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Health implications of sustainable housing: a double-edged sword

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Abstract

This paper examines the effect of making housing more energy efficient on health. Given the ongoing climate transition, it is crucial to assess the associated health impacts to achieve dual benefits and calculate the social optimality of subsidies for energy efficiency measures. Using an individual-dwelling year fixed effects strategy and focusing on social housing tenants, this study demonstrates that more energy efficient dwellings, on average, increase the likelihood of having asthma and COPD and decrease the likelihood of having rheumatoid arthritis and cardiovascular diseases. Furthermore, the study highlights the importance of ventilation in mitigating the adverse health effects of insulation. Additionally, only facade insulation was found to significantly impact health, while floor and roof insulation did not. Furthermore, the study suggests that heat pumps and balanced ventilation could lead to the largest healthcare cost savings and reduction in disease burden, but further research is needed to rule out sparse data bias. Besides, no conclusions can be drawn about smaller subgroups because of the sparse data, and further research is needed to investigate potential heterogeneous effects.

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1 Introduction

In 2013 an energy agreement ("Energieakkoord voor duurzame groei") was signed by the Dutch government, employers, trade unions and civil society organizations. They agreed that the Netherlands should be climate neutral by 2050 (Sociaal-Economische Raad (SER), 2013). To reach this goal, transition to an energy neutral built environment is needed as nearly a third of all energy consumption comes from dwellings, offices and other buildings (SER, 2013). Both energy savings and sustainable energy generation are necessary for achieving an energy neutral built environment. To promote energy savings, homeowners' associations (verenigingen van eigenaren (vve's) in Dutch), homeowners and housing corporations can apply for grants to improve the sustainability of their dwellings. Common energy efficiency measures are double glazing, better insulation, heat pumps and solar panels.

To adequately evaluate the social optimality of sustainability grants, it is necessary to consider all relevant effects, including health effects. Pediatricians and politicians have raised concerns about potential health effects of inadequate housing conditions (NOS, 2024; Vriend, 2024). In this paper, the size and significance of the effect of energy efficiency measures on health are investigated. Existing literature indicates that this effect can be substantial. In 2018, 0.5% of the Dutch disease burden could be attributed to the indoor environment according to the National Institute for Public Health and Environment (RIVM), which is equivalent to 23,000 disability-adjusted life years (DALYs).[1] This disease burden is associated with 400 million euros of yearly healthcare expenditures (RIVM, 2018). Both the disease burden and yearly healthcare expenditures are underestimated as sleep disturbance due to noise (which is equivalent to approximately 25,000 DALYs) and stress are not included in these estimations (Van der Ree et al., 2019).

The transition to an energy neutral built environment can influence the disease burden of the indoor environment. Main contributors to the disease burden of the indoor environment are passive smoking, radon and thoron from the soil and building materials, fine particulate matter, moisture and carbon monoxide poisoning (Van der Ree et al., 2019; Jantunen et al., 2011). On the one hand, energy efficiency measures can increase indoor temperature and decrease the amount of

[1] Disease burden (expressed in Disability-Adjusted Life Years) is a composite measure of health loss, incorporating the number of lost years of life due to premature death and years lived with health problems, weighted by their severity (RIVM, 2007).

moisture inside. On the other hand, improving insulation could negatively affect health by increasing the concentration of harmful substances discussed above. In the literature, it has been widely demonstrated that sustainability of housing and health are correlated. Individuals living in sustainable houses are, for example, less likely to have asthma and COPD compared to individuals living in unsustainable houses. However, studies can often not be interpreted causally due to potential endogeneity issues.

In this paper, a logistic regression with individual-dwelling and temporal fixed effects is used to address these concerns and answer what the effect of making dwellings more energy efficient is on health. This strategy was also used in Germany by Künn and Palacios (2022). This paper contributes to the existing literature by applying this approach to the Dutch context. More specifically, this paper first examines the health effects of improving energy inefficient dwellings with an Energy Performance Certificate (EPC) E, F or G to an EPC A or B, or C or D.[2] Secondly, the analysis focuses on the effect of specific energy efficiency measures on health. These measures, on which the EPC is based, include triple glazing, insulation, ventilation, solar water heaters, solar panels and heating systems. Besides individual-dwelling and temporal fixed effects, both regressions include five-year age groups as control variables. Lastly, this paper contributes to existing literature by not only investigating the effects on asthma, COPD and cardiovascular diseases, but also on rheumatoid arthritis and sleep.

The primary dataset for this study was obtained using multiple datasets from Statistics Netherlands (CBS). First, WoON datasets are used to construct a representative sample of dwellings that are rented out by social housing associations. Given that data on housing sustainability are only available from 2007 to 2021, our analysis focuses on residents who occupied these dwellings within this time frame. This data is then combined with administrative panel data on medication use and age. In total, 89,156 dwellings are identified, corresponding to a total of 270,618 tenants.

Interestingly, this study finds negative health effects of more energy efficient dwellings on asthma and COPD, and positive health effects on cardiovascular diseases and rheumatoid arthritis. The study underlines the need for a more nuanced understanding of how specific energy efficiency measures impact health, as for example insulation increases the probability to have asthma and

[2] By 2030, it will be prohibited to rent out dwellings with EPC E, F or G.

COPD, while ventilation has an opposite effect. Moreover, the study shows that the impact on asthma and COPD is predominantly observed amongst elderly, indicating that energy efficiency measures primarily affect COPD rather than asthma. Drawing conclusions on the effects of other energy efficiency measures on health is challenging due to limited variation in our sample.

The paper proceeds by first discussing the related literature on health and housing. Secondly, the data is described, followed by a discussion of the empirical strategy. Then the results are examined, and three robustness tests are performed. Lastly, the paper will conclude and discuss the limitations, future research recommendations and policy implications.

2 Related literature

This section provides an overview of related literature on the health effects of housing sustainability. First, indoor health determinants are analyzed, followed by how they can be influenced by energy efficiency measures according to theory and empirical literature. Next, a broader perspective is given, examining the sustainability of the Dutch housing market.

2.1 Health effects

In the literature, the relationship between dwelling characteristics and health has been widely discussed. Van der Ree et al. (2019) identify the following five main factors of disease burden due to the indoor environment: passive smoking, particulate matter, radon and thoron, moisture and carbon monoxide. This section first discusses how these factors influence health and then examines how energy efficiency measures can affect these channels. Lastly, empirical literature on the health effects of energy efficiency measures is discussed.

2.1.1 Indoor health determinants

The indoor environment can affect health in many ways. Table 1 gives an overview of health determinants in the indoor environment that are often mentioned in the literature and their importance. For some determinants the disease burden is estimated. In order to indicate the importance of the other determinants and to indicate how concentrated the problem is, the percentage of dwellings in which the problem occurs is given as well. These estimations must be interpreted with caution, as some estimates are outdated. The current situation has changed, for example, fewer dwellings are using gas, which may render these estimates inaccurate. Below, channels through which the determinants influence health are examined.

Passive smoking (inhaling smoke exhaled by a smoker or coming from a burning cigarette, pipe or cigar) increases the chance of having lung cancer, cardiovascular diseases, asthma and COPD (RIVM, 2007; Ter Weijde et al., 2015). The air inhaled contains carcinogenic substances that can lead to mutations in DNA, which can develop into cancer cells. Furthermore, the exposure to smoke can cause chronic irritation and inflammation of the airways, causing cardiovascular and lung diseases. Besides, nicotine can raise the blood pressure and heart rate, putting extra stress on the heart and increasing the risk of cardiovascular diseases.

Radon and thoron also affect health via inhalation. Radon and thoron are found in building materials and can turn into radioactive substances that stick to floating dust particles. These radioactive particles are then inhaled and emit radiation, increasing the chance of developing lung cancer (Van der Ree et al., 2019).

Compared to the previously discussed determinants, carbon monoxide is a smaller contributor to the indoor disease burden. Yearly, only a few individuals are affected, but the consequences are significant; annually, 10 to 15 individuals die from carbon monoxide poisoning (Van der Ree et al., 2019). Importantly, the estimated disease burden is likely to be three to five times as large, because carbon monoxide poisoning is often not recognized as the cause of death (Onderzoeksraad voor Veiligheid, 2015). Carbon monoxide poisoning occurs when carbon monoxide is inhaled. This colorless and odorless gas is released during the incomplete combustion of fuels. Incomplete combustion often occurs when using defective or poorly maintained gas-fired heating appliances but can also occur when using a fireplace or a stove (Van der Ree et al., 2019).

Another determinant that has recently garnered attention from both politicians and news outlets is moisture. Both resident behavior, such as breathing, cooking and showering, and construction-related causes, such as inadequate ventilation, building materials and leakage can lead to moisture in dwellings. Moisture in combination with low temperatures and nutrients can lead to mold formation. Moisture and mold increase the chance of developing asthma and worsen the symptoms of asthma, upper respiratory complaints and respiratory infections (World Health Organization (WHO), 2009). Furthermore, high humidity aggravates the symptoms of rheumatoid arthritis and increases the likelihood of developing it (Wang et al., 2023).

The largest estimated disease burden is of noise nuisance, although the estimate of its importance is subject to a high degree of uncertainty. Noise can lead to sleep disturbance, but also to cardiovascular diseases through increased stress (Knol & Staatsen, 2005).

Lastly, particulate matter and indoor temperature are mentioned in the literature to affect health, although estimates on the disease burden are missing. Particulate matter arises during combustion. Half of the particulate matter comes from outdoor combustion, such as traffic, and half of it is produced indoors by cooking and using candles, for example (Jacobs & Borsboom, 2019). Inhaling particulate matter increases the likelihood of developing cardiovascular and respiratory diseases (Knol & Staatsen, 2005). Besides, high indoor temperatures increase the risk of developing cardiovascular diseases. Increased sweating in combination with dehydration increases the plasma viscosity and cholesterol level, increasing the chance of developing cardiovascular diseases (Cheng & Su, 2010). This problem particularly exists among elderly, who more often hydrate too little because of a diminished thirst sensation (Jongeneel et al., 2009).

Table 1

Overview of determinants of indoor health and importance.

Determinant	Disease burden (in DALYs)	Frequency	Source frequency
Passive smoking	15,800	19% of parents with children younger than 18 years old smoke inside.	Nationaal Expertisecentrum Tabaksontmoediging (2015)
Moist	1,200	6-16% of dwellings have moisture problems	Jongeneel et al. (2019)
Radon and thoron	5,900	0.4% of Dutch dwellings exceeds the radon limit suggested by the WHO. Regarding thoron no international standards or limit values have yet been established.	Smetsers et al. (2018)
Carbon monoxide	350 - 1,750	In 2005 12% of dwellings have unvented gas water heaters, which do not vent air directly to the outside.	Van Egmond et al. (2007)
Noise nuisance	21,800 - 101,152*	11.1% of Dutch citizens experiences severe traffic noise nuisance	Van Poll & Simon (2023)
Particulate matter		In at least 17% of Dutch dwellings, the annual average fine particulate matter concentration exceeds the WHO guideline value.	Jacobs & Borsboom (2019)
High temperatures		17% of dwellings exceeded the maximum temperature for more than 300 hours a year.[3]	Kuindersma & Ruiter, (2007).

Note. Estimations of the disease burden without an asterisk are from Van der Ree et al. (2019). The estimation with an asterisk is from Knol & Staatsen (2005) and has a large prediction interval as it predicts the disease burden in 2020. In the fourth column the source of the estimations in the third column is given.

[3] Kuindersma & Ruiter (2007) do not define what guideline for temperature they use. It is expected to be between 25 degrees Celsius (NEN 5128 guideline from before 2004) and 26.5 degrees Celcius (GIW-ISSO guideline from 2008).

2.1.2. Impact of energy efficiency measures

The size of the effect of previously discussed health determinants can be affected by energy efficiency measures. Better insulation affects the largest number of determinants. On the one hand, better isolated dwellings are associated with more complaints of passive smoking, particulate matter, radon and thoron, moisture and carbon monoxide, since these substances stay longer inside the dwelling. However, this negative health effect can be countered by ventilation. Not isolated dwellings are automatically ventilated through cracks and seams. Well isolated dwellings require other types of ventilation mechanisms, such as balanced ventilation systems, or ventilation grids and windows. These forms of ventilation are often not used correctly due to a lack of knowledge on the importance of ventilation or in order to save energy costs (Duijm et al., 2009). Thus, the health effects of insulation depend on the degree of ventilation.

Additionally, insulation may reduce noise hindrance and cause a more stable indoor temperature; in the winter less energy is needed to heat dwellings and in the summer dwellings stay cooler (Van der Ree et al., 2019). Also, solar panels and heat pumps could indirectly improve health by making energy more affordable, which could lead to increased use of heating in the winter and forms of cooling, such as air-conditioning, in the summer (Mehlbaum et al., 2024; Rovers et al., 2021).

Furthermore, making dwellings gas-free will reduce the risk of carbon monoxide poisoning, which often results from incomplete combustion of gas-fired heating appliances. At the same time, some households that stop using gas switch to wood or pellet stoves, which in turn increases the exposure to fine particulate matter (Gooijer & Mennen, 2021).

2.1.3 Empirical literature

Now a clear overview is given on how energy efficiency measures could potentially affect health, this paragraph proceeds with examining empirical literature. First, most recent Dutch studies by Van Maurik et al. (2023) and Geijtenbeek et al. (2022) are discussed, followed by international literature that use more convincing empirical strategies.

Geijtenbeek et al. (2022) have investigated four relationships between the Dutch housing stock and health complaints by comparing tenants of housing corporations. They found that individuals aged under 50 are 4% more likely to use asthma or COPD medication when they use gas heating compared to district heating. Furthermore, dwellings that are more energy efficient (and are therefore given a more favorable EPC A or B) are 71% less likely to have damp or mold compared to energy inefficient dwellings (with EPC D, E, F or G). Residents in energy inefficient dwellings are also 2% more likely to use asthma and COPD medication compared to residents of energy efficient dwellings. Besides, facade insulation is associated with lower healthcare costs, but insulation of bedroom windows and floors is not. Also, a more favorable EPC is not associated with lower healthcare costs. This could be because higher EPCs can be obtained by using more renewable energy, which does not directly affect health. To know whether energy efficiency measures improve health, it is therefore important to investigate what exact measures are being taken.

The results by Geijtenbeek et al. (2022) cannot be interpreted causally, because residents are not as good as randomly assigned to the dwellings, conditional on the controls (age, gender and migration background). There could still be selection bias because tenants who are more willing to make health investments are also more interested in a healthy living environment and therefore more likely to live in an energy efficient dwelling. Additionally, it is plausible that individuals with a low income are more likely to live in energy inefficient dwellings (which tend to be more affordable) and there is also a higher probability that tenants with a low income smoke compared to wealthier tenants. Given that smoking is an important risk factor for numerous diseases, the negative health effect of smoking could be incorrectly attributed to the low energy efficiency of the dwelling.

Van Maurik et al. (2023) looked more specifically into the difference in healthcare costs between low and high incomes in relation to EPCs. In dwellings with EPC A and B, low incomes have on average 22% higher healthcare costs compared to high incomes, while in dwellings with EPC F and G, low incomes have on average 27% higher healthcare costs. Van Maurik et al. (2023) argue that the mechanism behind this result is that individuals with low incomes are more likely to keep their heating low. This in turn could lead to heightened negative health effects associated with poor housing conditions, such as mold. Again, this result cannot be interpreted causally, as there could be selection bias as they do not control for how important residents find health, for example. It does indicate that the largest health benefits may be achieved in the poorest neighborhoods.

A more convincing empirical strategy was used in Germany by Künn and Palacios (2022). They make use of the fact that after German reunification (between 1995 and 2002) 3.6 million dwellings in East Germany got renovated, upgrading their insulation and heating systems. They use panel data that contains information on both whether renovations were executed in the dwelling in a specific year and the health status of residents. Then they estimate the health effects of the renovations using an individual, dwelling, year fixed effects model. They find that improvement of housing quality reduces the hospitalization of individuals who are 45 years or older for cardiovascular reasons. No significant effect was found on hospital admissions related to respiratory diseases, nor on younger individuals. Potentially no effect on other diseases is found because hospital admissions only occur when individuals suffer from severe health issues. Our paper offers a valuable addition to the existing literature, focusing on medication, which also captures less severe health effects.

Furthermore, two small-scale experiments were conducted in the United Kingdom and in New Zealand. Green and Gilbertson (2008) investigated the British Warm Front Scheme, which provided low-income households with grants for insulation and new central heating systems. Households were randomly divided into two groups and the control group received the grant at the end of the trial. They found that indoor temperatures increased significantly with around 2 degrees Celsius, suggesting that energy savings are not used for other goals, but to increase temperature. Besides, Warm Front led to a significant reduction in stress about paying fuel bills.

In New Zealand, Howden-Chapman et al. (2007) looked more into physical health effects. In a randomized controlled trial, households with children having asthma living in wooden dwellings without insulation randomly received more effective heaters. Again, the control group received a better heater at the end of the trial for ethical reasons. No significant improvements in lung function were found, but children in the intervention group did have 1.8 fewer days off school and significantly fewer visits to the doctor and pharmacist for asthma. It could be the case that no effect on lung function was found because they only focus on health changes after one year, while it may take longer for these benefits to arise. Our empirical strategy allows us to detect health effects that arise later.

2.2 Dutch housing market

To fully understand the impact of housing sustainability on health in the Netherlands, context of the Dutch housing market and sustainability policies is needed. This section first discusses the Dutch measure for sustainability of the housing stock, followed by the status of the sustainability of the Dutch housing stock. Then the incentives of improving housing sustainability and the unique position of social housing associations in the Netherlands are discussed.

2.2.1. Energy Performance Certificate

In the Netherlands, EPCs are used to indicate the energy efficiency of buildings. This system stems from the European Energy Performance of Buildings Directive (EPBD) that is implemented in the Dutch legislation in the Besluit Energieprestatie Gebouwen (BEG). Since 2008, the BEG obliges buildings to have a valid energy efficiency certificate when being built, sold or rented out.[4] The EPC is valid for 10 years and provides information to purchasers or tenants on the energy efficiency of buildings and suggests possible improvements. Buildings with an EPC A++++ are the most energy efficient, while those with an EPC G are the least energy efficient.

Until 2021, the EPC was in principle based on the Energy-Index, a number with low values representing energy efficient buildings and high numbers representing energy inefficient buildings. The Energy-Index is calculated by correcting the total theoretical energy consumption of a building for the floor area of the building and the heat transmission areas (Filippidou et al., 2016). The total theoretical energy consumption includes the energy that is needed on average for space heating, hot water and lighting among other things, minus the energy generated by solar panels and combined heat and power systems.

In 2015, the method of calculating the Energy-Index and EPCs for existing buildings (ISSO 82.3) was replaced by the NEN7120 in combination with the addition “Nader Voorschrift”. Both before and after 2015, a certified energy adviser collected information on building characteristics and energy systems, which were then added to a software program in order to calculate the Energy-Index. After 2015, the calculation became more precise however, incorporating more characteristics to determine the total energy consumption and heat transmission areas. This increased precision was required because the Energy-Index was now used to determine the maximum allowed rental price. The change in method in 2015 caused 20% of the rental housing to get a 1 step better EPC and 17% to get a 1 step worse EPC (Kruithof & Valk, 2014). Thus, it appears that overall, the housing stock became more energy efficient. This change in methodology falls in the period analyzed in this paper and could result in an underestimation of the health effect

[4] New buildings do not need an EPC in the first 10 years, as their energy efficiency is already measured with another measurement, the “Energieprestatiecoefficient” (Article 6 of Regeling Energieprestatie Gebouwen (2006)).

in our analysis, as changes in EPC partly reflect methodological adjustments rather than actual improvements in energy efficiency of dwellings.

Between 2015 and 2021, an alternative method for calculating EPCs was permitted that did not require an Energy-Index. Homeowners and landlords could apply for a simplified EPC (Vereenvoudigd Energielabel (VEL) in Dutch). This VEL was determined based on information regarding the building's characteristics and energy systems provided by the homeowner. This made the process of assigning EPCs cheaper, but also more inaccurate compared to the Energy-Index. In the paper, we will therefore disregard VELs. This exclusion will not result in significant information loss, as landlords in the regulated rental market (with a rental price below the regulation level) often preferred to obtain an Energy-Index and not a VEL because of two reasons. First, to show that agreements made with municipalities and other stakeholders are kept. Secondly, when they only had a VEL, the maximum rental price was based on construction year, which often led to less favorable rental prices (Rijksoverheid, 2024).

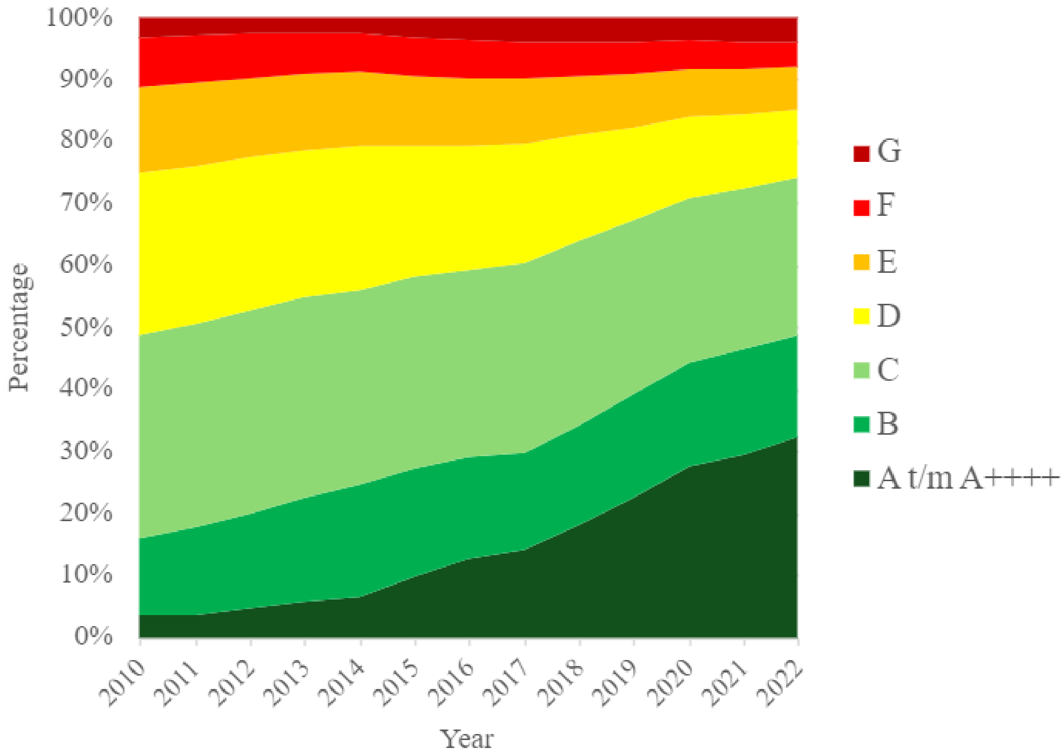
Lastly, in 2021 the new method named NTA 8800 was introduced, covering both new and existing buildings under the same standard. Instead of the Energy-Index, the EPC is based on the primary fossil energy usage measured in kWh/m2. This new methodology is expected to lead to more changes in the assignment of EPCs compared to 2015, since it is not only more precise but a completely different unit of measurement. Therefore, we disregard changes in EPC after 2020.

2.2.2 Sustainability of Dutch housing stock

As of December 31, 2022, more than 59% of the total housing stock in the Netherlands has an EPC and from 2019 onwards all rental properties owned by housing associations are provided with an EPC (Compendium voor de Leefomgeving (CLO), 2023; CLO, 2019). Furthermore, dwellings became more energy efficient, as depicted in Figure 1. The share of dwellings with EPC E, F or G decreased from 25% in 2010 to 15% in 2022. Besides, the share of highly energy efficient dwellings (EPC A or higher) increased from 3% in 2010 to 32% in 2022. However, 14.9% of the dwellings with a valid EPC still have EPC E or lower in 2022, accounting for 1.2 million dwellings. Approximately 40% of these dwellings are rental property and 60% are owner-occupied dwellings (Volkshuisvesting en Ruimtelijke Ordening (VRO), 2022a).

Figure 1

EPCs over time.



Note. This figure shows the distribution of EPCs. Over time, the number of valid EPCs increased, so a decrease in percentage does not necessarily entail an absolute decrease. Source: Rijksdienst voor Ondernemend Nederland (RVO), 2023.

2.2.3. Energy efficiency measures incentives

Energy efficiency measures are being implemented for both financial and non-financial reasons. The most important reason is energy savings, followed by wanting to contribute to the energy transition, enhanced living comfort and an increased property value (Mehlbaum et al., 2024). Energy savings are relatively large compared to the investment costs. For instance, solar panels have a cost recovery period of six years and heat pumps between seven and twelve years (Mehlbaum et al., 2024).

Discussed reasons only partly benefit residents and do not directly benefit landlords. As this paper specifically focuses on the rental market to minimize endogeneity issues (see section 4), it is crucial to gain a further understanding of why landlords invest in energy efficiency measures. One reason is that landlords are allowed to increase rent after renovation. In order to protect tenants, the Dutch civil code does obligate landlords to make a reasonable offer regarding rent increases when wanting to renovate (articles 7:220 and 7:255 BW). When tenants do not agree with the proposal, for example, because they believe the rent increase to be disproportionate to the improvement, the landlord can ask the judge to assess whether the proposal is reasonable. In residential complexes with more than 10 dwellings, a proposal is considered reasonable if 70% of the tenants agree. This makes it more difficult for individuals to interfere with sustainability plans. Still, the required participation takes time and is costly for landlords, potentially leading to an underinvestment in energy efficiency measures from a social perspective (RVO, 2022).

Besides having a reasonable rent increase, landlords in the regulated rental market must also make sure that the rent does not exceed the maximum rental price. This maximum rental price is based on the quality of the dwelling and since 2011, also the energy efficiency is taken into account.[5] The energy efficiency of a dwelling is estimated by the EPC. This incentivizes landlords to draw up a new EPC after making a dwelling more sustainable, as this gives room to a higher rental price increase.

Another incentive for landlords to renovate is that the minister of housing plans on prohibiting renting out energy inefficient dwellings from 2030 onwards (VRO, 2022a). In order to help finance this transition, the landlord levy is abolished, and subsidies are offered, resulting in investment capacity for landlords to improve the sustainability of their dwellings.

2.2.4. Social housing associations

An interesting player in the Dutch housing market are social housing associations. They own 2.3 million rental properties, which is approximately 28% of the Dutch housing stock (CBS, 2024a). Contrary to private landlords, they do not have a profit motive. Social housing associations are responsible for providing affordable housing to individuals with low incomes (Woningwet 2015). These corporations can offer cheap housing because they do not have a profit motive and because they are subsidized by the state. This non-profit motive of social housing associations is also reflected in the fact that they agreed upon not renting any dwellings with EPC E, F and G by 2028 instead of 2030, despite potential additional costs and risks of this acceleration (VRO, 2022b).

When renovating dwellings, social housing associations are still likely to increase rent, as rental income is their primary source of income. Rent increases are needed to fund expansion of their housing stock and to renovate other dwellings. Therefore, the mechanisms that are discussed

[5] The point system that determines the maximum rental price is called the Woningwaarderingsstelsel.

in the previous section also apply to social housing associations, although the rental increases may be smaller compared to private landlords. In the “Nationale Prestatieafspraken”, social housing associations have agreed upon not increasing rents after taking insulation measures from 2023 onwards in order to accelerate the energy transition. In the time period examined in this paper, the “Nationale Prestatieafspraken” were not into effect yet and therefore insulation did lead to rent increases.

3 Data and descriptive statistics

This section provides information on the data used in this paper. First, it addresses how the sample is selected. Then the data used to measure dwelling sustainability and health are examined.

3.1 Sample selection

In order to identify the relationship between sustainability and health outcomes, multiple datasets from CBS are used (see Table 2 for an overview). Data on EPCs is available at population level, but because of potential endogeneity issues, this paper only uses data on dwellings that are rented out by social housing associations (from now on: social rental, see section 4 for more details).[6] The WoON datasets are used to classify dwellings as social rental. The WoON survey is conducted every 3 years from 2006 onwards and consists of a representative sample of dwellings in the Netherlands. It contains information on, amongst other things, whether the dwelling was rented out by a social housing association in the year the survey was taken. In this paper, all the WoON surveys conducted between 2006 and 2021 are used to identify a total of 89,156 dwellings as social rental.

Given that data on housing sustainability are only available from 2007 to 2021, our analysis focuses on residents who occupied these dwellings within this time frame. They did not necessarily have not live in the dwelling for the whole research period. The dataset Gbaadresobjectbus is used to match individuals to dwellings. This data is then combined with administrative panel data on yearly medication use from the dataset Medicijntab and age from the dataset Gbapersoonktab. In total, the 89,156 identified dwellings correspond to a total of 270,618 individuals.

One potential issue is that we assume that dwellings identified as social rental in 2006, 2009, 2012, 2015, 2018 or 2021 remained social rental dwellings for the entire research period (from 2007-2021). There are two potential issues with this assumption. First of all, approximately 0.1% of the social rental dwellings is sold to former renters yearly.[7] Although this is a small number, it could weaken our identification strategy as renovations would then not be exogeneous anymore. For example, an income increase may incentivize homeowners to renovate their dwelling,

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[6] Social rental strictly entails both rental of dwellings by private renters and social housing associations. But from now on this paper uses the term solely for rentals by social housing associations.
[7] In 2012, 0.12% was sold to existing renters and in 2015, 0.06% (CBS, 2024a; Inspectie Leefomgeving en Transport (ILT), 2012; ILT, 2015).

while this increase in income can also affect health via being able to buy healthier, more expensive food. Secondly, part of the social rental dwellings was sold to or bought from non-housing corporations. Although the renovations are still exogeneous as landlords decide whether to renovate the dwellings, it could be that renovated dwellings are lifted out of the regulated sector. Then landlords would have fewer incentives to immediately update the EPC after a renovation (since there is no maximum rental price anymore), leading to more inaccurate EPCs and larger measurement errors.

Table 2

Overview of used datasets

Datafile	Includes	Level of measurement	Timespan
Dwelling variables			
WoON	Social housing, construction year, household size, income, education, ethnicity	Dwelling	2006, 2009, 2012, 2015, 2018, 2021
Gbaadresobjectbus	Adres, Move-in date, Move-out date	Individual	1995-2023
Energielabelcertificaten -woningen	EPC, specific energy efficiency measures, year of measurement	Dwelling	2007-2021
Health variables			
Medicijntab	Medication	Individual	2006-2022
Control variables			
Gbapersoonktab	Birthdate	Individual	2009-2023

Note. All datasets are from CBS. We use 6 cross-sectional WoON datasets. WoON contains dwelling information and personal information of the person who filled in the survey.

3.2 Dwelling data

There is no comprehensive panel dataset on the sustainability of dwellings in the Netherlands. This paper will use the EPC as an indicator of sustainability. Data on EPCs is from the CBS dataset Energielabelcertificaten. Besides the EPCs themselves, the dataset also includes dummy variables having the value one when dwellings have triple glazing, roof insulation, floor insulation, facade insulation, balanced ventilation, solar heating, solar panels, gas stove, heat pump or district heating. Triple glazing is defined as having triple glazing or HR+++ in both the bedroom and living room.

The insulation variables have a value of 1 when that part of the dwelling meets the RC3 standard. This RC3 standard is met if the thermal resistance of that part of the dwelling is at least 3 m^2K/W. This is lower than the currently required minimum thermal resistance for the roof, floor and facade, which are 6.3, 3.7 and 4.7 m^2K/W respectively (article 4.152, Besluit bouwwerken leefomgeving, 2024). Furthermore, the dataset includes whether the EPC and other information are based on inspection by a professional or on information provided by the homeowner (VEL). Information based on the latter is excluded from this analysis as this is often inaccurate (see section 2.2.1).

Table 3 provides summary statistics on the dwellings in our sample. Regarding energy efficiency measures, the largest differences between energy efficient (EPC A or B) and energy inefficient dwellings (EPC E, F or G) are triple isolated glass (52% versus 11%), solar panels (24% versus 15%) and insulation (9-18% versus 1%). Balanced ventilation and solar boilers occur less frequently in energy efficient dwellings (3% and 7% respectively), but almost solely in dwellings with EPC A or B.

Table 3

Descriptive statistics of energy efficiency measures per EPC group

	EPC A or B (N=24.591)	EPC C or D (N=29.266)	EPC E, F or G (N=9.193)
Triple glazing	.522 (0.5)	0.235 (0.424)	0.11 (0.312)
Facade insulation	0.089 (0.284)	0.011 (0.103)	0.001 (0.033)
Roof insulation	0.183 (0.387)	0.039 (1.94)	0.006 (0.079)
Floor insulation	0.121 (0.327)	0.03 (0.17)	0.008 (0.088)
Gas heating	0.001 (0.036)	0.005 (0.072)	0.113 (0.316)
Central heating	0.87 (0.336)	0.943 (0.233)	0.868 (0.339)
District heating	0.091 (0.288)	0.041 (0.198)	0.016 (126)
Heat pump	0.037 (0.189)	0.012 (0.107)	0.003 (0.059)
Balanced ventilation	0.065 (0.247)	0.003 (0.058)	<0.001 (0.01)
Solar water heater	0.031 (0.174)	0.013 (0.112)	0.01 (0.101)

Solar panels	0.24	0.063	0.023
	(4.27)	(0.243)	(0.149)

Note. The mean is given with the standard deviation below between brackets. Insulation is 1 when it is insulated at RC3 level. Data comes from Energielabelcertificaten, which only includes information on energy efficiency measures from 2015 onwards.

Table 4 shows that dwellings with different EPCs not only differ in energy efficiency measures taken, but also in other characteristics. Interestingly, less than 2% of the buildings with EPC C or lower are built after the year 2000. This is due to the stricter building regulations. Furthermore, dwellings with EPC A and B are, on average, larger in size and have a higher worth. When investigating the tenants, we also see that tenants in dwellings with EPC A or B have a higher household income and are 2 percentage points more likely to earn above the social minimum compared with tenants in less energy efficient dwellings. At the same time, tenants of dwellings with EPC E, F or G are more likely to be highly educated. The lower income can be explained by the fact that tenants living in EPC E, F or G dwellings are on average 3 years younger than tenants in dwellings with EPC A or B.

Table 4

Descriptive statistics of household and dwelling characteristics per EPC group.

	EPC A or B (N=14.843)	EPC C or D (N=29.335)	EPC E, F or G (N=10.566)
Household characteristics			
Above social minimum	0.877	0.86	0.858
	(0.329)	(0.347)	(0.35)
Disposable household income (CBS)	25,220.559	24,874.241	24,562.939
	(13,215.16)	(12,593.895)	(12,832.48)
Native	0.767	0.746	0.741
	(0.422)	(0.435)	(0.438)
Western migration background	0.135	0.152	0.158
	(0.341)	(0.359)	(0.364)
Non-western migration background	0.098	0.102	0.101
	(0.297)	(0.303)	(0.302)
Lower education level	0.449	0.469	0.442
	(0.497)	(0.499)	(0.497)
Medium education level	0.357	0.362	0.346
	(0.497)	(0.481)	(0.476)
High education level	0.194	0.168	0.212
	(0.396)	(0.374)	(0.409)
Age	57.42	55.799	54.745

	(19.147)	(18.113)	(18.236)
Number of persons in household	1.75	1.819	1.861
	(1.034)	(1.108)	(1.135)
Dwelling characteristics			
Construction year	1987.19	1970.685	1957.083
	(28.326)	(25.022)	(30.545)
Build after 2000	0.345	0.02	0.007
	(0.475)	(0.139)	(0.086)
Total living area (m^2)	86.355	83.691	81.475
	(32.118)	(33.603)	(33.442)
Property value (in 2015 prices)	148,186.67	134,338.81	130,805.87
	(50,501.173)	(44,420.936)	(51,775.214)

Note. The mean is given with the standard deviation below between brackets. Personal and dwelling characteristics are from the WoON survey and therefore this information is only about the year the survey was taken and from the person who filled in the survey. Property values and income have been adjusted for inflation and are given in 2015 prices. Information on education level and social minimum was only available for part of the sample.

In order to estimate whether the relationship found above is causal, this paper uses variation in EPC. Table 5 provides an overview of what changes in EPCs are registered for our sample. Remarkably, EPCs did not always improve; in 19% of the cases dwellings got a new lower EPC. Looking more specifically into these deteriorations shows that they all arise after 2015. This confirms that the methodology change in 2015 led to different results.

Table 5

Changes in EPCs between 2007 and 2021

		New EPC						
		A	B	C	D	E	F	G
Old EPC	A	-	285*	140*	10*	0*	0*	0*
	B	4280	-	1990*	280*	70*	10*	10*
	C	5680	6345	-	2335*	660*	120*	55*
	D	3225	2545	8690	-	2055*	705*	300*
	E	1705	800	3445	3040	-	1025*	360*
	F	990	330	1410	1520	1285	-	510*
	G	430	140	445	510	390	335	-

Note. All the numbers with an asterisk indicate that the new EPC was lower than the old one, indicating a deterioration in energy efficiency. All numbers are rounded to fives.

It must be noted that EPCs are not always up to date and do not always represent the current energy efficiency of a dwelling. Although housing corporations are incentivized to update the EPC to qualify for a higher maximum rental price, not all energy efficiency measures result in a new EPC due to the high costs of requesting one. Furthermore, there could be random measurement error, because of inaccuracies of the measurement tools or human errors, such as inconsistencies in how energy advisors conduct or interpret measurements. This can lead to attenuation bias, which occurs when measurement error causes the observed association between the independent and dependent variables to appear weaker than the true association (Carroll et al., 2006). This results in coefficients that are biased towards zero.

3.3 Health data

In this paper, medication is used to measure health. This administrative panel data comes from the dataset Medicijntab CBS, which includes yearly information on which drug group a person has been prescribed medication for through the pharmacy within basic insurance. The advantage of using medication is that this is a relatively objective measurement, as medication is only prescribed by a doctor when they are convinced of the presence of health problems. Contrary, survey data can suffer from response bias. A disadvantage of medication usage is that not all health changes will lead to a prescription of medication, but large effects will be captured. This is also supported by Geijtenbeek et al. (2022), who show that using asthma or COPD medication is a good estimator of having asthma or COPD; two-thirds of the respondents of a health survey who indicated to have asthma or COPD use asthma or COPD medication and only 3% of individuals who did not indicate to have asthma or COPD did use asthma or COPD medication.

The information on medication usage is a dummy, being one when an individual has used the medication type in a specific year. The medication types are divided into groups based on the WHO's Anatomical Therapeutic Chemical (ATC) classification system that groups drugs according to the organ or system on which they act and their chemical, pharmacological, and therapeutic characteristics (Sketris et al., 2004). This paper examines medicine groups associated with the following types of health issues: asthma or COPD (hereafter: asthma), cardiovascular problems, rheumatic arthritis, sleep problems and lung cancer. [8] Literature indicates that sustainability can affect these health issues. Additionally, the effect on epilepsy is estimated as a placebo test. No effects are anticipated as epilepsy is mainly determined by trauma (such as a

[8] As shown in Appendix A, the same medication is prescribed for asthma and COPD. From now on, the paper will use the term asthma to refer to both asthma and COPD. Besides, in tables and figures, the term heart is used to refer to cardiovascular problems for brevity.

stroke, brain tumor or head injuries), autoimmune causes and genetics (Perucca et al., 2020). Although stress does not affect the development of epilepsy, stress can impact the frequency of seizures for individuals who already have epilepsy; acute stress protects against seizures while chronic stressors exacerbate seizures (Espinosa-Garcia et al., 2021). This paper measures whether someone has used medication and not how much, and therefore we do not measure the effect on frequency that could be caused by stress. In Appendix A more detailed information is given on what medicine groups are linked to the diseases.

Figure 3 gives an overview of the proportion of tenants that use medication. Individuals in more energy efficient dwellings are more likely to use medication for all tested diseases except for rheumatoid arthritis compared to individuals in less energy efficient dwellings. Figure 4 presents the same analysis for a subset of individuals aged 30 years or younger. This shows that the results are partly driven by age (as younger individuals are more likely to live in energy inefficient dwellings as shown in Table 4). Contrary to Figure 3, individuals of 30 years or younger are less likely to have asthma when dwellings get more energy efficient and no significant differences regarding cardiovascular medication are found. Furthermore, individuals living in dwellings with EPC C or D are significantly less likely to have lung cancer or use sleep medication compared to EPC A or B and EPC E, F or G. This indicates that there are other factors driving health differences besides age and energy efficiency. In Appendix B this analysis has also been replicated on a sample of individuals aged 70 years or older and similar patterns as in Figure 4 are found; the likelihood to use asthma medication is significantly lower for EPC A or B compared to the other EPCs and there are no significant differences in the use of cardiovascular medication over different EPCs. These findings stress the importance of including age as a control variable.

Figure 3

Proportion of medication use per EPC group

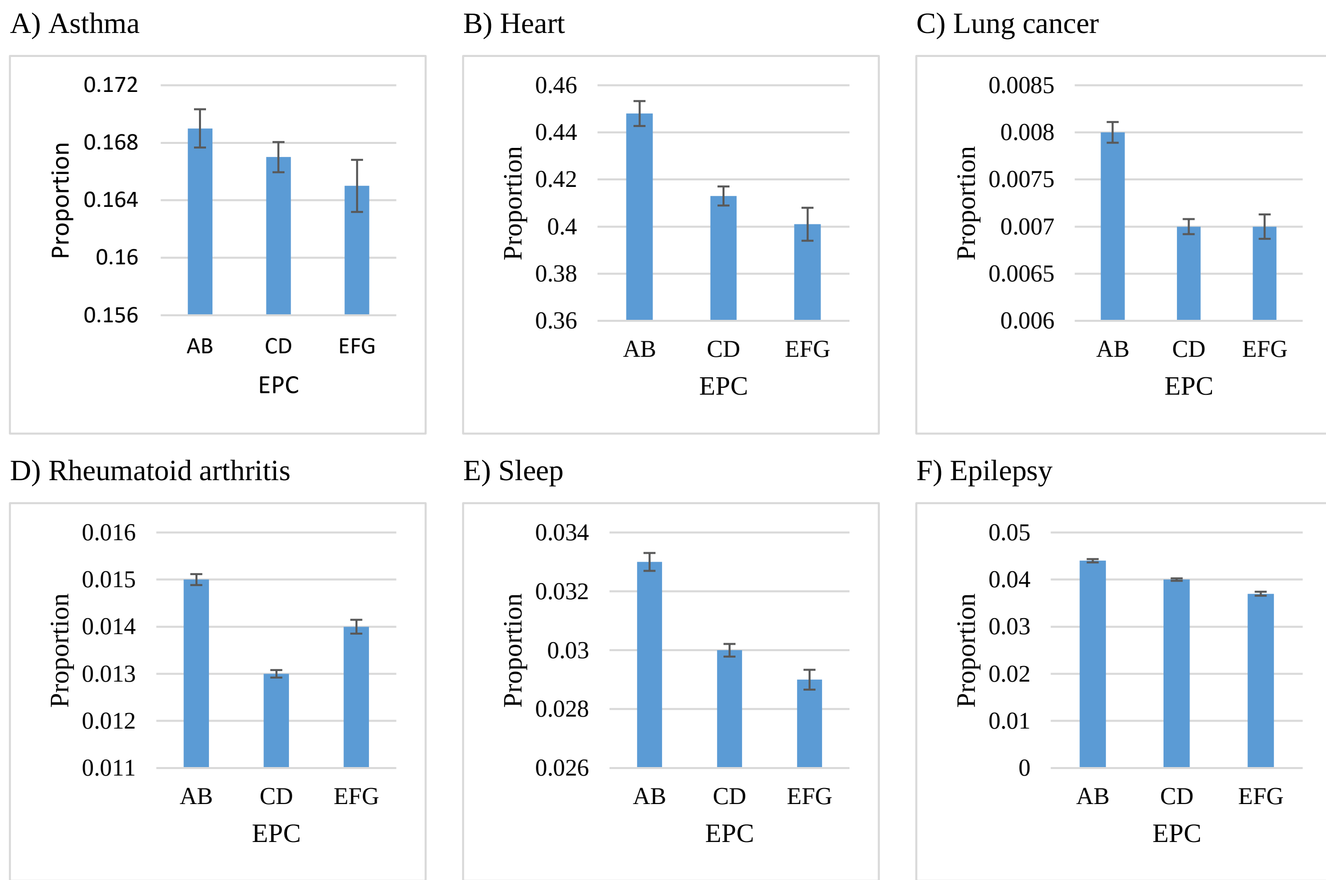
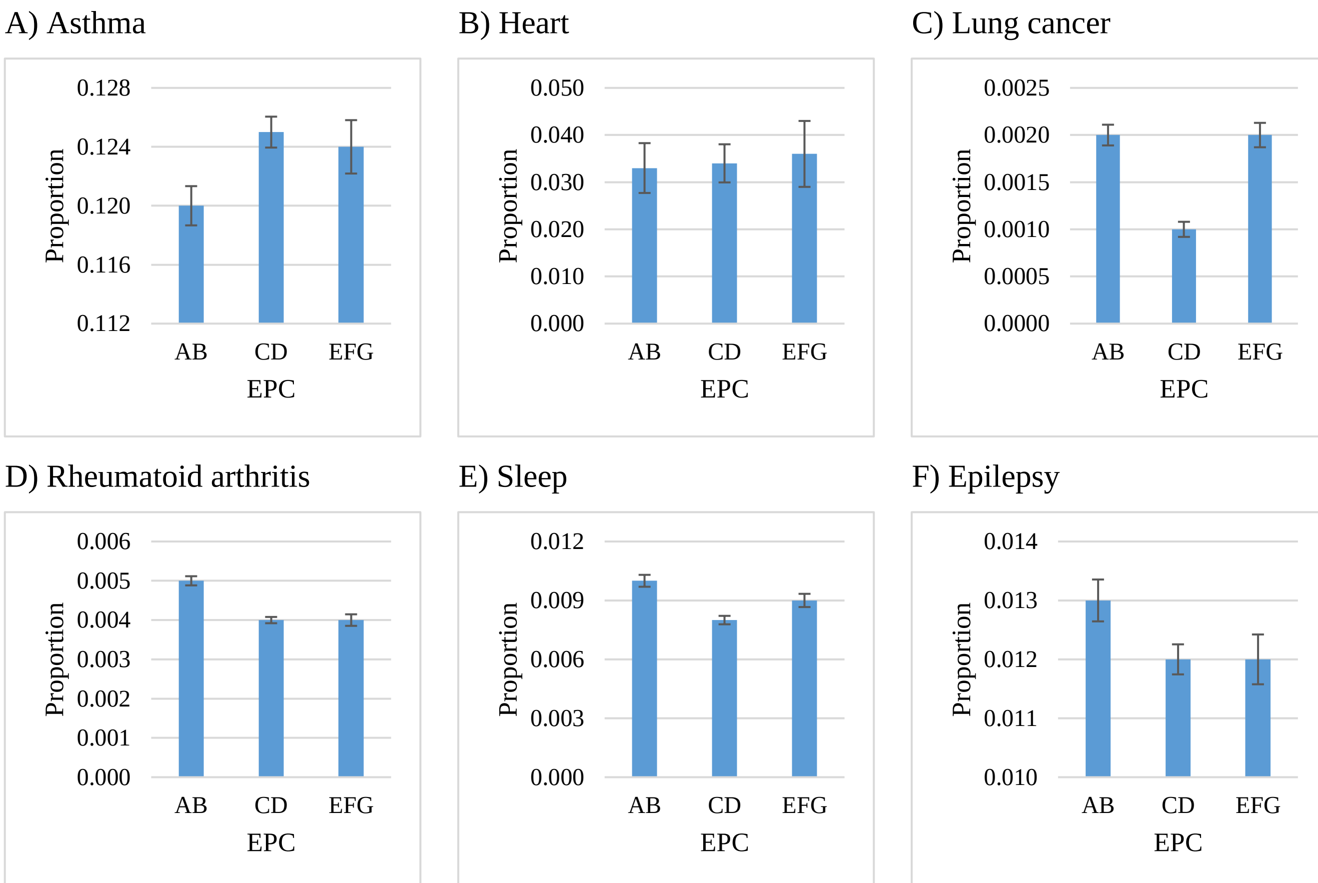


Figure 4

Proportion of medication use per EPC groups for individuals of 30 years or younger



4 Empirical strategy

Having a clear picture of the data, this section first presents the main empirical model. Secondly, it discusses how this strategy addresses endogeneity issues frequently observed in the literature. Then a more detailed empirical model is presented, followed by a description of the heterogeneous effects that will be investigated.

4.1 Empirical model

The logistic regression model used in this paper is represented by Equation 1. A logistic regression is used because of the binary nature of the dependent variable. P_{idt} is the probability that person i living in dwelling d uses medication at time t. EPC AB and EPC CD are dummy variables being 1 when the dwelling had an EPC A or B, or C or D at time t, respectively. Coefficients α_1 and α_2 are our parameters of interest, indicating the health effect of making a dwelling with EPC E, F or G more sustainable. EPC E, F or G is chosen as reference group because the government is already planning on phasing out this category (see section 2.2.2). Furthermore, age groups of five years are added as control. As a robustness check, we also assess whether results are robust to including age groups of one year instead. Lastly, γ_{id} denotes the individual-dwelling pair fixed effects, δ_t represents the year fixed effects and the error term is captured in ε_{idt}.

Equation 1

$$\ln\left(\frac{1-p_{idt}}{p_{idt}}\right) = \alpha_1\ EPC\ AB_{dt} + \alpha_2\ EPC\ CD_{dt} + \sum_{k=1}^{20} \tau_k\ Age\ group_{it}^{k} + \gamma_{id} + \delta_t + \varepsilon_{idt}$$

This paper estimates the effect of changes in EPC on various types of medication.[9] Separate regressions will be conducted for each type of medication. To validate our findings, a placebo test is performed by estimating the effect of housing sustainability on epilepsy medication, which is unlikely to be affected by changes in housing conditions. If the results show a significant effect on, for example, lung and cardiovascular medication, but not on epilepsy, this helps to ensure that our results are driven by the hypothesized mechanisms discussed in section 2, rather than being caused by other unexplained factors affecting medication use in general.

[9] This paper looks into medication that is used for the following health problems: asthma/COPD, cardiovascular diseases, lung cancer, rheumatic arthritis, sleep disorders and epilepsy.

4.2 Endogeneity issues

As discussed in section 2, papers on health and housing characteristics often suffer from endogeneity issues as many factors are correlated with both health and housing characteristics. When the regression model leaves out a variable that is correlated with both the dependent and independent variables, this leads to biased and inconsistent estimates. In order to deal with these endogeneity issues, this paper exploits changes in health outcomes resulting from changes in housing sustainability within individual-dwelling pairs. This allows to control for time-invariant characteristics of individuals, such as upbringing and cultural background. Additionally, the inclusion of dummy variables for each individual-dwelling pair ensures that we do not measure changes in health outcome due to relocations. This is necessary because moving to a new dwelling could not only affect health via the sustainability of the dwelling but also via a healthier neighborhood environment, for example. Moreover, including relocations could introduce bias due to reverse causality, if reallocations are driven by changes in health status. Besides individual-dwelling fixed effects, year fixed effects are included to control for time trends such as general changes in health policies.

The key identifying assumption is that the probability of receiving an energy efficiency measure is exogeneous. Homeowners decide themselves whether to renovate their dwellings, which could lead to endogeneity problems. For example, homeowners might choose to renovate their dwellings during less busy periods at work, which could also be correlated with fewer sleeping problems and a lower risk of cardiovascular diseases. Therefore, this paper focuses on tenants who largely depend on their landlord for renovations. Tenants have little influence on whether their dwelling is renovated, as discussed in section 2.2.3. Among tenants, those in social housing have the least influence on energy efficiency measures that are taken. This is because they often live in residential complexes in which the 70% rule applies (see section 2.2.3) and social housing associations are likely to make reasonable offers as they do not have a profit motive. Thus, this paper will focus solely on tenants of social housing associations, which has the additional advantage that these dwellings are more likely to have an EPC.

4.3 More detailed energy efficiency measures

As an additional analysis, we look more specifically into the impact of energy efficiency measures on health. Again, a logistic regression is used with individual-dwelling pair and year fixed effects and dummies for age groups (see Equation 2). The only difference is that the EPC variables are now changed into specific dwelling characteristics. The variable central heating is omitted due to perfect collinearity and now serves as the reference category for the variables gas stove, heat pump and district heating.

Equation 2

$$\ln\left(\frac{1-p_{idt}}{p_{idt}}\right) = \alpha_1\ Tripple\ glazing_{dt}\ + \beta_1\ Roof\ Insulation_{dt} + \beta_2\ Floor\ insulation_{dt}$$
$$+\beta_3\ \ Facade\ insulation_{dt}\ +\ \mu\ _1 Balanced\ ventilation_{dt}$$
$$+\rho_1\ Solar\ water\ heater_{dt} + \rho_2\ Solar\ panels_{dt} +\ \ \theta_1\ Gas\ stove_{dt}$$
$$+\theta_2\ Heat\ pump + \theta_3\ District\ heating\ \ + \textstyle\sum_{k=1}^{20} \tau_k\ Age\ group_{it}^{k}$$
$$+\ \gamma_{id} + \delta_t + \varepsilon_{idt}$$

All energy efficiency measures are included in one regression to ensure that the coefficients measure the effect of the specific energy efficiency measure and not the effect of other correlated measures. This is important as often multiple energy efficiency measures are taken at once. The downside of Equation 2 compared to Equation 1 is that data is only available from 2015 onwards.

4.4 Heterogeneous effects

This paper will also investigate heterogeneous treatment effects, as the literature suggests that these may exist. Elderly are expected to experience the largest negative health effects of high indoor temperatures as they often hydrate too little (Jongeneel et al., 2009). On the other hand, children could experience the largest adverse respiratory consequences of passive smoking and potentially other harmful substances because their organs are still developing (DiFranza et al., 2004). Additionally, the health effect of energy efficiency measures may also vary with income. Individuals with a low income may counter more adverse health effects of mold and low temperatures, because they are more likely to keep their heating low to save energy costs (Van Maurik et al., 2023). Furthermore, individuals with a low income living in energy inefficient dwellings are more likely to experience stress due to higher energy bills, potentially leading to sleeping problems.

To investigate these heterogeneous treatment effects, the sample will be divided into subgroups and the two regressions discussed above will be run for each sub-population. Although splitting the sample reduces the statistical power, it is preferred over adding interaction terms as the primary goal of this analysis is to understand whether the treatment effect within each subgroup is significant. Splitting the sample allows for a more straightforward interpretation of the odds ratios compared to including interaction terms (Chen, 2003).

5 Results

First, the effect of EPCs on health is investigated, followed by a more detailed overview of the effect of energy efficiency measures on health. Thirdly, heterogeneous effects for different income and age groups are examined.

5.1 Effect of EPC on health

Table 6 presents the odds ratios of the logistic regression model specified in Equation 1. An odds ratio compares the odds of an event occurring in one group to the odds of it occurring in another group. The odds themselves are defined as the ratio of the probability of the event happening to the probability of the event not happening. In this paper, an odds ratio greater than 1 indicates an increased likelihood of having the disease when the independent variable has a one-unit change, whereas an odds ratio smaller than 1 indicates a decreased likelihood of having the disease.

All columns in Table 6 represent different diseases. Tenants in dwellings with EPC A or B have, on average, 8.6% higher odds of using asthma medication compared to tenants in dwellings with EPC E, F or G and this difference is statistically significant. This suggests that the negative health effects of better insulation, such as increasing the concentration of harmful indoor substances, may outweigh the positive effects, like reduced mold. No significant differences are found with EPC C or D. This could be because the differences in housing characteristics are too small. Furthermore, tenants have 5.1% lower odds of using cardiovascular medication when living in a dwelling with EPC C or D compared to those living in a dwelling with EPC E, F or G. It must be noted that this difference is only mildly significant (at 10% significance level). In the other columns, no significant differences are found. This could partially be caused by the larger confidence intervals due to smaller sample sizes, as fewer individuals have these diseases and changes in the use of medication are less common.[10]

[10] Individuals who never or always use medication fall out of the sample, because of complete separation. Mathematically, the maximum likelihood estimate for the dummies of these individuals does not exist, as it would be optimal to increase the coefficient to (minus) infinity.

Table 6

Effect EPC on health

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
EPC C or D	1.039	0.949*	1.127	0.904	0.970	1.036
	(0.0292)	(0.0281)	(0.0915)	(0.0776)	(0.0506)	(0.0481)
EPC A or B	1.086**	1.005	1.065	0.843	0.953	1.022
	(0.0370)	(0.0363)	(0.104)	(0.0921)	(0.0605)	(0.0575)
Observations	303,035	301,568	44,096	28,820	113,616	123,645
Number of id	40,746	38,002	5,199	3,382	14,992	14,741
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. *** p<0.01, ** p<0.05, * p<0.1.

Interpreting the size of coefficients in logistic regressions is more complex compared to ordinary least squares (OLS) regressions. The odds ratio of 1.086 in Table 6 means that the odds of having medication are 8.6% larger for individuals in dwellings with EPC A or B compared to EPC E, F or G. To evaluate the economic significance of the estimates, it is useful to transform the odds to probabilities. Typically, this is done by reporting the marginal effect. However, in this research design marginal effects are meaningless because it would require assuming zero fixed effects (Kitazawa, 2011). Instead, the average elasticity should be calculated, which indicates by how much, on average, the probability of using medication changes with a one-unit increase in the independent variable.

The average elasticities corresponding to the odds ratios of Table 6 can be found in Appendix C. The odds ratio of 1.086 in column 1 of Table 6 can be interpreted as an increase in likelihood to have asthma by 6.9% when improving EPC E, F or G to EPC A or B. To give some perspective, this increase of 6.9% would be equivalent to an increase of 1.2 percentage points in the probability of having asthma, when assuming that the original probability of having asthma is the average probability of having asthma in the sample. Furthermore, switching from EPC E, F or G to EPC C or D decreases the probability of using cardiovascular medication by 3.0% (which would be equivalent to 1.3 percentage points).

In order to evaluate the economic significance of the discussed changes in probabilities of having diseases, a rough estimation on the associated effect on healthcare costs and the disease burden is made. In Appendix D, the effects of improving the energy efficiency of all dwellings with EPC E, F or G to EPC D or higher on the yearly healthcare costs for diseases are estimated. These estimations show that improving from EPC E, F or G to EPC A or B increases the yearly healthcare costs for asthma and COPD with 2.26 million euros and 3.84 million euros respectively. The improvement of EPC E, F or G to EPC C or D is furthermore associated with a decrease of healthcare costs for cardiovascular diseases of 15.05 million euros. Thus, it can be concluded that prohibiting dwellings with EPC E, F and G will not lead to major changes in total healthcare costs. Nor is it a cost-effective way of decreasing healthcare costs as improving the EPCs of 715,200 dwellings will also cost more than 3.5 billion euros when assuming that the energy efficiency measures cost around 5,000 euros per dwelling.[11]

Still, the effects are important to take into account, especially in light of the increasing shortages of healthcare workers (Aalbers & Roos, 2022). According to our estimates, the number of individuals with cardiovascular diseases will for example decrease by more than 3,800 when prohibiting all dwellings with EPC E, F or G, which could alleviate some of the pressure on the healthcare system. Additionally, this reduction in cardiovascular patients is estimated to result in approximately 1,500 fewer DALYs, meaning that the number of years lived in good health by the Dutch population increases by 1,500. This is comparable to the total Dutch disease burden attributed to aids and HIV infections or two-thirds of the Dutch disease burden attributed to testicular cancer (RIVM, 2021). This decrease in DALYs for cardiovascular reasons is larger than the estimated increase in DALYs for asthma and COPD, which are approximately 230 and 960 respectively. Consequently, improving EPCs from level E, F or G to D or higher would lead to a net (albeit small) decrease in DALYs. However, it is important to note that these estimations are subject to considerable uncertainty (for more details on the calculations and associated confidence intervals, see Appendix D).

As explained in section 3.3, changes in methodology also led to deteriorations of EPCs, while the energy efficiency of the dwelling did not change. In Table 7, the years in which the EPC deteriorated are excluded from the sample, providing more accurate estimates. As expected, the

[11] This is an underestimation of the average costs for the energy efficiency measures needed to improve from EPC E, F or G to at least D (Milieu Centraal, 2024).

coefficients are more pronounced, but comparable to Table 6. Tenants living in a dwelling with EPC C or D now also have a significantly lower probability of using cardiovascular medication compared to EPC E, F or G dwellings (at 5% significance level). Furthermore, tenants living in dwellings with EPC A or B now also have a significantly lower probability of having rheumatoid arthritis compared to tenants of energy inefficient dwellings. Besides, it can be noted that having EPC C or D leads to a mildly significant higher probability of having lung cancer. The fact that both the probability of getting lung cancer and asthma increase due to energy efficiency measures is in line with the literature that indicates that these diseases are affected in the same manner. Still no significant effect on sleep nor epilepsy are found.

Table 7

Effect EPC on health without deteriorations in EPC

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
EPC C or D	1.061*	0.927**	1.197*	0.839*	0.943	1.036
	(0.0352)	(0.0321)	(0.113)	(0.0841)	(0.0595)	(0.0567)
EPC A or B	1.109***	0.968	1.087	0.753**	0.932	1.052
	(0.0439)	(0.0404)	(0.123)	(0.0948)	(0.0701)	(0.0686)
Observations	279,212	276,873	40,490	26,483	104,294	113,390
Number of id	38,153	35,377	4,844	3,152	14,002	13,702
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. *** p<0.01, ** p<0.05, * p<0.1.

5.2 Effect of Energy efficiency measures on health

To get better insights in the mechanisms underlying the relationship of EPC and health, Table 8 represents the odds ratios of the logistic model specified in Equation 2. The negative effect of a better EPC on asthma seems to be driven by insulation of the facade. On average, insulating a facade significantly increases the odds of having asthma by 68%. Balanced ventilation, on the other hand, significantly decreases the odds of having asthma by 51%. In total, insulating dominates the positive health effect of balanced ventilation due to the larger effect and because facade insulation occurs more frequently (see Table 3). Furthermore, having solar panels significantly increases the probability of using asthma and cardiovascular medication, while using a heat pump decreases the probability of using cardiovascular medication. The decrease could be explained by cheaper energy, but the increase in the probability of using asthma and cardiovascular medication is not in line with literature.

When interpreting columns 3 to 6 of Table 8, it is important to note that these sample sizes are significantly smaller compared to the first two columns, as these diseases are less common.[12] This makes it more difficult to estimate the odds ratios. The odds ratios can suffer from bias away from one when certain combinations of variables are very rare, often referred to as sparse data bias (Greenland et al., 2016). In Equation 2 many covariates are added, besides all the fixed effects that were already included in Equation 1. This combined with the fact that information on the explanatory variables in Equation 2 is only available from 2015 onwards, leads to a smaller amount of observations per combination of variables. When having only a few observations per combination, a single observation can greatly affect the magnitude of the odds ratios.

The very large and small odds ratios for lung cancer and rheumatoid arthritis indeed indicate that these regressions suffer from sparse data bias. Therefore, the other odds ratios in these regressions should be interpreted with caution, such as that installing a heat pump is associated with a significant decrease of 95% in odds of having rheumatoid arthritis. The absence of extreme odds ratios in columns 5 and 6, in combination with the fact that these diseases are more common, suggests that sparse data bias is less of a concern for these models. Column 5 shows that using balanced ventilation significantly decreases the probability of using sleep medication, while solar panels significantly increase this probability. However, it cannot be ruled out that sparse data bias is present, potentially increasing the magnitude of both positive and negative effects. Lastly, the fact that most energy efficiency measures do not significantly affect epilepsy indicates a valid research design. However, it is unclear why the odds of having epilepsy are lower for individuals with district heating compared to central heating. Potentially, part of the significant results can be explained by the multiple comparisons problem that will be discussed in section 6.3.

[12] In our sample the likelihood of having one of the diseases are the following: asthma 17%, heart 41%, rheumatoid arthritis 1.3%, lung cancer 0.7%, sleeping issues 3%, epilepsy 4%.

Table 8

Effect of energy efficiency measures on health

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
Triple glazing	0.996	1.031	1.020	1.323	1.013	0.881
	(0.0894)	(0.105)	(0.259)	(0.446)	(0.173)	(0.128)
Facade insulation	1.683**	1.383	2.480*	0.132*	0.942	1.428
	(0.393)	(0.398)	(1.310)	(0.139)	(0.364)	(0.497)
Roof insulation	1.154	0.849	0.612*	0.624	1.103	0.965
	(0.128)	(0.104)	(0.171)	(0.246)	(0.244)	(0.168)
Floor insulation	0.927	1.100	0.593	1.116	0.854	0.793
	(0.136)	(0.163)	(0.201)	(0.554)	(0.215)	(0.164)
Balanced ventilation	0.486**	1.867	0.757	5.57×10^{-5}	0.287**	1.719
	(0.170)	(0.810)	(0.628)	(0.0580)	(0.168)	(0.934)
Solar water heater	1.749	2.492	1.735	3.429×10^{8}	3.384	0.903
	(0.822)	(1.388)	(2.415)	(8.488×10^{11})	(5.459)	(0.698)
Solar panels	1.204**	1.282**	1.566*	0.931	1.435**	1.065
	(0.113)	(0.131)	(0.399)	(0.296)	(0.260)	(0.155)
Gas heating	0.960	0.997	1.146	0	1.364	2.225*
	(0.312)	(0.347)	(1.039)	(4.06×10^{-10})	(0.652)	(0.992)
Heat pump	0.986	0.431***	0.570	0.0526**	1.637	1.317
	(0.274)	(0.126)	(0.352)	(0.0720)	(0.928)	(0.538)
District heating	0.610	0.663	1.23×10^{-7}		5.547*	0.105**
	(0.350)	(0.356)	(0.000132)		(5.681)	(0.0939)
Observations	40,529	33,794	5,950	3,724	14,128	16,113
Number of id	10,069	8,213	1,395	862	3,597	3,782
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. *** p<0.01, ** p<0.05, * p<0.1.

The average elasticities associated with the odds ratio of Table 8 can be found in Appendix E. Facade insulation increases the probability of having asthma by 43% (which is equivalent to 7.2 percentage points), while balanced ventilation decreases it by 60% (which is equivalent to 10 percentage points).[13] Furthermore, using heat pumps reduces the probability of using

[13] To calculate the percentage points change, we again assume that the original probability of having a disease is the average probability to have this disease in the sample.

cardiovascular medication by 48% (which is equivalent to 20 percentage points). Interestingly, having solar panels increases the probability of using medication by 14 to 35%, a considerable effect that is difficult to explain with the literature. The largest effect is found for balanced ventilation on sleep disorders, where the probability of using sleep medication decreases by 120%. Besides, district heating shows a significant decrease of 215% in the probability of having epilepsy.

These elasticities are larger compared to the elasticities related to the broader EPC categories used in Equation 1 (see Appendix C). This could be due to several factors. First of all, the use of more specific energy efficiency measures in Equation 2 allows to distinguish between the impact of energy efficiency measures that have pronounced effects on health versus those who do not, which was not possible with the composite EPC measure. Secondly, the issue of sparse data bias discussed earlier may lead to more extreme elasticities. This is particularly evident for health conditions that are less common or less frequently implemented energy efficiency measures, such as balanced ventilation.

In order to evaluate the economic significance of these estimated elasticities, a rough estimation is made of the effect of installing energy efficiency measures in all EPC E, F or G dwellings on yearly healthcare costs and DALYs (see Appendix F). These estimations suggest that certain energy efficiency measures can result in major healthcare cost savings and a decrease in DALYs. For instance, installing heat pumps is estimated to result in savings between 80 and 400 million for cardiovascular diseases, alongside a reduction of 20,000 DALYs. Furthermore, installing balanced ventilation is associated with between 2 and 60 million euros of healthcare costs savings for COPD and a decrease of approximately 2,000 DALYs. However, the results also indicate that implementing energy efficiency measures can lead to significant increases in yearly healthcare costs and DALYs; the largest increase is expected for installing solar panels, which is estimated to increase yearly healthcare costs for cardiovascular diseases by 14 to 128 million euros and add around 7,000 DALYs.

The estimations on the economic significance must be interpreted with caution. The estimations are based on the elasticities from Appendix E which could be too extreme due to sparse data bias, as explained previously. Furthermore, even substantial savings in healthcare costs do not necessarily indicate that this is a cost-effective method for improving health. In the most optimistic scenario, saving 1 euro in yearly healthcare costs would still require an investment of

11 euros (see Appendix F). Potentially cheaper alternatives for the investigated energy efficiency measures, such as manual ventilation, could lead to a more favorable cost-benefit outcome.

5.3 Heterogeneous effects

5.3.1 Age

Based on the literature, the largest health effects of energy efficiency improvements would be expected for elderly or young individuals. Tables 9 and 10 show that the effect of EPCs on health is driven by the group of individuals above 70. For individuals of 30 years or younger, no significant differences are found regarding any health problem. This could be because of the smaller sample sizes, which lead to larger standard errors. The probability of having asthma does increase for individuals of 70 years or older when their EPC changes from E, F or G to a better EPC. Contrary to the analysis on the whole sample, no significant effect on cardiovascular medication is found.

The significant increase in the use of asthma medication (defined as using asthma or COPD medication) among elderly, but not among younger individuals could indicate that the energy efficiency measures mainly affect COPD rather than asthma. Asthma is mainly prevalent amongst individuals under 30 years old with a prevalence of 1% compared to a prevalence of 0.3% for individuals of 70 years or older (Wijga & Smit, 2004). Contrary, 44% of the individuals of 70 years or older have COPD, while only 0.3% of individuals under 30 years do so (Smit et al., 2004). The larger effect of energy efficiency measures on COPD would be in line with literature stating that the main risk factor of COPD is smoking, of which the negative effects can be worsened by insulation, whereas the main risk factor of asthma is genetic (Hagstad et al., 2014). However, this is merely a hypothesis and further research is needed; the lower prevalence of asthma and smaller sample size could also drive these results.

Table 9

Effect of EPC on health for individuals of 30 or younger

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
EPC C or D	0.952	1.253*	0.404	0.608	1.054	0.774
	(0.0721)	(0.154)	(0.232)	(0.218)	(0.244)	(0.203)
EPC A or B	1.001	1.119	0.508	0.824	0.724	1.465
	(0.0904)	(0.167)	(0.341)	(0.367)	(0.199)	(0.454)
Observations	58,062	27,140	1,173	2,348	6,994	5,325
Number of id	11,469	5,348	207	403	1,415	1,011
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. *** p<0.01, ** p<0.05, * p<0.1.

Table 10

Effect of EPC on health for individuals of 70 years or older

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
EPC C or D	1.230***	0.992	1.306*	1.211	0.880	1.154
	(0.0918)	(0.0801)	(0.179)	(0.280)	(0.116)	(0.124)
EPC A or B	1.281***	1.131	1.273	1.147	0.915	1.132
	(0.115)	(0.109)	(0.208)	(0.330)	(0.145)	(0.143)
Observations	63,675	55,832	21,757	5,888	37,502	34,227
Number of id	8,775	7,861	2,921	812	5,595	4,613
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. *** p<0.01, ** p<0.05, * p<0.1.

When looking at heterogeneous effects of age for more specific energy efficiency measures, a similar problem as under 5.2 arises; the small samples make it difficult to predict the odds ratios. This is also likely to explain the large confidence intervals and the large and small odds ratios in Table G1 and G2 (see Appendix G). These odds ratios indicate that all regressions, except for Column 1 of Table G1, suffer from sparse data bias, leading to unreliable results. Column 1 of

Table G1 suggests that insulating a facade significantly increases the odds of having asthma by 294% for individuals of 30 years or younger. Although the model for asthma does not include as impossibly large or small odds ratios as in the other columns, this odds ratio is still very large. Thus, it is unclear whether the effect on asthma is larger for individuals below 30 or whether this finding is driven by bias.

5.3.2 Income

Besides heterogeneous effects on different age groups, the literature also suggests that individuals with a low income may counter more adverse health effects. To explore this, Equations 1 and 2 are performed for a group of tenants who live below the social minimum in Appendix H. Contrary to the analysis on the total sample, no significant effect on asthma or cardiovascular diseases is found. Thus, no evidence is found that improving from EPC E, F or G to a better EPC has adverse health effects for individuals below the social minimum, but this is likely due to the small sample size and large confidence intervals. Also, the estimations of the specific energy measures in Table H2 cannot be used to confidently conclude anything on whether low incomes counter more adverse health effects. The very large and small odds ratios and small sample size indicate that all regressions suffer from sparse data bias, leading to unreliable results.

Focusing on households living above the social minimum, the results are similar to those for the entire sample (see Table H3). This similarity could be expected since the subgroup of individuals earning above the social minimum makes up more than half of the sample that was used in the main analysis.[14] However, some disparities do arise when estimating the effect of specific energy efficiency measures in Table H4. Insulating the roof (and not insulating the facade) leads to a significant increase in the probability of having asthma. The results must be interpreted with caution. Balanced ventilation, for instance, decreases the odds of using sleep medication by 95% in this subgroup, compared to a 71% reduction in the whole sample (see Table 8). This significant increase in effect size could indicate sparse data bias as the sample size is smaller and,

[14] 12% of the dropped observations were individuals who earned below the social minimum. The remaining 78% are respondents who did not provide information regarding their income. The lack of response is likely due to the overall length of the WoON survey, as many respondents did not complete a significant number of questions. Thus, it does not seem like the lack of response indicates discomfort with the specific question. Consequently, we expect a low correlation between responding and income.

at the same time, individuals in the sample are not expected to differ much from the individuals in the main analysis.

6 Robustness

This section will perform three tests to check whether the findings discussed previously are robust. First, one-year age dummies are added to account for confounding age effects. Next, the sensitivity of our findings to the 2015 change in method of calculating EPCs is examined. Finally, the multiple comparisons problem is addressed and a correction method is applied.

6.1 Age dummies

This analysis included age groups in five-year intervals as control variables. Still, the odds of using medication could change due to age rather than the energy efficiency measures. Therefore, the same analyses are performed but with yearly age dummies (see Appendix I). Including all these one-year age dummies causes non-convergence issues; the maximum likelihood estimation that is used in the logistic regression can not find coefficients that maximize the likelihood function (the function that makes the observed data points most probable). Reduced variance, especially for the elderly, makes it difficult to estimate the fixed effects for those ages. To solve this non-convergence issue, age dummies of 95 and higher are aggregated into one category. The odds ratios in Appendix I are similar as in the main analysis. This indicates that our findings are not confounded by age effects on health and that the non-convergence issues are related to the fixed effects estimates.

6.2 After 2015

Secondly, it is important to test whether the results are driven by methodological changes. Section 3 already showed that the methodology adjustment in 2015 led to many changes in EPCs. Therefore, Equation 1 is estimated on the sample from 2015 onwards in Appendix J.[15] Contrary to Table 6, no significant differences are found regarding the odds of using cardiovascular medication. This can be explained by the lower sample size. Similar to before, individuals living in a dwelling with EPC A or B have significantly larger odds of having asthma compared to tenants of dwellings with EPC E, F or G (26% now compared to 9% before). The increase in effect size does not necessarily indicate that the methodology change in 2015 has affected the results from the main analysis. In line with the rest of the paper, it seems more plausible that the lower sample size leads

[15] Regression 2 was estimated on the sample from 2015 onwards anyways since only then these energy measures were recorded.

to sparse data bias, which increases the apparent effect sizes. In conclusion, this robustness check does not indicate that the results are driven by the 2015 methodology change.

6.3 Multiple comparisons problem

Lastly, it must be noted that this paper estimates many coefficients. Testing multiple hypotheses increases the probability of Type 1 errors, the rejection of the null hypothesis when it is actually true. To counteract this so-called multiple comparisons problem and to decrease the probability of obtaining significant results purely by chance, the Bonferroni correction can be applied (Rice, 1989). Each individual hypothesis is measured at significance level of α/m, where α is the desired overall alpha level and m is the number of hypotheses. This correction becomes more conservative as m increases; reducing the likelihood of Type 1 errors comes at the cost of increasing the likelihood of Type II errors, which occur when the null hypothesis is not rejected despite it being false. In our analyses we estimate the effect of at least two variables on seven diseases, leading to an m of 14. Applying the Bonferroni correction results in zero significant differences. However, as stated above, this result is partly driven by Type II errors. Future research could counter this problem by focusing on effects that are highlighted in this paper and increasing the sample size to improve the statistical power of the analyses.

7 Discussion

Having examined the impact of energy efficiency of dwellings on various health indicators, this section now explorers the implications of these results and contextualizes these findings within existing literature. First the findings and implied policy implications are discussed, followed by limitations and suggestions for future research.

7.1 Findings and policy implications

In line with the literature, the results indicate that the energy efficiency of dwellings indeed affects health. Individuals living in dwellings with different EPCs differ significantly in characteristics, making cross-sectional comparisons, like those used by Geijtenbeek et al. (2022), less reliable. Using a fixed effects strategy allows to control for most of these differences. Contrary to Geijtenbeek et al. (2022), who found that increasing energy efficiency resulted in a lower probability of having asthma, our results indicate that more energy efficient dwellings increase the probability of using asthma or COPD medication. This result appears to be driven by facade insulation and is counteracted by balanced ventilation, which decreases the probability of using asthma or COPD medication. Interestingly, floor and roof insulation did not have significant health effects. Furthermore, tenants living in more energy efficient dwellings have significantly lower probabilities of having cardiovascular problems and rheumatoid arthritis. Further breakdowns of the effects are likely to suffer from sparse data bias, which is indicated by the extreme large and small odds ratios.

Our results have several policy implications. First of all, it underlines the importance of ventilation. The adverse health effects of insulation on asthma and potentially lung cancer can be countered by ventilation. Individuals can be stimulated to install balanced ventilation systems, or when installing balanced ventilation is too costly, individuals could be informed about the importance of continuous ventilation and how to use ventilation grates correctly. Furthermore, cardiovascular problems decrease when dwellings get more energy efficient, which is in line with the literature. As many individuals have cardiovascular diseases, subsidizing energy efficiency measures could lead to a significant reduction in healthcare costs and DALYs. Lastly, the results indicate that only facade insulation has a significant negative health effects, while floor and roof insulation do not. This could suggest that floor and roof insulation are also less effective in preventing heat from escaping out of dwellings. From a sustainability perspective, facade insulation should then be preferred over floor and roof insulation, while from a health perspective it is less favorable. Consequently, alternative energy efficiency measures should be considered that enhance both sustainability and health outcomes, such as balanced ventilation and heat pumps.

7.2 Limitations

It is important to stress the caveats of this analysis. First, EPCs are an imperfect proxy of the energy efficiency of dwellings. EPCs are being criticized to depend on the certified advisor (Stichting W/E adviseurs, 2022). This measurement error can lead to estimates that are biased towards zero. Furthermore, landlords can file a complaint if they disagree with the assigned EPC. This results in upward adjustment of EPCs that were initially underestimated, but EPCs that are too positive are rarely downgraded. In 2022, the Rent Tribunal (Huurcommissie in Dutch) started a pilot in which tenants could ask for a downgrade, but this was after the research period and only led to 81 downgrades of EPC in 2023 (Huurcommissie, 2023). Consequently, the outcomes are likely to be biased towards zero.

Besides measurement error, our results may also suffer from reverse causality. Reverse causality bias occurs when the dependent variable is incorrectly identified as the cause of the independent variable, rather than the other way around. Here the assumption that tenants cannot influence what energy efficiency measures are taken plays an important role. Reverse causality bias could arise when, contrary to this assumption, tenants who start using asthma medication urge their landlords to take energy efficiency measures.

Omitted variable bias may also arise when efficiency measures are not taken randomly, but correlate with other variables affecting the health of tenants. For instance, tenants who work less may be more likely to prevent housing sustainability improvements as they are more affected by the short-term inconveniences of the renovations. In this scenario, the negative health effect of lower income, such as reduced means to afford healthy food and participate in wellness programs, could be wrongly attributed to the energy efficiency measures. One way to assess whether the energy efficiency measures were taken randomly and if nothing else changed over time, would be to include other personal and dwelling characteristics over time, such as income. In this paper, we did not have access to this information.

Besides, a downside of our fixed effects strategy is that the small sample and group size could introduce sparse data bias, potentially increasing the magnitude of both positive and negative effects and limiting the ability to conduct detailed breakdowns of the effects. Furthermore, this study does not capture long-term effects, as most individuals are only in the sample for 5 to 10 years. This short time frame may not be sufficient to observe the full impact of energy efficiency improvement on health outcomes. Lastly, our dataset does not provide information on variations in the quantity of medication prescribed. Therefore, this paper could not capture more subtle changes in health.

7.3 Future research

Future research could address these weaknesses. First of all, additional panel data on personal characteristics, such as income, should be used. These variables can then be included as control variables to minimize potential endogeneity issues. Information on additional characteristics could also be used to investigate why solar panels are associated with higher medication use. Secondly, future research should include all social housing (not only those from the WoON datasets) in order to improve precision. This would also allow for better estimated breakdowns. Lastly, our analysis showed the importance of balanced ventilation, but this is expensive. Further research should investigate other effective, cheaper ways to improve ventilation, such as information provision. By focusing on feasible, cost-effective solutions, housing corporations and other landlords can implement these recommendations successfully, translating this paper into actual real-world impact.

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Appendix A

Medication

In order to match the medicine groups, which are determined at ATC4-level, to diseases, the website “Farmacotherapeutischkompas.nl” (FK) is used. This website is developed by the Dutch National Health Care Institute and provides healthcare professionals with evidence-based information on medication. For this paper, we investigated the medication recommendations on FK for the health problems discussed in section 2.1.1. Subsequently, we examined under which ATC4-group the recommended medication for treatment could be grouped. Table A1 gives an overview of what ATC4-codes are used to indicate diseases.

Medication that could be prescribed for a wide range of diseases was not included. For example, prednisone was prescribed for both COPD and rheumatoid arthritis. Prednisone is therefore excluded from this analysis since it would not give information on what specific disease is affected. Besides, Table A1 shows that the same type of medication is prescribed for COPD and asthma. Therefore, these two diseases are grouped in the paper. Lastly, we did not investigate carbon monoxide poisoning, as this is often not recognized and if it is, no unique medication is prescribed (only extra oxygen is given).

Lung cancer and cardiovascular diseases were not listed as indications on the FK website. Cardiovascular diseases were subdivided into many different problems. As this subdivision is not relevant for the paper, all medication related to the heart and blood vessels (starting with the letter C in the ATC4-classification) is included. Regarding treatment of lung cancer, we looked at recommended medication on the website “Richtlijnendatabase.nl”. This website is property of the Federation of Medical Specialists and describes guidelines for secondary care.

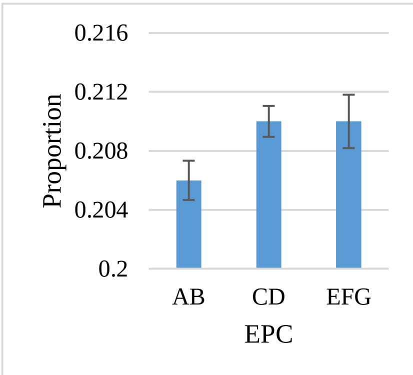
Table A1. *Health problem and related ATC4 code*

Health problem	ATC4 code
COPD	R03A, R03B
Asthma	R03A, R03B
Cardiovascular diseases	All medication codes beginning with C
Lung cancer	L01A, L01B, L01C, L01D, L01E, L01F, L01X
Rheumatic arthritis	L04A
Sleep problems	N05C
Epilepsy	N03A

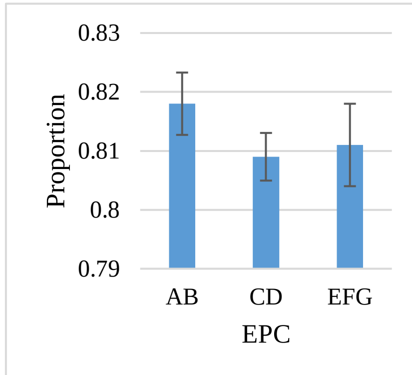
Appendix B

Medication per EPC group for individuals of 70 or older

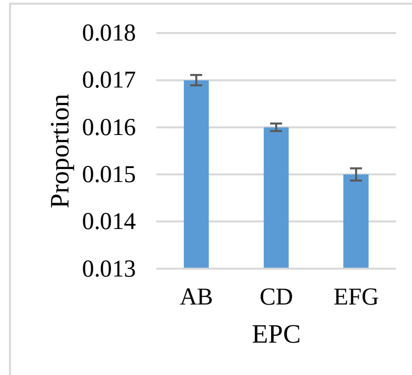
A) Asthma



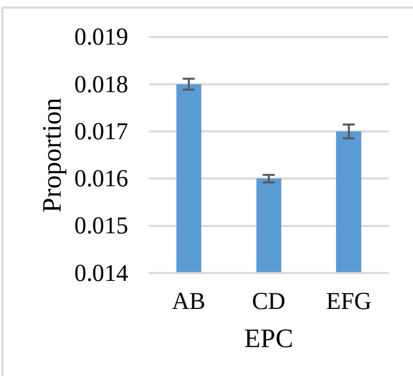
B) Heart



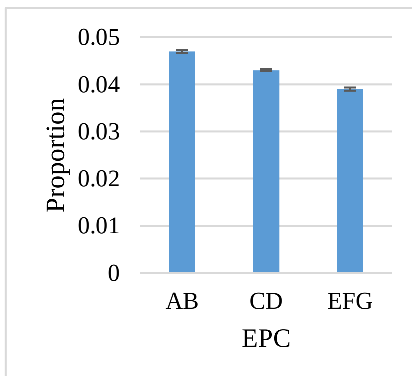
C) Lung cancer



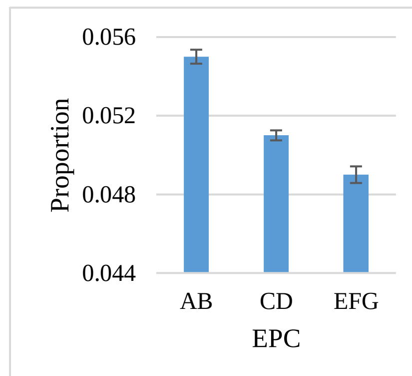
D Rheumatoid arthritis



E) Sleep



F) Epilepsy



Appendix C

Average elasticities EPC and health

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
EPC C or D	0.0318	-0.0301*	0.119	-0.0994	-0.0300	0.0341
	(0.0234)	(0.0172)	(0.0806)	(0.0847)	(0.0506)	(0.0446)
EPC A or B	0.0687**	0.00283	0.0624	-0.169	-0.0468	0.0209
	(0.0284)	(0.0210)	(0.0973)	(0.108)	(0.0616)	(0.0540)

Note. Standard error in parentheses. LC stands for lung cancer and RA for rheumatoid arthritis. *** p<0.01, ** p<0.05, * p<0.1.

Appendix D

Rough estimation of effect EPC changes on healthcare costs and DALYs

In order to gain a better understanding of the economic significance of our results, a rough estimation is made of the effect of improving all EPCs E, F or G to A or B or to C or D in the Netherlands on yearly healthcare costs and DALYs.[16] First, a rough estimation of the effect on health costs is given, followed by an estimation of the effect on the amount of DALYs.

Yearly healthcare costs

The calculation of the effect on yearly healthcare costs consists of 2 steps. First, the share of the Dutch population that is affected by the energy efficiency measures is calculated. In Table D2, we estimate that if all dwellings with EPC E, F or G are prohibited, 7.4% of the Dutch population will experience an improvement in their energy efficiency.

Table D1. *Step 1: Calculation of affected share of Dutch population when all dwellings with EPC E, F or G are prohibited*

Affected	Amount	Source
Dwellings	715,200	CLO (2023)
Average household size	*1.861*	WoON (2006, 2009, 2012, 2015, 2018 & 2021)
Individuals	1,330,987	Calculated
Dutch population	*17,988,091*	CBS (2024b)
Individuals as share of total Dutch population	7.40%	Calculated

Next, the yearly healthcare costs estimates of the RIVM (see Table D2) and the estimated average elasticities (see Appendix C) are combined in Table D3. The yearly healthcare cost estimates include costs for medication, hospitalizations, nursing and sick leave. Here we assume that if changing from EPC E, F or G to, for example, EPC A or B increases the probability of having a

[16] This appendix only includes estimates of the effects that were significant at 10% level in Table 6.

disease by a certain percentage, the yearly healthcare costs also increase by the same percentage. Upper and lower bound estimates are given to quantify the uncertainty around the estimated effect and are derived from the 95% confidence intervals of the average elasticities.

Improving from EPC E, F or G to EPC A or B was associated with an average elasticity of 6.9% with a lower bound of 1.31% and an upper bound of 12.43%. Thus 7.4% of the 443.9 million euros of yearly asthma healthcare costs will increase by between 1.31 and 12.43%, which is equivalent to an increase in costs of between 0.43 and 4.08 million euros. Using a similar calculation, COPD costs are expected to increase by between 0.72 and 6.93 million euros. Contrary, improving EPCs from E, F or G to C or D is likely to decrease the yearly healthcare costs, but could in the worst case increase the cardiovascular healthcare costs by 1.8 million.

Table D2. *Yearly healthcare costs estimates*

	Asthma	COPD	Heart	LC	RA	Epilepsy
Yearly healthcare costs (millions)	443.9	752.9	6,756.8	736.9	292.2	192.3

Note. Costs are expressed in euros. LC stands for lung cancer and RA for rheumatoid arthritis. These estimates are based on healthcare costs data from 2019. Estimations for sleeping medication are missing. Source: CBS (2022).

Table D3. *Step 2: Rough estimation of effect changes in EPC on yearly healthcare costs*

What	Change in yearly healthcare costs	Calculation	
		Lower bound	Upper bound
Effect of EPC E, F or G to EPC A or B on asthma	0.43 to 4.08 million	443.9 × 7.40% × 1.31% = 0.43 million	443.9 × 7.40% × 12.43% = 4.08 million
Effect of EPC E, F or G to EPC A or B on COPD	0.72 to 6.93 million	752.9 × 7.40% × 1.31% = 0.72 million	752.9 × 7.40% × 12.43% = 6.93 million
Effect of EPC E, F or G to EPC C or D on cardiovascular diseases	-31.9 to 1.8 million	6,756.8 × 7.40% × -6.38% = -31.9 million	6,756.8 × 7.40% × 0.36% = 1.8 million

Note. Costs are expressed in euros. This table only includes estimates on effects that were significant at 10% level in Table 6. The first factor in the calculations is the yearly healthcare costs from Table D2, the second factor is the share of individuals that are affected by the change in EPC from Table D1 and the third factor is how much the probability to have the disease will change. Negative numbers imply that improving energy efficiency decreased the yearly healthcare costs. The lower and upper bounds are calculated using a 95% confidence interval for the estimated average elasticity.

DALYs

In order to estimate the effect of changes in EPC on DALYs, we use data on the disease burden in DALYs in 2023 and data on the prevalence of the diseases. First, the disease burden per patient is calculated in Table D4. In Table D5, this estimated disease burden is combined with the expected change of individuals with the disease, resulting in an estimation of the total change in disease burden if all dwellings with EPC E, F or G are prohibited. We assume that the share of patients living in a dwelling with EPC E, F or G is 7.4%, equal to the share of Dutch citizens living in a dwelling with EPC E, F or G (see Table D1).[17]

Table D4. *Disease burden per disease in 2023*

	Asthma	COPD	Heart	LC	RA	Epilepsy
Total disease burden (DALYs)	44,800	188,500	693,700	165,800	47,500	17,400
Number of patients	527,716	557,000	1,738,749	36,834	275,490	63,771
Disease burden per patient	0.08489	0.33842	0.39897	0.00450	0.17242	0.27285

Note. LC stands for lung cancer and RA for rheumatoid arthritis. Estimations for sleep problems are missing. Furthermore, the number of individuals with diseases in 2023 is calculated by multiplying the percentage of individuals with diseases in 2021 by the size of the Dutch population in July 2023. Source: RIVM (2021) & RIVM (2022)

Table D5. *Rough estimation of effect changes in EPC on disease burden*

What	Change in DALYs	Calculation	
		Lower bound	Upper bound
Effect of EPC E, F or G to EPC A or B on asthma	43 to 412	0.08489 × 1.31% × 7.40% × 527,716 = 43	0.08489 × 12.43% × 7.40% × 527,716 = 412
Effect of EPC E, F or G to EPC A or B on COPD	182 to 1,733	0.33842 × 1.31% × 7.40% × 557,000 = 182	0.33842 × 12.43% × 7.40% × 557,000 = 1,733
Effect of EPC E, F or G to EPC C or D on cardiovascular diseases	-3,275 to 185	0.39897 × -6.38% × 7.40% × 1,738,749 = -3,275	0.39897 × 0.36% × 7.40% × 1,738,749 = 185

Note. This table only includes estimates on effects that were significant at 10% level in Table 6. The lower and upper bound are calculated using a 95% confidence interval for the estimated average elasticity.

[17] This is an underestimation, as the prevalences of the diseases in our sample are higher than in the population.

Appendix E

Average elasticities energy efficiency measures and health

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
Triple glazing	-0.00296	0.0178	0.0198	0.275	0.0124	-0.121
	(0.0745)	(0.0587)	(0.252)	(0.332)	(0.165)	(0.139)
Facade insulation	0.432**	0.187	0.902*	-1.993*	-0.0581	0.340
	(0.194)	(0.166)	(0.524)	(1.037)	(0.374)	(0.332)
Roof insulation	0.119	-0.0940	-0.488*	-0.465	0.0951	-0.0336
	(0.0918)	(0.0701)	(0.277)	(0.388)	(0.214)	(0.166)
Floor insulation	-0.0626	0.0549	-0.520	0.108	-0.153	-0.222
	(0.122)	(0.0854)	(0.337)	(0.489)	(0.243)	(0.197)
Balanced ventilation	-0.599**	0.359	-0.276	-9.644	-1.207**	0.517
	(0.290)	(0.249)	(0.824)	(1,025)	(0.568)	(0.519)
Solar water heater	0.464	0.525	0.547	19.35	1.178	-0.0976
	(0.390)	(0.320)	(1.382)	(2,437)	(1.559)	(0.738)
Solar panels	0.154**	0.143**	0.445*	-0.0699	0.349**	0.0605
	(0.0778)	(0.0586)	(0.253)	(0.313)	(0.175)	(0.139)
Gas heating	-0.0335	-0.00160	0.135	-28.47	0.300	0.763*
	(0.269)	(0.200)	(0.900)	(1,453)	(0.462)	(0.426)
Heat pump	-0.0118	-0.484***	-0.558	-2.899**	0.476	0.263
	(0.231)	(0.168)	(0.612)	(1.347)	(0.548)	(0.390)
District heating	-0.410	-0.236	-15.80		1.656*	-2.151**
	(0.476)	(0.308)	(1,063)		(0.990)	(0.853)

Note. Standard error in parentheses. LC stands for lung cancer and RA for rheumatoid arthritis. *** p<0.01, ** p<0.05, * p<0.1.

Appendix F

Rough estimation of effect specific energy measures on healthcare costs and DALYs

In order to gain a better understanding of the economic significance of our results, a rough estimation is made of the effect of taking energy efficiency measures on yearly healthcare costs and DALYs.[18] This approach is similar to the approach in Appendix D. We test the effect of the scenario in which energy efficiency measures are taken in all dwellings with EPC E, F or G (affecting a total of 715,200 dwellings and 1,330,987 individuals, see Table D1).[19] In reality, homeowners of these dwellings will not need to take all specified energy efficiency measures in order to improve the EPC of their dwelling to a D or higher, but this scenario is taken to illustrate the potential impact of 715,200 improvements. Furthermore, the costs of the energy measures are compared to the associated health effects to give insight into the cost effectiveness of the measures. First, the effect on yearly healthcare costs is given, followed by the effect on DALYs

Healthcare costs

Similar to Appendix D, the first step is to calculate the share of individuals that is affected when all dwellings with EPC E, F or G are renovated (see Table F1). Table F2 then shows the lower and upper bounds of the estimated yearly healthcare costs that are associated with installing the specified energy measures in all dwellings with EPC E, F or G. In order to calculate the effect of installing the specified energy measures in the dwellings with EPC E, F or G, the share of individuals with EPC E, F or G is multiplied with the yearly healthcare costs (see Table F2) and the lower and upper bounds of the average elasticities (see Appendix E).[20] As expected, the changes in healthcare costs in Table F3 are larger compared to Table D3, because of the sparse data bias that leads to overestimations of the effects.

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[18] This appendix only includes estimates of the effects that were significant at 5% level in Table 8.
[19] Between 1 and 2 percent of the dwellings with EPC E, F or G already had taken the energy efficiency measures stated in Table F1 (see Table 3). The health effect in Table F1 is therefore slightly overestimated.
[20] For example, the lower bound of the effect of facade insulation on asthma is calculated in the following manner: first the lower bound of the average elasticity is calculated: 0.432 × 0.194 × 1.96 = 5.3%. Then this is multiplied by the share of individuals living in a dwelling with EPC E, F or G and the yearly health costs: 5.3% × 7.40% × 443.9 = 1.74 million.

Table F1. *Step 1: Calculation of the share of Dutch population living in dwellings with EPC E, F and G*

Affected	Amount	Source
Dwellings	715,200	CLO (2023)
Average household size	*1.861*	WoON (2006, 2009, 2012, 2015, 2018 & 2021)
Individuals	1,330,987	Calculated
Dutch population	*17,988,091*	CBS (2024b)
Individuals as share of total Dutch population	7.40%	Calculated

Table F2. *Yearly healthcare costs estimates*

	Asthma	COPD	Heart	LC	RA	Epilepsy
Yearly healthcare costs (millions)	443.9	752.9	6,756.8	736.9	292.2	192.3

Note. Costs are expressed in euros. LC stands for lung cancer and RA for rheumatoid arthritis. These estimates are based on healthcare costs data from 2019. Estimations for sleeping medication are missing. Source: CBS (2022).

Table F3. Step 2: *Rough estimation of change in yearly healthcare costs for change in energy efficiency measures*

Effect of	Effect on yearly healthcare costs for	Change in yearly healthcare costs
Solar panels	Cardiovascular diseases	14.07 to 128.93 million
Facade insulation	COPD	2.95 to 45.18 million
Facade insulation.	Asthma	1.74 to 26.64 million
Solar panels	COPD	0.08 to 17.08 million
Solar panels	Asthma	0.05 to 10.07 million
Balanced ventilation	Asthma	-38.35 to -1.01 million
District heating	Epilepsy	-54.40 to 6.82 million
Balanced ventilation	COPD	-62.04 to -1.70 million
Heat pump	Rheumatoid arthritis	-120 to -5.60 million
Heat pump	Cardiovascular diseases	-406.64 to -77.36 million

Note. Costs are expressed in euros. This table only includes estimates on effects that were significant in Table 8 except for effects on sleep as there are no estimations regarding the healthcare costs for sleep medication. Negative numbers imply that improving energy efficiency decreased the yearly healthcare costs. The lower and upper bounds are calculated using a 95% confidence interval for the estimated average elasticity.

The yearly healthcare cost savings can be contextualized by comparing them to the costs of implementing energy efficiency measures (see Table F4). The most significant impact observed in Table F3 was from installing heat pumps on cardiovascular diseases. Installing a heat pump in all the dwellings with EPC E, F or G would cost approximately 4,395 million euros. Even with the most optimistic estimated savings of 407 million euros, this implies that saving 1 euro in healthcare costs would require an investment of 11 euros. This suggests that implementing these energy efficiency measures may not be the most cost-effective strategy for reducing healthcare costs.

Table F4. *Rough estimation of costs of energy efficiency measures*

Energy measure	Costs (without subsidy)
Solar panels (6)	3,218
Heat pump	6,146
Facade insulation	6,172
Balanced ventilation	6,599

Note**.** Costs are expressed in euros. This estimations are from Milieu Centraal (2024), an independent organization funded by the Dutch government that provides advise for sustainability. The prices are based on an average terraced house that is built in 1980.

DALYs

Besides yearly healthcare costs, energy efficiency measures also affect the disease burden. Similarly as in Appendix D, we first calculate the disease burden per patient in Table F5. In Table F6 this estimated disease burden in DALYs is combined with the expected change of individuals with the disease, resulting in an estimation of the total change in the disease burden if all dwellings with EPC E, F or G implement the energy measures. We assume that the share of patients living in a dwelling with EPC E, F or G is 7.4%, equal to the share of Dutch citizens living in a dwelling with EPC E, F or G (see Table F1).[21]

[21] This is an underestimation, as the prevalences of the diseases in our sample are higher than in the population.

Table F5. *Disease burden per disease in 2023*

	Asthma	COPD	Heart	LC	RA	Epilepsy
Total disease burden (DALYs)	44,800	188,500	693,700	165,800	47,500	17,400
Number of patients	527,716	557,000	1,738,749	36,834	275,490	63,771
Disease burden per patient	0.08489	0.33842	0.39897	0.00450	0.17242	0.27285

Note. LC stands for lung cancer and RA for rheumatoid arthritis. Estimations for sleep problems are missing. Furthermore, the number of individuals with diseases in 2023 is calculated by multiplying the percentage of individuals with diseases in 2021 by the size of the Dutch population in July 2023. Source: RIVM (2021) & RIVM (2022)

Table F**6.** *Rough estimation of effect of energy efficiency measures on disease burden*

Effect of	Effect on yearly healthcare costs for	Change DALYs
Solar panels	Cardiovascular diseases	1,445 to 13,237
Facade insulation	COPD	793 to 11,259
Solar panels	COPD	21 to 4,275
Facade insulation.	Asthma	172 to 2,693
Solar panels	Asthma	5 to 1,016
Balanced ventilation	Asthma	-3,870 to 101
Balanced ventilation	COPD	-4,085 to -107
District heating	Epilepsy	-4,922 to -617
Heat pump	Rheumatoid arthritis	-19,470 to -211
Heat pump	Cardiovascular diseases	-41,749 to -7,942

Note. The lower and upper bound are calculated using a 95% confidence interval for the estimated average elasticity.

Appendix G

Heterogeneous effect age

Table G1

Effect of energy efficiency measures on health for individuals of 30 or younger

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
Triple glazing	1.230	0.890	1.434×10^{16}	0.252	1.683	0.286
	(0.241)	(0.288)	(3.594×10^{24})	(0.538)	(1.173)	(0.301)
Facade insulation	2.942**	4.010			0.777	1.327×10^{17}
	(1.548)	(7.019)			(1.263)	(3.75×10^{25})
Roof insulation	0.897	0.809		3.621	0.227	1.459
	(0.215)	(0.327)		(6.532)	(0.238)	(1.641)
Floor insulation	0.919	0.344*		0.0775	0.966	0.517
	(0.279)	(0.216)		(0.128)	(0.935)	(0.646)
Balanced ventilation	0.466	1.427				1.597×10^{20}
	(0.325)	(1.471)				(1.46×10^{29})
Solar water heater	0.420					
	(0.542)					
Solar panels	1.172	1.205		5.748	5.867*	1.775
	(0.246)	(0.390)		(8.880)	(6.119)	(1.663)
Gas heating	0.905	1.047			0	
	(0.676)	(1.615)			(4.17×10^{-9})	
Heat pump	1.283	0.330				0
	(0.880)	(0.419)				(0)
District heating	0.264	1.003×10^{6}				1.85×10^{22}
	(0.270)	(8.588×10^{8})				(0)
Observations	8,983	3,523	178	381	1,134	861
Number of id	2,653	1,028	49	105	326	245
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. *** p<0.01, ** p<0.05, * p<0.1.

Table G2

Effect of energy efficiency measures on health for individuals of 70 or older

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
Triple glazing	0.931	1.428	0.695	6.857**	0.601	0.875
	(0.179)	(0.323)	(0.206)	(6.046)	(0.191)	(0.222)
Facade insulation	1.126	1.199	2.824*	0	0.524	0.967
	(0.474)	(0.591)	(1.763)	(6.99×10^{-11})	(0.359)	(0.587)
Roof insulation	0.974	0.571**	0.564*	0.0290***	1.431	0.707
	(0.232)	(0.143)	(0.194)	(0.0315)	(0.605)	(0.217)
Floor insulation	1.293	1.641	0.560	3.907	0.428*	0.843
	(0.450)	(0.541)	(0.249)	(3.973)	(0.195)	(0.301)
Balanced ventilation	0.673	6.609×10^{6}	0.592		0.886	4.332
	(0.590)	(1.261×10^{10})	(0.532)		(1.666)	(5.763)
Solar water heater	4.270	1.396	2.093	1.278×10^{28}	1.489	0.387
	(3.794)	(1.810)	(3.001)	(2.091×10^{35})	(6.095)	(0.519)
Solar panels	0.991	1.912***	2.154**	0.791	2.158*	1.496
	(0.187)	(0.442)	(0.704)	(0.548)	(0.874)	(0.379)
Gas heating	6.440**	1.889	7.62×10^{-7}	0	0.594	1.319
	(5.699)	(1.255)	(0.000815)	(1.01×10^{-8})	(0.591)	(1.287)
Heat pump	0.713	0.396*	0.669	0	2.254×10^{6}	2.216
	(0.368)	(0.211)	(0.442)	(1.00×10^{-7})	(1.841×10^{9})	(1.696)
District heating	1.40×10^{-6}	1.95×10^{-7}	1.65×10^{-7}		2.066	2.13×10^{-6}
	(0.000897)	(0.000349)	(0.000155)		(3.601)	(0.00197)
Observations	10,149	7,983	4,055	866	5,544	5,404
Number of id	2,464	1,993	983	218	1,488	1,300
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. *** p<0.01, ** p<0.05, * p<0.1.

Appendix H

Heterogeneous effect income

Table H1

Effect EPC on health for individuals below social minimum

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
EPC C or D	1.035	1.145	1.165	0.574	0.733	1.006
	(0.128)	(0.146)	(0.514)	(0.228)	(0.155)	(0.186)
EPC A or B	1.043	1.212	1.175	1.343	0.768	1.031
	(0.156)	(0.190)	(0.691)	(0.722)	(0.196)	(0.244)
Observations	19,579	19,402	1,714	1,628	7,843	8,235
Number of id	2,444	2,308	201	181	921	925
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. EPC deteriorations are deleted to increase precision. *** p<0.01, ** p<0.05, * p<0.1.

Table H2

Effect of energy efficiency measures on health for individuals below social minimum

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
Triple glazing	0.690	0.898	0.798	0.967	0.502	0.956
	(0.305)	(0.433)	(1.152)	(1.717)	(0.307)	(0.683)
Facade insulation	3.799	765,459		0	2.503	1.679×10^{16}
	(5.042)	(1.014×10^{9})		(0)	(5.129)	(1.274×10^{24})
Roof insulation	1.536	0.330*	1.787	2.657	0.268	0.0991**
	(0.811)	(0.194)	(3.879)	(6.163)	(0.283)	(0.105)
Floor insulation	0.982	7.227	104,783	334,482	1.481	0.332
	(0.967)	(9.132)	(1.872×10^{14})	(1.361×10^{7})	(1.599)	(0.462)
Balanced ventilation	0.497	1.107×10^{6}		0		3.036×10^{16}
	(0.734)	(1.250×10^{9})		(0)		(3.684×10^{24})
Solar water heater	3.11×10^{-6}	0.839				
	(0.00160)	(1.749)				
Solar panels	1.021	2.119	0.0658	1.852	1.780	2.872
	(0.445)	(1.089)	(0.773)	(2.921)	(1.534)	(2.272)
Gas heating	0.775	0.334		0		4.906×10^{16}
	(0.953)	(0.437)		(0)		(6.052×10^{24})
Heat pump	3.461	0.356	11.14	0		2.414×10^{26}
	(5.859)	(0.498)	(132.0)	(0)		(4.708×10^{34})
District heating	1.239	1.084×10^{6}			2.997×10^{16}	0
	(1.560)	(2.916×10^{9})			(6.300×10^{24})	(1.82×10^{-9})
Observations	2,503	2,051	215	218	875	1,064
Number of id	588	485	44	46	215	234
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. *** p<0.01, ** p<0.05, * p<0.1.

Table H3

Effect EPC on health for individuals above social minimum

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
EPC C or D	1.077*	0.904**	1.315**	0.821	0.986	1.005
	(0.0454)	(0.0386)	(0.143)	(0.100)	(0.0799)	(0.0676)
EPC A or B	1.127**	0.919	1.230	0.756*	0.933	1.041
	(0.0573)	(0.0475)	(0.160)	(0.116)	(0.0903)	(0.0830)
Observations	169,102	177,647	28,655	17,316	64,982	74,340
Number of id	19,917	20,393	3,159	1,846	7,708	8,092
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. EPC deteriorations are deleted to increase precision. *** p<0.01, ** p<0.05, * p<0.1.

Table H4

Effect of energy efficiency measures on health for individuals above social minimum

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
Triple glazing	1.108	1.106	0.973	1.517	1.543*	0.864
	(0.138)	(0.146)	(0.300)	(0.617)	(0.377)	(0.163)
Facade insulation	0.968	1.428	2.860*	0.126*	0.990	1.214
	(0.309)	(0.490)	(1.755)	(0.136)	(0.624)	(0.582)
Roof insulation	1.495***	0.897	0.598	1.188	0.716	0.972
	(0.223)	(0.141)	(0.206)	(0.664)	(0.210)	(0.212)
Floor insulation	0.799	1.013	0.653	0.898	0.772	0.823
	(0.162)	(0.194)	(0.257)	(0.550)	(0.284)	(0.218)
Balanced ventilation	0.507	1.292	0.637		0.0549***	4.127
	(0.267)	(0.721)	(0.613)		(0.0537)	(3.707)
Solar water heater	1.364	2.626	1.849	9.760×10^{86}	4.812	0.329
	(0.839)	(2.100)	(2.622)	(0)	(7.776)	(0.409)
Solar panels	1.075	1.206	1.830**	0.581	1.452	0.959
	(0.137)	(0.160)	(0.554)	(0.235)	(0.379)	(0.183)
Gas heating	1.839	1.172	1.530	0	1.546	1.367
	(0.869)	(0.465)	(1.449)	(0)	(0.859)	(0.672)
Heat pump	0.592	0.375***	1.490	0	2.890	1.600
	(0.245)	(0.138)	(1.407)	(0)	(2.731)	(0.774)
District heating	0.609	0.448	2.43×10^{-7}		18.23**	8.86×10^{-8}
	(0.913)	(0.323)	(0.000190)		(22.03)	(0.000180)
Observations	20,907	18,691	4,094	2,138	7,850	9,114
Number of id	4,866	4,310	927	470	1,915	2,043
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. *** p<0.01, ** p<0.05, * p<0.1.

Appendix I

Robustness check: age dummies

Table I1

Effect of EPC on health with one year age dummies

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
EPC C or D	1.047	0.945*	1.132	0.902	0.973	1.034
	(0.0296)	(0.0282)	(0.0923)	(0.0779)	(0.0511)	(0.0481)
EPC A or B	1.090**	0.997	1.076	0.837	0.968	1.019
	(0.0374)	(0.0363)	(0.106)	(0.0921)	(0.0618)	(0.0574)
Observations	303,035	301,568	44,096	28,820	113,616	123,645
Number of id	40,746	38,002	5,199	3,382	14,992	14,741
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
1 year Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. Due to the limited number of observations ages of 95 and older are aggregated into one category. *** p<0.01, ** p<0.05, * p<0.1.

Table I2

Effect of energy efficiency measures on health with one year age dummies

	(1) Asthma	(2) Heart	(3) LC	(4) RA	(5) Sleep	(6) Epilepsy
Triple glazing	0.983	1.030	0.947	1.340	0.921	0.888
	(0.0915)	(0.109)	(0.257)	(0.476)	(0.167)	(0.134)
Facade insulation	1.709**	1.433	2.427	0.129*	0.750	1.452
	(0.405)	(0.422)	(1.413)	(0.142)	(0.312)	(0.516)
Roof insulation	1.158	0.854	0.618*	0.609	1.180	0.961
	(0.129)	(0.105)	(0.175)	(0.247)	(0.269)	(0.170)
Floor insulation	0.923	1.058	0.640	1.165	0.843	0.800
	(0.137)	(0.158)	(0.222)	(0.598)	(0.219)	(0.166)
Balanced ventilation	0.503*	1.981	0.876	3.92×10^{-10}	0.428	1.724
	(0.177)	(0.866)	(0.756)	(0.000172)	(0.253)	(0.949)
Solar water heater	1.738	2.845*	1.755	7.426×10^{17}	3.789	0.988
	(0.825)	(1.624)	(2.567)	(7.768×10^{25})	(8.225)	(0.769)
Solar panels	1.203*	1.244**	1.699**	1.020	1.593**	1.081
	(0.113)	(0.128)	(0.441)	(0.339)	(0.299)	(0.158)
Gas heating	1.161	1.181	1.917	0	1.658	2.284
	(0.440)	(0.509)	(2.067)	(0)	(1.144)	(1.253)
Heat pump	0.941	0.449***	0.575	0.0409**	1.623	1.296
	(0.262)	(0.134)	(0.363)	(0.0559)	(0.979)	(0.531)
District heating	0.654	0.666	0		10.38**	0.0948**
	(0.376)	(0.364)	(0)		(12.11)	(0.0870)
Observations	40,529	33,794	5,950	3,724	14,128	16,113
Number of id	10,069	8,213	1,395	862	3,597	3,782
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. *** p<0.01, ** p<0.05, * p<0.1.

Appendix J

Robustness check: after 2015

	(1)	(2)	(3)	(4)	(5)	(6)
	Asthma	Heart	LC	RA	Sleep	Epilepsy
EPC C or D	1.184*	1.047	1.392	0.894	1.198	0.980
	(0.105)	(0.107)	(0.327)	(0.258)	(0.214)	(0.140)
EPC A or B	1.258***	1.155	1.335	0.842	1.314	0.972
	(0.111)	(0.117)	(0.325)	(0.248)	(0.234)	(0.139)
Observations	43,304	36,063	6,410	3,982	15,150	10,443
Number of id	10,744	8,779	1,496	922	3,866	2,424
Individual-dwelling FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Age dummies	YES	YES	YES	YES	YES	YES

Note. Standard error in parentheses. Odds ratios are given. LC stands for lung cancer and RA for rheumatoid arthritis. Number of id means number of individual-dwelling pairs. *** p<0.01, ** p<0.05, * p<0.1.