\bar{\theta} - \theta^*)}\right)^\sigma - \frac{\theta^* - \theta_0}{q} p_g, \tag{4}$$

and

$$x^*(q, w) = w - \frac{\theta^* - \theta_0}{q} p_g. \tag{5}$$

3. *For* $w \geq \underline{w}(q)$, $x^*(q, w)$ *and* $\theta^*(q, w)$ *increase in* w.

4. *The optimal thermal comfort* $\theta^*(q, w)$ *increases in* q *and approaches* $\bar{\theta}$ *when* q *or* w *increase unboundedly.*

The proof of the proposition is in Appendix A. For low income levels that are below $\underline{w}(q)$, the optimal consumption is a corner solution, where the household uses no gas and stays at the natural house temperature $\theta^*(q, w) = \theta_0$. The household spends then all its income w on consumption, $x^*(q, w) = w$. For higher income levels, $w > \underline{w}(q)$, the optimal thermal comfort θ^* is an interior solution satisfying $\theta^* \in (\theta_0, \bar{\theta})$. Both thermal comfort and composite good consumption are normal goods and their optimal levels increase with income w.

Figure 1a illustrates Proposition 1. It shows the optimal indoor temperature θ^* as a function of income w for two values q_L and q_H of the heating efficiency parameter q, with $q_L < q_H$. For the lowest income levels, the optimal thermal comfort is at its natural level θ_0. With rising income, the optimal thermal comfort also rises and converges in the limit to the satiety threshold $\bar{\theta}$. With the increase in q, the optimal thermal comfort starts to increase at lower income levels.

The optimal gas use $g^*(q, w)$ is determined by $\theta^*(q, w)$:

$$g^*(q, w) = \frac{1}{q}(\theta^*(q, w) - \theta_0). \tag{6}$$

The following proposition provides a characterization of $g^*(q, w)$.

Proposition 2 *Optimal gas use* $g^*(q, w)$ *has the following properties:*

1. $g^*(q, w)) = 0$ *for* $w \leq \underline{w}(q)$.

2. $g^*(q, w)$ *increases in* w *for* $w > \underline{w}(q)$ *and converges to* $\frac{1}{q}(\bar{\theta} - \theta_0)$ *when* w *increases unboundedly.*

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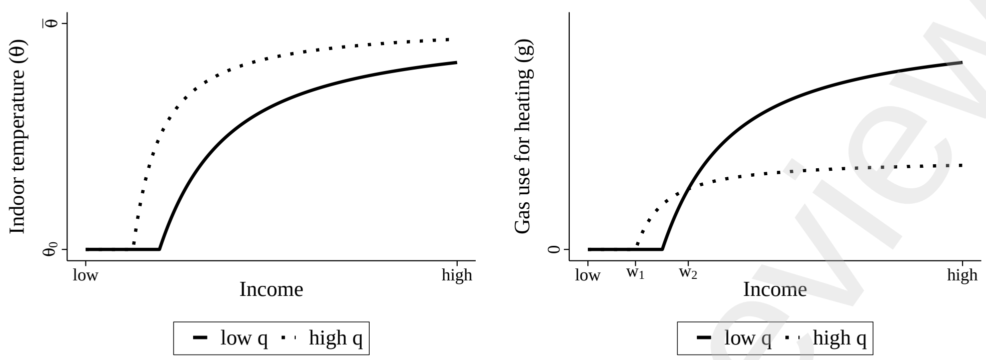
Figure 1: Optimal thermal comfort θ^* and gas use g^*.

(a) Thermal comfort (b) Gas use



Notes: The lines show the optimal levels of indoor temperature respectively natural gas use as a function of income ($\theta^*(w)$ respectively $g^*(w)$) as implied by the utility maximization problem Equations (1) and (2). See Appendix A for the derivations. $q \geq 0$ is the home heating efficiency parameter.

3. *For any q_L and q_H, $q_H > q_L > 0$, there are two income thresholds $w_1(q_L, q_H)$ and $w_2(q_L, q_H)$ satisfying $w_2(q_L, q_H) \geq w_1(q_L, q_H) > \underline{w}(q_L)$ such that:*

$$g^*(q_H, w) > g^*(q_L, w) \text{ for } w < w_1(q_L, q_H)$$
$$g^*(q_H, w) < g^*(q_L, w) \text{ for } w > w_2(q_L, q_H)$$

The proof of the proposition is in Appendix A. Figure 1b illustrates Proposition 2. It shows the optimal gas use g^* as a function of income w for two values q_L and q_H of the heating efficiency parameter q, with $q_L < q_H$. Since the graph of $g^*(q_H, w)$ starts to increase at a lower income level $\underline{w}(q_H)$ and converges to a lower limit $\frac{1}{q_H}(\bar{\theta} - \theta_0)$ than the graph of $g^*(q_L, w)$ does, the graphs necessarily intersect, and the income thresholds w_1 and w_2 are the lowest and the highest intersection income levels. For low income levels when $w < w_1$, the upgrade from q_L to q_H results in an increase of the optimal gas use, $g^*(q_H, w) > g^*(q_L, w)$. For larger income levels when $w > w_2$, the optimal gas use decreases, $g^*(q_H, w) < g^*(q_L, w)$.

Summarizing, when the heating efficiency of a house increases, all households re-optimize their consumption patterns, trading-off potential natural gas savings against an increase in the level of thermal comfort. Households with a sufficiently low income increase their gas use because they are further away from the satiety threshold and, therefore, face a larger marginal benefit of a unit temperature

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increase. High-income households, to the contrary, decrease their gas use because for them, the marginal benefit of a unit temperature increase is low. This results in lower gas savings for the poor, as compared to the rich.

2.3 Household Welfare Analysis

Using the household optimal thermal comfort $\theta^*(q, w)$ and optimal consumption, we write the household indirect utility $V(q, w)$ as follows:

$$V(q, w) \stackrel{\text{def}}{=} u(x^*(q, w), \theta^*(q, w)),$$

where u, θ^*, and x^* are defined by Equations (1), (4) and (6) respectively. The exact household welfare gain for the change in heating efficiency q from $q = q_L$ to $q = q_H$ is given by the compensating variation CV, which is implicitly defined by:

$$V(q_H, w - CV) = V(q_L, w). \tag{7}$$

Compensating variation $CV(q_L, q_H, w)$ is the household willingness to pay for the heating efficiency improvement, it is the income effect of the heating efficiency improvement. We compute CV in Section 5 (Table 6) after fitting the model parameters from data.

Compensating variation CV accounts for changes in both thermal comfort θ^* and consumption x^* driven by the upgrade and cannot be easily decomposed into two effects that come from those changes. To overcome this difficulty, we use two facts form micro-economic theory (see chapters 2.F and 3.I.1 in Mas-Colell et al. 1995). First, the amount negative to the compensating variation is called Hicksian compensation of the heating efficiency change:

$$\Delta^H \stackrel{\text{def}}{=} -CV.$$

Second, an imprecise measure of the Hicksian compensation Δ^H is the Slutsky compensation defined by:

$$\Delta^S \stackrel{\text{def}}{=} \left(p_x x^*(q_L, w) + \frac{p_g}{q_H}(\theta^*(q_L, w) - \theta_0) \right) - w.$$

By construction, $(-\Delta^S)$ equals the income of the household that remains after the thermal upgrade from q_L to q_H if the household maintains the pre-upgrade

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consumption levels $x^*(q_L, w)$ and $\theta^*(q_L, w)$. Using Walras law

$$w = x^*(q_H, w) + \frac{p_g}{q_H}(\theta^*(q_H, w) - \theta_0),$$

we rewrite $(-\Delta^S)$ as follows:

$$(-\Delta^S) = (-\Delta^S_x) + (-\Delta^S_\theta),$$

where

$$(-\Delta^S_x) \stackrel{\text{def}}{=} x^*(q_H, w) - x^*(q_L, w), \tag{8}$$

is the effect on composite good consumption, and

$$(-\Delta^S_\theta) \stackrel{\text{def}}{=} \frac{p_g}{q_H}(\theta^*(q_H, w) - \theta^*(q_L, w)), \tag{9}$$

is the effect on thermal comfort.

The share of the thermal comfort effect in the Slutsky compensation:

$$\epsilon \stackrel{\text{def}}{=} \frac{\Delta^S_\theta}{\Delta^S}. \tag{10}$$

is the so-called *rebound effect*, defined by Gillingham et al. (2016) as the difference between the actual energy savings and those forecast without any consumer and market responses to the energy efficiency improvement.

In Section 4, we exploit quasi-experimental improvements in the heating efficiency of Dutch houses to estimate $g^*(q, w)$ as a function of income and heating efficiency. Then, in Section 5, these results are used to fit the parameters of the model Equations (1) and (2), and then to compute CV and its approximate decomposition into $(-\Delta^S_x)$ and $(-\Delta^S_\theta)$. According to theory, $\Delta^S \geq \Delta^H$. Hence, the sum of the effects $(-\Delta^S_x)$ and $(-\Delta^S_\theta)$ does not exceed CV:

$$(-\Delta^S_x) + (-\Delta^S_\theta) = (-\Delta^S) \leq (-\Delta^H) = CV.$$

Therefore, the sum of these effects always underestimates the exact income effect CV.

3 Quasi-experiment, data and sample

Before discussing the empirical model, we first introduce the quasi-experiment and the data. We start with describing the institutional background of the Dutch social housing as this is crucial for our identification strategy.

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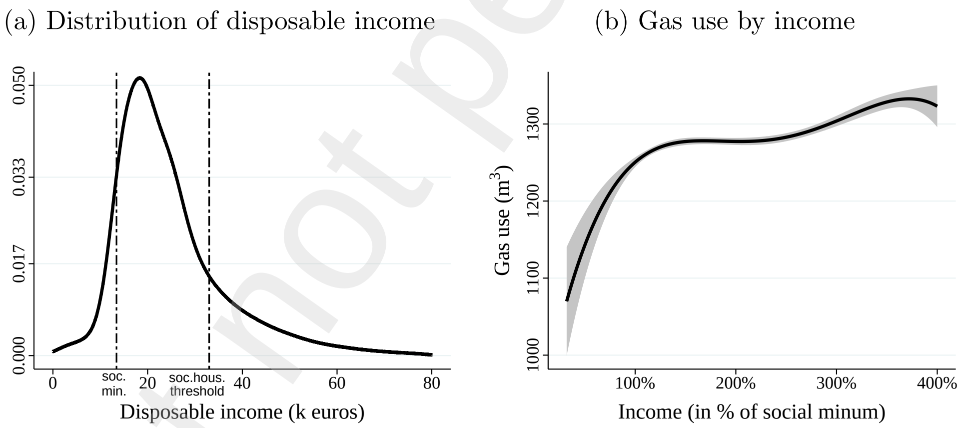
3.1 Dutch social housing: residents and dwellings

This study focuses on the households living in Dutch social housing. The social housing sector in the Netherlands is large and includes 2.2 million dwellings (one third of the Dutch housing stock). It offers housing at regulated rent levels to households with an income below the median. In 2020 the threshold to be eligible for social housing was around 40.000 euro yearly gross income per household (this amounts to some 33.000 euro disposable income). However the income check is only done once, when the renter signs a contract for a new dwelling. Therefore, although the majority of social renters are low-income people, also households with incomes higher than the threshold live in the social dwellings. Figure 2a shows the distribution of the social housing residents by income; our data offers considerable variation by income on both tails (below the social minimum and above the threshold), which we will use in our study.

Figure 2: Income and gas use in social housing 2016



Notes: Figure (a) shows the distribution of the disposable income, for the residents of social houses. The vertical line of the left indicates the median income of households below the social minimum (this social minimum is computed by Statistics Netherlands, its value depends on the household type). The vertical line of the right indicates the maximum income threshold to enter social housing. Figure (b) shows a polynomial fit (of degree 4) of household's gas use against income, whereby income is measured in percent of social minimum, in 2016.

Figure 2b plots households' yearly natural gas use against their disposable incomes, for the same households as in Figure 2a. The insights of the Figure

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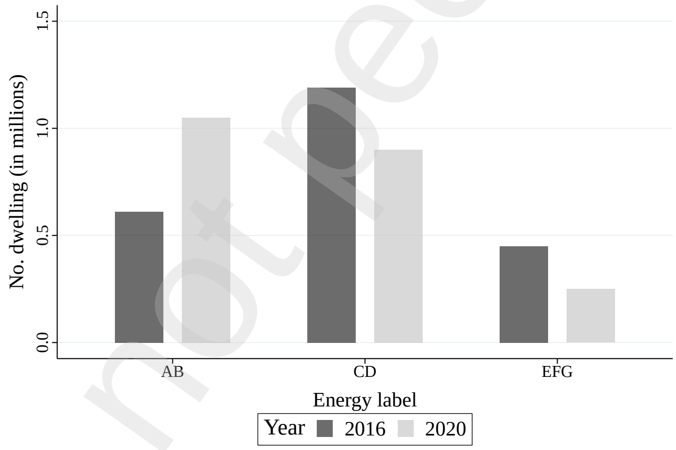
are in line with the theoretical conclusions of the previous Section.[9] On the one hand, gas use increases in income. On the other hand, there is a diminishing marginal effect. While the median gas use in the social housing lies around 1270 m^3/year, the poorest consume up some 20% less.

We turn now from the residents of social houses to the dwellings they live in. The potential for energy and environmental savings in the social housing sector is high. About two-thirds of the stock was built before 1993, according to the low energy efficiency building standards of that time. Social housing owners - the so-called housing associations - are required by the government to improve the energy efficiency of these properties. Home upgrades started with the 2012 Energy efficiency covenant which aimed at 33% CO_2 savings by 2020. Until 2020 half a million homes was improved, still leaving one million homes to go.

Figure 3: Energy efficiency in social housing



Notes: The Figure reports the number of social houses in the Netherlands in millions, by energy efficiency label, in 2016 and 2020. Source: Aedes (2016,2020).

Figure 3 plots the distribution of the social dwellings by energy efficiency in 2016 and 2020, as measured by the European energy label. This label is derived from the thermal quality of the dwelling and is assigned to dwellings by trained professionals after a technical inspection. The label takes elements such as insulation quality, heating installation, (natural) ventilation and indoor air

[9] Note that 95% of the yearly gas used by a household is spent on thermal comfort (space heating and hot water) (Eurostat (2023)).

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climate, solar systems, and built-in lighting into account. The label is based on a simple universal indicator of the energy use – the energy index, which reflects the engineering projection of primary energy use under average conditions. Labels 'A-B' are considered good, labels 'E-F-G' are considered bad and need to be improved in the first place. Figure 3 shows that the share of the labels 'C' to 'G' (medium to poor energy efficiency) fell between 2016 and 2020, and the share of the labels 'A' and 'B' grew. This mostly happened through heating and electricity system upgrades.[10] In this paper we will study the effects of the heating efficiency upgrades applied to the dwellings of labels ranging from 'C' to 'G'.

3.2 Heating efficiency upgrades; quasi-experiment

One of the most frequent heating efficiency upgrades in the social housing is *insulation of the building*, whereby materials are added to the walls and the roof in order to reduce the heat losses and the natural gas quantity required for heating. Insulation is often seen as a prerequisite for many other energetic improvements. In this and next Sections we study the effects of the insulation upgrades undertaken by the Dutch social housing associations in 2017-2019, on the natural gas use of the social housing residents.[11] Two characteristics of these upgrades are important for our identification strategy and allow for a quasi-experimental approach; we highlight these here. First, as discussed above, the number of old and energy-inefficient dwellings qualifying for an insulation upgrade was very large in 2016. Therefore, these houses could not be allocated to a retrofit simultaneously, and a selection rule was necessary. From discussions with renovation managers of a number of Dutch housing associations[12] we learned that, during the study period, the decision which of the qualifying dwellings to prioritize for an insulation upgrade in which year, was mainly based on cost and efficiency consider-

[10] New construction was another factor that affected this shift.

[11] Insulation upgrades in our data include roof, floor, facade insulation as well as replacing window frames and glass for energy-efficient ones. In the vast majority of cases, insulation is accompanied by installation of a mechanic ventilation system that prevents air quality deterioration.

[12] We are grateful for these discussions to the experts of Bazalt Wonen, Elan Wonen, PreWonen, Woonbedrijf.

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ations rather than on the housing and tenant characteristics. More specifically, insulation upgrades in qualifying dwellings were synchronized with the regular maintenance schedule for these dwellings (including painting of exterior walls, replacement of lighting, pipes and tubes in the building).[13] Regular maintenance is a cyclical process for which planning is known for many years to go (e.g. painting is usually scheduled every 6 years, etc.) It is performed by *complex* - a block of adjacent houses sharing the same building year and similar technical characteristics. The timing of regular maintenance can thus be assumed independent of and uncorrelated with the potential outcomes of insulation upgrades.[14] As a result, the assignment of the houses to treatment can be seen as random, conditional on a house qualifying for a heating efficiency upgrade based on observables like construction year, energy efficiency and dwelling type.

The second useful feature of the social housing insulation upgrade program is that self-selection in or out of it was impossible for individual tenants. By Dutch law, if 70% tenants of a complex agree with the retrofit plans (and this was usually the case in social housing), individual tenants do not have a right to opt out any more, even if they wish so (see e.g. Ossokina et al. 2021). This means that, next to the conditionally random assignment to treatment, we can take advantage of the treated sample being representative of the social renters' population in the country.[15]

The randomness of the treatment conditional on observed building characteristics is an important identification assumption in the quasi-experimental evaluation we aim to use. We will also formally test this assumption in Section 3.4.

[13] Recently, due to the rising energy prices, other criteria - like tackling poor households first - have also been used in prioritizing. This change is outside the time scope of our study.

[14] Note that replacement of the boiler - an intervention that does affect gas use - does not fall under regular maintenance and follows an own cycle, which is often dwelling-specific. We control for the boiler replacement by including it explicitly as a time-varying variable in the econometric model.

[15] We note that people could vote with their feet and relocate to another house if they did not agree with the upgrade. We will show formally that this did not happen.

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3.3 Sample and data

We exploit information on insulation upgrades performed by 128 Dutch social housing associations in 2017-2019. The housing associations in the sample collectively own about 1 million dwellings located in all regions of the country. Our sample covers 40% of the total social housing stock and is representative for the Dutch social housing sector.

We combine two data sets. The first one includes detailed longitudinal dwelling-level data on building characteristics and energy efficiency indicators, as well as the year of retrofit if any, this for 2016-2021.[16] The second, also longitudinal, dataset contains restricted access microdata on household level made available by Statistics Netherlands. These include socio-economic characteristics of the households as well as their yearly gas and electricity use for the years 2012-2021. Two datasets are merged on address level. This yields, for one million houses, information on (1) structural house characteristics 2012-2021, (2) incidence and characteristics of insulation upgrades 2016-2021, (3) resident household characteristics 2012-2021 and (4) energy use 2012-2021.

Our main outcome variable is yearly gas use per dwelling in cubic meters. The main covariate is the binary indicator of whether a dwelling got an insulation upgrade in or before a specific year. Further, as the type and size of the insulation upgrade may differ by house, we derive a retrofit intensity index and include it - in a standardized form - as a control.[17] The intensity is a continuous variable based on the engineering projections of the change in dwelling heating efficiency after the upgrade (i.e. change in the engineering projected log gas use). Engineering projections are conventionally made under the NEN 7120 guidelines by the building performance software VABI, which is used by all housing associations in our data. Figure 4 reports a histogram of the standardized retrofit intensity. Other covariates used as controls are: house and household character-

[16] We thank engineering bureau Atriensis for sharing with us their Energy Monitor data, and social housing associations Bazalt Wonen, Elan Wonen, PreWonen, Woonbedrijf for sharing their expertise and additional data on retrofits.

[17] We also run regressions with retrofit intensity included as a different order flexible polynomial and regressions without retrofit intensity, see Appendix D, this does not affect the conclusions.

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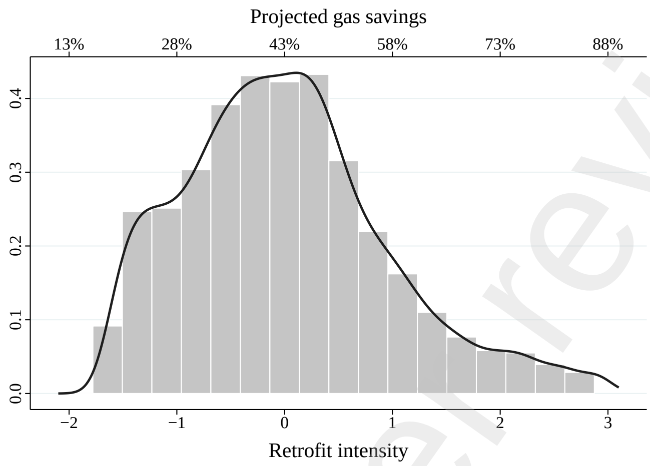
istics (dwelling type, construction period, surface, energy efficiency of the house, household type, number of persons, education, income, etc.) as well as energy use before retrofit.

Figure 4: Distribution of retrofit intensity



Notes: The figure shows the distribution of the retrofit intensity in the data sample used in this paper. We define the retrofit intensity as the standardized projected gas savings. The projected gas savings are the difference between pre- and post-retrofit projected log gas use. Projected gas use is computed by the engineering building performance model VABI.

To test the hypothesis about divergent responses of households on the left tail of the income distribution, we make use of the social minimum indicators defined by Statistics Netherlands. The definition of the social minimum is the 'minimal amount one needs in order to cover basic personal needs' (Statistics Netherlands). The amount is determined yearly and is derived from the size of the social welfare benefits. It therefore depends on the composition of the household. E.g. in 2017 the social minimum equaled a monthly disposable income of 1 040 euro for a single person, 1 380 euro a one-parent family with one child and 1 960 euro for a couple with two children. We will distinguish three strata of poor households: those below (i) 100%, (ii) 130%, (iii) 150% of the social minimum.

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3.4 Treatment and control group, balancing test

In the main analysis we will focus on single-family dwellings that qualified for an insulation upgrade in 2016, according to two criteria: building year before 1993, energy label 'C' to 'G'.[18] We drop dwellings with missing data on energy efficiency and energy use, student condominiums and dwellings without individual natural-gas-based heating during the study period. The resulting study sample contains 124,300 single-family dwellings, of which 13,409 belong to the treatment group and 110,891 to the control group. The treatment group is defined as houses which got an insulation upgrade between 2017 and 2019 and did not change tenant between one year before and one year after the retrofit. The control group is defined as dwellings that did not experience an energy efficiency upgrade between 2000 and 2021.

Table 1 reports the descriptive statistics for the treatment and control groups in 2016, the year before the first treatment in the sample. We distinguish three groups of characteristics: dwelling (panel A), household socio-economics (panel B) and energy use (panel C) and report the balancing tests. The socio-economics are balanced well between treatment and control groups, while the dwelling characteristics and energy use are not. This is in line with the assumption of the random assignment to treatment, conditional on dwelling characteristics (see Section 3.2). To test this assumption formally, we perform a randomization test for covariate imbalance as suggested in e.g. Hennessy et al. (2016). First, we regress the observed gas use in 2016 on the building covariates. The residuals from this regression we call "adjusted gas use". Then, we carry out the randomization test by calculating the test statistic - the difference of means of adjusted gas use between treatment and control groups. The test yields a statistic of $-3m^3$ with a p-value of 0.35 (calculated over 10,000 random permutations), suggesting that the gas use adjusted for building covariates is well-balanced. We therefore cannot reject the null hypothesis that the (adjusted) gas use does not differ between the control and treatment groups. In sum, socio-economics and energy use covariates are balanced. This is consistent with the assumption that the

[18] In Appendix G the whole analysis is replicated for apartments. We did not pool the two due to sizable differences in gas use and the retrofit intensity.

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Table 1: Comparison of treatment and control groups

	Treatment	Control	p-value	SMD	VR
Panel A: Socio-economics					
No. persons	2.13	2.09	0.00	0.03	1.10
No. children	0.63	0.58	0.00	0.06	1.11
No. seniors	0.51	0.51	0.68	0.00	1.00
Income (k euro/yr)	26.63	27.43	0.00	0.07	0.89
Education high (0/1)	0.10	0.10	0.15	0.01	0.97
Migration background foreign (0/1)	0.22	0.20	0.00	0.05	1.07
Below 100% social min. (0/1)	0.03	0.03	0.62	0.00	0.98
Below 130% social min. (0/1)	0.27	0.26	0.46	0.01	1.01
Below 150% social min. (0/1)	0.38	0.37	0.06	0.02	1.01
Panel B: House characteristics					
Surface (m^2)	94.79	94.27	0.00	0.03	0.87
Constr. Period 1906-1939 (0/1)	0.06	0.07	0.00	0.05	0.83
Constr. Period 1940-1965 (0/1)	0.53	0.30	0.00	0.48	1.18
Constr. Period 1966-1976 (0/1)	0.38	0.32	0.00	0.13	1.08
Constr. Period 1977-1992 (0/1)	0.03	0.31	0.00	0.79	0.15
Energy label EFG (0/1)	0.45	0.26	0.00	0.40	1.28
Panel C: Energy use					
Electricity (kWh/yr)	2538.12	2601.39	0.00	0.05	0.95
Gas (m^3/yr)	1371.25	1270.60	0.00	0.21	1.07
No. houses	13409.00	110891.00			
No. complexes	980.00	9957.00			
No. housing associations	113.00	96.00			

Notes: The table reports a balancing test between treatment and control dwellings. The columns *mean treated* and *mean control* report the mean values of selected covariates. The column *p-value* reports the p-value of a mean equality test between treatment and control group. The column *SMD* reports the standardised mean difference between the treatment and the control group. The column *VR* reports the variance ratio. $SMD = |\bar{X}_{treated} - \bar{X}_{control}| / \sqrt{\left(S^2_{treated} + S^2_{control}\right)/2}$ and $VR = S^2_{treated}/S^2_{control}$, where $\bar{X}$ is the sample mean and S^2 is the sample variance. The balancing is considered good for *SMD* smaller than 0.25 *VR* between 0.5 and 2 (Rubin, 2001; Stuart, 2010).

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treatment assignment is determined by observed building characteristics only. We will account for the imbalance in dwelling characteristics by controlling for them explicitly in the empirical model.

4 Gas savings from retrofits: average and poor

4.1 Empirical model

Our main empirical method is a two-way fixed-effect panel regression with year and household/dwelling fixed effects (Angrist and Pischke, 2008).[19] As the sample is defined to only include households that lived in the dwelling at the time of the retrofit, the dwelling and household fixed effects coincide. We will start with an event study specification:

$$g_{i,t} = \sum_{L=-5}^{4} R_{i,t-L}\alpha_L + \delta X_{i,t} + \gamma_i + \phi T_t + u_{i,t}. \tag{11}$$

Here $g_{i,t}$ is the (log) yearly gas use of household/dwelling i in year t. The binary treatment variable $R_{i,t}$ takes value 1 in the years following retrofit and value 0 before; L are lags that account for dynamic effects; X_i controls for time-varying observable characteristics of the household (e.g. size) and dwelling (e.g. new boiler installed); γ_i are household/dwelling time invariant fixed effects; T_t are year fixed effects and $u_{i,t}$ is the idiosyncratic error term.

For heterogeneity analysis, the average treatment effect in years 2 to 4 after the home upgrade will be estimated:[20]

$$g_{i,t} = R_{i,t}\left(\alpha + \beta S_i\right) + \delta X_{i,t} + \gamma_i + \phi T_t + u_{i,t}. \tag{12}$$

We allow for a two-way interaction. Here S_i is the heterogeneity variable, for example, the retrofit intensity (see Section 3.3 for the definition) or the income level of a household.[21]

[19] We will also test the robustness of the results to the recent advances in staggered treatment effect estimation (Callaway and Sant'Anna, 2021; Sun and Abraham, 2021).

[20] We control separately for the retrofit year because of the noise in the data - we do not know in which month the retrofit was performed. We also control separately for year 1, based on the results of the event study.

[21] When S is the retrofit intensity - a standardized variable - the coefficient α can be interpreted as the effect of an insulation upgrade of *average intensity*.

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4.2 Identification

To derive a causal effect of a heating efficiency improvement on natural gas use, we exploit a treatment and a control group as defined in Section 3.4. The internal validity of this approach hinges on the assumption that the treatment assignment was random, conditional on observed dwelling characteristics. Section 3.1 provided institutional arguments and Section 3.4 a formal test to support the assumption. Inclusion in the regression of dwelling fixed effects and dwelling time-varying controls accounts for the imbalance in dwelling characteristics.

Below we discuss a number of possible remaining identification concerns. The first concern is related to the retrofit intensity. We argued above that, conditional on the building characteristics, the assignment to treatment can be seen as random. The retrofit intensity (included as heterogeneity term in Equation (12)) is however not random. The 2012 Energy efficiency covenant prescribed an improvement of homes' energy efficiency at least to a (high) energy label B.[22] Consequently, the lower the initial energy efficiency, the larger the assigned retrofit intensity would be, ceteris paribus. Equation (12) accounts for this by including the retrofit intensity in a linear way in the regression. We also test alternative specifications with a flexible higher order polynomial in retrofit intensity, to allow for a non-linear relationship, as well as a specification without retrofit intensity. We will show that the average treatment effect stays robust to including or removing the retrofit intensity from the equation. Still, one may be concerned about the possible correlation between the retrofit intensity and specific socio-economic characteristics of a household. If, for example, people with lowest income systematically get larger upgrades, the specific treatment coefficient for this group may be biased. To tackle this concern, we show that retrofit intensity is not correlated to socio-economic variables nor to pre-retrofit gas use. Table B1 in Appendix B reports the estimation results from regressing the retrofit intensity on dwelling, income and energy use characteristics of the households. As expected, the pre-retrofit energy efficiency of the dwelling is negatively correlated with the retrofit intensity. Coefficients by socio-economic and gas use variables are however small in size and predominantly not statistically

[22] See Section 3.1 for an explanation of the energy label system.

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significant.

The second concern is related to the self-selection into/ out of the treatment group and attrition. As discussed in Section 3.1, by law tenants could not opt out of the insulation retrofit program while living in the dwelling. They could, however, avoid the retrofit by moving out of the dwelling. We compare the moving rates between households in the treatment and control groups in 2016 and conclude that these are almost identical: people did not move out to avoid insulation upgrade. After the treatment however, we do see a difference in attrition. Tenants move less frequently from renovated houses. This needs not be a problem however as long as the movers in the treatment and control group do not differ in gas use. We show that this is the case (Appendix B). Additionally, in one of the robustness checks we will remove the never-treated control observations from the sample and re-estimate the treatment effect using the not-yet-treated as a control group. We will show that the results are robust to this exercise, see Appendix E, Table E1.

4.3 Empirical results

4.3.1 Average treatment effect

We start with reporting the yearly effects of insulation upgrades from the event study Equation (11). These are plotted in Figure 5. As expected, the Figure shows point estimates close to zero in the five years before the upgrade, and a gradual increase in the absolute size of the effect after, from 19% gas savings in the first year to 22% in the years two to four. Note that the effect in the year of the upgrade is not informative, because we do not know the exact month in which the retrofit was performed. In sum, households need (some) time to adjust their behavior; this adjustment process reaches its equilibrium quickly however.

Table 2 reports the estimated average treatment effect from Equation (12) where heterogeneity variable S is retrofit intensity. To account for the slow adjustment found in Figure 5, we control for the year of retrofit and the year after with separate dummies. The results in the table should thus be interpreted as the estimated effect in the years two-four after the insulation upgrade. Columns (1) to (4) report different specifications: with or without household/dwelling fixed

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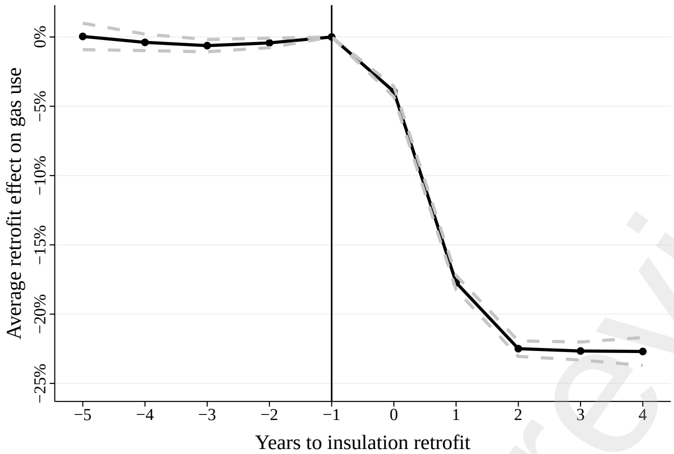
Figure 5: Gas savings from heating efficiency upgrade: event study by year



Notes: Plotted values are the coefficients of the interaction effect of the treatment indicator with the year-to-retrofit, see Equation (11). Year -1 (vertical line) is the last pre-retrofit year. The dashed lines represent the 95% confidence interval. Standard errors are clustered at household level.

effects and with or without controls.[23] Our preferred specification (4) includes household and year fixed effect, as well as household controls. The main finding is that an insulation of average intensity reduces natural gas use of households by about 22%. One standard deviation increase in retrofit intensity reduces gas use by another eight percentage points.[24] We note that this table further supports our assumption that the treatment assignment is random, conditional on dwelling characteristics. Indeed, controlling explicitly for observed dwelling characteristics (Column (3)) or using dwelling fixed-effects (Columns (2) and (4)) yield an almost identical average treatment effect.

4.3.2 Effects for the poor and underlying mechanisms

Table 3 reports the estimated average treatment effect for the poor households. Here Equation (12) was run three times, including a two-way interaction of the After retrofit indicator with each time another poverty dummy indicator,

[23]Table C1 in Appendix C reports the full set of coefficients for the four specifications.

[24]In Appendix F we include retrofit intensity in different functional specifications, including a flexible polynomial and a specification without the intensity variable. The average treatment effect is robust, the higher order terms are not statistically significant.

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Table 2: Average effects of insulation retrofit on gas consumption

Dependent: log of yearly natural gas use	(1)	(2)	(3)	(4)
After retrofit (year $\geq$ 2)	-0.149***	-0.228***	-0.228***	-0.218***
	(0.004)	(0.003)	(0.004)	(0.003)
$\times$ Retrofit intensity	-0.058***	-0.077***	-0.100***	-0.078***
	(0.004)	(0.003)	(0.004)	(0.003)
No. obs.	963459	963459	959073	959073
No. treatment houses	13409	13409	13409	13409
No. control houses	110891	110891	110891	110891
R^2 Adj.	0.021	0.822	0.144	0.826
Year fixed-effect	X	X	X	X
Household fixed-effect		X		X
Controls			X	X

Notes: The table shows estimates of four separate regressions. The dependent variable is the log of gas use. Standard errors in parentheses are clustered at household level. Statistical significance: *p<0.1; **p<0.05; ***p<0.01.

as defined in Section 3.3. In line with the theoretical model, we find that the magnitude of the gas savings falls with income, more so on the very left tail of the income distribution. The poorest (below 100% social minimum) show one third smaller savings than the average; those below 130% of the social minimum one tenth lower savings.

The above analysis provides empirical support for the hypothesis that the lowest incomes realize smaller gas savings after a heating efficiency upgrade. The underlying mechanism we hypothesized in the theoretical model is that poor households reoptimize their heating use patterns after retrofit more than others, because their pre-retrofit thermal comfort was relatively far from the satiety threshold. Re-optimization can however take place through other channels too. An obvious candidate is adjustment in electricity use. Our data allow to test for the existence of substitution effects between gas and electricity following insulation upgrades. Some 5300 dwellings in the treatment sample got solar panels (amounting, on average, to 2 000 kWh renewable electricity per year), simultaneously with the insulation. We test whether these households responded

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Table 3: Effects of retrofits for poor households

	Baseline
After retrofit (year ≥ 2)	-0.218 (0.003)***
$\times$ Below 100% soc.min.	0.062 (0.016)***
$\times$ Below 130% soc.min.	0.025 (0.006)***
$\times$ Below 150% soc.min.	0.018 (0.006)***

Notes: The table shows estimates of Equation (12) for 4 separate regressions. Coefficients reported are two- and three-way interactions. The symbol $\times$ indicates an effect as compared to the reference level (non-poor). The combination of the column and row name indicates the interaction. The dependent variable is log of gas. Each regression includes controls, household fixed-effects and year fixed-effects. The sample size is 13409 treated and 110891 control units. Standard errors in parentheses are clustered at household level. Statistical significance: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

to insulation in a different way than households without solar panels. If there is substitution between gas and electricity in heating, we should see larger gas savings for the solar-households, as they can make use of additional free solar energy at their disposal. Also, we should see a rise in grid electricity use for the non-solar households. Table 4 reports the results of running Equation (12) with two-way and three-way interactions of treatment, solar and poverty indicators. We use as outcome variables both the log gas use and the log grid electricity use.

Availability of solar electricity does not seem to have much effect on gas use: the gas savings after retrofit are practically the same in the solar and no-solar dwellings. Grid electricity use however, shows a small increase (1 to 4%) in no-solar dwellings. A likely explanation for this is the additional electricity demand due to the installation of mechanical ventilation that is necessary to ensure sufficient air quality in well-insulated dwellings. The solar-dwellings, on the other hand, reduce grid electricity use by almost 30% on average, which is in line with the literature. Concluding, we do not find convincing evidence of large substitution effects between gas and electricity for heating purposes after

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Table 4: Effects of retrofits on gas and electricity, by solar panel availability

	Dependent: log gas		Dependent: log electricity	
	No solar	Yes solar	No solar	Yes solar
After retrofit (year $\geq$ 2)	-0.223 (0.003)***	-0.237 (0.004)***	0.010 (0.004)***	-0.286 (0.007)***
$\times$ Below 100% soc.min.	0.054 (0.019)***	0.063 (0.025)**	0.037 (0.022)*	0.037 (0.039)
$\times$ Below 130% soc.min.	0.013 (0.008)*	0.041 (0.009)***	0.014 (0.008)*	0.006 (0.016)
$\times$ Below 150% soc.min.	0.011 (0.007)	0.027 (0.008)***	0.010 (0.007)	-0.011 (0.015)

Notes: The table shows estimates of Equation (12) for 8 separate regressions. Coefficients reported are two- and three-way interactions. The symbol $\times$ indicates an effect as compared to the reference level (non-poor). The combination of the column and row name indicates the interaction (e.g. below 100% soc.min. $\times$ Yes solar). The dependent variable is log of gas or log of electricity. Each regression includes controls, household fixed-effects and year fixed-effects. The sample size is 13409 treated and 110891 control units. Standard errors in parentheses are clustered at household level. Statistical significance: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

insulation.[25]

Results of Table 4 provide additional insights into the working of the income and substitution effects after insulation upgrades. The income effect implies that households use the monetary savings from higher heating efficiency to increase their consumption of other goods. We do not observe evidence of this for electricity use. The substitution effect, on the other hand, implies that when electricity becomes more affordable, households may start producing part of their thermal comfort through electricity instead of gas, effectively reducing further their gas use (e.g. by buying electric space heaters). Households may perceive that solar panels make electricity more affordable. Our results however show that solar panel installations hardly change the effect of insulation upgrades on gas use.

4.4 Robustness checks

We have subjected the results of Table 3 to a range of sensitivity analyses. First, in Appendix D, we re-estimate the model of Equation (12) for various

[25]We note that our data only include 4 years after retrofit. It might be that such substitution effects take a longer time to manifest. On the other hand, substituting gas for electricity often requires an investment upfront (e.g. buying an electric space heater). Low-income households we are studying might face binding credit constraints prohibiting such investments.

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subsamples, allowing the treatment effect to differ by: (i) year in which the insulation upgrade took place (2017, 2018 and 2019), Table D1; (ii) pre-retrofit energy efficiency as defined by the energy label of the dwelling (C, D, E, F, G), Table D2; (iii) socio-economic characteristics of households, Table D3; (iv) pre-retrofit gas use quintile, Table D4. Results are robust across all the year and energy label subsamples. The treatment effect however differs by household type. For instance, singles reach larger savings, while households with migration background reduce gas use less than average. The effect also differs by pre-retrofit gas use: not only absolute but also relative savings are higher for households with higher heating demand. The low-income specific response to the home upgrade is however robust in all the subsamples.

In Appendix E, we replicate the results of Table 3 using two state-of-the-art methods that account for possible biases due to the staggered treatment: Sun and Abraham (2021) and Callaway and Sant'Anna (2021). The results are reported in Table E1 and are robust.

Then we rerun the model using alternative model specifications, see Appendix F. These include: (i) various functional form specifications to include the retrofit intensity in the model, Table F1; (ii) including group-specific time trends, Table F2. Both the average treatment effect and the specific low-income response shown in Table 3 hold under these modeling specifications.

Finally, Appendix G shows that the above findings that were obtained on a sample of single-family dwellings, also hold for apartments.

5 Welfare effects

In this section, we develop a computable version of the consumer choice model Equations (1) and (2). The model is then used to assess the welfare effects of the heating efficiency retrofits that took place in the Dutch social housing sector between 2017 and 2019, this in different scenarios and for different income groups.

5.1 Parameters of the computable model

We derive the empirical values for the model parameters in the following way. The gas price is set to the 2016 (the year before the insulation upgrades in our

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data started) level of consumer gas price according to Statistics Netherlands, $p_g =$ € 0.65 per cubic meter (Statistics Netherlands, 2024). The price of other consumption is normalized to 1. The rest of the parameters (preference parameters $\bar{\theta}, \sigma$, natural temperature θ_0, pre-retrofit heating efficiency $q = q_L$ and post-retrofit heating efficiency $q = q_H$) are assumed to take the same values for all households. These assumptions ensure that, conditional on q, any differences in the consumer choices come through variation in income. Then the model parameters are derived by fitting the consumer choice model solutions to data, using non-linear weighted least squares. More specifically, we simultaneously fit (i) the model prediction of low-heating-efficiency gas use by income, $g^*(q_L, w)$, to the observed distribution of gas use g by income in 2016 and (ii) the model prediction of gas savings by income $[g^*(q_H, w) - g^*(q_L, w)]$ to the quasi-experimental estimates of gas savings after retrofit $\hat{\alpha}$ from Equation (12), again by income. Below the procedure is described in detail.

We approximate the income distribution by a set of income deciles. For this, the study sample of 124,300 households (treatment and control) is split into ten deciles $d = 1, \ldots, 10$, based on household income expressed in percentage of the social minimum. For each decile d, income w_d and pre-retrofit gas use g_d are set to the median values in that decile. We also assign to each decile the quasi-experimental estimate of the retrofit effect α_d from Equation (12), measured as the change in cubic meters of gas use following the heating efficiency upgrade. Then we fit the values of the parameters ($\bar{\theta}$, σ, θ_0, q_L and q_H) by solving with non-linear weighted least squares the following optimization problem:

$$(min)S = W_1 \sum_d (g^*(q_L, w_d) - g_d)^2 + W_2 \sum_d (g^*(q_H, w_d) - g^*(q_L, w_d) - \hat{\alpha}_d)^2,$$

subject to the following constraints:

$$q_L > 0, q_H > 0, \theta_0 \geq 10, \bar{\theta} \in [18, 24], \sigma \geq 0,$$

where $W_1 = [\mathrm{SD}\,(g_d)]^{-2}$ and $W_2 = [\mathrm{SD}\,(\hat{\alpha}_d)]^{-2}$ are weights and SD stands for standard deviation. The weights equalize the scale of the two terms in S, in order to balance the goodness of fit before and after the heating efficiency upgrade.

Table 5 reports the resulting parameter values. Note that the estimated value of the elasticity of substitution parameter σ is very close to unity, which implies

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that the household utility is close to the Cobb-Douglas utility specification.

Table 5: Computable model parameters

Description	Parameter	Value
Exogenously chosen parameters		
Price of gas (euro/m^3)	p_g	0.65
Price of other consumption	p_x	1.00
Estimated parameters		
Indoor temperature at g=0 (^{o} C)	θ_0	11.10
Elasticity of substitution	σ	1.00
Satiety level of thermal comfort (^{o} C)	$\bar{\theta}$	23.80
Energy efficiency before retrofit (^{o} C/m^3)	q_L	$\frac{1}{103}$
Energy efficiency after retrofit (^{o} C/m^3)	q_H	$\frac{1}{80}$

5.2 Validation of the computable model

We perform a number of validation tests for the model parameters. First, Figure 6 shows that the model fits the gas use by income distribution well, both before and after the heating efficiency upgrade. If anything, we note that the model overestimates the gas savings in the lowest income decile and underestimates these in the highest income decile.

Second, we aim to evaluate how realistic is the model prediction of the retrofit-induced temperature change $\theta^*(q_H, w_d) - \theta^*(q_L, w_d)$ that arises due to households re-optimizing their consumption towards a higher thermal comfort after the heating efficiency improvement. The temperature increase generated by the model ranges from 0.1 to 0.7 degrees Celsius, this value decreases with income. We are only aware of few - small-scale - empirical measurements of the effect of heating efficiency upgrades on indoor temperature; these document temperature adjustments of similar magnitude, e.g., Fisk et al. (2020), Fowlie et al. (2018).

Finally, we can validate the implied price elasticity of gas use, which, in our model, ranges from -0.04 to -0.27. This is again well in line with the earlier findings, see, e.g., Asche et al. (2008). Concluding, our computable consumer choice model yields realistic responses to exogenous shocks in heating efficiency and gas prices.

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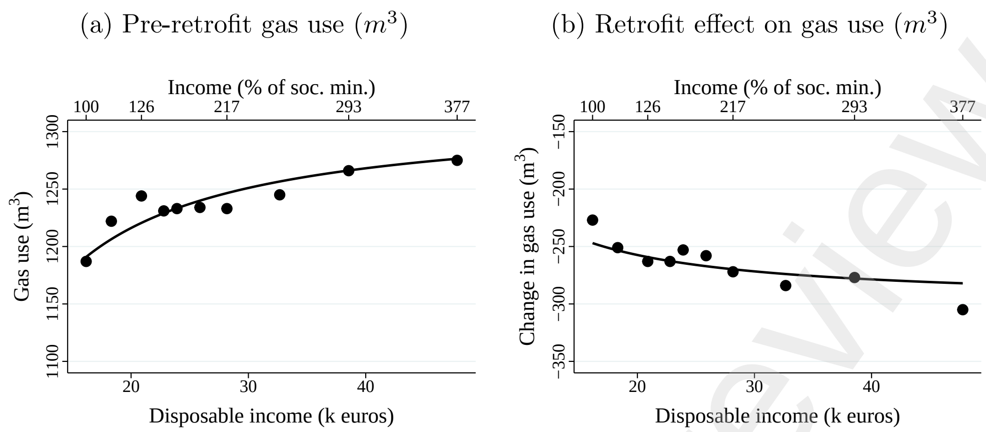
Figure 6: Model fit: gas use before and after heating efficiency upgrades



Notes: The dots are observed values (left) respectively quasi-experimental estimates (right). The lines are predictions of the computable model. Panel (a) depicts the median gas use, across income deciles. Panel (b) depicts the average effect of a heating efficiency upgrade on gas use across income deciles. Both figures use the data from the baseline sample of 124,300 households (treatment + control).

5.3 Welfare outcomes

Now we apply the computable consumer choice model to value the benefits from the Dutch heating efficiency program 2017-2019 that was described in Section 3 and exploited in the quasi-experiment of Section 4.[26] Two scenarios are defined: (i) a reference scenario, for which the model parameters were fit (Table 5); (ii) a counterfactual, in which the gas price is set to the high level $p_g = 1.36$ euro/m^3 it reached in 2022, while the rest of the parameters stay unchanged. For both scenarios, we evaluate the private benefits from heating efficiency upgrades (i.e. following the change from q_L to q_H). We use the Hicksian compensating variation (Equation (7)) as well as the Slutsky decomposition into the benefits of increased thermal comfort (Equation (9)) and the benefits of increased other consumption (Equation (8)). Table 6 reports these welfare effects in euro as well as the underlying changes in indoor temperature, natural gas use and related CO_2 emissions, for three income levels: low (below the social minimum), average (median of the income distribution in our study sample) and high (75 percentile

[26] Parameters q_L (low heating efficiency, before the upgrade) and q_H (high heating efficiency, after the upgrade) in Table 5 describe the upgrade homes received through the program, on average.

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of the same income distribution).[27] Figure 7 shows the size and the Slutsky decomposition of the welfare benefits for the whole income distribution.

We start by discussing the physical changes in gas use and thermal comfort after the home upgrade (columns 2-3 Table 6). Note first that, in the counterfactual, the indoor temperature increase is twice as large as and the gas savings are 1.5 times smaller than in the reference. The reason is that more expensive heating services in the counterfactual make that households increasingly sacrifice thermal comfort and choose for uncomfortably low temperatures when $q = q_L$. The resulting high marginal utility of one degree temperature increase leads to larger adjustments in indoor temperature after the home upgrade. Lower natural gas savings follow. Second, fully in line with the theoretical insights of Section 2, indoor temperature improvement falls with income, while natural gas savings rise with income. For example, for the poor, the temperature increase after retrofit reaches 0.3 degrees in the reference scenario and 0.7 degrees in the counterfactual; this is thrice as much as for the higher income households. The gas (and CO_2) savings of the low-income households are 13% to 30% lower than those of their more well-off peers.

Looking at the monetary valuation of the above changes (see columns (5)-(8) of Table 6 and Figure 7), we note that the private benefits of the home upgrades are distributed unevenly among income levels: the gains for the poor are 6 to 14% lower in comparison with their higher income peers. This is again intuitive. Remember that low-income households use less gas before the upgrade (see e.g. Figure 2b). Therefore their potential savings from heating efficiency upgrades are also smaller. By trading off potential gas savings (increase in composite good consumption) for a comfort increase, households improve their welfare, but the resulting gains still stay below the benefits that higher income groups can obtain.

Figure 7 illustrates graphically the income heterogeneity in the distribution of the private benefits of home upgrade between thermal comfort improvement,

[27] Changes in indoor temperature and natural gas use follow from the solutions of the consumer maximization problem under q_L and q_H, see Appendix A. CO_2 reduction is computed from natural gas savings under the usual assumption of 1.79kg CO_2 emissions per cubic meter of natural gas use (RVO, 2021).

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Table 6: Program effects and private benefits, by income

Income	Private and external effects			Private benefits (euro)			
	Δ Temp.	Δ Gas	ΔCO_2	Slutsky valuation			Hicksian val.
	$^\circ C$	m^3	kg	$-\Delta^S$	$-\Delta^S_\theta$	$-\Delta^S_x$	CV
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	In prices 2016 (0.65 euro/m^3)						
low	0.30	-245	-439	175	15	159	177
average	0.19	-265	-474	182	10	172	183
high	0.10	-280	-501	187	5	182	188
	In prices 2022 (1.36 euro/m^3)						
low	0.65	-182	-326	320	71	249	329
average	0.41	-225	-402	352	45	307	358
high	0.22	-258	-463	377	24	353	381

Notes: The Table reports the effects of the average retrofit in our data, as predicted by the computable choice model. This is done for two scenarios (reference with gas prices of 2016 and counterfactual with gas prices of 2022) and for three income groups (low, average and high, respectively 16keuro, 24keuro and 43keuro in disposable yearly income). Columns (2) and (3) document the changes in consumption of temperature respectively yearly gas, following the retrofits. Column (4) reports the change in annual CO_2 emissions, assuming 1.79kg CO_2 per m^3 of natural gas. Column (5) reports the valuation of the private benefits of the retrofits using the Slutsky compensation. Column (8) reports the same valuation using the Hicksian compensation (compensating variation). Columns (6) and (7) decompose the Slutsky compensation into the parts that arise due to the change in temperature consumption respectively the change in consumption of other goods. The Table shows yearly outcomes.

on the one hand, and other consumption, on the other. It is noteworthy that the comfort benefits from temperature increase make a substantial part of the total gains, more so for the low-income households. In the reference scenario with low gas prices, the comfort benefits amount to 9% of the total utility increase for the social minima and only 3% for the richer households. In the counterfactual with high gas prices, the comfort benefits make 21% respectively 6% of the total gains for the two groups. This share of thermal comfort improvement in the overall welfare benefits represents what in the literature is called *rebound effect*: the difference between the achieved reductions in energy use and those forecast without any consumer and market responses to the energy efficiency improvement (Gillingham et al. 2016 and Equation (10)). While the average

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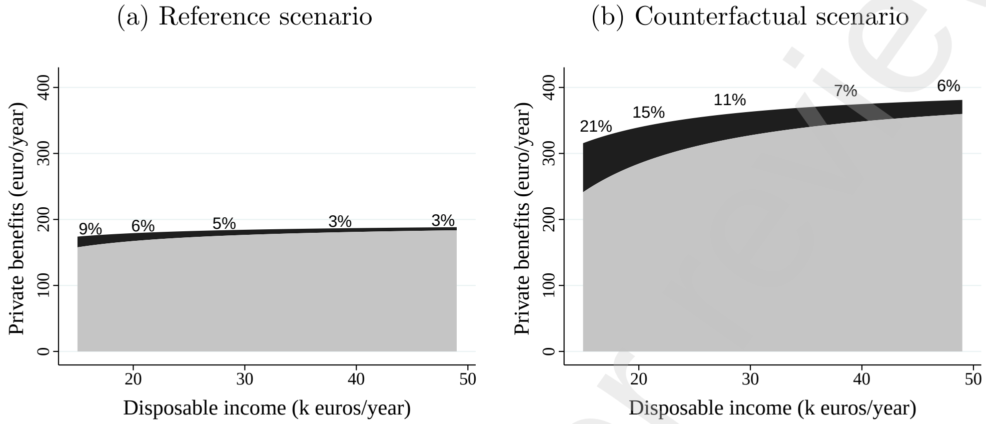
rebound effect for our data equals 5.3% and is in line with the literature (e.g. Christensen et al. 2023; Fowlie et al. 2018), we note the large heterogeneity by income.

Figure 7: Size and Slutsky decomposition of welfare gains, by income



Notes: The graph shows the Slutsky compensation (i.e. private benefits) over the income distribution. The black and grey ribbons are the Slutsky compensation due to increase in thermal comfort and consumption of composite good respectively. The percentage above the black ribbon is the share of thermal comfort in the private benefits (i.e. the rebound effect).

So far we have valued the *private* benefits of heating efficiency upgrades. The next logical step is to extend the welfare analysis by including the external effects on the environment. Two counteracting forces need to be accounted for. The first is the *positive* externality of avoided CO_2 emissions. Here again income heterogeneity plays a role: smaller gas savings of the poor translate one-to-one to lower environmental (CO_2) benefits (Table 6). From a policy perspective, this insight points at a trade-off that accompanies policies subsidizing heating efficiency improvements for low-income households. Reducing poverty and increasing living comfort for the poor comes at the expense of lower environmental benefits. There is however also a second - *negative* - externality that arises due to the fact that the consumer price of natural gas in the Netherlands for 50% consists of the excise duty. Lower gas consumption after the upgrade results in a decrease in tax revenues and therefore less governmental spending on public goods. Which sign (positive, zero or negative) the sum of the two externalities will have, depends on whether the excise duty is set equal, lower or higher

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than the optimal (Pigouvian) tax. Our quasi-experimental results provide some support to the assumption that the excise duty exactly internalizes the negative environmental externality and can be seen as Pigouvian.[28] Then the positive and negative externality exactly compensate each other and the private and the social benefits from home upgrades coincide.

To get insight into the returns to the heating efficiency program, we compare the net present value (NPV) of the welfare gains from home upgrades reported in Table 6 to the investment cost. We use a discount rate of 2.25%, which is prescribed for the Dutch cost-benefit analyses and take a time horizon of 30 years, which equals around half of the technically feasible lifetime for home insulation upgrades in the Netherlands. Then the NPV ranges between 3.8 to 4.0 thousand euro per household in the reference scenario, and 7.1 to 8.2 thousand euro in the counterfactual (the left respectively right endpoint of the reported ranges are for low respectively high income households from Table 6). Based on various sources we consulted, the cost of an average home upgrade in our data lies around 7 thousand euro, in prices 2016, including VAT.[29] Our analysis suggests therefore that the private benefits from gas savings and comfort increase are comparable to the investment cost at high gas prices, but fall short of these otherwise.

It is instructive to compare the reported above costs and benefits of the insulation upgrades in the Netherlands with the documented welfare effects of the

[28]Take the consumer gas price of 0.65 euro/m^3 in the reference scenario, then the tax equals 0.33 euro/m^3. Based on our quasi-experimental results, the average reduction in tax revenue is 265m^3/year*0.33euro/m^3=90 euro/household/year. The corresponding reduction in CO_2 amounts to 474kg/household/year, implying an implicit valuation of 90/0.474=190euro per ton CO_2. This valuation is very close to the mean of the existing estimates for the societal benefits of CO_2 reduction, which range from 40 to 400 euro/ton/year (Rennert et al., 2022).

[29]Based on Schep et al. (2022) but also talks with housing associations' employees, a full insulation upgrade costs between 12 and 14 thousand euro in prices 2016, including VAT. A full upgrade implies that a house that did not have insulation at all, gets HR+ glass in all windows; insulation of the roof, wall and floor to the level of RC=5, RC=2, RC=3.5 respectively; and mechanical ventilation to preserve the air quality. Our consumer choice model works with the insulation upgrade of average retrofit intensity which is approximately half as effective as the full upgrade (see Figure 4). Therefore, we take 50% of the upper bound of the cost, arriving at 7 thousand euro.

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widely studied US Weatherization program (e.g. Fowlie et al. 2018; Christensen et al. 2024, 2023). The Weatherization retrofits studied by these authors, involved attic and wall insulation, infiltration reduction and furnace replacement and are thus comparable to the Dutch heating efficiency program. While the Weatherization program results in comparable relative gas savings of 20%,[30] its corresponding benefits are much lower due to (i) lower gas prices (0.35 dollar/m^3 against 0.65 euro in the reference and 1.36 euro in the counterfactual in our study) and (ii) a shorter expected life cycle of the home upgrade (16 years in the US). Further it is noteworthy that the documented investment cost in the US is around 1.5 times smaller than in the Netherlands (4600 dollar against 7000 euro).

Summarizing, we find a possibility of positive private returns from heating efficiency retrofits in the counterfactual, but not in the reference. The question naturally arises which scenario is more likely to take place in the coming years. For Europe, we argue that there are reasons to expect positive returns. First, in many European countries, governments are keen to use price instruments like the excise duty to stimulate households to switch to energy-saving technologies. For instance, in the Netherlands, gas prices peaked in 2022 due to exogenous factors, but stay high in 2024 because of the increased excise. Second, one could expect heating efficiency upgrades to yield other private benefits as well, besides those studied in our paper. These are, among other things: health improvement due to reduced exposure to draught and extreme temperatures (Maidment et al., 2014) and poverty alleviation gains (Banerjee et al., 2021).

6 Conclusion

Energy efficiency improvements in low-income housing are increasingly used as a policy instrument to tackle poverty. Our paper explored the welfare trade-offs of these policies and showed that targeting the poor comes at the expense of lower environmental benefits. We performed a quasi-experimental evaluation of a large Dutch nationwide residential heating efficiency program in social housing,

[30]The absolute gas savings are larger in (Fowlie et al., 2018) as the average household there uses 80MMbtu or 2400m^3 gas per year, this almost twice the average for the Netherlands.

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examining the income heterogeneity in program effects and the behavioral mechanisms behind this heterogeneity. We followed a sample of 125,000 households during eight years, leveraging considerable variation in income in the sample and exploiting a unique conditionally random treatment assignment. The program evaluation used quasi-experimental two-way fixed effects econometrics on the one hand, and, on the other hand, a computable microeconomic consumer choice model, in which people choose between thermal comfort and other consumption.

Four primary findings of our study should be emphasized. First, we documented empirically that lowest-income households realize considerably smaller than average natural gas savings from home heating efficiency retrofits. The quasi-experimental estimates suggest that, after a heating efficiency upgrade, the social minima reduced their gas use by 16%, while the average gas savings in the sample were 22%. Second, this heterogeneity in gas savings can be explained from income-specific behavioral responses to the retrofit. Our computable consumer choice model suggests that the poor reinvest up to 20% of the potential monetary savings from a heating efficiency upgrade into thermal comfort improvement, i.e. a higher temperature in house. The more well-off peers only reinvest 5%, because their thermal comfort was already high before retrofit. Third, even accounting for the benefits from comfort improvement, the monetary value of the private welfare gain from home upgrades is lower for the poor, as compared to their richer peers. Fourth, when gas prices are low, the size of the studied private welfare benefits falls short of the costs of an average heating efficiency retrofit. However, when gas prices reach the levels they have been peaking at since 2022, the heating efficiency investments have positive private return, also for lowest incomes. For Europe, we argue that there are reasons to expect positive returns.

Our study provides novel evidence into the benefits and trade-offs of using heating efficiency upgrades as an instrument to alleviate poverty. We also contribute to the literature and public discussion about the returns to such policies. However, the welfare effects we computed are likely an underestimation of the society's benefits due to the heating efficiency upgrades. Among other things,

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insulation-induced reduction in draught and extreme temperatures in house may have a positive impact on the inhabitants' health (Maidment et al., 2014). Moreover, specifically for the left tail of the income distribution, additional societal gain may be achieved through poverty alleviation (Banerjee et al., 2021). In this paper, we find the environmental benefits and monetary savings from reduced gas use to be smaller for the poorest. Comfort gains are however higher, so will be poverty reduction benefits and - possibly - the health effects. Further research into these latter aspects is desirable to facilitate a complete cost-benefit test of heating efficiency upgrades by income group. Our paper suggests a methodology to make the welfare trade-offs explicit and quantify them.

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This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4910517

References

Adan, H. and Fuerst, F. (2016). Do energy efficiency measures really reduce household energy consumption? A difference-in-difference analysis. *Energy Efficiency*, 9(5):1207–1219.

Allcott, H. and Greenstone, M. (2017). Measuring the Welfare Effects of Residential Energy Efficiency Programs. *National Bureau of Economic Research*, page 97.

Angrist, J. D. and Pischke, J.-S. (2008). *Mostly Harmless Econometrics: An Empiricist's Companion.* Princeton University Press.

Asche, F., Bjarte Nilsen, O., and Tveteras, R. (2008). Natural Gas Demand in the European Household Sector. *The Energy Journal*, 29(3).

Aydin, E., Kok, N., and Brounen, D. (2017). Energy efficiency and household behavior: the rebound effect in the residential sector. *The RAND Journal of Economics*, 48(3):749–782.

Banerjee, A., Duflo, E., and Sharma, G. (2021). Long-Term Effects of the Targeting the Ultra Poor Program. *American Economic Review: Insights*, 3(4):471–486.

Callaway, B. and Sant'Anna, P. H. (2021). Difference-in-Differences with multiple time periods. *Journal of Econometrics*, 225(2):200–230.

Christensen, P., Francisco, P., Myers, E., Shao, H., and Souza, M. (2024). Energy efficiency can deliver for climate policy: Evidence from machine learning-based targeting. *Journal of Public Economics*, 234:105098.

Christensen, P., Francisco, P., Myers, E., and Souza, M. (2023). Decomposing the Wedge between Projected and Realized Returns in Energy Efficiency Programs. *Review of Economics and Statistics*, 105(4):798–817.

Davis, L. W., Fuchs, A., and Gertler, P. (2014). Cash for Coolers: Evaluating a Large-Scale Appliance Replacement Program in Mexico. *American Economic Journal: Economic Policy*, 6(4):207–238.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4910517

European Commission (2023). Energy poverty in the EU (https://energy.ec.europa.eu/archived-pages/energy-poverty-eu_en).

Eurostat (2023). Disaggregated final energy consumption in households [Online, accessed 2023-11-12, https://ec.europa.eu/eurostat/databrowser/view/NRG_d_hhq__custom_8936568/default/table?lang=

Eurostat (2024). Natural gas price statistics [Online, accessed 2024-05-14, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics].

Fisk, W. J., Singer, B. C., and Chan, W. R. (2020). Association of residential energy efficiency retrofits with indoor environmental quality, comfort, and health: A review of empirical data. *Building and Environment*, 180:107067.

Fowlie, M., Greenstone, M., and Wolfram, C. (2018). Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program*. *The Quarterly Journal of Economics*, 133(3):1597–1644.

Gerarden, T., Newell, R. G., and Stavins, R. N. (2015). Deconstructing the Energy-Efficiency Gap: Conceptual Frameworks and Evidence. *American Economic Review*, 105(5):183–186.

Gillingham, K., Keyes, A., and Palmer, K. (2018). Advances in Evaluating Energy Efficiency Policies and Programs. *Annual Review of Resource Economics*, 10(1):511–532.

Gillingham, K., Rapson, D., and Wagner, G. (2016). The Rebound Effect and Energy Efficiency Policy. *Review of Environmental Economics and Policy*, 10(1):68–88.

Hammerle, M. and Burke, P. J. (2022). From natural gas to electric appliances: Energy use and emissions implications in Australian homes. *Energy Economics*, 110:106050.

Hennessy, J., Dasgupta, T., Miratrix, L., Pattanayak, C., and Sarkar, P. (2016). A Conditional Randomization Test to Account for Covariate Imbalance in Randomized Experiments. *Journal of Causal Inference*, 4(1):61–80.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4910517

Liang, J., Qiu, Y., James, T., Ruddell, B. L., Dalrymple, M., Earl, S., and Castelazo, A. (2018). Do energy retrofits work? Evidence from commercial and residential buildings in Phoenix. *Journal of Environmental Economics and Management*, 92:726–743.

Maidment, C. D., Jones, C. R., Webb, T. L., Hathway, E. A., and Gilbertson, J. M. (2014). The impact of household energy efficiency measures on health: A meta-analysis. *Energy Policy*, 65:583–593.

Mas-Colell, A., Whinston, M. D., and Green, J. R. (1995). *Microeconomic theory*. Oxford University Press, New York.

McCoy, D. and Kotsch, R. A. (2021). Quantifying the Distributional Impact of Energy Efficiency Measures. *The Energy Journal*, 42(01).

Milne, G. and Boardman, B. (2000). Making cold homes warmer: the effect of energy efficiency improvements in low-income homes A report to the Energy Action Grants Agency Charitable Trust. *Energy Policy*, 28(6-7):411–424.

Ministry of the Interior and Kingdom Relations (2012). Convenant Huursector.

Ossokina, I. V., Kerperien, S., and Arentze, T. A. (2021). Does information encourage or discourage tenants to accept energy retrofitting of homes? *Energy Economics*, 103:105534.

Peñasco, C. and Anadón, L. D. (2023). Assessing the effectiveness of energy efficiency measures in the residential sector gas consumption through dynamic treatment effects: Evidence from England and Wales. *Energy Economics*, 117:106435.

Rennert, K., Errickson, F., Prest, B. C., Rennels, L., Newell, R. G., Pizer, W., Kingdon, C., Wingenroth, J., Cooke, R., Parthum, B., Smith, D., Cromar, K., Diaz, D., Moore, F. C., Müller, U. K., Plevin, R. J., Raftery, A. E., Ševčíková, H., Sheets, H., Stock, J. H., Tan, T., Watson, M., Wong, T. E., and Anthoff, D. (2022). Comprehensive evidence implies a higher social cost of CO2. *Nature*, 610(7933):687–692.

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4910517

Rubin, D. B. (2001). Using Propensity Scores to Help Design Observational Studies: Application to the Tobacco Litigation. *Health Services and Outcomes Research Methodology*, 2(3/4):169–188.

RVO (2021). The Netherlands: list of fuels and standard CO2 emission factors version of January 2021 (PDF). *Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO).*

Saunders, H. D., Roy, J., Azevedo, I. M., Chakravarty, D., Dasgupta, S., de la Rue du Can, S., Druckman, A., Fouquet, R., Grubb, M., Lin, B., Lowe, R., Madlener, R., McCoy, D. M., Mundaca, L., Oreszczyn, T., Sorrell, S., Stern, D., Tanaka, K., and Wei, T. (2021). Energy Efficiency: What Has Research Delivered in the Last 40 Years? *Annual Review of Environment and Resources*, 46(1):135–165.

Schep, E., Dehens, J., and Kruit, K. (2022). Terugverdientijd verduurzamingsmaatregelen [Online, accessed 06-06-2024 from https://ce.nl/publicaties/terugverdientijd-verduurzamingsmaatregelen/].

Sorrell, S. and Dimitropoulos, J. (2008). The rebound effect: Microeconomic definitions, limitations and extensions. *Ecological Economics*, 65(3):636–649.

Sovacool, B. K. (2015). Fuel poverty, affordability, and energy justice in England: Policy insights from the Warm Front Program. *Energy*, 93:361–371.

Statistics Netherlands (2024). StatLine - Eindverbruikersprijzen aardgas en elektriciteit [Online, accessed 06-06-2024 from https://opendata.cbs.nl/#/CBS/nl/dataset/85666NED/table?dl=A7483].

Stuart, E. A. (2010). Matching Methods for Causal Inference: A Review and a Look Forward. *Statistical Science*, 25(1).

Sun, L. and Abraham, S. (2021). Estimating dynamic treatment effects in event studies with heterogeneous treatment effects. *Journal of Econometrics*, 225(2):175–199.

Webber, P., Gouldson, A., and Kerr, N. (2015). The impacts of household retrofit

Preprint not peer reviewed

This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4910517

and domestic energy efficiency schemes: A large scale, ex post evaluation. *Energy Policy*, 84:35–43.

Preprint not peer reviewed

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A Appendix Utility maximization problem solutions

In this Appendix we offer Proofs of Proposition 1 and Proposition 2.

Proof of Proposition 1. We write the Lagrangian for the household utility maximization problem (UMP) as follows:

$$L = \left(x^{\frac{\sigma-1}{\sigma}} + \left((2\bar{\theta}-\theta)\theta\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} + \lambda\left(w - x - \frac{\theta-\theta_0}{q}p_g\right)$$

Due to the strict monotonicity of $u(x,\theta)$ w.r.t. x, it follows that $\lambda > 0$ and the F.O.C.s for an interior solution are:

$$\begin{cases} 0 = \left(x^{\frac{\sigma-1}{\sigma}} + \left((2\bar{\theta}-\theta)\theta\right)^{\frac{\sigma-1}{\sigma}}\right)^{-\frac{1}{\sigma}} x^{-\frac{1}{\sigma}} - \lambda \\ 0 = 2\left(x^{\frac{\sigma-1}{\sigma}} + \left((2\bar{\theta}-\theta)\theta\right)^{\frac{\sigma-1}{\sigma}}\right)^{-\frac{1}{\sigma}} \left((2\bar{\theta}-\theta)\theta\right)^{-\frac{1}{\sigma}}(\bar{\theta}-\theta) - \frac{p_g}{q}\lambda \\ 0 = w - x - \frac{\theta-\theta_0}{q}p_g \end{cases}$$

The first two equations imply:

$$x = (2\bar{\theta}-\theta)\theta\left(\frac{p_g}{2q(\bar{\theta}-\theta)}\right)^{\sigma}.$$

Then, the third equation implies that θ^* satisfies Equation (4), which can be written as

$$F(\theta^*, w, q) = 0, \tag{13}$$

where

$$F(\theta, w, q) \stackrel{\text{def}}{=} w - (2\bar{\theta}-\theta)\theta\left(\frac{p_g}{2q(\bar{\theta}-\theta)}\right)^{\sigma} - \frac{\theta-\theta_0}{q}p_g. \tag{14}$$

It can be seen that for $w \geq 0$, $q > 0$, and $\theta \in [\theta_0, \bar{\theta})$, F increases with w and q and decreases with θ, because its derivatives are:

$$\begin{aligned} F_\theta &= -\left(\frac{p_g}{2q}\right)^{\sigma}\left(2(\bar{\theta}-\theta)^2 + \sigma(2\bar{\theta}-\theta)\theta\right)\left(\bar{\theta}-\theta\right)^{-\sigma-1} - \frac{p_g}{q} < 0, \\ F_w &= 1 > 0, \\ F_q &= \frac{\sigma}{q}\left(\frac{p_g}{2q}\right)^{\sigma}(2\bar{\theta}-\theta\theta)(\bar{\theta}-\theta)^{-\sigma} > 0. \end{aligned}$$

Therefore, if Equation (13) has a solution $\theta^*(w,q)$, it is monotone increasing and continuous.

Since $F(\theta_0, \underline{w}, q) = 0$, where $\underline{w}$ is defined in Equation (3), it follows that for $w < \underline{w}$, Equation (13) has no solution satisfying $\theta \geq \theta_0$. For such low income

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levels, the UMP has a corner solution in which $\theta^* = \theta_0$ and $x^* = w$. This proves part 1 of the proposition.

For $w > \underline{w}$, Equation (13) defines a unique solution $\theta^*(w, q)$. The solution always exists because for any income $w > \underline{w}$:

$$F(\theta_0, w, q) > 0,$$
$$\lim_{\theta \uparrow \bar{\theta}} F(\theta, w, q) = -\infty,$$

and F continuously decreases with θ. This proves part 2 of the proposition. The monotonicity properties of θ^* follow from the monotonicity properties of F:

$$\theta^*_w = -\frac{F_w}{F_\theta} = -\frac{1}{F_\theta} > 0,$$
$$\theta^*_q = -\frac{F_q}{F_\theta} > 0.$$

The monotonicity of x^* can be seen from:

$$x^*_w = 1 - \frac{p_g}{q}\theta^*_w > 0.$$

This proves part 3 of the proposition. Finally, since F in unbounded in w and θ, the solution θ^* approaches $\bar{\theta}$ when w increases unboundedly. Similarly, for any $\theta < \bar{\theta}$ and $w > 0$, $F(\theta, w, q)$ converges to $w > 0$ when q increases unboundedly. Therefore, in the limit, it must be that the solution θ^* converges to $\bar{\theta}$. This proves part 4 of the proposition.

Proof of Proposition 2. The proof of the proposition is a straightforward application of the results of Proposition 1. By the construction of $\underline{w}(q)$, $g^*(q, w) = 0$ for $w \leq \underline{w}(q)$, which is part 1 of the Proposition. Since $\theta^*(q, w)$ increases with w and converges to $\bar{\theta}$, eq. (6) implies $g^*(q, w)$ increases with w and converges to $\frac{1}{q}(\bar{\theta} - \theta_0)$, which is part 2 of the Proposition. The existence of income thresholds $w_1(q_L, q_H)$ $w_2(q_L, q_H)$ follows from continuity of $g^*(q, w)$ and two facts:

$$g^*(q_H, \underline{w}(q_L)) > g^*(q_L, \underline{w}(q_L)) = 0,$$

and

$$\lim_{w \to \infty} g^*(q_H, w) = \frac{1}{q_H}(\bar{\theta} - \theta_0) < \frac{1}{q_L}(\bar{\theta} - \theta_0) = \lim_{w \to \infty} g^*(q_L, w),$$

which is part 3 of the Proposition.

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B Appendix Identification

Table B1 reports the estimation results from an OLS regression of the retrofit intensity on pre-retrofit dwelling, income and energy use characteristics of the households. The sample includes all 13409 retrofitted houses from our baseline sample. The results indicate that retrofit intensity is mainly determined by house characteristics. Among energy use and socio-economics, only few variables are statistically significant and their effect on the retrofit intensity is small. For example, a one standard deviation increase in pre-retrofit gas use leads to a retrofit intensity up to 0.054 smaller, i.e. projected gas savings 0.83 percentage points smaller - this is negligible as compared to the 43% average projected gas savings.

The attrition rates between household in the treatment and the control groups are almost identical (3.33% resp. 3.30%) in 2016, before any retrofit take place in our sample. Furthermore, the average difference in gas use between households that moved or stayed is lower than 2% and is not statistically significant, this in pre-retrofit and post-retrofit years (2016 and 2021).

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Table B1: Determinants of retrofit intensity

	(1)	(2)
(Intercept)	-0.004 (0.009)	0.110* (0.061)
Panel A: Socio-economics		
Log income (standardized)	-0.036*** (0.009)	-0.035*** (0.010)
No. children (standardized)		-0.050 (0.067)
No. persons (standardized)		0.039 (0.074)
No. persons squared (standardized)		0.052 (0.091)
No. senior squared (standardized)		-0.024 (0.039)
No. children squared (standardized)		-0.018 (0.053)
No. seniors (standardized)		0.024 (0.049)
No. females (standardized)		0.019 (0.021)
No. females squared (standardized)		-0.019 (0.021)
Employed 0/1		0.031* (0.018)
Household type one adult (ref)		
Household type nuclear family 0/1		0.076 (0.060)
Household type one senior 0/1		0.039 (0.046)
Household type single parent 0/1		0.149*** (0.051)
Household type two adults 0/1		0.031 (0.049)
Education high (ref)		
Education low 0/1		0.025 (0.024)
Education medium 0/1		0.031 (0.025)
Education unknown 0/1		0.009 (0.025)
Panel B: House characteristics		
Log surface (standardized)		-0.241*** (0.008)
Log projected gas (standardized)		0.516*** (0.008)
Log construction year (standardized)		0.214*** (0.016)
Solar panels 0/1		0.153** (0.064)
Boiler changed 0/1		0.311*** (0.025)
Energy label C (ref)		
Energy label D 0/1		0.207*** (0.018)
Energy label E 0/1		0.459*** (0.019)
Energy label F 0/1		0.514*** (0.026)
Energy label G 0/1		0.733*** (0.028)
Constr. Period 1906-1940 (ref)		
Constr. Period 1940-1965 0/1		-0.616*** (0.051)
Constr. Period 1966-1976 0/1		-0.418*** (0.066)
Constr. Period 1977-1992 0/1		-0.794*** (0.085)
Panel C: Energy use		
Log gas (standardized)	0.046*** (0.009)	-0.054*** (0.007)
Num.Obs.	13401	13401
R2	0.003	0.443
R2 Adj.	0.003	0.442

Notes: The tables shows estimates of two separate OLS regressions. The dependent variable is the retrofit intensity. The independent variables are all pre-retrofit observed controls. Statistical significance: *p<0.1; **p<0.05; ***p<0.01.

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C Appendix Main results - full table

Table C1 reports the full set of coefficients behind Table 2.

Table C1: Average effects of insulation retrofit

Dependent: log of yearly natural gas use	(1)	(2)	(3)	(4)
Panel A: Retrofit				
After retrofit (year $\geq$ 2)	-0.149***	-0.228***	-0.228***	-0.218***
	(0.004)	(0.003)	(0.004)	(0.003)
After retrofit (year < 2)	-0.028***	-0.109***	-0.105***	-0.100***
	(0.004)	(0.002)	(0.004)	(0.002)
After retrofit (year $\geq$ 2) x Retrofit intensity	-0.058***	-0.077***	-0.100***	-0.078***
	(0.004)	(0.003)	(0.004)	(0.003)
After retrofit (year < 2) x Retrofit intensity	-0.024***	-0.039***	-0.065***	-0.038***
	(0.004)	(0.002)	(0.003)	(0.002)
Panel B: Socio-economics				
No. children			-0.019**	0.018***
			(0.008)	(0.004)
No. persons			0.115***	0.022***
			(0.008)	(0.004)
No. persons squared			-0.014***	-0.002**
			(0.002)	(0.001)
No. senior squared			0.002	-0.002
			(0.003)	(0.002)
No. children squared			0.011***	0.000
			(0.002)	(0.001)
No. seniors			0.020**	-0.001
			(0.008)	(0.005)
No. females			0.050***	0.061***
			(0.008)	(0.007)
No. females squared			-0.009	-0.024***
			(0.006)	(0.004)
Household type nuclear family			0.084***	0.059***
			(0.007)	(0.004)
Household type one senior			0.055***	0.001
			(0.006)	(0.004)
Household type single parent			0.094***	0.047***
			(0.007)	(0.004)
Household type two adults			0.033***	0.042***
			(0.006)	(0.003)
Household type two seniors				0.035***
				(0.003)

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Employed			-0.013***	-0.001
			(0.002)	(0.001)
Log income			0.034***	0.044***
			(0.003)	(0.002)
Education low			0.051***	0.016*
			(0.004)	(0.009)
Education medium			0.035***	0.005
			(0.004)	(0.008)
Education unknown			0.050***	0.035***
			(0.004)	(0.010)
Panel C: House characteristics				
Boiler changed			-0.019***	-0.042***
			(0.005)	(0.003)
Solar installation			-0.036***	-0.035***
			(0.003)	(0.002)
Log proj. gas use			0.257***	
			(0.004)	
Constr. Period 1940-1965			0.017***	
			(0.005)	
Constr. Period 1966-1976			0.006	
			(0.005)	
Constr. Period 1977-1992			-0.021***	
			(0.005)	
Log surface			0.215***	
			(0.007)	
Energy label D			0.018***	
			(0.003)	
Energy label E			0.034***	
			(0.003)	
Energy label F			0.042***	
			(0.005)	
Energy label G			0.049***	
			(0.005)	
No. obs.	963459	963459	959073	959073
No. treatment houses	13409	13409	13409	13409
No. control houses	110891	110891	110891	110891
R^2 Adj.	0.021	0.822	0.144	0.826
Year fixed-effect	X	X	X	X
Household fixed-effect		X		X
Controls			X	X

Notes: The table shows estimates of four separate regressions. The dependent variable is the log of gas consumption. Standard errors in parentheses are clustered at household level. Significance levels: *p<0.1; **p<0.05; ***p<0.01.

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D Appendix Sensitivity checks

In this Appendix we subject the results of Table 3 to a range of sensitivity analyses. We re-estimate the model Equation (12) for various subsamples, allowing the retrofit effect to differ by: (i) year in which insulation retrofit took place (2017, 2018 and 2019), Table D1; (ii) pre-retrofit energy efficiency as defined by the energy label (C, D, E, F, G), Table D2; (iii) socio-economic characteristics of households, Table D3; (iv) pre-retrofit gas use quintile, Table D4. Results are robust across all the year and energy label subsamples. The average effect of insulation however differs by household type. For instance, singles reach larger savings, while households with migration background reduce gas use less than average. The average effect also differs by pre-retrofit gas use: households with low gas demand experience almost half lower savings than average. The low-income specific response to insulation is however robust in all the subsamples.

Table D1: Effects of retrofits by retrofit year

		Retrofit year		
	Baseline	2017	2018	2019
After retrofit (year ≥ 2)	-0.218 (0.003)***	-0.217 (0.005)***	-0.221 (0.004)***	-0.212 (0.005)***
$\times$ Below 100% soc.min.	0.062 (0.016)***	0.088 (0.031)***	0.046 (0.024)*	0.040 (0.027)
$\times$ Below 130% soc.min.	0.025 (0.006)***	0.022 (0.011)*	0.021 (0.010)**	0.032 (0.011)***
$\times$ Below 150% soc.min.	0.018 (0.006)***	0.022 (0.010)**	0.012 (0.008)	0.017 (0.010)

Notes: The table shows estimates of Equation (12) for 8 separate regressions. Coefficients reported are two- and three-way interactions. The symbol $\times$ indicates an effect as compared to the reference level (non-poor). The combination of the column and row name indicates the interaction. The dependent variable is log of gas. Each regression includes controls, household fixed-effects and year fixed-effects. The sample size is 13409 treated and 110891 control units. Standard errors in parentheses are clustered at household level. Statistical significance: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

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Table D2: Effects of retrofits by energy label

	Baseline	Energy label C	D	E	F	G
After retrofit (year ≥ 2)	−0.218***	−0.223***	−0.218***	−0.228***	−0.228***	−0.225***
	(0.003)	(0.007)	(0.005)	(0.005)	(0.008)	(0.012)
× Below 100% soc.min.	0.062***	0.083*	0.071**	0.050*	0.027	0.169*
	(0.016)	(0.044)	(0.030)	(0.028)	(0.066)	(0.088)
× Below 130% soc.min.	0.025***	0.035**	0.022*	0.025**	−0.011	0.020
	(0.006)	(0.017)	(0.013)	(0.012)	(0.019)	(0.031)
× Below 150% soc.min.	0.018***	0.023	0.010	0.020*	−0.004	0.011
	(0.006)	(0.015)	(0.011)	(0.011)	(0.017)	(0.026)

Notes: The table shows estimates of Equation (12) for 8 separate regressions. Coefficients reported are two- and three-way interactions. The symbol × indicates an effect as compared to the reference level (non-poor). The combination of the column and row name indicates the interaction. The dependent variable is log of gas. Each regression includes controls, household fixed-effects and year fixed-effects. The sample size is 13409 treated and 110891 control units. Standard errors in parentheses are clustered at household level. Statistical significance: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

Table D3: Effects of retrofits by household type

	Mig. BG	Household type					
	Yes	one adult	nuclear family	one senior	single parent	two adults	two seniors
After retrofit (year ≥ 2)	−0.176***	−0.252***	−0.193***	−0.223***	−0.202***	−0.225***	−0.209***
	(0.006)	(0.007)	(0.006)	(0.005)	(0.007)	(0.007)	(0.005)
× Below 100% soc.min.	0.090***	0.083**	0.047	0.064**	0.008	0.126	0.120**
	(0.026)	(0.034)	(0.043)	(0.027)	(0.031)	(0.075)	(0.047)
× Below 130% soc.min.	0.028**	0.005	0.044***	0.028**	0.028*	0.032	0.053***
	(0.013)	(0.017)	(0.015)	(0.011)	(0.014)	(0.026)	(0.013)
× Below 150% soc.min.	0.023*	−0.009	0.047***	0.021*	0.019	0.027	0.033***
	(0.012)	(0.015)	(0.013)	(0.011)	(0.013)	(0.022)	(0.010)

Notes: The table shows estimates of Equation (12) for 8 separate regressions. Migration background (Mig. Bg) is "Yes" when all household members are born outside the Netherlands (first and second generation). Coefficients reported are two- and three-way interactions. The symbol × indicates an effect as compared to the reference level (non-poor). The combination of the column and row name indicates the interaction (e.g. below 100% soc.min. × Yes Migration background). The dependent variable is log of gas. Each regression includes controls, household fixed-effects and year fixed-effects. The sample size is 13409 treated and 110891 control units. Standard errors in parentheses are clustered at household level. Statistical significance: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

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Table D4: Effects of retrofits by pre-retrofit gas use quintiles

		Pre-retrofit gas use quintile	
	Baseline	first quintile	last quintile
After retrofit (year $\geq$ 2)	-0.218^{***}	-0.128^{***}	-0.265^{***}
	(0.003)	(0.010)	(0.005)
$\times$ Below 100% soc.min.	0.062^{***}	0.152^{***}	0.047^{*}
	(0.016)	(0.049)	(0.027)
$\times$ Below 130% soc.min.	0.025^{***}	0.047^{**}	0.014
	(0.006)	(0.022)	(0.011)
$\times$ Below 150% soc.min.	0.018^{***}	0.031	0.013
	(0.006)	(0.020)	(0.010)

Notes: The table shows estimates of Equation (12) for 12 separate regressions. Coefficients reported are two- and three-way interactions. The symbol $\times$ indicates an effect as compared to the reference level (non-poor). The combination of the column and row name indicates the interaction (e.g. below 100% soc.min. $\times$ first quintile). The dependent variable is log of gas. Each regression includes controls, household fixed-effects and year fixed-effects. The sample size is 13409 treated and 110891 control units. Standard errors in parentheses are clustered at household level. Statistical significance: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

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E Appendix Alternative estimation techniques staggered treatment

The coefficient of treatment effect can be biased in studies where the treatment timing differs across units, as is shown in Callaway and Sant'Anna (2021); Sun and Abraham (2021). First we re-estimate the results of Table 3, using the estimator from Sun and Abraham (2021) that corrects for the variation in treatment timing (staggered treatment), but still uses the never-treated control group. Then we use the estimator from Callaway and Sant'Anna (2021) that corrects for the variation in treatment timing and uses the not-yet-treated houses as control (the sample then contains only houses treated between 2017 and 2019, all other houses are discarded). Table E1 column Sunab respectively CS show that in both cases, the results stay robust to the alternative estimation techniques.

Table E1: Alternative estimation techniques staggered treatment

	TWFE	Sunab	CS
After retrofit (year ≥ 2)	-0.218 (0.003)***	-0.225 (0.003)***	-0.197 (0.007)***
Below 100% soc.min.	-0.155 (0.017)***	-0.161 (0.017)***	-0.169 (0.038)***
Below 130% soc.min.	-0.209 (0.006)***	-0.224 (0.006)***	-0.205 (0.013)***
Below 150% soc.min.	-0.215 (0.005)***	-0.228 (0.005)***	-0.200 (0.011)***

Notes: The table shows estimates of Equation (12) for 12 separate regressions. "Sunab" stands for Sun and Abraham estimator (Sun and Abraham, 2021) and "CS" stands for Callaway and Sant'Anna estimator (Callaway and Sant'Anna, 2021). "TWFE" stands for two-way fixed effects, our baseline estimator. All coefficients (except "After retrofit") are estimated on the sub-samples of poor households.The dependent variable is log of gas. Each regression includes controls, household fixed-effects and year fixed-effects. The sample size is 13409 treated and 110891 control units for "Sunab" and "TWFE". The sample size is 13409 treated for "CS". Standard errors in parentheses are clustered at household level. Statistical significance: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

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F Alternative model specifications

F.1 Functional form retrofit intensity

Table F1 shows the retrofit effect on poor households for various specifications of the retrofit intensity: the first column is the baseline specification Equation (12), the second column excludes the largest retrofits (retrofit intensity > 2), the third column allows for non-linear effects of the retrofit intensity and the last column discards the retrofit intensity. Low-income response is robust across all these specifications.

Table F1: Effects of retrofits across various retrofit intensity specifications

	Specification of retrofit intensity			
	Baseline	Linear and ≤2	Polynomial	Not controlled for
After retrofit (year ≥ 2)	−0.218 (0.003)***	−0.222 (0.006)***	−0.223 (0.003)***	−0.217 (0.003)***
× Below 100% soc.min.	0.062 (0.016)***	0.064 (0.017)***	0.062 (0.022)***	0.063 (0.017)***
× Below 130% soc.min.	0.025 (0.006)***	0.023 (0.007)***	0.013 (0.008)	0.023 (0.006)***
× Below 150% soc.min.	0.018 (0.006)***	0.017 (0.006)***	0.009 (0.007)	0.016 (0.006)***

Notes: The table shows estimates of Equation (12) for 16 separate regressions. In the first column, the retrofit intensity enters the model linearly. In second column, observations with the retrofit intensity larger than 2 are discarded. In the third column, the retrofit intensity and its second and third orders enter the model. In the last column, the retrofit intensity is discarded from the model. Coefficients reported are two- and three-way interactions. The symbol × indicates an effect as compared to the reference level (non-poor). The combination of the column and row name indicates the interaction. The dependent variable is log of gas. Each regression includes controls, household fixed-effects and year fixed-effects. The sample size is 13409 treated and 110891 control units. Standard errors in parentheses are clustered at household level. Statistical significance: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

F.2 Heterogeneous time trends

Table F2 shows the retrofit effect on poor households where the time-fixed effect is allowed to differ between poor and non-poor households. Low-income response is robust to this specification.

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Table F2: Effects of retrofits, allowing heterogenous time trends

	Baseline	Heterogeneous time trends
After retrofit (year $\geq$ 2)	-0.218 (0.003)***	-0.218 (0.003)***
$\times$ Below 100% soc.min.	0.062 (0.016)***	0.054 (0.017)***
$\times$ Below 130% soc.min.	0.025 (0.006)***	0.010 (0.007)
$\times$ Below 150% soc.min.	0.018 (0.006)***	0.002 (0.006)

Notes: The table shows estimates of Equation (12) for 8 separate regressions. Coefficients reported are two- and three-way interactions. The symbol $\times$ indicates an effect as compared to the reference level (non-poor). The combination of the column and row name indicates the interaction. The dependent variable is log of gas. Each regression includes controls, household fixed-effects and year fixed-effects. The sample size is 13409 treated and 110891 control units. Standard errors in parentheses are clustered at household level. Statistical significance: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

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G Replication of the analysis for the apartments

In this section, we replicate our main analysis for apartments.

G.1 Treatment and control group

Table G1 shows mean values of selected covariates, for the treatment and control group. As expected, house characteristics are not balanced: treated houses are older and have a lower energy efficiency. Various socio-economics covariates are well balanced: poverty status, education, number of seniors and income.

G.2 Gas savings

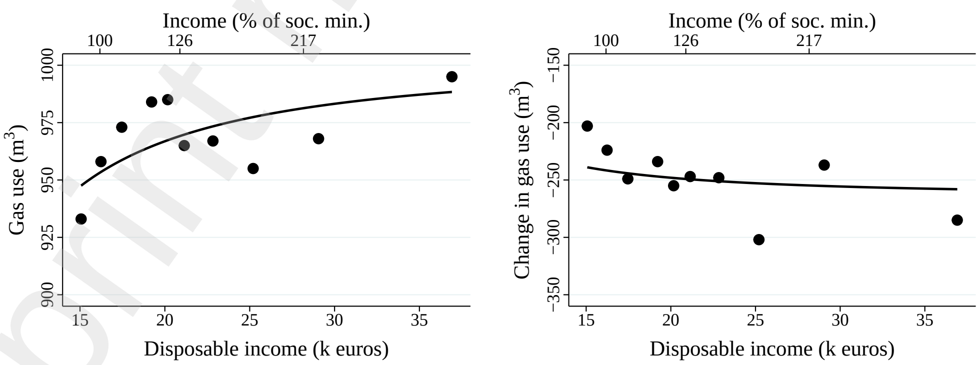
Table G2 reports the treatment effect, average and for the three low-income groups.

G.3 Computable model: parameters and validation

Figure G1 shows how well the model fits the data. Left the model predictions and the observed data for gas use are plotted, right the model predictions and the quasi-experimental estimates of the treatment effect is plotted, by income decile.

Figure G1: Model fit: gas use before and after heating efficiency upgrades

(a) Pre-retrofit gas use (m^3) (b) Retrofit effect on gas use (m^3)



Notes: The dots are observed values (left) respectively quasi-experimental estimates (right). The lines are predictions of the computable model. Panel (a) depicts the median gas use, across income deciles. Panel (b) depicts the average effect of a heating efficiency upgrade on gas use across income deciles. Both figures use the data from the apartment sample of 67,769 households (treatment + control).

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Table G1: Comparison of treatment and control groups

	Treatment	Control	p-value	SMD	VR
Panel A: Socio-economics					
No. persons	1.85	1.55	0.00	0.28	1.52
No. children	0.55	0.30	0.00	0.28	1.72
No. seniors	0.36	0.43	0.00	0.10	0.91
Income (k euro/yr)	23.12	22.08	0.00	0.11	1.15
Education high (0/1)	0.15	0.14	0.07	0.03	1.05
Migration background foreign (0/1)	0.46	0.35	0.00	0.22	1.09
Heating burden	0.05	0.04	0.00	0.23	1.26
Below 100% social min. (0/1)	0.05	0.05	0.53	0.01	1.04
Below 130% social min. (0/1)	0.34	0.36	0.01	0.04	0.98
Below 150% social min. (0/1)	0.44	0.46	0.00	0.05	0.99
Panel B: House characteristics					
Surface (m^2)	73.69	71.57	0.00	0.13	0.86
Constr. Period 1906-1939 (0/1)	0.04	0.03	0.59	0.01	1.04
Constr. Period 1940-1965 (0/1)	0.33	0.24	0.00	0.18	1.19
Constr. Period 1966-1976 (0/1)	0.48	0.28	0.00	0.42	1.25
Constr. Period 1977-1992 (0/1)	0.16	0.45	0.00	0.65	0.55
Energy label EFG (0/1)	0.48	0.31	0.00	0.35	1.16
Panel C: Energy use					
Electricity (kWh/yr)	2013.94	1912.91	0.00	0.10	1.18
Gas (m^3/yr)	1158.51	952.88	0.00	0.41	1.43
No. houses	5049.00	62720.00			
No. complexes	228.00	4770.00			
No. housing associations	56.00	93.00			

Notes: The table reports a balancing test between treatment and control dwellings. The columns *mean treated* and *mean control* report the mean values of selected covariates. The column *p-value* reports the p-value of a mean equality test between treatment and control group. The column *SMD* reports the standardised mean difference between the treatment and the control group. The column *VR* reports the variance ratio. $SMD = |\bar{X}_{treated} - \bar{X}_{control}|/\sqrt{\left(S^2_{treated} + S^2_{control}\right)/2}$ and $VR = S^2_{treated}/S^2_{control}$, where $\bar{X}$ is the sample mean and S^2 is the sample variance. The balancing is considered good for *SMD* smaller than 0.25 *VR* between 0.5 and 2 (Rubin, 2001; Stuart, 2010).

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Table G2: Effects of retrofits for energy poor (apartments)

	baseline
After retrofit (year $\geq$ 2)	-0.257 (0.008)***
$\times$ Below 100% soc.min.	0.095 (0.038)**
$\times$ Below 130% soc.min.	0.029 (0.015)*
$\times$ Below 150% soc.min.	0.036 (0.015)**

Notes: The table shows estimates of Equation (12) for 4 separate regressions. Coefficients reported are two- and three-way interactions. The symbol $\times$ indicates an effect as compared to the reference level (non-poor). The combination of the column and row name indicates the interaction. The dependent variable is log of gas. Each regression includes controls, household fixed-effects and year fixed-effects. The sample size is 5049 treated and 62720 control units. Standard errors in parentheses are clustered at household level. Statistical significance: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

G.4 Welfare outcomes

Table G4 reports the (welfare) effects as predicted by the computable consumer choice model for the apartments. Columns (2)-(3) of Table G4 describe the effects of the retrofits on the households' optimal indoor temperature and natural gas use. Columns (4)-(7) of Table G4 report the private welfare gains from the upgrade: total and decomposed into the benefits of increased temperature respectively of other consumption, as derived in Equations (7) to (9). It is noteworthy that the benefits from home upgrades are of similar magnitude in apartments as in the single-family dwellings; the costs are however smaller. In the case of apartments, positive returns to the heating efficiency retrofits are easier to achieve.

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Table G3: Computable model parameters

Description	Parameter	Value
Exogenously chosen parameters		
Price of gas (euro/m^3)	p_g	0.65
Price of other consumption	p_x	1.00
Calibrated parameters		
Indoor temperature at g=0 (^{o} C)	θ_0	15.19
Elasticity of substitution	σ	0.67
Satiety level of thermal comfort (^{o} C)	$\bar{\theta}$	20.92
Energy efficiency before retrofit (^{o} C/m^3)	q_L	$\frac{1}{175}$
Energy efficiency after retrofit (^{o} C/m^3)	q_H	$\frac{1}{129}$

Table G4: Welfare outcomes

Income	Private and external effects			Private benefits (euro)			
	Δ Temp.	Δ Gas	ΔCO_2	Slutsky valuation			Hicksian val.
	$^\circ C$	m^3	kg	$-\Delta^S$	$-\Delta^S_\theta$	$-\Delta^S_x$	CV
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	In prices 2016 (0.65 euro/m^3)						
low	0.08	-240	-430	163	7	156	164
average	0.04	-252	-451	167	3	164	168
high	0.02	-259	-464	170	1	169	170
	In prices 2022 (1.36 euro/m^3)						
low	0.19	-210	-376	320	33	287	325
average	0.09	-237	-425	340	16	324	343
high	0.04	-253	-454	352	7	346	354

Notes: The Table reports the effects of the average retrofit in our data, as predicted by the computable choice model. This is done for two scenarios (reference with gas prices of 2016 and counterfactual with gas prices of 2022) and for three income groups (low, average and high, respectively 16keuro, 24keuro and 43keuro in disposable yearly income). Columns (2) and (3) document the changes in consumption of temperature respectively yearly gas, following the retrofits. Column (4) reports the change in annual CO_2 emissions, assuming 1.79kg CO_2 per m^3 of natural gas. Column (5) reports the valuation of the private benefits of the retrofits using the Slutsky compensation. Column (8) reports the same valuation using the Hicksian compensation (compensating variation). Columns (6) and (7) decompose the Slutsky compensation into the parts that arise due to the change in temperature consumption respectively the change in consumption of other goods. The Table shows yearly outcomes.

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