The Efficacy of Energy Efficiency: Measuring the Returns to Home Insulation

Linde Kattenberg[*] Piet Eichholtz[†] Nils Kok[‡]

January 2023

Abstract

Energy efficiency in the housing market is considered an important tool to reduce energy consumption and carbon emissions, as well as to enhance national energy independence and protect consumer balance sheets. Home insulation plays an important role in improving the energy efficiency of a home. However, the impact of insulation measures on actual gas consumption is typically based on engineering predictions, and the efficacy of insulation measures is subject to debate. This study exploits a unique home insulation sample, combined with detailed household data on actual gas consumption before and after these interventions, and information on the socio-economic characteristics of occupants. Using a difference-in-difference approach, we document that home insulation reduces gas consumption by about 20%, on average, both for owner-occupied and rental homes. For the latter, the treatment is plausibly exogenous. We find no evidence of a temporal rebound effect: the reduction in gas consumption is consistent up to ten years after the intervention. At 2022 gas prices, the average treatment effect translates into an €866 reduction in the annual gas bill, and an average rate of return of 41.6% on the initial investment.

[*]Maastricht University, The Netherlands; l.kattenberg@maastrichtuniversity.nl
[†]Maastricht University, The Netherlands; p.eichholtz@maastrichtuniversity.nl
[‡]Maastricht University, The Netherlands; n.kok@maastrichtuniversity.nl

1 Introduction

The real estate sector plays a key role in the reduction of carbon emissions that is needed to mitigate climate change. The housing market, for instance, is a major consumer of energy, accounting for about 27% of final energy consumption in the EU (Eurostat, 2020). At the same time, real estate is also a sector where many CO_2-reducing interventions are readily available – instruments to improve the energy efficiency of a home include, for example, solar PV, triple glazing, heat pumps, and cavity wall and basement insulation (Granade et al., 2009). In addition to reducing CO_2 emissions, the improved energy efficiency of homes can lead to a reduction in the monthly energy expenses of households and improved living comfort. Indeed, popular belief holds that investing in home energy efficiency measures provides a relatively high return on investment, but that belief is typically not based on hard evidence. The exact returns on energy efficiency investments in homes are difficult to quantify, simply because realized energy savings are home-specific, difficult to observe, and ultimately prone to selection bias (and thus hard to generalize).

The uncertainty around actual energy savings from investments in energy efficiency is an important consideration in the discussion of the 'energy efficiency gap.' This term has been coined to explain the slow uptake of energy efficiency measures for society in general, and for homes specifically (Jaffe and Stavins, 1994). However, the size of the gap is up for debate (Allcott and Greenstone, 2012), as different factors could lead to overoptimistic predictions of profitability of energy efficiency investments. Indeed, numerous studies report a sizable disparity between expected and realized savings from energy efficiency retrofits in the housing market (Allcott and Greenstone, 2017; Fowlie et al., 2018; Christensen et al., 2021), with multiple explanations for the wedge. For instance, Christensen et al. (2021) find that heterogeneity in quality of installment, engineering mistakes, or a rebound effect have a contribution of 43%, 41%, and 6% respectively. More accurate estimates on predicted savings and the profitability of energy efficiency investments can contribute to a better

[1]We are grateful for the comments of Erdal Aydin, Dirk Brounen, and seminar participants at the AREUEA International Conference Dublin, the 2022 ODISSEI Conference and the MIT Climate and Real Estate Initiative Symposium. We thank the Dutch Ministry of the Interior for funding this research project, Bameco BV. for providing their data on insulation interventions, and Floor van Gulik for excellent research assistance. All errors pertain to the authors.

understanding of the size of the energy efficiency gap. This paper exploits unit-level costs and energy savings to precisely estimate the return to a variety of insulation measures across heterogeneous households.

Gaining a better understanding on the economics of insulation investments is also important given the dependence of other energy efficiency measures on the presence of insulation in the home. For instance, heat pumps, which are slated to replace gas-fired furnaces and boilers in many parts of the world, are currently suitable just for homes that can be heated using low-temperature water – for that, proper insulation is needed.[1]

In this study, we examine the effect of cavity wall, basement, and roof insulation on the actual energy consumption of households in the Netherlands, allowing for a detailed calculation of return on investment that can be generalized to a large part of the Western housing stock. Using hand-collected, proprietary information from a large insulation company, we identify homes where insulation measures were applied, including details on the type of insulation and the installation costs. We link this information to annual data on gas and electricity consumption, observable characteristics of the home, and extensive micro data on the household, including income, age and education level. The data set includes both rental and owner-occupied homes – this is important, given that the choice to install insulation is plausibly exogenous for tenants (i.e. the landlord decides on such measure). Furthermore, we can split the sample of rental homes into the homes that are owned by a housing corporation (i.e. affordable housing), and those that are rented in the free market. We empirically assess the energy consumption of treated homes, before and after the implementation of the insulation measures, constructing a control group of comparable homes where no insulation measures took place. We assess the causal effect of home insulation on household gas consumption using a difference-in-difference estimation.

The results of the empirical analysis show that gas consumption decreases, on average, by 20% after insulation is installed. Cavity wall and roof insulation are the most effective interventions, whereas the effects of basement insulation are smaller, but still economically and statistically significant. The results are robust to a variety of robustness checks, including

[1] In fact, Austria will ban gas-fired furnaces per 2023, and in the Netherlands, gas-fired furnaces can be replaced just by heat pumps as of 2026.

the construction of different control samples. The reduction in gas consumption does not differ substantially across household types, although the effect is slightly smaller for lower income households in rental homes. Importantly, our 2010-2020 data set also allows for an analysis of the persistence of energy savings over time. We do not find evidence of a temporal rebound effect: the observed reduction in gas consumption remains around 20% for up to ten years after insulation measures have been taken.

A simple cost-benefit calculation on the economics of insulation investments indicates that, for an average household living in an average home, the yearly gas bill is reduced by €300, based on gas prices at the time of the investment. Using gas prices observed in July 2022 (during a period of war-induced spikes in energy prices), the annual savings equal €866, on average. These savings translate into payback periods of 5.5 years and 2.4 years, respectively. Assuming perpetuity of the savings, the return to insulation measures is 18.3% using gas prices at the time of investment, and 41.6% at 2022 prices (rather than using the assumption of perpetuity, in case of a home sale the capitalization of energy savings in the home price would represent part of this return, see Aydin et al. (2020)).

This paper adds to the broader literature on energy efficiency in the residential sector. The early literature focuses primarily on understanding the cross-sectional and temporal variation in household energy consumption patterns (see, for example, Brounen et al. (2013)), while a more recent strand of literature attempts to identify the effect of behavioral interventions to reduce energy consumption (Allcott and Mullainathan, 2010; Aydin et al., 2018). Large-scale studies on the effect of structural interventions is scant. There are some studies that empirically assess the effect of improved insulation (Metcalf and Hassett, 1999; Hong et al., 2006; Liang et al., 2018), or weatherization more broadly (Schweitzer, 2005; Allcott and Greenstone, 2017; Fowlie et al., 2018; Christensen et al., 2021). Generally, these studies find a sizeable decrease in energy consumption after insulation measures, or from a combined package of measures that include insulation. However, the size of the effect varies and is strongly context-dependent. Moreover, studies comparing actual energy savings to projected savings based on engineering estimates find large disparities between those two. For example, Allcott and Greenstone (2017), Fowlie et al. (2018), and Christensen et al. (2021) find realized energy savings of just 58%, 30%, and 51% of predictions, respectively.

Importantly, rather than comparing engineering estimates with actual energy savings, this paper focuses on the initial investment versus ex-post monetary savings on the utility bill, allowing for the estimation of a rate of return on insulation measures [2].

Another unique factor of this study is that the data covers a relatively long time period – we include treated observations where home insulation took place more than 10 years ago. As such, we can also measure the long-run effects of home insulation. An increase in energy efficiency can lead to an *increase* in the use of energy-consuming appliances, because the unit costs of energy consumption decrease. This concept is defined in the literature as the ”rebound effect.” In a meta study of Sorrell et al. (2009), an average rebound effect of 20% is documented across 21 studies on household energy consumption in the OECD. In the Netherlands, for a sample of 560,000 Dutch dwellings, Aydin et al. (2017) document a rebound effect of 41.3% in rental homes, and of 26.7% in owner-occupied homes. Such an effect would be important to consider in order to make a reliable estimate of the true savings in gas consumption following home insulation measures. We investigate the long-term gas consumption after insulation, and can therefore check for the presence of a temporal rebound effect, which does not seems to be present in our results.

The results in this paper have implications for homeowners, (public) investors in residential homes, as well as policy makers. Given the paucity of reliable information of the efficacy of home insulation measures, it is often challenging for a home owner, be it an owner-occupier or a landlord, to make well-informed decisions regarding the investments needed to improve the energy efficiency of the building. The return calculations in this paper may help to provide further insight into the real, monetary effects of insulation programs. The results also provide an indication that blanket subsidy programs should, in principle, not be necessary for home insulation, given the short payback period and high return on investment. Such subsidy programs should be targeted at homeowners with limited net wealth, or rather be changed to loan programs, to overcome upfront financing constraints. In addition, government policy efforts may be directed to the home rental market, where

[2] For instance, Christensen et al. (2021) examine unit-specific net benefits of home insulation measures and find that 42% of homes in their sample, while underperforming predictions, have a positive net benefit from investment through energy savings. The authors highlight that the presence of a performance ”wedge” does not tell the full story and that the investment can still be profitable.

investors incur the capital cost and tenants typically benefit from energy savings.

Importantly, our return calculations include the dampening effect of a possible ”rebound” effect, and thus reflect the true financial return to consumers or investors. Of course, we cannot observe the presence of an immediate rebound effect. That is, the difference between actual energy savings and energy savings based on engineering predictions that can be attributed to a behavior change *immediately after* the intervention (Fowlie et al., 2018; Christensen et al., 2021). In case of such immediate rebound, the total welfare effect would also include the consumer benefit of additional heating. In addition, we ignore the possible welfare effects from enhanced comfort through reducing cold and draft. As recently pointed out by Palacios et al. (2021), these effects may include reduced incidence of illness and frequency of doctor visits, which also has broader societal welfare effects.

The remainder of this paper proceeds as follows. We first provide a brief overview of the data sources used in the paper, including sample statistics and the results of the parallel trend analyses. Section 3 elaborates on the methodology. The regression results are presented in section 4. The final part of the paper includes a section on implications for home owners and policy makers, based on a range of cost/benefit analyses of the insulation measures, and a brief conclusion.

2 Data

The main source of data used in this paper is from Bameco BV, a private insulation company based in the Netherlands. This company is a large insulation provider in Limburg, the most southern province of the country. The sole business of Bameco is home insulation, with a focus on basement insulation, cavity wall insulation, and roof insulation. The company maintains a (paper) archive for each home where an insulation intervention was carried out, including information on the cost of the installation, the type of insulation, and the date of the installation. We manually digitize the invoice data over the full period of operation, which started in 2010. In the sample, we include all insulation measures up to 2019, such that we have at least one year for post-insulation measurement of energy consumption.

In total, we identify 2,351 households with a home insulation intervention in the period between 2010 and 2019. Figure 1 provides an overview of the insulation interventions for every year in the sample. Note that households can opt for just a single measure, or for multiple measures at the same time. Clearly, wall insulation is the most popular form of insulation, with 88% percent of households opting for that measure. Floor insulation (typically installed in the basement) is applied in some 17% of the sample, while roof insulation is least popular, at 3%. There is a clear upward trend in insulation interventions over the sample period – the 2016 dip likely represents an artefact of the data collection rather than a true decrease in interventions, given that some of the archive for that year was no longer retrievable due to a change in administrative systems.

—Insert Figure 1—

Table 1 provides further insight into the insulation measures. In our sample, 91% of households include just one measure, 8% include two measures, whereas three measures are rarely taken at the same time. From an investment perspective, the average investment for wall insulation equals some €1,600 (in nominal terms), which is about 0.7% of the home value at time of the intervention. Roof insulation is the most expensive intervention, whereas floor insulation is the cheapest form of home insulation.Note that the investment costs do not incorporate local, regional or national subsidies. Such subsidy programs have come in and out throughout the sample period, and while they may influence the propensity to insulate, such subsidies should not affect the outcome of the intervention. We differentiate between homes that are owner-occupied (in the Netherlands, the homeowner rate is 57%), owned by housing corporations (slightly less than a third of the Dutch stock) and homes owned by private investors (15% of homes in the Netherlands). Homes owned by housing corporations are regulated, with rents considered "affordable," while the latter are typically rented out at market prices. There is quite some difference between the insulation types installed in owner-occupied homes versus the insulation that is applied to rental corporation homes – private owners hardly opt for roof insulation, whereas housing corporations are more likely to install roof (and floor) insulation. The difference in choice for the type of insulation per housing category may be related to the types of homes in each category. For instance, the share of apartments is much higher in the rental corporation sample, as compared to the rest of the sample. In the case of an apartment, wall insulation can may be less beneficial from a savings perspective as compared to other dwelling types.

—Insert Table 1—

The insulation interventions are matched to micro data on household and dwelling characteristics provided by the Central Bureau for Statistics (CBS). Each observation is matched to the CBS files, where we include all treated observation until 2019, which requires household data until 2020 (one year after the last intervention). At the time of the analysis, household data on 2021 was not yet available. Out of the 2,351 observations, we have energy consumption and household data on 1,345 observations. The control group in our baseline analysis consists of all households that are based in the same province (Limburg), leading to a control sample of 301,035 observations (we further restrict the control group in the robustness checks of the analysis).

Table 2 provides the descriptive statistics of the treatment and the control group – the descriptive statistics are based on the year before any observation was treated, 2009. We distinguish treated observations that are owner-occupied from observations that are rental homes in the free market sector, or owned by a housing corporation. Quite clearly, in all sectors we observe that homes with higher gas consumption are more likely to opt for insulation measures. Semi-detached homes, which have more exposed walls, are more likely to be insulated. We also observe that homes that are constructed between 1945 and 1980 have a higher propensity to be treated. Most homes in the Netherlands are constructed using two brick layers with a cavity wall in between, an innovation first introduced in the early 1900s, for insulation, health, and comfort purposes (Vekemans, 2016). In the 1970s, large scale cavity wall insulation programs were introduced for new and existing homes, but with a type of insulation that turned out to last for just 15-20 years, rendering most cavity walls currently empty, or not properly insulated. Interestingly, we observe that homes constructed after 1980 are much less likely to be treated, even though the ”original” insulation in those homes may well have disappeared by now.

For the owner-occupied sample, there seems to be some selection bias in the type of homeowners that are in the treated sample: they have a higher income and higher net wealth. They also have a larger average family size, and more female occupants. Sorting into treatment is much less likely for tenants of rental units – the decision to renovate should be orthogonal to characteristics of the tenants, and rather be based on the quality and/or vintage of the rental home. Analyzing the household characteristics of treated observations in the free rental sector, we observe some significant differences with the control group – they have higher wealth and home value. Potentially, this has to do with the type of landlord and the segment in which they operate. As shown by the significantly higher home value in the treatment group, it could be the case that homes in a certain segment have had better maintenance. These concerns are not present in the sample of homes owned by housing corporations. Here, we observe no significant difference between the characteristics of the inhabitants of treated and control homes. We only observe that homes presumably benefiting most from improved insulation, older homes and homes with higher gas consumption, are more likely to be insulated during the sample period.

—Insert Table 2—

3 Methodology

We employ a difference-in-difference approach to estimate a causal relationship between the installation of insulation in the home and its subsequent gas consumption. Equation 1 provides the empirical model:

$$ln(Gas\ use_{it}) = \beta_0 + \beta_1 Insulation_{it} + X_{it} + \lambda_i + \mu_t + \epsilon_{it} \qquad (1)$$

where $Insulation_{it}$ is a dummy variable that equals one when an observation falls in the treatment period, that is one year after insulation, and has been subject to insulation treatment. X_{it} is a vector of home and household characteristics that can vary over time. λ_i and μ_t represent home and time-fixed effects, respectively. ϵ_{it} is the error term, assumed to be independent from treatment and normally distributed.

To get a first sense for the effect of the treatment (i.e. insulation) on subsequent gas consumption, Figure 2 plots the mean gas consumption for the treatment and control group for the 2010 insulation year (Appendix B provides similar figures for the other years in the sample). Year 0 indicates the year of the insulation treatment. An important assumption is that gas consumption of the treated homes in the sample follows a trend that is parallel to the gas consumption trend of the group of control homes. Indeed, we clearly observe that the two groups have different levels of gas consumption before insulation, where households in the treatment group consume more gas, but the slope of the pre-trend across both samples is exactly the same. There are some shocks that are visible, which occur simultaneously and in a similar magnitude for the treatment and the control group. These shocks can likely be attributed to weather conditions, such as colder or warmer winters. After the installation of insulation, gas consumption drops in the treatment group and the consumption pattern of both groups becomes more similar. Note that there is a slightly downward long-term trend in gas consumption in the control group, perhaps due to unobservable energy-efficiency investments (e.g. new heating system, etc) or perhaps consistently warmer winters. We also note that the possible presence of treatment in the control group could lead to an underestimation of the true treatment effect – there are multiple insulation companies active in the Netherlands. In the robustness checks, we address this issue by creating control samples that are more restrictive as compared to the general control sample.

—Insert Figure 2—

4 Results

4.1 Main Effects

Table 3 presents the results of the difference-in-difference analysis, where the dependent variable is the logarithm of annual gas consumption. Column (1) includes year-fixed effects to control for time variation in gas consumption (e.g. weather) and household-fixed effects to control for cross-sectional variation in gas consumption (e.g. family size, construction year, size of the dwelling, etc). Standard errors are clustered at the household level. We document an average treatment effect of 20.2% after the insulation intervention, as compared to the control group of non-treated homes in the same province. Column (2) includes further control variables that could affect gas consumption and that can vary over time, such as the number of heating degree days (varying locally), the number of household members, and household income. The treatment effect stays constant, with a decrease of 20.8% in annual gas consumption after the application of insulation measures in the home.

Of course, we may overestimate the effects of insulation on gas consumption given the selection bias of sorting into the treatment – environmentally-conscious consumers may be more likely to invest in insulation, and may also take other energy saving measures. We therefore split the sample into owner-occupied homes and tenant-occupied homes, including those homes in the free market and those owned by housing corporations. Presumably, the insulation treatment is exogenous for the sub-sample of rental homes, given that the landlord decides on investments in the energy efficiency of rental homes, while the renter pays the energy bill (in the Netherlands, a landlord very rarely pays for energy costs when leasing out independent units). We document that gas consumption decreases with 21.8% in the sample of owner-occupied homes, and with 27.8% for households in rental homes in the free sector. We find a smaller effect for homes owned by housing corporations, at 15.6%, but this effect is mainly driven by one outlier year. Figure 3B shows the estimated treatment effect per year. Here we observe that only the last observation in the rental corporation sample is significantly different from the remainder of the measurement period. This effect may be caused by a relatively small sample of housing corporation homes being observed for the extended time period, and this estimate may therefore be less reliable. Thus, we conclude that there are no substantial differences in the effect of insulation treatment on gas consumption across the three groups – if anything, the results are stronger for rental homes (in the free market). These stratified estimates provide some comfort that the size of the treatment effect is consistent across owner-occupied and rental homes, and that a possible selection effect among homeowners is not driving our results.

—Insert Table 3—

The data set allows us to identify different types of insulation measures, including basement, wall and roof insulation. We estimate the treatment effects for each of these insulation types separately in Table 4. In Columns 1, 2, and 3 we include homes where just one insulation measure has been installed. Roof insulation leads to the largest reduction in gas consumption, with an average of 23.2%. Wall insulation yields average savings in gas consumption of 20.7%. For floor insulation, we find a smaller, but still significant effect of 12.5% reduction in gas consumption. We also examine the interventions where two insulation types have been installed, for each of the different combinations. Columns 4, 5 and 6 of Table 4 provide the results. We find that all combinations yield higher gas savings than one individual measure, and that the combination of wall and roof insulation yields the highest reduction. However, we note that we have a rather small number of observations in this part of the analysis, such that the differences in effect sizes can be the result of the selected group of observations.

—Insert Table 4—

4.2 Heterogeneity Analysis

As a first analysis of heterogeneity in the average treatment effect, we stratify the treated sample on different types of dwellings, as well as different income groups, to explore whether the average effect size varies across these groups. Table 5 divides the sample into different dwelling types. We observe effects that are of similar magnitude for corner homes, semi-detached homes, and detached homes – respectively 21.7%, 21.5%, and 21.7%. For dwellings that are wedged between other homes, so-called ”row homes”, the effect is somewhat smaller, at 18.6%. For apartments, we do not observe a significant reduction in gas consumption after insulation treatment, and the point estimate is close to zero as well. These results can be explained by the fact that insulation is most effective for homes that are (semi-)detached, since these homes have a large area of exposed walls, which enhances the effectiveness of insulation. This reasoning could also explain why the effect is smaller for row homes. However, we also note that the share of apartments in our sample is relatively small, which decreases the statistical power of the analysis. A larger sample of treated apartments could help in providing more conclusive results on the effect of insulation for this dwelling type.

—Insert Table 5—

We subsequently split the sample according to the lower and upper 50% of the income distribution, separately for owner-occupied homes and rental homes in the free sector and those owned by housing corporations. Household income levels may affect the impact of energy efficiency improvements on energy consumption through a different baseline consumption level. If income constraints lead to a below-optimal consumption of energy in the baseline case, improvements in energy efficiency standards of the home may have smaller-than-anticipated effects due to partial increase in energy consumption by the household (Saunders, 2013). Table 6 Columns 1 and 2 include owner-occupied dwellings, where the treatment effect is 21.8% for low income households, and 19.9% for the upper half of households in the income distribution. These estimates have overlapping confidence intervals and we therefore conclude that income does not influence the effect of insulation on gas consumption among owner-occupied homes. For rental homes in the free sector, in Columns 3 and 4, we observe a larger difference between low and high income households. Here, low income households save 38.5% in gas consumption following insulation, whereas high income households save 28.6%. Again, confidence intervals of both point estimates are overlapping, such that the point estimates are not statistically different. For homes owned by housing corporations, the lower income households show a smaller effect following insulation investments, with 12.8% savings as compared to 18.7%. This is in line with the previous literature, indicating smaller effect sizes after energy efficiency improvements for lower income households. However, it should be noted that the confidence intervals also slightly overlap in this case, such that the estimated effect size still falls in the same range.

—Insert Table 6—

4.3 Persistence of Treatment Effect

The average treatment effect is not just an average effect across households, but also an average effect over the treatment period. The sample includes insulation interventions that took place between 2010 and 2019, and we observe gas consumption after the intervention up to a period of ten years after the installation year. We therefore explore whether the reduction in gas consumption is persistent over time. Figure 3 plots the coefficients of the difference-in-difference analysis as in equation (1), with post-treatment year interaction dummies for each year after the treatment. Each dot represents the difference in gas consumption between the treatment and the control group, relative to the year before insulation, as well as the 95% confidence interval. The figure shows that the difference between treatment and control group is stable before insulation is installed. After installing the insulation there is a sharp drop, leading to an average reduction in gas consumption of about 20%. Over time, the confidence interval widens. This is related to the fact that we have fewer observations at the start of the sample period, which subsequently leads to fewer observations with a long time-span. Moreover, there can be households in the sample that move, such that the observed time period is shorter for these observations. However, we observe that the estimated size of the treatment effect is quite consistent over time – the effect of insulation as a structural change in the home remains as time progresses. As opposed to the attenuating effect of behavioral treatments, such as the Opower social comparison-based treatment Allcott and Rogers (2014), we do not find a change in gas consumption over time due to adjustment in household behavior.

Similar to Figure 3A, Figure 3B plots the coefficient estimates of gas consumption over time separately for owner-occupied homes and rental homes. Since the first two years of the sample period include insulation interventions in owner-occupied homes only, the analysis includes just seven years after insulation for rental homes. The figure shows that over time, there is no significant difference in the reduction of gas consumption across these different ownership types, with merely a widening confidence interval (likely due to fewer observations early in the sample period). Reductions in gas consumption are persistent across types of homes, notwithstanding the tenure choice.

—Insert Figure 3—

4.4 Robustness Checks

4.4.1 Substitution Effect

The decrease in gas consumption following an insulation retrofit, could also be due to a substitution effect. That is, gas consumption would be decreasing, while electricity consumption is increasing. This could be the case if, for instance, households that insulate their home all install a heat pump and heat their home with electricity instead of gas. In such case, we would overestimate total energy savings by only considering the effect of insulation on gas consumption. Therefore, we perform the same analysis as our baseline difference-in-difference model, but substitute gas consumption with electricity consumption as the dependent variable. Using this estimation strategy, we can observe whether the group of households (or landlords) that invest in insulation substitutes gas consumption with electricity consumption.

The results of the analysis are presented in Table 7. We document that electricity consumption decreases in the treatment sample, with a small but significant effect of 4% on an annual basis. Thus, households that installed insulation do not only significantly decrease their gas consumption, they also have significantly lower electricity consumption after the insulation treatment, as compared to the control group. There could be two reasons explaining the result that electricity consumption also decreases in the treatment group. First, treated household also invest in other energy efficiency improvements at the time of home insulation – such improvements (e.g. replacing light bulbs, a more efficient fridge or washing machine, etc.) may affect electricity consumption. Second, the household becomes more aware of its energy consumption after the treatment, and adapts its consumption behavior. With the data available to us, we are not able to observe which effect (or combination thereof) is at play here. However, at the very least we can conclude that there is no substitution effect – installing insulation leads, on average, to a *reduction* in home electricity consumption, not an increase. In addition, we analyze the distribution of savings in gas consumption through a non-parametric estimate in Figure A.1(a). Here, we observe that just a very small group of households realizes a 100% reduction in gas consumption after the insulation intervention. This means that completely substituting natural gas, for example using electricity as an energy source, is not typically observed in our sample. We also note that the use of electric heat pumps was rare in the recent past – in the future, due to more stringent policy regarding gas consumption, and due to increased profitability of heat pumps, adoption of heat pumps could be quite different.

—Insert Table 7—

4.4.2 Restricting the Control Group

In the baseline model, the control group consists of all homes in the same province. In this control group, there could also be homes in which insulation was improved during the sample period. If that is the case, our baseline estimate would underestimate the true treatment effect. In Table 8, we restrict the control group in a variety of ways, such that we can more certain that insulation improvements in the control group are not influencing our results. In column 1, we first exclude households where gas consumption decreased by more than the median change in gas consumption in the treatment sample (31.13%) between any two consecutive years during the treatment period. In these homes, we expect that the energy efficiency has been changed through a) insulation installed by a different provider, or b) different energy efficiency measures. In column 2, we only include homes in the control sample that were constructed after the year 2000. In this case, we can be rather sure that there are no changes to the home insulation, as the current insulation is of high quality. In column 3, the sample is restricted in terms of geographical area. Rather than considering the full province of Limburg (some 1.1 million inhabitants), we consider just the city of Maastricht (some 120,000 inhabitants), where the company has their largest clientele. In this case, there is a lower likelihood that homes in the control have improved home insulation through another company. We observe that in Columns 1 and 2, the effect size increases quite drastically as compared to the baseline model in Table 3. These findings are a strong indication that the baseline analysis provides an underestimation of the treatment effect, and that improved energy efficiency of homes in the control group is an important to consider. In Column 3, the effect size remains in the same range as compared to what is observed in the baseline model. Therefore, ruling out unobserved treatment in the control group is not likely not solved through applying a geographical restriction.

—Insert Table 8—

5 Discussion

Home insulation has a sizeable effect on household gas consumption. The question remains what the reduction in energy consumption implies for private individuals, facing an upfront financial outlay to improve the energy efficiency of their home. (For investors, the return calculation is complicated due to tenants benefiting from the investment in energy efficiency by the investor.) In the results section, we estimated the average treatment effect, per insulation type. We use these estimates to perform a back-of-the-envelope calculation on the returns to different insulation types, exploiting invoice data of the insulation company to calculate the average investment costs in our sample. Importantly, this simple calculation ignores the possible presence of subsidies [3]. The possibility of subsidies implies that our return calculations are lower-bound estimates. On the benefit side, we assume perpetuity of energy savings to calculate the return. While homes may be sold at some point, it is reasonable to assume the capitalization of energy efficiency into home prices (see, for example, Aydin et al. (2020)). In estimating yearly savings, we consider the gas consumption and gas prices in the year before the insulation was installed. These prices are inflation-adjusted to the year 2019. In addition, we substitute the gas prices that the households (and landlords) used at the time of their decision making process, with July 2022 prices (the period of a resource shock caused by the war in Ukraine). In this scenario, we also adjust the investment costs to 2022 levels. We do this by taking into account the average increase in insulation costs provided by the insulation company.

Table 9 displays investment costs, yearly savings, annual return, and the payback period. In column 1, we consider all insulation types in the sample (including treatments with multiple measures), whereas in columns 2, 3, and 4 we only consider homes where just one type of insulation was used. The average results show an annual return of 18.3%, which corresponds to a payback period of 5.5 years. We observe that annual returns from wall insulation are particularly high, with an average of 18.1%. For floor and roof insulation, the annual return is 11.4% and 14.6%, respectively[4]. Considering the payback period, the average wall insulation investment of €1,656 will be earned back in about 5.5 years. For floor and roof insulation, the average payback period is 8.8 and 6.8 years, respectively.

[3] Indeed, over the past decade, the Netherlands had a variety of subsidy programs to stimulate energy efficiency, for example for solar PV. At the time of writing, there was a government subsidy in place for home insulation measures, which required at least two forms of insulation. The level of the subsidy was at about 30% of the initial investment. See https://www.milieucentraal.nl/energie-besparen/isoleren-en-besparen.

[4] Figure A.1(c) displays the distribution of non-parametric estimated annual returns in the sample. Here it becomes visible that there are more extreme cases present in the sample in terms of positive as well as negative annual returns.

Of course, using July 2022 gas prices changes the investment decision considerably, with significantly shortened payback periods. The average annual return increases to 41.6%, a return that will be challenging to find for many other investments. For wall insulation, an average investment can be earned back already within 2.5 years. Floor insulation has a payback period of 4.0 years, and roof insulation has a payback period of 3.1 years. Considering that a household lives in a dwelling for around 10 years, all insulation types would be earned back within this period, under both energy price scenarios. That is, in the financial decision, the extent of capitalization of the insulation investment into the selling price is not relevant anymore.

—Insert Table 9—

6 Conclusion

Improving the energy efficiency of the building stock is important to decrease household energy consumption, and with that to reduce the negative externality from carbon emissions. In addition, home energy efficiency may shield household balance sheets from negative price shocks such as those experienced by European consumers in 2022. The baseline measure to enhance the energy efficiency of a home is wall, roof, or basement insulation. Such insulation also provides the basis for subsequent installation of a heat pump, which would allow for the home to be taken off natural gas. Using unique, hand-collected data on home insulation measures, this study examines the effect of roof, wall and basement insulation on gas consumption in a large sample of (rental and owner-occupied) residential homes.

The results of the difference-in-difference analysis show that home insulation measures significantly reduce gas consumption, with an average treatment effect of about 20%. The effect is slightly higher for rental homes in the free market sector, where insulation is plausibly exogenous, and is mostly stemming from wall insulation and roof insulation. We test for heterogeneous effects across types of homes, and across household characteristics. Not surprisingly, homes with the largest fraction of exposed walls (e.g. detached homes) benefit most from home insulation, while low-income households in rental corporation homes have slightly lower gas savings as compared to higher-income households in similar homes, which may be explained by the fact that the marginal demand for heating is highest for lower income households. Furthermore, we investigate long-run gas consumption for up to ten years after the energy efficiency improvements, to address potential concerns of a longitudinal rebound effect. Importantly, the point estimates remain stable in the long-run, which provides some indication that the gas use reduction can be attributed to the changed physical characteristics of the home, rather than behavioral changes of the household.

Translating our findings to financial savings, we observe an average reduction in the energy bill of €300 per year. Compared to the investment to install insulation, this yield a yearly return of 18.3%, translating into a payback period of 5.5 years. Wall insulation has the highest return, of 18.1%, while roof insulation returns 14.6% and floor insulation returns 11.4% per year. If the gas prices that households in our sample pay would be substituted by the July 2022 gas price, an average annual return on investment of 41.6% would be realized, and the payback period of investing in insulation would be just 2.4 years.

Insights from this study contribute to better estimates on the returns to home insulation. Most papers in the literature focus on the dearth of energy efficiency adoption, and explanations for the difference between predicted savings and realized savings (Allcott and Greenstone, 2017; Fowlie et al., 2018; Christensen et al., 2021). There are no papers that study the actual *returns* to energy efficiency investment at scale in a setting where selection effects can be overcome. The results in this paper can inform homeowners, investors, and housing corporations in their home retrofitting decision, reducing investment uncertainty. The results can also inform policymakers on the efficacy of energy efficiency in the housing market, which represents an important pillar in reducing carbon emissions. First, the information in this paper can be used to make more realistic expectations of the energy savings from insulation. Second, our findings can be used to address behavioral change as it relates to energy efficiency, and to create policy that targets energy conservation to those groups that are most prone to possible "rebound" effects. Third, given the financial rates of return documented in this paper, there seems to be limited necessity for subsidy programs aimed at stimulating home energy efficiency measures in general, and home insulation in particular.

Of course, the consideration of energy efficiency measures hinges on more than financial returns alone. Upfront capital outlays (no matter the relatively small size of that investment), the ”hassle” factor, energy illiteracy (Brounen et al., 2013) and the perceived risks of home insulation (e.g. an increase in mold) are all barriers that hold back private consumers from improving the energy efficiency of their homes. For landlords, an important (albeit solvable) consideration is the split incentive, where tenants reap the benefits of landlord-driven improvements in energy efficiency. Finally, an important but often ignored issue is the presence of supply-side constraints for energy efficiency improvements. Many of these measures are highly labor-intensive, and jobs can be hard to fill. Equally, more advanced energy efficiency improvements (e.g. heat pumps) require components that are in scarce supply, leading to long waiting times. Given the efficacy of investments in home energy efficiency, policies addressing supply-side issues, for example through workforce training, or targeted visa-waivers, may help to more quickly improve the efficiency of the buildings stock, helping to reduce both energy dependence and global carbon emissions.

References

Allcott, H. and Greenstone, M. (2012). Is there an energy efficiency gap? *Journal of Economic perspectives*, 26(1):3–28.

Allcott, H. and Greenstone, M. (2017). Measuring the welfare effects of residential energy efficiency programs. Technical report, National Bureau of Economic Research.

Allcott, H. and Mullainathan, S. (2010). Behavior and energy policy. *Science*, 327(5970):1204–1205.

Allcott, H. and Rogers, T. (2014). The short-run and long-run effects of behavioral interventions: Experimental evidence from energy conservation. *American Economic Review*, 104(10):3003–37.

Aydin, E., Brounen, D., and Kok, N. (2018). Information provision and energy consumption: Evidence from a field experiment. *Energy Economics*, 71:403–410.

Aydin, E., Brounen, D., and Kok, N. (2020). The capitalization of energy efficiency: Evidence from the housing market. *Journal of Urban Economics*, 117:103243.

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.

Brounen, D., Kok, N., and Quigley, J. M. (2013). Energy literacy, awareness, and conservation behavior of residential households. *Energy Economics*, 38:42–50.

Christensen, P., Francisco, P., Myers, E., and Souza, M. (2021). Decomposing the wedge between projected and realized returns in energy efficiency programs. *The Review of Economics and Statistics*, pages 1–46.

Eurostat (2020). Energy consumption in households. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy$_{c}onsumption_{i}n_{h}ouseholds$.

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.

Granade, H. C., Creyts, J., Derkach, A., Farese, P., Nyquist, S., and Ostrowski, K. (2009). Unlocking energy efficiency in the us economy. *McKinsey & Company*.

Hong, S. H., Oreszczyn, T., Ridley, I., Group, W. F. S., et al. (2006). The impact of energy efficient refurbishment on the space heating fuel consumption in english dwellings. *Energy and buildings*, 38(10):1171–1181.

Jaffe, A. B. and Stavins, R. N. (1994). The energy-efficiency gap what does it mean? *Energy policy*, 22(10):804–810.

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.

Metcalf, G. E. and Hassett, K. A. (1999). Measuring the energy savings from home improvement investments: evidence from monthly billing data. *Review of economics and statistics*, 81(3):516–528.

Palacios, J., Eichholtz, P., Kok, N., and Aydin, E. (2021). The impact of housing conditions on health outcomes. *Real Estate Economics*, 49(4):1172–1200.

Saunders, H. D. (2013). Historical evidence for energy efficiency rebound in 30 us sectors and a toolkit for rebound analysts. *Technological Forecasting and Social Change*, 80(7):1317–1330.

Schweitzer, M. (2005). Estimating the national effects of the us department of energy's weatherization assistance program with state-level data: A metaevaluation using studies from 1993 to 2005. *ORNL/CON-493. http://weatherization. ornl. gov/pdf/CON-493FINAL10-10-05. pdf. Washington, DC: US Department of Energy, Office of the Weatherization and Intergovernmental Program.*

Sorrell, S., Dimitropoulos, J., and Sommerville, M. (2009). Empirical estimates of the direct rebound effect: A review. *Energy policy*, 37(4):1356–1371.

Vekemans, B. (2016). *Legislation and Brickwork Facades in a Historical Perspective.*

Table 1: Descriptive Statistics

	(1) Full sample	(2) Owner-occupied	(3) Rental free sector	(4) Rental corporation
# of insulation measures	1.09	1.08	1.11	1.14
	(0.30)	(0.29)	(0.33)	(0.35)
Wall				
Percentage	0.88	0.91	0.89	0.57
	(0.32)	(0.28)	(0.31)	(0.50)
Total cost in €	1579.05	1621.08	1562.62	1036.24
	(601.79)	(602.99)	(573.06)	(355.00)
Surface in m^2	104.50	106.83	105.61	68.58
	(42.20)	(42.13)	(40.84)	(29.30)
Floor				
Percentage	0.17	0.15	0.19	0.35
	(0.38)	(0.36)	(0.39)	(0.48)
Total cost in €	1272.09	1255.87	1268.26	1337.24
	(513.80)	(503.24)	(514.83)	(558.91)
Surface in m^2	53.14	52.02	50.39	60.17
	(21.66)	(20.88)	(21.57)	(23.66)
Roof				
Percentage	0.03	0.02	0.02	0.21
	(0.18)	(0.12)	(0.15)	(0.41)
Total cost in €	1764.56	1884.80	1348.60	1771.05
	(820.48)	(892.27)	(598.80)	(811.50)
Surface in m^2	50.97	60.21	44.00	46.27
	(18.74)	(20.82)	(21.52)	(14.67)
Other				
Percentage	0.00	0.00	.	0.01
	(0.05)	(0.05)	.	(0.09)
Total cost in €	1011.48	897.64	.	1353.00
	(769.43)	(900.16)	.	.
Surface in m^2	39.25	27.33	.	75.00
	(30.84)	(23.97)	.	.
Observations	1345	1016	214	115

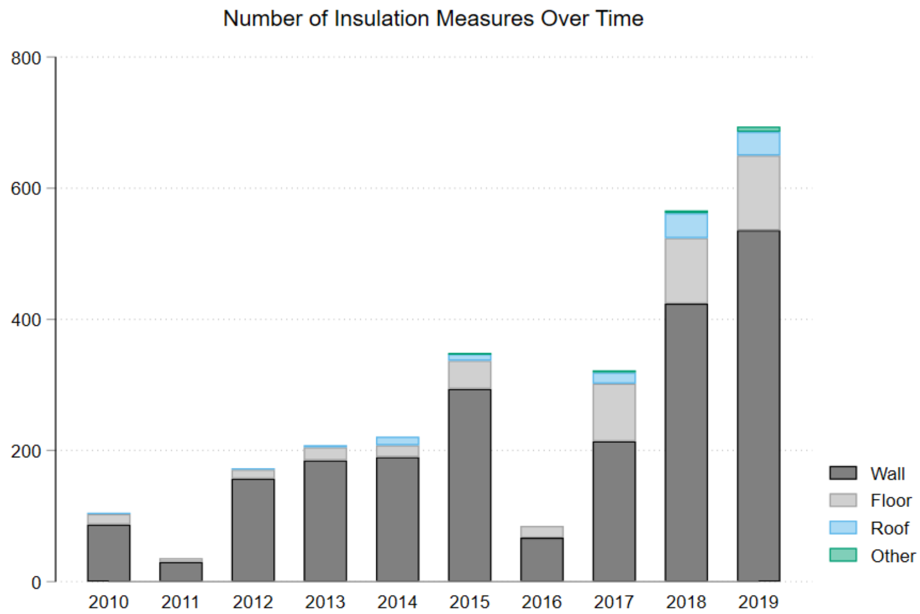
Notes: Table 1 presents the insulation characteristics per type of insulation, separately for the full sample, owner-occupied dwellings and rental dwellings, where rental is reported separately for corporation and free market homes. The "percentage" reports what share of households in the particular column installed that type of insulation. Standard deviations are reported in parenthesis.

Table 2: Descriptive Statistics

	(1) Treatment owner-occupied	(2) Control owner-occupied		(3) Treatment rental free sector	(4) Control rental free sector		(5) Treatment rental corporation	(6) Control rental corporation	
Energy consumption									
Annual gas consumption	2357.165	1991.715	***	2381.549	1768.621	***	1604.210	1344.093	***
in m^3	(751.1)	(811.3)		(777.7)	(893.9)		(565.9)	(598.8)	
Annual electricity	3967.824	3796.137	**	3253.868	2941.964		2703.818	2468.165	*
consumption in kWh	(1636.2)	(1743.9)		(1795.7)	(1575.0)		(1469.8)	(1315.0)	
Household characteristics									
# of household	2.347	2.222	***	1.705	1.676		1.772	1.668	
members	(1.067)	(1.109)		(0.797)	(0.914)		(0.927)	(0.931)	
# of children	0.425	0.382		0.095	0.176		0.191	0.194	
	(0.831)	(0.795)		(0.388)	(0.558)		(0.551)	(0.593)	
# of elderly (>65)	0.629	0.673		0.937	0.780		0.706	0.718	
	(0.911)	(0.948)		(0.823)	(0.835)		(0.761)	(0.859)	
# of females	1.053	0.966	***	0.926	0.806		0.875	0.816	
	(0.743)	(0.764)		(0.510)	(0.651)		(0.602)	(0.669)	
Household wealth	206.224	193.994	*	240.334	130.355	***	12.968	19.874	
(x €1000)	(165.5)	(174.8)		(208.5)	(180.1)		(23.23)	(52.32)	
Annual household	38.483	35.023	***	29.365	27.408		22.216	21.608	
income (x €1000)	(16.48)	(15.64)		(14.10)	(14.08)		(9.445)	(9.037)	
Dwelling characteristics									
Home value (x €1000)	216.835	214.451		214.652	181.168	***	127.971	124.137	
	(74.59)	(85.37)		(60.99)	(80.97)		(31.21)	(34.30)	
Dwelling surface in m^2	152.296	142.405	***	148.315	120.709	***	92.618	91.855	
	(39.99)	(44.57)		(39.36)	(45.27)		(21.32)	(22.36)	
Dwelling type									
Apartment	0.006	0.093	***	0.063	0.383	***	0.221	0.446	***
	(0.0771)	(0.290)		(0.245)	(0.486)		(0.416)	(0.497)	
Corner	0.178	0.179		0.168	0.130		0.309	0.161	***
	(0.383)	(0.383)		(0.376)	(0.336)		(0.464)	(0.368)	
Semi-detached	0.337	0.193	***	0.253	0.116	***	0.154	0.062	***
	(0.473)	(0.395)		(0.437)	(0.320)		(0.363)	(0.242)	
Row	0.259	0.338	***	0.263	0.270		0.316	0.329	
	(0.438)	(0.473)		(0.443)	(0.444)		(0.467)	(0.470)	
Detached	0.220	0.198		0.253	0.101	***	0.000	0.001	
	(0.414)	(0.398)		(0.437)	(0.302)		(0)	(0.0372)	
Building period									
1900-1929	0.031	0.079	***	0.053	0.097		0.000	0.042	*
	(0.173)	(0.270)		(0.226)	(0.296)		(0)	(0.201)	
1930-1944	0.070	0.064		0.011	0.073	*	0.007	0.021	
	(0.255)	(0.245)		(0.103)	(0.260)		(0.0861)	(0.144)	
1945-1959	0.243	0.137	***	0.160	0.141		0.200	0.194	
	(0.429)	(0.344)		(0.368)	(0.348)		(0.401)	(0.396)	
1960-1969	0.281	0.176	***	0.362	0.156	***	0.407	0.212	***
	(0.450)	(0.380)		(0.483)	(0.363)		(0.493)	(0.409)	
1970-1979	0.335	0.222	***	0.298	0.178	**	0.348	0.177	***
	(0.472)	(0.416)		(0.460)	(0.382)		(0.478)	(0.381)	
1980-1989	0.027	0.141	***	0.021	0.177	***	0.030	0.210	***
	(0.162)	(0.348)		(0.145)	(0.381)		(0.170)	(0.407)	
1990-1999	0.011	0.119	***	0.032	0.124	**	0.007	0.107	***
	(0.104)	(0.324)		(0.177)	(0.329)		(0.0861)	(0.310)	
>2000	0.002	0.062	***	0.064	0.055		0.000	0.036	*
	(0.0447)	(0.242)		(0.246)	(0.229)		(0)	(0.187)	
Observations	1005	171520	172525	95	29412	29507	136	100103	100239

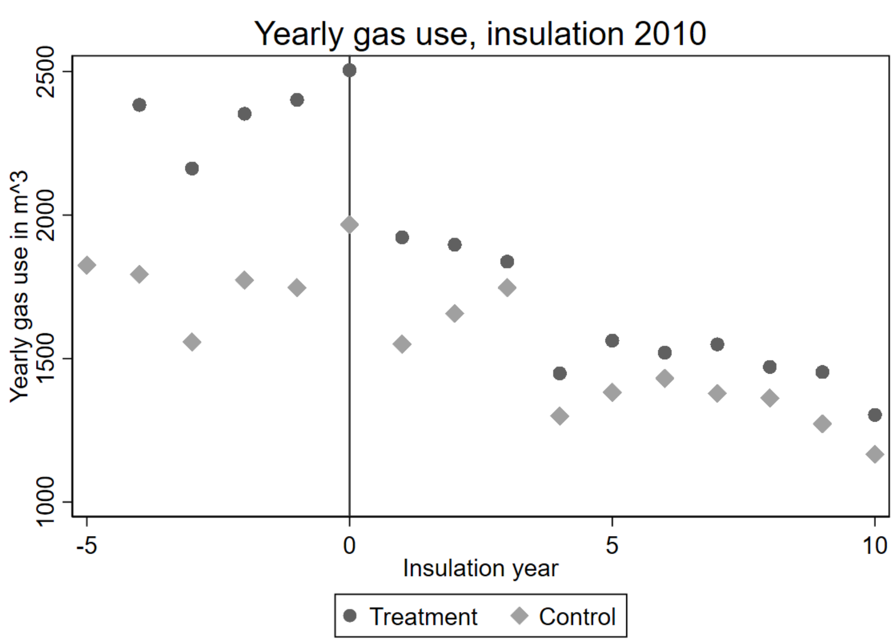
Notes: Table 2 presents the descriptive statistics. The control group consists of all non-treated households in the same region. The table splits between owner-occupied homes and rental homes. The table displays the statistics for the year 2009, before any of the households in the treatment group installed insulation. Standard deviations are reported in parenthesis. * P<0.05. ** P<0.01. *** P<0.001

Figure 1: Insulation Measures Over Time



Notes: Figure 1 presents the number of recorded insulation measures in our sample over the sample period, split up per type of insulation.

Figure 2: Gas Consumption in Treated versus Non-Treated Homes



Notes: Figure 2 presents the mean of yearly gas use in the treatment and control group. Year 0 is the year of insulation.

Table 3: Insulation and Gas Consumption

	(1) Full sample	(2) Full sample	(3) Owner-occupied	(4) Rental free sector	(5) Rental corporation
Insulation * Treatment Period	-0.202***	-0.208***	-0.218***	-0.278***	-0.156***
	(0.00991)	(0.00986)	(0.0106)	(0.0409)	(0.0383)
Treatment Period	0.00512	0.00727	0.0114*	0.0691**	-0.0343
	(0.00665)	(0.00667)	(0.00678)	(0.0320)	(0.0255)
Constant	7.430***	4.209***	4.384***	4.160***	4.058***
	(0.000505)	(0.0446)	(0.0454)	(0.214)	(0.169)
Observations	4,926,373	4,914,210	2,935,245	443,215	1,535,750
R-squared	0.193	0.200	0.252	0.139	0.161
Number of homes	481,377	481,298	293,658	57,929	146,461
Year FE	YES	YES	YES	YES	YES
Household FE	YES	YES	YES	YES	YES
Controls	NO	YES	YES	YES	YES

Notes: Dependent variable: log annual gas consumption. Standard errors are clustered at the household level. Standard deviations are reported in parenthesis. * P<0.05. ** P<0.01. *** P<0.001

Table 4: Heterogeneity by Insulation Type

	(1) Wall	(2) Floor	(3) Roof	(4) Wall & Floor	(5) Wall & Roof	(6) Floor & Roof
Insulation * Treatment Period	-0.207***	-0.125***	-0.232***	-0.268***	-0.423***	-0.294***
	(0.0115)	(0.0259)	(0.0888)	(0.0333)	(0.0683)	(0.0653)
Treatment Period	0.00945	0.0314	-0.0157	0.00577	0.236*	0.0234
	(0.00802)	(0.0192)	(0.0435)	(0.0231)	(0.127)	(0.0690)
Constant	4.194***	4.048***	4.361***	4.222***	2.698***	4.105***
	(0.0536)	(0.127)	(0.289)	(0.153)	(0.839)	(0.458)
Observations	4,906,540	4,894,358	4,892,566	5,179,125	5,177,651	5,177,751
R-squared	0.200	0.199	0.199	0.217	0.217	0.217
Number of homes	480,563	479,522	479,380	479,741	479,626	479,632
Year FE	YES	YES	YES	YES	YES	YES
Household FE	YES	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES	YES

Notes: Dependent variable: log annual gas consumption. Columns 1, 2, and 3 only include households where one insulation measure is installed. Columns 4, 5, and 6 only include households where only two insulation measures are installed. Households where more than two insulation are installed are excluded from the table, since the sample only has 4 of these observations. Standard errors are clustered at the household level. Standard deviations are reported in parenthesis. * P<0.05. ** P<0.01. *** P<0.001

Table 5: Heterogeneity by Dwelling Type

	(1) Apartment	(2) Corner	(3) Semi-detached	(4) Row	(5) Detached
Insulation * Treatment Period	0.00835	-0.217***	-0.215***	-0.186***	-0.217***
	(0.0785)	(0.0247)	(0.0178)	(0.0200)	(0.0185)
Treatment Period	-0.0708	0.0158	0.00758	-0.000401	0.0252*
	(0.0825)	(0.0135)	(0.0116)	(0.0123)	(0.0130)
Constant	3.406***	3.164***	3.354***	3.152***	3.859***
	(0.899)	(0.148)	(0.127)	(0.134)	(0.142)
Observations	1,011,768	803,457	687,125	1,564,221	611,061
R-squared	0.094	0.247	0.259	0.226	0.244
Number of homes	111,754	78,143	66,799	152,285	65,334
Year FE	YES	YES	YES	YES	YES
Household FE	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES

Notes: Dependent variable: log annual gas consumption. Standard errors are clustered at the household level. Standard deviations are reported in parenthesis. * P<0.05. ** P<0.01. *** P<0.001

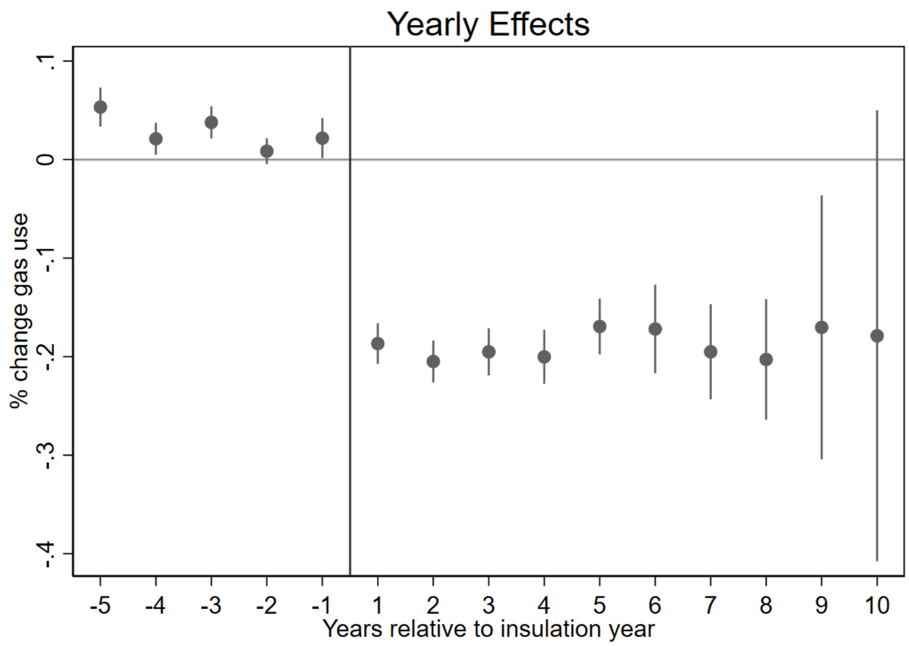
Table 6: Heterogeneity by Income Levels

	(1) Owner-Occupied Low Income	(2) Owner-Occupied High Income	(3) Rental Free Sector Low Income	(4) Rental Free Sector High Income	(5) Rental Corporation Low Income	(6) Rental Corporation High Income
Insulation * Treatment Period	-0.218***	-0.199***	-0.385***	-0.286***	-0.128*	-0.187***
	(0.0193)	(0.0123)	(0.0709)	(0.0461)	(0.0685)	(0.0306)
Treatment Period	0.0124	0.00155	0.0920*	0.0849**	-0.0796*	-0.0190
	(0.0113)	(0.00765)	(0.0556)	(0.0369)	(0.0451)	(0.0234)
Constant	4.351***	4.585***	4.019***	4.104***	4.063***	4.189***
	(0.0762)	(0.0512)	(0.372)	(0.247)	(0.300)	(0.156)
Observations	1,470,524	1,464,721	223,548	219,667	768,696	767,054
R-squared	0.204	0.320	0.104	0.185	0.129	0.208
Number of homes	222,894	234,325	41,462	43,689	113,656	119,703
Year FE	YES	YES	YES	YES	YES	YES
Household FE	YES	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES	YES

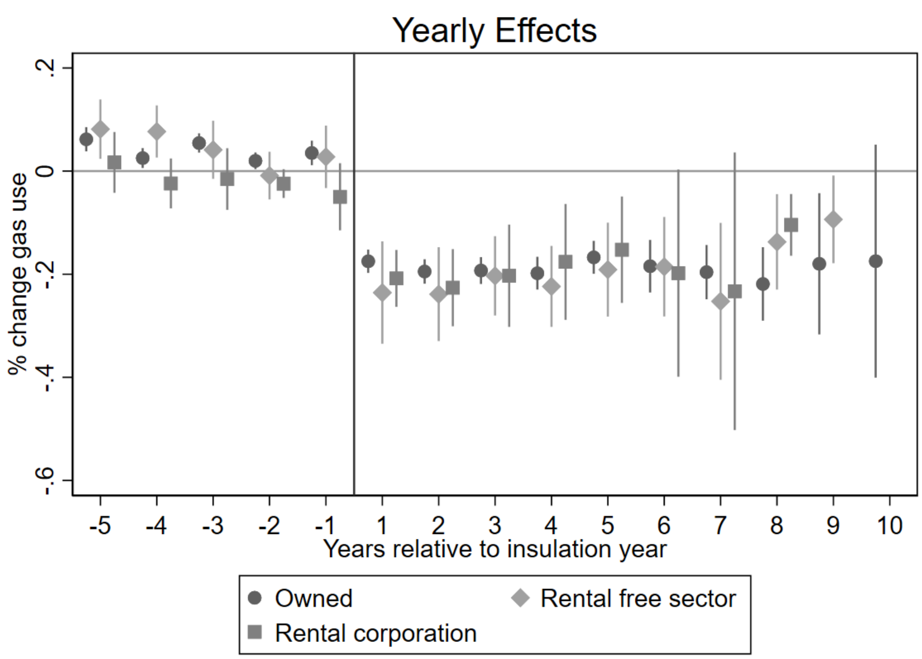
Notes: Dependent variable: log annual gas consumption. Standard errors are clustered at the household level. Standard deviations are reported in parenthesis. * P<0.05. ** P<0.01. *** P<0.001

Figure 3: Insulation Effect Over Time

(a) Full Sample



(b) Owner-occupied and Rental Homes



Notes: Figure displays annual gas consumption relative to year 0, the last year before insulation. The figure shows the point estimates, with the 95% confidence interval.

Table 7: Substitution Effects: Insulation and Electricity Consumption

	(1) Full Sample	(2) Full Sample	(3) Owner-Occupied	(4) Rental Free Sector	(5) Rental Corporation
Insulation * Treatment Period	-0.0277**	-0.0396***	-0.0399***	-0.00990	-0.0597
	(0.0129)	(0.0114)	(0.0120)	(0.0497)	(0.0384)
Treatment Period	0.000158	0.0100	-0.00357	0.00857	0.0522*
	(0.00915)	(0.00835)	(0.00887)	(0.0344)	(0.0282)
Constant	8.007***	5.297***	6.136***	6.245***	5.720***
	(0.000595)	(0.0915)	(0.0593)	(0.229)	(0.187)
Observations	4,869,172	4,618,748	2,895,374	439,627	1,522,334
R-squared	0.063	0.148	0.194	0.139	0.115
Number of house_id	483,252	472,512	294,514	58,046	147,434
Year FE	YES	YES	YES	YES	YES
Household FE	YES	YES	YES	YES	YES
Controls	NO	YES	YES	YES	YES

Notes: Dependent variable: log annual electricity consumption. Standard errors are clustered at the household level. Standard deviations are reported in parenthesis. * P<0.05. ** P<0.01. *** P<0.001

Table 8: Robustness Checks: Restricting the Control Sample

	1 Same City	2 Gas Consumption Change	3 Building Year >2000	4 Label Jump	5 Improved Insulation	6 Low Window Quality
Insulation *	-0.220***	-0.336***	-0.339***	-0.231***	-0.215***	-0.205***
Treatment Period	(0.0195)	(0.00991)	(0.0103)	(0.00987)	(0.00987)	(0.0100)
Treatment Period	0.00651	0.0888***	0.0854***	0.0185***	0.00978	0.00837
	(0.0103)	(0.00671)	(0.00716)	(0.00668)	(0.00667)	(0.00683)
Constant	4.270***	4.983***	4.735***	4.472***	4.271***	4.202***
	(0.0701)	(0.0447)	(0.0514)	(0.0448)	(0.0447)	(0.0457)
Observations	666,676	2,515,713	329,603	2,613,950	4,263,430	4,912,960
R-squared	0.187	0.242	0.142	0.232	0.198	0.200
Number of homes	67,424	260,177	66,737	263,243	422,309	481,190
Year FE	YES	YES	YES	YES	YES	YES
Household FE	YES	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES	YES

Notes: In Table 8 shows we restrict the sample in different ways. In column 1, we remove households from the control group where gas consumption dropped with more that the median gas consumption reduction in the treatment group (31.13%). In column 2, we only include homes built after 2000 in the control group. Column 3 only includes homes that are located in the city of Maastricht, both in the treatment and the control group. Dependent variable: log annual electricity consumption. Standard errors are clustered at the household level. Standard deviations are reported in parenthesis. * P<0.05. ** P<0.01. *** P<0.001

Table 9: Returns to Insulation Measures

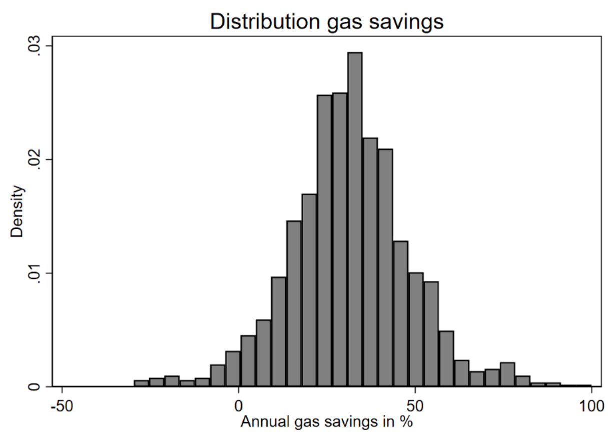
	Actual prices				2022 prices			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	All	Wall	Floor	Roof	All	Wall	Floor	Roof
Yearly savings	€300	€299	€164	€301	€866	€857	€460	€847
Investment	€1,640	€1,656	€1,437	€2,055	€2,084	€2,104	€1,825	€2,610
Annual return	18.3%	18.1%	11.4%	14.6%	41.6%	40.7%	25.2%	32.5%
Payback period	5.5	5.5	8.8	6.8	2.4	2.5	4.0	3.1

Notes: Table 9 displays average yearly savings and investment costs. Savings are calculated based on the average estimated effect size per insulation measure. The investment costs are obtained from the invoices of the insulation company. In column 1 to 4, we multiply the average savings by the gas price in the year before installation. In column 5 to 8, we use the July 2022 gas price. Investment costs are adjusted to 2022 prices, based on the average price development of the insulation company.

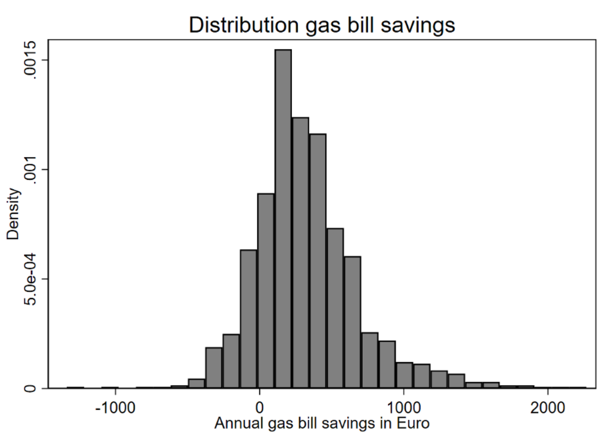
A Histograms

Figure A.1: Insulation Effect Over Time

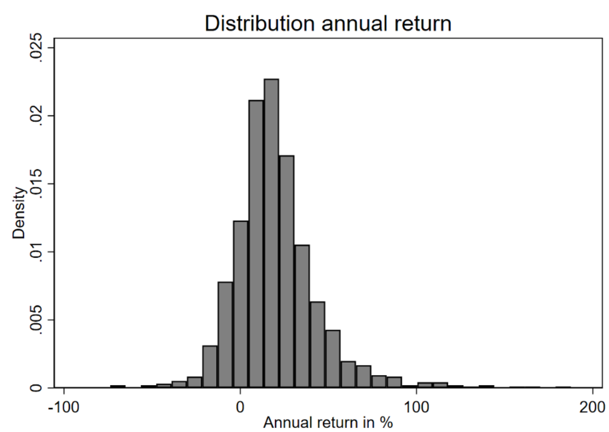
(a) Gas savings in percentages



(b) Gas savings in Euro



(c) Annual return investment



Notes: Figure A.1 displays the non-parametric distribution of gas savings based on the 5 years before, until maximally 10 years after improved insulation. Gas use in the year of insulation is not included in this calculation. Firstly, A.1(a) shows the annual gas savings in percentage terms. A.1(b) shows the annual gas bill savings in Euro, while A.1(c) displays the annual return through gas bill savings on the total investment in insulation in percentages.