# CO2 emissions reduction from residential buildings: cost estimate and policy design[*]

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February 28, 2024

## Abstract

We assess the efficiency of a bonus financed by the government to support energy renovation of dwellings and the related CO2 emissions reduction. The bonus considered is a fixed percentage of the cost of the energy retrofit. Efficiency of this policy is assessed by comparing the cost of such a bonus with the cost of individually tailored subsidies that a fully informed government would have paid to achieve the same CO2 reduction.

Relying on an Energy Performance Certificates (EPCs) dataset, which includes information on characteristics of the buildings, recommendations to improve their energy efficiency and related CO2 reduction, we derive the costs and benefits of three bonuses that refund different shares (25%, 50%, and 75%) of the upfront cost to implement EPCs recommendation.

Matching our data with the socio-economic characteristics of the household most likely to live in the observed dwellings shows that without any bonus, only 15% of the recommended energy efficiency enhancing investments have a positive private net present value (NPV) and their upfront cost averages about 22% of annual household spending; a bonus of 50% of the upfront costs brings the percentage of recommended investments with private positive NPV to 30% and reduces the incidence on the annual household budget to 11%.

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[*] This study was funded by the European Union – NextGenerationEU, in the framework of the GRINS - Growing Resilient, INclusive and Sustainable project (GRINS PE00000018 – CUP B13D22001400004.

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# 1 Introduction

Residential buildings have a significant carbon footprint (IEA, 2022), amounting to about 11.9% of all CO2 emissions in Europe in 2020 (EU, 2023). According to the EU Commission, roughly 75% of the EU building stock is energy inefficient,[1] highlighting the need for action to reduce emissions in that sector. However, renovating existing buildings requires an upfront investment that not all households can afford: given the large and positive externalities from CO2 emissions reduction, a government's intervention is desirable in the aim to support cost-effective improvements for the energy performance of housing. And indeed, different forms of financial and fiscal mechanisms are used by governments to support the energy renovation of buildings in many EU Member States and in the US.[2]

This paper investigates the *efficiency* of a mechanism financed by the government to support residential energy efficiency interventions resulting in an overall reduction in CO2 emissions from the housing sector. Efficiency is here assessed by comparing the cost to the government of this mechanism with the cost of individually tailored subsidies that a fully informed social planner would have paid to achieve the same CO2 reduction.

We use micro-level data from the archives of the Energy Performance Certificates (EPCs) for homes in a specific territory, the Treviso Province in Italy.[3] For each dwelling, the certificate provides data on energy efficiency based on an estimate of standardized energy consumption and conditional on the building characteristics and energy technology adopted, related CO2 emissions, as well as recommendations for improvingits energy performance. EPCs are not available for all dwellings: to ensure that our data are statistically representative, we construct sample weights using information from the General Population and Housing Census, whose data is less detailed than EPCs, but covers all dwellings. Note that both the EPCs and census data are available for all European countries: thus, our analysis can be easily replicated for any territory in the European Union and can inform local, regional and national policymakers in the design of cost-effective policies to support building renovation and the path toward carbon neutrality.

Our empirical analysis on the Treviso Province shows that, with no government support, only about 15% of the recommendations proposed in the EPCs have a positive private Net Present Value (NPV) and, therefore, are likely to be implemented. These recommendations would result in a CO2 reduction of approximately 165 million tonnes per year with respect to the *status quo*. In the same setting, if the government pays a bonus that covers a percentage of the energy renovation cost, the number of recommendations potentially implemented can increase and lead to lower emissions: for example, with a bonus of 50%, the reduction in CO2 emissions is 55.8% more than in the baseline scenario of no support (i.e. leading to a reduction of about 257 million tonnes per year), with a cost for the government of about 300 million euros (341 euros per inhabitant). As the bonus increases, so does the total CO2 emissions reduction and the cost to the government: the policymaker can therefore set a specific CO2 reduction target, design the appropriate level of bonus to achieve that target, and meet the cost of that policy. However, by setting an equal reimbursement percentage for everyone, the government inevitably also finances those families for whom energy restructuring would be convenient even in the absence of public intervention. A policymaker who is fully informed about building

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[1] Source: energy.ec.europa.eu.

[2] The most common mechanisms used in the EU Member States fall into two categories: non-repayable reward (grants, subsidies, tax incentives) and debt financing (loans, leasings). For a country-by-country overview of the most important ongoing European public schemes, see: Economidou et al. (2019). In the US, the Federal Tax Credit for Solar Photovoltaics is a tax credit of 30% of the cost of the system. These types of policies supporting energy efficiency have been used for decades. For a summary in OECD countries, see Geller et al. (2006).

[3] This area has fairly homogeneous climate conditions, and is a densely populated area −population: 877,405− in the Veneto region, in the north-east of Italy.

characteristics could adopt a more cost-effective strategy by paying dwelling-specific bonuses such to make the implementation of the recommendations just marginally convenient for the households, and hence can achieve the same goal at a lower cost. Comparing the flat bonus with this latter policy -which targets the households' support relatively to the characteristics of the dwellings they live - allows the assessment of its efficiency.

Our empirical analysis shows that low levels of flat bonus are particularly inefficient. For example, a bonus covering 25% of the cost to implement the EPCs' recommendation for energy efficiency of housing is 6.02 times more expensive than individual subsidies achieving the same CO2 reduction. This is because low bonus levels do little to induce household adopting EPCs' recommendation, and the government ends up subsidizing interventions that would have been carried out anyway. In contrast, a high level of flat bonus (i.e., 75%) is more efficient (only 2.18 times more expensive than individual subsidies), but it is 7 times more expensive for the government than a 25% bonus.

By matching each dwelling for which we have the EPC with information - from the Italian census and the Household Budget Survey (HBS) - on the socio-economic characteristics of the household most likely to occupy it we can study. Our analysis shows that −in the period 2015-2017, when medium to low levels of bonuses are in place − the average upfront costs of implementing the EPCs' recommendations are in the range of 10%-30% of the annual household expenditure. Note that these apparently high costs become affordable if they can be paid in instalments over the useful life of the intervention, thus suggesting that any support for improving the efficiency of dwellings should be complemented by measures to facilitate access to credit.

In addition, we use this rich dataset to investigate whether household characteristics, in particular spending capacity, correlate with the probability that the suggested improvement, if subsidized, is worth implementing. This analysis can be particularly interesting from a political economy perspective: if - even in absence of liquidity and credit constraints - bonuses are more likely to be enjoyable mostly by the richest households, political support for this intervention − financed with public funds − may fade. Our empirical results show that this is not the case: building characteristics play a far more important role, except for a very high level of bonus (i.e., 75%).

We contribute to three main strands of literature using micro-level data to investigate the cost of investment in energy efficiency improvements in residential buildings and, in turn, the reduction of CO2 emissions. A first strand of this literature has focused on the role of housing prices. These studies consistently found that green buildings command a premium compared to non-labeled homes, highlighting the positive price effects of mandatory and voluntary EPC labels (Eichholtz et al., 2013; Kahn and Kok, 2014; Fuerst et al., 2015; Aydin et al., 2019). Other studies have demonstrated a positive impact of energy efficiency for rental markets, underlining the value that tenants place on energy-efficient properties. In contrast to most papers, a different strand of the literature reported limited or negligible effects of energy labels on dwelling prices (Murphy, 2014; Fregonara et al., 2017; Olaussen et al., 2019; Myers, 2019). Finally, Taruttis and Weber (2022) suggest that the impact of EPCs is weaker in large cities, while rural regions exhibit a stronger effect.[4] Furthermore, some studies have investigated the relationship between subsidized investments in energy efficiency and subsequent capitalization. These papers have found that upfront investment costs are approximately double the actual energy savings (Fowlie et al., 2018), as the engineering models predicting higher expected savings are flawed. Christensen et al. (2022) show that targeting the public subsidies to homes with specific characteristics improves the effectiveness of investment in energy efficiency dramatically.

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[4] The relationship between EPCs and house prices has also been studied in Brounen and Kok (2011), Cerin et al. (2014), Fuerst et al. (2016), Loberto et al. (2023) and −for commercial property assets− in Fuerst and McAllister (2011).

We add to this literature original results on the effects of government's bonuses supporting investments in the dwelling's energy efficiency improvements (and increasing the dwelling's price).

A second strand of literature looks at CO2 emissions from residential buildings and related policies for their reduction. Goldstein et al. (2020) use building-level data from the US to compare greenhouse gas emissions from neighborhoods differing in income and urban density. They propose using home retrofits to reduce energy demand and model different greenhouse gas emissions reduction scenarios depending on the level of government intervention. Differently from these authors, which focus on the aggregate outcome of the policy, in our paper we investigate its design and relative efficiency. In this literature, engineers usually use EPCs to derive optimization models to be adopted in identifying the best combination of retrofit options (see, among others, Fan and Xia, 2018, Delmastro et al., 2016, and Ali et al., 2020,) and to design the energy planning at local/regional scales (Dall'O' et al., 2012, 2015). We contribute to this literature by taking into account the fact that policy makers are not always fully informed and that they are limited in the set of policies they can implement.

Finally, our research relates to the strand of literature on the methodological exploitation of EPCs datasets. [5]Curtis et al. (2015), for example, use EPCs to show that the location and occupancy type of energy inefficient buildings can be derived using census and other commonly available data. Differently from Curtis et al. (2015), in this paper, we propose a novel approach: starting from a subset of houses for which EPC data are available, we use appropriate weights to make the data representative of the entire housing stock of the area under study. In a recent paper (see: Camboni et al. (2021)), we link each EPC to the characteristics of the household (from the census) most likely to live there, using a non-parametric micro approach called (conditional) random hotdeck. We borrow the approach developed in Camboni et al. (2021) - used to investigate fuel poverty -, and adopt it for the present analysis.

The remainder of the paper is organized as follows. Section 2 illustrates our data and presents descriptive statistics to guide the subsequent analysis. Section 3 discusses how the micro-level data can be used to assess the efficiency of a policy that subsidizes a fixed proportion of the cost of building renovation. The results of our analysis are presented in Section 4 and, with the addition of household information, in Section 5. Finally, Section 6 concludes with policy implications.

# 2 Data and descriptive statistics

In this Section we present datasets our analysis relies on. The first data source is the register of EPCs for the Treviso Province (2.1), which provides information on CO2 emissions and standardized heating costs. The second data source is the 2011 General Population and Housing Census, run every ten years by the Italian National Statistical Institute (ISTAT), which provides information on the entire residential building stock (2.2). Finally, we illustrate and discuss related descriptive statistics (2.3).

## 2.1 Energy Performance Certificates, EPCs

EPCs were introduced in the European Union Member States by the 2002 Energy Performance of Buildings Directive (EPBD) and, since then, have been amended several times, most recently

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[5] For a survey of the origins and historical development of energy certification schemes for buildings, see Pérez-Lombard et al. (2009), while Pasichnyi et al. (2019) review existing applications of EPC data and highlight critical aspects of their implementation. Among these, concerns have been raised about data quality (Hårsman et al., 2016; Jenkins et al., 2017; Las-Heras-Casas et al., 2018). To address these concerns, a new EU regulation mandates the monitoring of a statistically significant random sample of EPCs issued annually, starting in 2015.

by the EPBD 2018/844. These directives aim to improve the energy performance of buildings by informing owners, tenants and potential buyers of a dwelling of its energy efficiency expressed by the primary energy use in kWh/$m^2$/year. The information contained in EPCs is the same for all EU Member States,[6] and several countries currently provide open access to their local EPC registers.[7]

We accessed the EPCs of around 25,000 homes located in the province of Treviso. The certificates were issued between September 2015 and December 2017 in the format adopted in Italy from Q4-2015. Each EPC contains information on the surface and volume of the home, its date of construction, its geo-location (latitude and longitude) and the characteristics of the building. In particular, EPCs provide information on the type(s) of energy sources available, separately, for heating, cooling, hot water, and mechanical ventilation; the use of renewable energy sources; insulation; and the orientation of the home/building (north, south, etc.). Based on this information, each certificate provides an estimate of the energy required to meet the various needs associated with what the regulation considers a standard use of the home over a year and the associated level of CO2 emissions. The estimates of the energy requirements are available separately for each energy vector and an overall measure expressed in kWh/$m^2$/year is also provided. These estimates are used to create a simple alphabetical grading of dwellings from most to least efficient, i.e.: A4-A3-A2-A1-B-C-D-E-F-G.[8]

Using these data, we construct a home-specific standardized measure of heating costs, $CS_i$. Specifically, we construct the sum, for all energy vectors $v = 1, ..., V$ used for heating, of the unit cost of the fuel $p_v$ multiplied by the scaled consumption $C_{iv}$ in home $i$:[9]

$$CS_i = \sum_{v=1}^{V} p_v C_{iv} \tag{1}$$

EPCs are also issued to suggest ways to reduce energy consumption (Pérez-Lombard et al., 2009) by providing from 1 to 6 different recommendations that describe the type of improvement suggested and the level of energy efficiency that can be achieved.

We use textual analysis to classify the type of improvement recommended in 7 different categories: insulation (external, internal, loft, roof), doors and windows, water heater, solar thermal panels, photovoltaic solar panels, heat pump, and mechanical ventilation systems. Using these categories and information on the size and technical characteristics of each dwelling, we then assign a standardized cost to each recommendation.[10]

The new level of energy efficiency after the implementation of each recommendation is expressed in kWh/$m^2$/year and is also shown in the EPC. We assume that the associated reductions in CO2 levels and heating costs are proportional to the increase in energy efficiency due to the recommendation.[11] Specifically, CO2 emissions of home $i$ after implementing the

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[6] *"The energy performance of a building shall be expressed by a numeric indicator of primary energy use in kWh/$m^2$/year for the purpose of both energy performance certification and compliance with minimum energy performance requirements. The methodology applied for the determination of the energy performance of a building shall be transparent and open to innovation"* (Directive 2018/844).

[7] Directive 2018/844 requires only aggregate data to be made available for research or statistical purposes (Article 8(6b)). In Italy, public access to the EPC register depends on Regional Authorities. The Veneto register, used in this analysis, is not available to the general public. An open dataset of EPCs is available for a nearby region, Lombardy, see `http://www.cened.it/statistiche_cened`. This open dataset does not include the exact geo-location of dwellings.

[8] There is a strongly significant relation between residential buildings energy efficiency labels and household energy expenditure, that has been quantified in Curtis and Pentecost (2015).

[9] Appendix C provides a detailed description of the methodology used to construct this standardized measure of heating costs. The same methodology was used by Camboni et al. (2021).

[10] Appendix D provides a detailed description of the methodology used to construct the recommendation costs. Costs refer to implementing a recommendation in the period 2015 to 2018.

[11] Appendix E presents a scatter plot that illustrates the relationship between CO2 emissions and energy

recommendation are set equal to:

$$CO2_{i1} = \frac{EP_{i1}}{EP_{i0}} CO2_{i0} \tag{2}$$

where $EP_{i0}$ and $EP_{i1}$ measure the energy required (in kWh-equivalent/$m^2$/year ) and $CO2_{i0}$ and $CO2_{i1}$ measure CO2 emissions (in kg/$m^2$/year), respectively before ($t = 0$) and after ($t = 1$) implementing the recommendation. In a similar vein to equation (2), we also derive the standardized heating costs in $t = 1$, i.e. should a recommendation be implemented. Specifically, we assume that the consumption of each energy vector used for heating is reduced in proportion to the increase in energy efficiency.[12]

After cleaning the data, we were left with 19,838 recommendations for 17,017 different dwellings.[13] When multiple recommendations are proposed for the same dwelling, we assume that each recommendation can be implemented independently of the others and that the CO2 emission reduction associated with a recommendation does not depend on the sequence in which the recommendations for a given dwelling are implemented. In other words, we assume that an intervention has the same effect regardless of whether or not another intervention has previously been carried out in the same dwelling. In our opinion, the measurement error is negligible since in 86% of the cases recommendations are the only intervention suggested for the dwelling, and only 2% of dwellings have more than two recommendations.

## 2.2 Census Data

According to the Italian legislation, an EPC is required for every dwelling on the housing market, whether for sale or for rent, and to have access to the tax incentives associated with energy renovations. We use the 2011 General Population and Housing Census data to compute the weights necessary to extend the results obtainable on certified dwellings to the universe of dwellings. Census data are also used in Section 5 to match the dwellings with the socio-demographic characteristics of the households most likely to inhabit them.[14] Specifically, the had access to Census micro data on 347,883 households and 399,815 homes in the Treviso province in 2011.[15]

In our exercise, we focus on inhabited homes and on records that have all the information needed to associate the houses in the Census with the EPCs records. This reduces the number of useful homes in the Census dataset to 279,964 which we consider our reference population from now on. Our EPC data covers only 6.3% of the housing stock considered in the province of Treviso, and, unsurprisingly, the characteristics of certified accommodations are different from those of the overall housing stock (see Table 1a). We calculate weights for EPCs relying on Census data and defining strata based on the date of construction of the houses, their size, the main heating fuel (natural gas or other), and the degree of urbanization (below/above 500 inhabitants/km2). Weighting the EPC data renders them representative of the housing stock of the province and improves the external validity of our exercise.

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efficiency in our dataset before implementing recommendations. The scatter plot, along with the R-squared value of 0.82 obtained from regressing energy efficiency on CO2 emissions using OLS, suggests a linear relationship between the two variables.

[12] This assumption is reasonable for the two most frequently observed categories of recommendations in our dataset: improvements to building insulation and the replacement of old natural gas boilers with new condensing boilers.

[13] Starting from the original 25,182 of EPCs, we classify in the 7 categories listed above 20,610 recommendations for 17,506 different dwellings. From these, we remove: (i) 489 dwellings and their 587 recommendations because the EPCs contained no information on heating costs, and, (ii) 185 recommendations because they were duplicate records in the same dwelling.

[14] The 2011 Census was used because we do not have access to the micro data of more recent Censuses.

[15] Aggregated data are available at `http://dati-censimentopopolazione.istat.it/Index.aspx`. The municipality is the smallest area for which Census data are publicly available.

## 2.3 Descriptive statistics

Table 1a shows the characteristics of the homes based on Census data (column 1), EPC data (Column 2) and weighted EPC data (Column 3). Table 1a highlights two important features. First, homes with a valid EPC (column 2) are substantially different from the overall housing stock (column 1): homes with an EPC are, on average, newer, smaller, more likely to use natural gas and to be located in an urbanized area (above 500 inhabitants/km2). Once weighted, as expected, the marginal distributions of the variables used to define the strata are equivalent between EPC and Census. Second, using the weights allows us to effectively reduce the difference between the average size based on EPC and Census data, less for the average population density. In the analysis which follows, all the statistics are computed using EPC weighted data.

**Table 1a:** Descriptive statistics of Census and EPC, unweighted and weighted data, Treviso province.

| | **CENSUS**<br>% | **EPC data unweighted**<br>% | **EPC data weighted**<br>% |
|---|---|---|---|
| Construction period | | | |
| Before 1961 | 20.92 | 13.09 | 20.92 |
| 1961–1970 | 17.28 | 14.80 | 17.28 |
| 1971–1980 | 19.28 | 14.04 | 19.28 |
| 1981–1990 | 13.29 | 10.40 | 13.29 |
| 1991–2000 | 12.70 | 15.29 | 12.70 |
| From 2001 | 16.52 | 32.39 | 16.52 |
| Surface (sqm) | | | |
| <= 60 | 11.03 | 20.68 | 11.03 |
| 61-80 | 18.26 | 22.88 | 18.26 |
| 81-100 | 23.25 | 19.62 | 23.25 |
| 101-120 | 15.58 | 13.04 | 15.58 |
| 121-140 | 8.42 | 7.62 | 8.42 |
| > 140 | 23.46 | 16.17 | 23.46 |
| Heating fuel: Natural gas | 73.14 | 85.25 | 73.14 |
| 500+ inhabitants / km2 | 28.48 | 40.72 | 28.48 |
| | **mean** | **mean** | **mean** |
| Surface (sqm) | 114.469 | 98.696 | 112.116 |
| Degree of urbanization | 456.184 | 609.767 | 526.240 |

Notes. *Construction period* and *Surface* area are a set of dummy variables denoting, respectively, the decade in which the building was constructed and its total size. Note that we also include the mean surface area of the dwellings in the two datasets. *Heating fuel* is a dummy variable equal to one if the main energy vector used for heating is natural gas. *500+ inhabitants / km2* denotes the share of dwellings in municipalities with a density above 500 inhabitants / km2.

Table 1b shows the descriptive statistics of the energy requirements, CO2 emissions, and heating costs (where subscript *0* and subscript *1* refer to before and after implementing the recommendation). *EP* and *CO2* represent the energy required and the CO2 emitted to heat 1 sqm per year, respectively. The variable *Heating cost* measures the standard heating cost of a dwelling (see Appendix C). Statistics for the recommendations are also set out, including the upfront total cost (*Recommendation total cost*), the same cost divided by the serving life of the recommendation (i.e. an annual cost, *Recommendation annual cost*) and the difference between the annual savings in heating costs and the annual cost (*Recommendation value*).

Table 1b includes three interesting empirical evidence. First, the total recommendation cost largely exceeds the reduction in the heating costs for one year ($Heating\ cost_1 - Heating\ cost_0$), even even spreading the initial costs over the entire serving life, more than half of the recommendations have a negative *Recommendation value* and therefore would not be implemented without an external incentive. Second, any energy efficiency intervention requires a large up-front payment, whilst producing benefits over a much longer period (the median useful life for a recommendation is 25 years), therefore, although restructuring may be convenient, households either have sufficient cumulated savings or they need access to credit to finance the intervention. Third, recommendation values vary between homes with different energy performances: recommendations in the least efficient houses (EPC classes F-G) produce the largest median benefits.

**Table 1b:** Descriptive statistics of the EPC weighted data, Treviso province.

| | All observations | | | by EPC class | | |
|---|---|---|---|---|---|---|
| | | | | A-B | C-E | F-G |
| *percentile* | $10^{th}$ | $50^{th}$ | $90^{th}$ | $50^{th}$ | $50^{th}$ | $50^{th}$ |
| Surface (sqm) | 58.9 | 98.1 | 187.0 | 121.9 | 95.1 | 98.2 |
| $EP_0$ (Kwh/sqm/year) | 79.5 | 171.8 | 326.0 | 66.5 | 130.9 | 239.1 |
| $EP_1$ (Kwh/sqm/year) | 58.2 | 124.6 | 239.5 | 52.2 | 102.3 | 168.0 |
| $CO2_0$ (Kg/sqm/year) | 16.9 | 36.6 | 71.7 | 14.0 | 27.8 | 51.1 |
| $CO2_1$ (Kg/sqm/year) | 12.0 | 26.9 | 53.6 | 11.2 | 22.1 | 35.7 |
| Heating $\text{cost}_0$ (€) | 315.2 | 847.9 | 3147.2 | 447.3 | 612.0 | 1241.3 |
| Heating $\text{cost}_1$ (€) | 226.9 | 626.0 | 2354.1 | 350.3 | 473.5 | 841.9 |
| Recommendation cost TOTAL (€) | 3500.0 | 5830.1 | 18000.0 | 6000.0 | 5390.4 | 6193.0 |
| Recommendation cost YEAR (€) | 91.7 | 176.2 | 767.6 | 233.3 | 176.2 | 171.5 |
| Recommendation value YEAR (€) | -682.7 | -17.7 | 692.6 | -152.4 | -59.8 | 103.6 |
| Recommendation useful life (Y) | 20 | 25 | 50 | 20 | 20 | 50 |

Notes. For a given variable, the subscripts 0 and 1 denote, respectively, before and after implementing the recommendation. $EP$ and $CO2$ measure, respectively, the energy required and the CO2 emitted to warm 1 sqm per year; *heating cost* measures the standardised heating cost of a dwelling; *Recommendation cost* gives the implementation cost; we include the overall (TOTAL) cost, and the overall cost divided by the useful life of the intervention (YEAR); *Recommendation value* is the difference between the reduction in the heating costs from 0 to 1 and *Recommendation cost YEAR*. *Recommendation useful life* is the expected useful life of the recommendation if implemented, in years. Weighted sample.

# 3 Methodology

For a government, choosing which recommendations to support with a bonus in the aim to reduce CO2 emissions from the residential building sector is crucial. Indeed, a poor choice would lead to waste of public resources and more CO2 in the atmosphere than would otherwise be the case.

The efficient choice depends on the policymaker's objectives and the information available. We begin with the simplest case, where the government is perfectly informed of the characteristics of the dwellings and the possible efficiency interventions connected to them and pays all the implementation costs. We then relax both these assumptions. First, the government exploits its full information and only covers any fraction of the costs needed to make it cost-effective for the homeowner to carry out the renovation. This is akin to the optimum policy of a social planner with full information. Second, we use the social planner's optimum decision as a benchmark for evaluating the efficiency of a policy where the government - under imperfect information, being unable to provide tailored bonuses - simply covers a certain percentage of the cost to implement an EPC recommendation for anyone who requests it.

## 3.1 The aggregate total cost curve for CO2 emissions reduction

Denote with $C_r$ the total implementation cost of a recommendation $r \in \{1, ..., R\}$, and $E_r$ the related reduction in the CO2 emissions, in kg. Define $c_r$ as the cost of reducing 1 Kg of CO2 per year:

$$c_r = \frac{C_r}{E_r} \tag{3}$$

This measure informs in relation to cost-efficiency: the prices equal, one recommendation is more efficient than another if it reduces more CO2 when implemented. We use $c_r$ to order all recommendations from the most to the least cost-efficient −i.e. from the lowest to the highest value of $c_r$.

$$c_1 \leq c_2 \leq ...c_r \leq ... \leq c_{R-1} \leq c_R. \tag{4}$$

Then, consider an emission reduction target $\mathcal{T}$ which is feasible (that is, $\mathcal{T} \leq \sum_{r=1}^{R} E_r$). The most cost-efficient way to achieve it is to implement all recommendations from the most cost-efficient, $c_1$, up to the recommendation with the unitary CO2 abatement cost $c_X$ such that $\mathcal{T} = \sum_{r=1}^{X} E_r$, $X \leq R$.

Following this intuition, publicly available information from EPCs can be used to construct a total cost curve for CO2 emissions reduction relating every feasible target $\mathcal{T}$ (on the horizontal axis) with the lowest total cost $C(\mathcal{T})$ that has to be paid to achieve it (on the vertical axis).[16] In symbols:

$$\begin{aligned} C(\mathcal{T}) &= \min_X \sum_{r=1}^{X} C_r \\ s.t. \quad & c_1 \leq ... \leq c_X \leq ... \leq c_R \\ s.t. \quad & \sum_{r=1}^{X} E_r \geq \mathcal{T} \end{aligned} \tag{5}$$

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[16] In the same vein, it is possible to derive the aggregate marginal cost curve for reducing CO2 emissions by an additional kg, relating $c_r$ with a reduction target $\mathcal{T}$.

Relying on this curve, the policymaker can establish a given CO2 emissions reduction policy and target those recommendations whose energy improvements have to be supported with bonuses.

### 3.2 A fully informed social planner

Implementing a EPC recommendation - leading to an increase in the dwelling's energy efficiency - produces, on the one hand, a private benefit (i.e. a decrease in heating costs) and, on the other hand, a positive externality (i.e. the reduction of CO2 emissions). Therefore, a fully informed policy maker −akin to a social planner− should design a policy intervention where the owners of the dwellings pay part of the total cost required to achieve an emissions reduction target $\mathcal{T}$. In this framework, the social planner's problem becomes not only selecting which recommendations to subsidize but also the size of the bonus to be given for each dwelling. Intuitively, this bonus should be designed so that the household is indifferent if the recommendation is implemented or not. For a household, a recommendation can be viewed as an investment that, in return for an initial payment $C_r$, produces a stream of future payoffs. Without any policy intervention, its net present value (NPV) can be expressed as:

$$NPV_r = B_r - C_r \tag{6}$$

where $B_r = \sum_{t=0}^{T} \frac{|h_r^1 - h_r^0|}{(1+\delta)^t}$ is the actual value of the future private benefit; $h_r^0$ and $h_r^1$ are, respectively, the heating costs before and after implementing recommendation $r$, $\delta$ is the intertemporal discount factor and $T$ is the useful life of the intervention (i.e., the useful working life of a new heater).

Note that future heating costs are only known in expectation, as they depend on the future cost of the energy vector used and on future weather conditions and temperatures. This is a problem for a risk-averse household. In this case, we would need to include this risk aversion in equation 6 through an additional parameter. Unfortunately, we do not have separate information on households' risk attitudes and intertemporal preferences. For this reason, we allow $\delta$ to capture both effects.[17]

Assuming no friction in the financial market, a fully informed social planner knows that a policy intervention should target only those recommendations with a negative NPV, as the others will be implemented regardless of any subsidy. Define $c_r^P$ as the cost for the social planner *net of private benefit* for reducing 1 Kg of CO2 per year:

$$c_r^P = \begin{cases} \frac{C_r - B_r}{E_r} = -\frac{NPV_r}{E_r} & if\ C_r \geq B_r \quad (i.e.\ if\ NPV_r \leq 0) \\ 0 \quad if\ C_r < B_r & (i.e.\ if\ NPV_r > 0) \end{cases} \tag{7}$$

Equation 7 informs the social planner on the level of subsidy per Kg of reduced CO2 each recommendation should receive if funded. The total subsidy for $r$ is simply $S_r = c_r^P E_r = -\mathbf{1}(NPV_r \leq 0)NPV_r$, where $\mathbf{1}()$ is an indicator function.

We now turn to the problem of choosing which recommendation to subsidize. $c_r^P$ defines the cost-efficiency *net of the private benefit* for each recommendation: given two recommendations with the same subsidy $S$, the one with the lowest level of $c_r^P$ provides the highest emissions reduction $E_r$. As in the previous section, we order all recommendations from the most to the least cost-efficient *for the social planner*:

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[17] Note that equation 6 abstracts from two additional factors that could potentially alter the NPV of a recommendation. First, if the house is rented, $h_r^1 - h_r^0$ represents the increase in rent that the owner can obtain by implementing the recommendation. This increase is a number between 0 (if the tenant has all the bargaining power) and the reduction in heating costs (if the owner has all the bargaining power). Note that, in our data, 71.1% of the houses are homeowner occupied. Second, we do not take into account the potential increase in the value of the house as a result of implementing the recommendation, in case the house is sold before time $T$.

$$c_1^P \leq c_r^P \leq ...c_r^P \leq ... \leq c_{R-1}^P \leq c_R^P. \tag{8}$$

Therefore, the minimum cost for the social planner through a subsidy to reach an emissions reduction target $\mathcal{T}$ is given by the sum of all subsidies for the minimum number of recommendations $X$ such that $\sum_{r=1}^{X} E_r \geq \mathcal{T}$.

Hence ordering all recommendations from the most to the least cost-efficient, it is possible to construct a total bonus curve relating to a given level of CO2 emissions reduction $\mathcal{T}$ (on the horizontal axis) the lowest possible amount of public money $C^P(T)$ required to achieve this policy intervention (on the vertical axis). In symbols:

$$\begin{aligned} C^P(T) &= \min_X \sum_{r=1}^{X} C_r - B_r \\ s.t. \quad & c_1^P \leq ... \leq c_X^P \leq ... \leq c_R^P \\ s.t. \quad & \sum_{r=1}^{X} E_r \geq \mathcal{T} \end{aligned} \tag{9}$$

### 3.3 A real-world policy intervention: the implementation bonus

So far, we have relied on the policymaker having complete information about the technological characteristics of all dwellings. More realistically, when this information is not available, second-best policies need to be used. Typically, governments commit to paying a percentage of the implementation cost, i.e. a bonus, to those who can demonstrate that the costs incurred are for energy efficiency improvements (and emissions reductions). This bonus increases the number of recommendations implemented and reduces the level of CO2 in the atmosphere, compared to a non-intervention scenario; however, the policy is more expensive for the government than the benchmark case of a fully informed social planner.

Specifically, we simulate a policy financing a fraction $p \in [0, 1]$ of the total recommendation cost $C_r$. Given $p$, all recommendations satisfying the following condition are likely to be implemented:

$$\sum_{t=0}^{T} \frac{|h_r^1 - h_r^0|}{(1+\delta)^t} > (1-p)C_r \tag{10}$$

Or:

$$p > \frac{C_r - B_r}{C_r} = -\frac{NPV_r}{C_r} \tag{11}$$

The total cost of the policy, for the state, and the related CO2 emissions reduction are equal, respectively, to:

$$C^B(p) = p \left( \sum_{r \in \{R_p\}} C_r \right) \tag{12}$$

$$E^B(p) = \sum_{r \in \{R_p\}} E_r \tag{13}$$

where $\{R_p\}$ is the set of all recommendations such that $p > \frac{C_r - B_r}{C_r}$, or equivalently $pC_r > -NPV_r$, that is, the amount of the bonus is such as to compensate for any negative NPV. Note that, if a recommendation is implemented with a bonus $p$, then it is implemented for any bonus $p' \in [p, 1]$. As a result, each value of $p$ corresponds to an emissions reduction $E^B(p)$ and a total subsidy cost $C^B(p)$, both increasing in $p$.

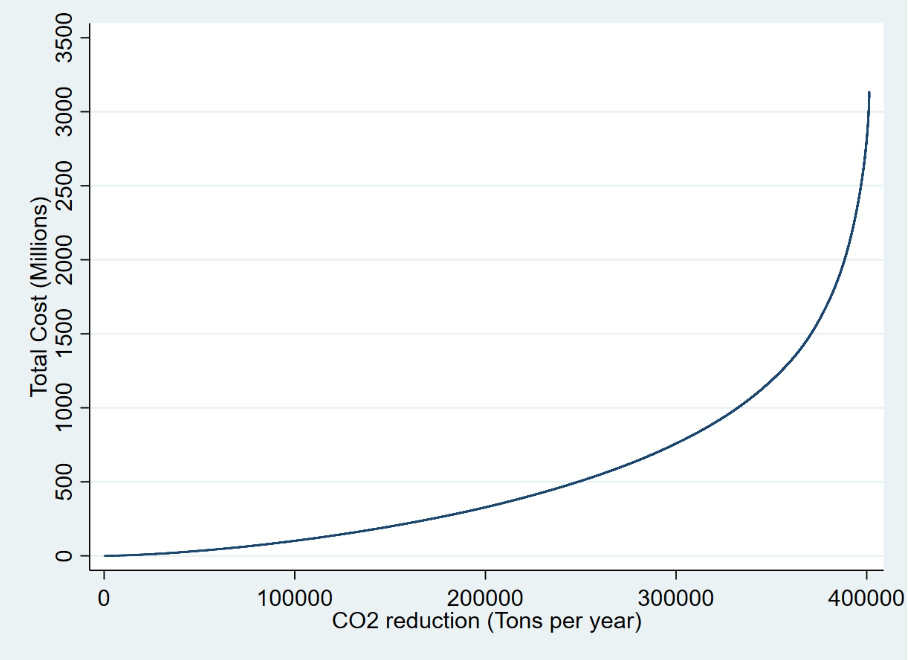
Note also that the relationship between $p$ and $E^B(p)$ can be inverted: that is, for a given emission reduction target $\mathcal{T}$, it is possible to derive the level of bonus $p$ required to achieve $\mathcal{T}$, and the associated costs to the state. This cost can be compared to what a fully informed social planner would have paid to achieve the same emissions reduction target $\mathcal{T}$.

Finally, all the recommendations with positive $NPV_r$ are implementable, no matter the level of $p$, which causes the inefficiency of this policy with respect to the benchmark case of the fully informed policy maker.

## 4 Results and policy simulation

We now turn to empirical analysis. Our goal is to estimate the cost of reducing CO2 emissions from residential buildings. For each target reduction, we estimate the total cost potentially financed by the social planner, the cost for a fully informed social planner, and the cost of an implementation bonus. To assess these costs, we use micro-level data from EPCs, weighted using census information.[18] We carry out our simulations for the province of Treviso, but the exercise can be replicated in other areas with similar data available. Note that temperatures in the Treviso province (13.1°C on average) are comparable to those of other large western cities (e.g., Baltimore).

**Figure 1:** *The aggregate total cost curve for CO2 emissions reduction.*



The horizontal axis indicates the target total CO2 reduction, in tons per year. The vertical axis shows the lowest possible total cost to achieve that emission reduction, in millions of euros. Weighted sample.

Figure 1 shows the aggregate total cost curve for different target CO2 emission reduction. The horizontal axis indicates the total CO2 reduction in tons per year. The vertical axis shows the lowest total cost to achieve each level of emission reduction, in millions of euros. It is interesting to highlight that the highest feasible reduction - 401,083 tons per year when implementing all the 19,838 recommendations, weighted using census information - is significant and represents a 31.88% cut in current emissions (equivalent to 1,258,275 tons per year). This

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[18] Appendix A provides all the estimates using unweighted data. Qualitatively, our results are unaffected by the weighting methodology used.

maximum reduction comes at a very high price, 3,134 million euros (i.e., more than 3,400 euros per inhabitant in the province[19]), because costs increase exponentially with CO2 reduction. Indeed, CO2 emissions reduction targets of 100,000, 200,000, and 300,000 tons per year (i.e., about one, two, and three quarters of the maximum reduction, respectively) can be achieved at a cost of 101 million euros (about 1/32 of the maximum reduction costs), 329 million euros (about 1/10), and 761 million euros (about 1/4), respectively.

When the total cost of reducing CO2 emissions is shared between the government and homeowners, the cost curve for the government can be estimated using equations (6) and (10), for the two cases of a fully informed social planner and of an implementation bonus, respectively. These curves are presented in Figure 2, and they are constructed setting $\delta = 0.1$.[20] Our choice on the value for $\delta$ is motivated by the fact that it can capture both the intertemporal preferences of households as well as their risk aversion (see section 3.2).

In Figure 2, panel (a), the costs incurred by a fully informed social planner to achieve a given CO2 emissions reduction are shown using a dashed blue line. For levels up to 164,984 tons per year, the social planner incurs no cost. In fact, these targets can be achieved by implementing recommendations with a positive NPV for households, and where government intervention is unnecessary. Above this threshold, the cost function for the social planner grows exponentially, and monetary transfers to selected households − those with negative NPV − are required to incentivize implementation. In all cases, the social planner pays less than the total cost (as shown in Figure 1). For example, a reduction of 300,000 tons of CO2 per year corresponds to a total cost of 761 million euros (see Figure 1). Of this cost, only 208 million euros are paid by the social planner, while the rest is paid by households (that enjoy the private benefit of reduced heating costs).

In Figure 2, panel (a), with a solid red line, we also show the results of a policy where the government pays a certain percentage $p$ (or 'bonus') of the recommendation cost to anyone who implements it. Once the bonus is set, all recommendations with a positive NPV, i.e., satisfying equation 10, are implemented. Each generates a cost to the government (which finances part of it) and a benefit (reduction of CO2 emissions). The sum of all costs and benefits for three bonus levels (25%, 50%, and 75%) are highlighted above the solid red line, and the corresponding data are shown in Table 2a. The higher the bonus increases, the greater the cost to the government and the reduction in CO2: first, more recommendations are implemented (the condition in equation 10 becomes less stringent); second, the share of the cost $p$ paid by the government for the implemented recommendations also becomes larger.

Although the increase in the bonus level leads to a greater reduction in CO2 emissions, this policy is always inefficient compared to the allocation of a fully informed social planner: given a CO2 reduction target (i.e. 300,000 tons per year), the required bonus $p = 0.66$ (not highlighted in the figure) generates higher costs for the state (561 million euros) than those incurred by a fully informed social planner (208 million euros).[21] Graphically, the vertical distance between the solid red and dashed blue lines in Figure 2, panel (a), indicates the magnitude of this inefficiency. Figure 2, panel (b), shows the log-ratio between the costs of the two policies for every CO2 reduction target. Implementing a bonus of 25% of the recommendation cost is 7.21 times more expensive than the cost a social planner with full information would have sustained to obtain the same CO2 emissions reduction. This proportion falls to 3.60 and 2.39 for a bonus equal to, respectively, 50% and 75% of the cost to implement recommendation. Overall, increasing bonus levels are associated with a decrease in policy inefficiency. This is

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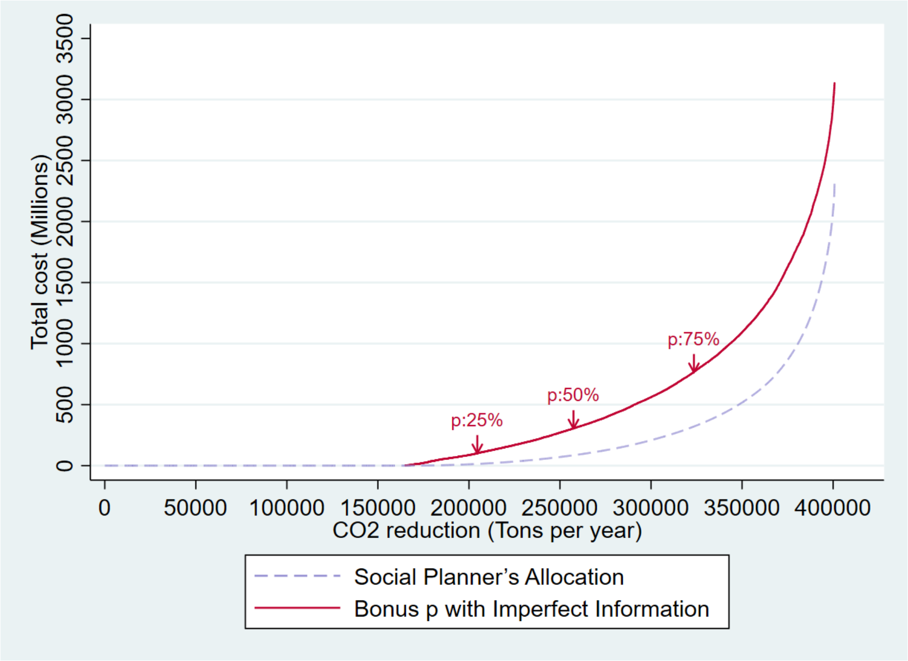
[19] Note that for the period 2020-2023, the Italian government has implemented a policy that, under certain conditions, covers the entire cost of improving the energy efficiency of a building. The per capita cost of this policy was around 1,600 euros.

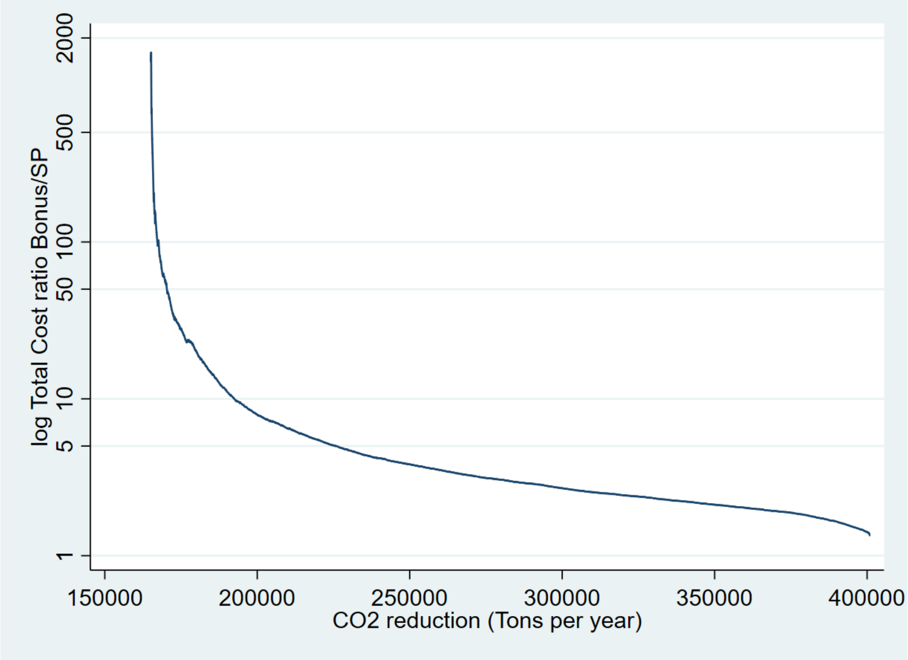
[20] In Appendix B, all the following estimates are repeated setting $\delta = 0.05$.

[21] Indeed, for each recommendation the monetary transfer with a bonus policy is always greater than or equal to the transfer of a fully informed social planner.

**Figure 2:** *Policy interventions cost for CO2 emissions reduction.*



(a) Policy interventions cost



(b) Bonus inefficiency

The horizontal axis represents the target total CO2 reduction, in tons per year. Panel (a) indicates the total cost of two policy interventions for different targets of CO2 reductions: social planner (dashed blue line) and bonus (solid red line). For the bonus, setting a CO2 reduction target is equivalent to setting the level of the benefit $p$. The costs for three bonus levels (25%, 50% and 75%) are highlighted. Panel (b), shows the log-ratio between the costs of the bonus and the social planner policy. The intertemporal discount rate used is 10%. Weighted sample.

unsurprising: low bonuses are extremely inefficient because the government is mostly subsidizing recommendations that would be implemented even without its intervention.[22]

These results highlight the fundamental trade-off that each government faces when setting the level of the bonus. On the one hand, a low bonus −corresponding to a small reduction in CO2 emissions− is inefficient (Figure 2(b)); on the other hand, a high bonus −corresponding to a large reduction− is very expensive (Figure 2(a)). These results suggest that intermediate bonus levels seem to be reasonable.

**Table 2a:** Policy intervention and average characteristics of the recommendations.

| (1) | (2) | (3) | (4) | (5) | | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| Policy level | Total cost government (MM. €) | CO2 reduction (tons/y) | Policy log-inefficiency | Share of implemented and not implemented recommendations | | Average characteristics of the recommendations | | | |
| | | | | | | Cost (€) | Benefit (Y €) | CO2 red. (Y kg) | Useful Life (Y) |
| 0% | 0 | 164,984 | | NI | 85.04% | 10069.9 | 199.2 | 834.2 | 33.0 |
| | | | | I | 14.96% | 5757.0 | 1547.3 | 3311.6 | 44.6 |
| 25% | 100.38 | 204450.5 | 7.211 | NI | 79.83% | 10353.5 | 178.9 | 739.9 | 32.3 |
| | | | | I | 20.17% | 5749.3 | 1279.6 | 3044.7 | 44.4 |
| 50% | 304.15 | 257269.4 | 3.600 | NI | 70.28% | 10969.0 | 151.9 | 614.7 | 31.0 |
| | | | | I | 29.72% | 5775.1 | 989.9 | 2599.9 | 43.6 |
| 75% | 764.38 | 323355.6 | 2.393 | NI | 52.08% | 12638.9 | 118.4 | 447.3 | 28.8 |
| | | | | I | 47.92% | 5930.6 | 708.4 | 2028.9 | 41.2 |

Notes. Column (1) lists the percentage of subsidized cost $p$ of 4 alternative policies. Columns (2) to (4) show the policy total cost to the government, the CO2 reduction, and the log-inefficiency compared to the fully informed social planner policy as in Fig. 2. Column (5) shows the proportion of recommendations implemented (I) and not implemented (NI) for each level of bonus considered; columns (6) to (9) indicate the average cost, savings on heating, CO2 reduction, years of the useful life of the implemented and not implemented recommendations. The intertemporal discount rate used is 10%. Weighted sample.

With the aim of investigating this trade-off, Table 2a shows the effects of three different levels of bonus: 25%, 50%, and 75%, compared to the baseline scenario of no government intervention. A bonus of 25% increases CO2 reduction by 23.9% from the baseline scenario, at a cost of around 100 million euros (about 114 euros per inhabitant of the province). An increase of CO2 emissions reductions of 55.9% and 96% from the baseline can be achieved with bonus levels of 50% and 75%, respectively. These reductions come with a significantly higher cost: 3 and 7.6 times more than a 25% bonus, respectively (i.e., 341 and 864 euros per inhabitant). There is also an increase in the proportion of recommendations implemented from 15% in the absence of government intervention to 48% with a bonus of 75%.

In terms of average recommendation costs, we do not see substantial differences across levels of bonus: for the implemented recommendation, the average cost ranges between 5,700 and 5,900 euros, whereas for non implemented recommendations the average costs are between 10,000 and 11,000 euros. Inspection of the types of recommendations implemented shows that the mix of recommendations does not change substantially moving from low to high levels of subsidies. A more generous policy tends to increase the number of houses with at least one recommendation implemented, rather than increasing the number of interventions per house [23]. On the contrary,

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[22] For CO2 emissions reduction targets below 164,984 tons per year, a bonus makes no sense (i.e., such a policy would have infinite inefficiency) since the targets can be achieved by implementing only recommendations with a positive NPV.

[23] Non-implemented recommendations become approximately 15% more expensive at a bonus level of 75%

as the bonus increases, both the average private (lower heating costs) and average public (lower CO2 emissions) benefits of the implemented recommendation decrease. The former falls from 1,547 to 708 euros/year, while the latter from 3,312 to 2,029 kg of CO2/year.

# 5 Household Characteristics

The policy simulations carried out in the previous section can be used to assess the level of public investment required to achieve a given reduction in CO2 emissions from residential buildings, given the policy maker's objectives and the information available. However, they do not provide information on the type of households affected by these policies. In this section, we investigate the characteristics of households benefiting more from government subsidies. In doing so, we link our EPC data with two additional data sources: the census data, already introduced in section 3.2 to define the sample weights, and the Household Budget Survey (HBS) data.

Specifically, we match EPCs with census data on about 280,000 dwellings in the province of Treviso to obtain socio-demographic information on the households living there. We then impute household expenditure based on HBS data. This multi-source statistical approach, combining different data sources (EPC, census, and HBS data), all available in EU countries, drew on Camboni et al. (2021).

The following subsections describe the information provided by the Census and HBS data and how we link it to our EPC data.

## 5.1 EPC-Census matching

The census data include information on the dwellings and the demographic characteristics of their occupants for the entire population of the Treviso province. Among dwelling characteristics, we identify those in common with the EPC data, which we call background variables, i.e., variables present in both the EPC and the census, allowing us to link these two datasets. They relate to the year of construction, the size of the dwelling, the main heating fuel (natural gas or other), the main heating system (central heating for the whole building, central heating per dwelling, or independent appliances), the domestic hot water system (natural gas, electricity or other), and renewable energy sources (with or without). In addition, the census data include census tracts, i.e. the geographical location of small contiguous areas in which each dwelling is located. In the Treviso province, a census tract has 75 households on average. Census tracts can be used as background variables because the EPC register provides georeferenced zero-dimensional information (i.e. point data) on the location of each certified dwelling.[24]

We, therefore, match the records in the EPC with those in the census to obtain a synthetic matched EPC-census dataset which enriches the original EPC records with the socio-demographic characteristics of the households most likely to live in the dwellings. To do so, we follow Camboni et al. (2021), and use a non parametric micro approach called *(conditional) random hot deck* matching.

## 5.2 Imputation of expenditure from the HBS

To retrieve household economic information, we rely on the Italian Household Budget Survey (HBS, `https://www.istat.it/en/archivio/180353`). The HBS collects detailed information on the expenditures incurred by households to purchase goods and services intended for

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compared to a bonus level of 50%.

[24] Geo-localized positions typically have a 20m error. Addresses are not shown in our data for privacy reasons.

household consumption. The survey is representative at the (NUTS-2) regional level; we use the subsample of 1,155 households surveyed in 2015 for the Veneto region.[25]

In addition to expenditure information, the HBS includes socio-demographic and housing descriptors that are consistent with census data, which allows us to integrate the previously matched EPC-census dataset with the household expenditure information available from the HBS data. To do so, we again follow Camboni et al. (2021) and impute the total monthly expenditure from the HBS to our dataset using a parametric micro approach called *stochastic regression imputation* (see, for example, D'Orazio et al. (2006)). First, we estimate a total family expenditure function from the HBS data based on dwelling and household characteristics. We then use the estimated function and the distribution of its stochastic term to impute the total family expenditure to the records in the matched EPC-census dataset.

The final output is a matched EPC-Census-HBS dataset that allows us to study how households with different socio-economic characteristics are affected differently by policies aimed at reducing CO2 emissions from residential buildings. The matching and imputation procedures reduce the sample from the 17,017 houses of the EPC dataset to 16,739 in the matched dataset, corresponding to 19,525 recommendations. As in the previous section, we calculate a new set of weights adding family type (singles, couples, couples with children, single parents, other) as a stratification criterion. Below, all the statistics are computed using these weights.

## 5.3 Policy intervention and household characteristics

The matched EPC-Census-HBS dataset allows us to investigate the characteristics of the households most likely to occupy dwellings associated with given recommendations. Table 2b presents the average household characteristics for four different levels of policy bonuses, i.e., no bonus, bonus at 25%, 50%, and 75%, distinguishing between households that occupy dwellings where recommendations have positive NPV from households in dwellings where recommendations are not implemented (that is, with negative NPV)[26]. Column (3) of Table 2b shows that the average total annual household expenditure of households with and without implemented recommendations is similar, regardless of the level of the policy bonus. The only exception is that expenditure is slightly higher for families living in dwellings with implemented recommendations when $p > 50\%$. Column (4) also shows that there is little variation in the cost of heating for households, expressed as a percentage of their total expenditure. Column (5) shows the average cost incurred by households to implement a recommendation, net of the bonus received as a partial refund from the government, i.e., $(1-p)TC_r$; column (6) sets out the average incidence of this cost on household total expenditure, $(1-p)TC_r/Exp$.

These statistics highlight how the cost for the households, and their incidence on household budgets, decrease as the bonus level increases. This is because the type of recommendations implemented does not vary with the level of the policy, $p$, nor their useful life and cost. Therefore, the cost for the households falls merely due to the increase in the refund. Nevertheless, this cost represents a large proportion of annual household expenditure for all but the highest level of the bonus; the average incidence for implemented recommendations ranges from 22.63% (with no government intervention) to 5.80% (with a bonus level of 75%). Finally, column (7) of Table 2b shows that the annual cost of the recommendations, $AC$, defined as the cost to households divided by the useful life of the recommendation, is less than 2% of total annual household expenditures, $Exp$, for each level of bonus. In other words, if the upfront cost to be paid can be spread over the entire useful life of the recommendation, its impact on annual household expenditures becomes negligible.

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[25] The province of Treviso is a one-level down administrative subdivision (NUTS-3) located in the Veneto region.

[26] The share of implemented and non implemented recommendations is slightly different than in table 2a due to sample reduction after matching.

Table 3 presents the maximum likelihood estimates of logit models for the probability of a recommendation to have a positive NPV, i.e. a positive recommendation value. Such a probability is a function of the characteristics of both the home and the household associated with the recommendation. It is estimated for four levels of policy bonuses, and the coefficients are expressed as odds ratios. Standard errors are obtained by bootstrapping 100 times the entire data matching procedure, the computation of the post-stratification weights, and the expenditure imputation.

The energy class of the home and its surface area are crucial factors determining the implementation of a recommendation, for any level of bonus. Indeed, in the absence of a bonus, $p = 0\%$, the odds of positive recommendations for homes with energy class G is 66.75 times that of the recommendations for class A homes, all else being equal. This odds ratio falls when $p$ increases, but still remains at 49.95 when $p = 75\%$. Regarding the surface area, when $p = 0\%$, the odds of implementing the recommendations in homes larger than 140 sqm is 46.02 times that of homes smaller than 41 sqm. In this case, the odds ratio increases with $p$, reaching 66.49 when $p = 75\%$. There are two additional interesting results. First, recommendations are less likely to be implemented in buildings with 9 or more dwellings, for every level of bonus. For instance, when there is no bonus, the odds of implementing recommendations in buildings with at least 9 dwellings are 0.674 times the odds for implementing recommendations in buildings with a single dwelling, i.e., in a detached house. Second, when the bonus reaches $p = 75\%$, the odds of implementing a recommendation for households belonging to the 4th quartile of the expenditure distribution are 1.267 times the odds for the households in the first quartile. The latter finding is in line with Table 2b: the gap in household expenditure between those who implement a recommendation and those who do not increases with $p$.

**Table 2b:** Policy intervention and average characteristics of the households.

| (1) | (2) | | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| Policy level | Share of implemented and not implemented recommendations | | Average HH expenditure | | $(1-p)TC_r$ | *TC Exp* | *AC Exp* |
| | | | Tot. (Y €) | % heating cost | (€) | (%) | (%) |
| 0% | NI | 84.74% | 33157.5 | 6.05% | 10573.1 | 39.95% | 1.66% |
| | I | 15.26% | 33229.2 | 6.55% | 5824.0 | 22.63% | 0.55% |
| 25% | NI | 79.48% | 33139.3 | 6.03% | 8163.2 | 30.81% | 1.30% |
| | I | 20.52% | 33281.1 | 6.49% | 4377.5 | 17.00% | 0.41% |
| 50% | NI | 70.04% | 32998.2 | 6.00% | 5776.6 | 21.79% | 0.94% |
| | I | 29.96% | 33566.1 | 6.40% | 2932.6 | 11.32% | 0.28% |
| 75% | NI | 52.05% | 32828.2 | 6.00% | 3346.9 | 12.57% | 0.56% |
| | I | 47.95% | 33537.4 | 6.26% | 1502.2 | 5.80% | 0.16% |

Notes. Column (1) lists 4 different policies that vary with the level of bonus considered. Column (2) shows the proportion of recommendations implemented (I) and not implemented (NI) if such a policy is adopted. Columns (3) and (4) indicate, on average for each recommendation (implemented or not), the yearly expenditure of the household most likely to occupy the dwelling (in euros) and the heating costs as a percentage of this expenditure. Columns (5) to (7) show the average cost of the recommendation for the household net of the benefit, in euros (specifically, $(1-p)TC_r$), its incidence on total household annual expenditure $Exp$ (specifically, $TC\_Exp = (1-p)TC_r/Exp$), and its incidence on household annual expenditure when the cost of the recommendation is spread over its useful life (specifically, $AC\_Exp = (1-p)TC_r/useful\_life/Exp$). The intertemporal discount rate used is 10%. Weighted sample.

**Table 3:** Probability of implementing the recommendation. Logit models: odds ratio. Standard errors are clustered by dwelling ID and obtained by bootstrapping 100 times the entire matching procedure, the computation of the post-stratification weights and the expenditure imputation. Number of observations: 19,525. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

| Bonus | 0% | 25% | 50% | 75% |
|---|---|---|---|---|
| Ln Recommendation cost | 0.108*** | 0.103*** | 0.096*** | 0.081*** |
| | (0.007) | (0.006) | (0.005) | (0.004) |
| EPC class. Ref: A (A1 to A4) | | | | |
| B | 2.008** | 1.998*** | 1.402 | 1.063 |
| | (0.612) | (0.523) | (0.296) | (0.160) |
| C | 1.751** | 1.910*** | 1.744*** | 2.030*** |
| | (0.469) | (0.460) | (0.324) | (0.315) |
| D | 4.540*** | 4.267*** | 3.404*** | 4.531*** |
| | (1.085) | (0.883) | (0.534) | (0.603) |
| E | 9.207*** | 9.574*** | 9.253*** | 10.591*** |
| | (2.173) | (1.896) | (1.481) | (1.451) |
| F | 23.999*** | 26.95*** | 21.955*** | 23.127*** |
| | (5.688) | (5.336) | (3.601) | (3.261) |
| G | 66.753*** | 75.717*** | 61.806*** | 49.949*** |
| | (16.221) | (15.295) | (10.136) | (7.043) |
| Construction period. Ref: before 1960 | | | | |
| 1960-1969 | 0.621*** | 0.663*** | 0.820** | 0.918 |
| | (0.061) | (0.059) | (0.068) | (0.063) |
| 1970-1979 | 0.483*** | 0.595*** | 0.743*** | 0.794*** |
| | (0.042) | (0.050) | (0.050) | (0.058) |
| 1980-1989 | 0.392*** | 0.488*** | 0.573*** | 0.682*** |
| | (0.047) | (0.049) | (0.044) | (0.044) |
| 1990-1999 | 0.478*** | 0.453*** | 0.459*** | 0.489*** |
| | (0.055) | (0.045) | (0.037) | (0.033) |
| From 2000 | 0.517*** | 0.494*** | 0.457*** | 0.457*** |
| | (0.072) | (0.060) | (0.042) | (0.030) |
| Surface, sqm. Ref: ≤40 | | | | |
| 41-60 | 2.266** | 2.670*** | 2.606*** | 3.391*** |
| | (0.861) | (0.798) | (0.722) | (0.688) |
| 61-80 | 3.310*** | 4.183*** | 4.860*** | 7.308*** |
| | (1.238) | (1.280) | (1.312) | (1.440) |
| 81-100 | 8.602*** | 9.309*** | 9.934*** | 14.658*** |
| | (3.217) | (2.839) | (2.722) | (2.917) |
| 101-120 | 17.288*** | 18.156*** | 18.247*** | 23.012*** |
| | (6.587) | (5.665) | (5.200) | (4.717) |
| 121-140 | 22.466*** | 27.385*** | 24.361*** | 32.983*** |
| | (8.852) | (8.736) | (7.089) | (6.630) |
| >140 | 46.016*** | 47.942*** | 47.087*** | 66.487*** |
| | (18.038) | (15.198) | (13.420) | (13.430) |
| Primary heating fuel: natural gas | 0.118*** | 0.192*** | 0.285*** | 0.389*** |
| | (0.009) | (0.012) | (0.019) | (0.024) |
| No central heating | 1.174 | 1.029 | 1.151** | 1.060 |
| | (0.126) | (0.091) | (0.080) | (0.062) |
| Renewable sources | 0.773 | 0.848 | 0.902 | 0.939 |
| | (0.157) | (0.159) | (0.142) | (0.126) |
| Number of dwellings in the building (Ref: One) | | | | |
| 2 | 0.999 | 1.050 | 1.148 | 1.038 |
| | (0.132) | (0.125) | (0.117) | (0.089) |
| 3-4 | 0.765** | 0.860 | 0.951 | 0.868* |
| | (0.105) | (0.106) | (0.092) | (0.066) |
| 5-8 | 0.898 | 0.928 | 0.925 | 0.867 |
| | (0.162) | (0.132) | (0.116) | (0.075) |
| 9+ | 0.674*** | 0.680*** | 0.733*** | 0.682*** |
| | (0.095) | (0.085) | (0.071) | (0.055) |
| Household income quartile (Ref: first) | | | | |
| second | 1.131 | 1.071 | 1.027 | 1.055 |
| | (0.182) | (0.133) | (0.115) | (0.101) |
| third | 1.174 | 1.131 | 1.137 | 1.165 |
| | (0.209) | (0.164) | (0.142) | (0.117) |
| fourth | 1.094 | 1.039 | 1.141 | 1.267** |
| | (0.193) | (0.154) | (0.155) | (0.143) |
| Household members | 0.898 | 0.918 | 0.969 | 0.943 |
| | (0.065) | (0.060) | (0.059) | (0.047) |
| Homeowner occupied | 1.179 | 1.110 | 1.093 | 0.925 |
| | (0.164) | (0.121) | (0.097) | (0.079) |
| Household type (Ref: single) | | | | |
| Couple with children | 1.140 | 1.005 | 1.096 | 1.192* |
| | (0.231) | (0.173) | (0.167) | (0.116) |
| Couple without children | 1.373 | 1.254 | 1.074 | 1.204 |
| | (0.331) | (0.267) | (0.207) | (0.195) |
| Single parents | 0.933 | 1.140 | 1.000 | 1.102 |
| | (0.208) | (0.220) | (0.160) | (0.153) |
| Others | 1.239 | 1.323 | 1.157 | 1.235 |
| | (0.390) | (0.400) | (0.317) | (0.275) |
| At least high school | 1.123 | 1.061 | 1.099 | 1.019 |
| | (0.118) | (0.097) | (0.074) | (0.064) |
| Age class (Ref: at most 40) | | | | |
| 41-65 | 0.965 | 0.998 | 1.051 | 1.108 |
| | (0.133) | (0.121) | (0.091) | (0.086) |
| at least 65 | 1.098 | 1.170 | 1.139 | 1.042 |
| | (0.220) | (0.211) | (0.171) | (0.127) |
| Female | 1.031 | 0.941 | 1.224** | 1.148** |
| | (0.153) | (0.115) | (0.118) | (0.075) |
| Immigrants | 1.067 | 1.079 | 0.954 | 0.980 |
| | (0.216) | (0.155) | (0.111) | (0.099) |
| Occupational status (Ref: employed) | | | | |
| Retired | 0.908 | 0.904 | 0.871 | 0.995 |
| | (0.145) | (0.127) | (0.117) | (0.114) |
| Other not employed | 0.834 | 0.858 | 0.773** | 0.881 |
| | (0.161) | (0.143) | (0.101) | (0.098) |

# 6 Conclusions

The residential building sector has a large carbon footprint and rapid change is needed to meet the specific EU target of reducing greenhouse gas emissions by at least 55% below 1990 levels by 2030 and, in general, to fight one relevant determinant of climate change. Improving the energy efficiency of buildings is an effective way to meet these targets. These improvements not only determine a positive externality for society in the form of reduced CO2 emissions, but also generate private benefits in the form of reduced heating costs. However, their upfront cost is generally high and requires a household with access to credit or sufficient savings to carry them out, limiting their adoption. Such effects can be exacerbated by the landlord/tenant dilemma, i.e. a situation where the interests of landlords and tenants are not in line, creating a barrier to the energy efficient renovation of residential properties (Ástmarsson et al., 2013).

All of this suggests that governments should intervene. Several policies have been introduced in Europe to support the energy renovation of buildings. In this paper, we assess the cost and efficiency of a policy where the government pays a percentage of the cost of improvements to anyone who applies for them. We use micro data from EPCs for the province of Treviso, Italy, containing information on the characteristics of the building as well as the type of recommendation proposed to improve energy efficiency. We weight our observations using census data. This ensures that they are representative of the local housing stock.

We find that governments face an important trade-off when setting the level of intervention, i.e. the percentage of improvement costs financed by public funds. On the one hand, low bonus levels are barely effective and poorly efficient. Low effectiveness, because the government ends up subsidizing recommendations that would have been implemented anyway. Low efficiency, compared to a fully informed social planner who would set the same CO2 reduction target and minimize the amount of public money used to achieve it. On the other hand, high levels of bonus are very expensive, as our results highlight that policy costs grow exponentially with the level of the bonus and the associated CO2 reduction. Finding the right balance depends on the public resources available and the political support for these measures. Household characteristics play a far less important role than dwelling characteristics in determining the likelihood of a recommendation being implemented. Finally, recommendation costs represent a significant proportion of annual household expenditure for all but the highest bonus levels, highlighting the importance of spreading these costs over several years.

Our empirical findings highlight the relevance of households' access to credit in particular to implement the large number of EPCs recommendations with a positive NPV; differently, bonuses by the government should be focused on those recommendations with a slightly negative NPV, which are the most cost-effective in terms of reducing CO2 emissions.

Finally, our methodology uses EPCs data which are available for any area in the European Union: accordingly, our analysis can be replicated and can help policymakers to design locally tailored policies for cost-effective improvements in the energy performance of buildings.

# References

Ali, U., M. H. Shamsi, M. Bohacek, C. Hoare, K. Purcell, E. Mangina, and J. O'Donnell (2020). A data-driven approach to optimize urban scale energy retrofit decisions for residential buildings. *Applied Energy 267*, 114861. doi.org/10.1016/j.apenergy.2020.114861.

Aydin, E., S. B. Correa, and D. Brounen (2019). Energy performance certification and time on the market. *Journal of Environmental Economics and Management 98*, 102270. doi.org/10.1016/j.jeem.2019.102270.

Brounen, D. and N. Kok (2011). On the economics of energy labels in the housing market. *Journal of Environmental Economics and Management 62*(2), 166–179. doi.org/10.1016/j.jeem.2010.11.006.

Camboni, R., A. Corsini, R. Miniaci, and P. Valbonesi (2021). Mapping fuel poverty risk at the municipal level. A small-scale analysis of italian energy performance certificate, census and survey data. *Energy Policy 155*, 112324. doi.org/10.1016/j.enpol.2021.112324.

Cerin, P., L. G. Hassel, and N. Semenova (2014). Energy performance and housing prices. *Sustainable Development 22*(6), 404–419. doi.org/10.1002/sd.1566.

Christensen, P., P. Francisco, E. Myers, H. Shao, and M. Souza (2022). Do energy efficiency investments deliver? evidence from the weatherization assistance program. *NBER Working Paper*, 30467. doi.org/10.3386/w30467.

Curtis, J., N. Devitt, and A. Whelan (2015). Using census and administrative records to identify the location and occupancy type of energy inefficient residential properties. *Sustainable Cities and Society 18*, 56–65. doi.org/10.1016/j.scs.2015.06.001.

Curtis, J. and A. Pentecost (2015). Household fuel expenditure and residential building energy efficiency ratings in ireland. *Energy Policy 76*, 57–65. doi.org/10.1016/j.enpol.2014.10.010.

Dall'O', G., A. Galante, and M. Torri (2012). A methodology for the energy performance classification of residential building stock on an urban scale. *Energy and Buildings 48*, 211–219. doi.org/10.1016/j.enbuild.2012.01.034.

Dall'O', G., L. Sarto, N. Sanna, V. Tonetti, and M. Ventura (2015). On the use of an energy certification database to create indicators for energy planning purposes: Application in northern italy. *Energy Policy 85*, 207–217. doi.org/10.1016/j.enpol.2015.06.015.

Delmastro, C., G. Mutani, and S. P. Corgnati (2016). A supporting method for selecting cost-optimal energy retrofit policies for residential buildings at the urban scale. *Energy Policy 99*, 42–56. doi.org/10.1016/j.enpol.2016.09.051.

D'Orazio, M., M. D. Zio, and M. Scanu (2006). *Statistical Matching: Theory and Practice.* Wiley.

Economidou, M., V. Todeschi, and P. Bertoldi (2019). Accelerating energy renovation investments in buildings. *EU-JRC Report JRC117816*, 1–169. doi/10.2760/086805.

Eichholtz, P., N. Kok, and J. M. Quigley (2013). The economics of green building. *The Review of Economics and Statistics 95*(1), 50–63. /doi.org/10.1162/REST_a_00291.

EU (2023). *EU energy in figures: statistical pocketbook 2023.* European Commission and Directorate-General for Energy. doi/10.2833/502436.

Fan, Y. and X. Xia (2018). Energy-efficiency building retrofit planning for green building compliance. *Building and Environment 136*, 312–321. doi.org/10.1016/j.buildenv.2018.03.044.

Fowlie, M., M. Greenstone, and C. Wolfram (2018). Do energy efficiency investments deliver? evidence from the weatherization assistance program. *The Quarterly Journal of Economics 133*(3), 1597–1644. doi.org/10.1093/qje/qjy005.

Fregonara, E., D. Rolando, and P. Semeraro (2017). Energy performance certificates in the turin real estate market. *Journal of European Real Estate Research 10*(2), 149–169. doi.org/10.1108/JERER-05-2016-0022.

Fuerst, F. and P. McAllister (2011). The impact of energy performance certificates on the rental and capital values of commercial property assets. *Energy Policy 39*(10), 6608–6614. doi.org/10.1016/j.enpol.2011.08.005.

Fuerst, F., P. McAllister, A. Nanda, and P. Wyatt (2015). Does energy efficiency matter to home-buyers? an investigation of epc ratings and transaction prices in england. *Energy Economics 48*, 145–156. doi.org/10.1016/j.eneco.2014.12.012.

Fuerst, F., P. McAllister, A. Nanda, and P. Wyatt (2016). Energy performance ratings and house prices in wales: An empirical study. *Energy Policy 92*, 20–33. doi.org/10.1016/j.enpol.2016.01.024.

Geller, H., P. Harrington, A. H. Rosenfeld, S. Tanishima, and F. Unander (2006). Polices for increasing energy efficiency: Thirty years of experience in oecd countries. *Energy Policy 34*(5), 556–573. doi.org/10.1016/j.enpol.2005.11.010.

Goldstein, B., D. Gounaridis, and J. P. Newell (2020). The carbon footprint of household energy use in the united states. *Proceedings of the National Academy of Sciences 117*(32), 19122–19130. doi.org/10.1073/pnas.1922205117.

Hårsman, B., Z. Daghbashyan, and P. Chaudhary (2016). On the quality and impact of residential energy performance certificates. *Energy and Buildings 133*, 711–723. doi.org/10.1016/j.enbuild.2016.10.033.

IEA (2022). *World Energy Outlook 2022.* International Energy Agencye.

Jenkins, D., S. Simpson, and A. Peacock (2017). Investigating the consistency and quality of epc ratings and assessments. *Energy 138*, 480–489. doi.org/10.1016/j.energy.2017.07.105.

Kahn, M. E. and N. Kok (2014). The capitalization of green labels in the california housing market. *Regional Science and Urban Economics 47*, 25–34. doi.org/10.1016/j.regsciurbeco.2013.07.001.

Las-Heras-Casas, J., L. M. López-Ochoa, L. M. López-González, and J. P. Paredes-Sánchez (2018). A tool for verifying energy performance certificates and improving the knowledge of the residential sector: A case study of the autonomous community of aragón (spain). *Sustainable Cities and Society 41*, 62–72. doi.org/10.1016/j.scs.2018.05.016.

Loberto, M., A. Mistretta, and M. Spuri (2023). *The capitalization of energy labels into house prices. Evidence from Italy.* Quaderni di Economia e Finanza, 818, Bank of Italy. www.bancaditalia.it/pubblicazioni/qef/2023-0818/QEF_818_23.pdf.

Murphy, L. (2014). The influence of the energy performance certificate: The dutch case. *Energy Policy 67*, 664–672. doi.org/10.1016/j.enpol.2013.11.054.

Myers, E. (2019). Are home buyers inattentive? evidence from capitalization of energy costs. *American Economic Journal: Economic Policy 11*(2), 165–188. doi.org/10.1257/pol.20170481.

Olaussen, J. O., A. Oust, J. T. Solstade, and L. Kristiansen (2019). Energy performance certificates—the role of the energy price. *Energies 12*(18), 3563. doi.org/10.3390/en12183563.

Pasichnyi, O., J. Wallin, F. Levihn, H. Shahrokni, and O. Kordas (2019). Energy performance certificates — new opportunities for data-enabled urban energy policy instruments? *Energy Policy 127*, 486–499. doi.org/10.1016/j.enpol.2018.11.051.

Pérez-Lombard, L., J. Ortiz, R. González, and I. R. Maestre (2009). A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes. *Energy and Buildings 41*(3), 272–278. doi.org/10.1016/j.enbuild.2008.10.004.

Taruttis, L. and C. Weber (2022). Estimating the impact of energy efficiency on housing prices in germany: Does regional disparity matte. *Energy Economics 105*, 105750. doi.org/10.1016/j.eneco.2021.105750.

Ástmarsson, B., P. A. Jensen, and E. Maslesa (2013). Sustainable renovation of residential buildings and the landlord/tenant dilemma. *Energy Policy 63*, 355–362. doi.org/10.1016/j.enpol.2013.08.046.

# Appendix A Unweighted results

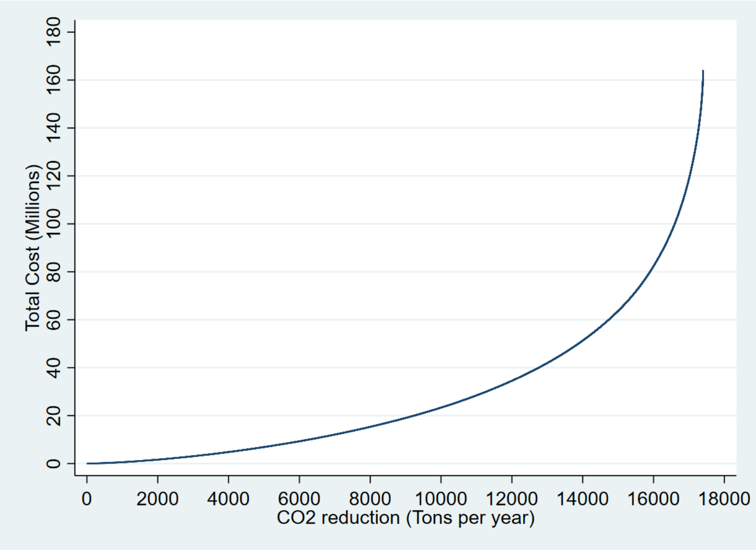
All results presented in Appendix A are derived from EPC micro-level data that are NOT weighted with census information.

**Table A1:** Descriptive statistics of the EPCs data, Treviso province.

| | All observations | | | by EPC class | | |
|---|---|---|---|---|---|---|
| | | | | A-B | C-E | F-G |
| *percentile* | $10^{th}$ | $50^{th}$ | $90^{th}$ | $50^{th}$ | $50^{th}$ | $50^{th}$ |
| Surface (sqm) | 48.1 | 86.5 | 166.8 | 120.0 | 78.2 | 89.3 |
| $EP_0$ (Kwh/sqm/year) | 69.4 | 149.8 | 291.7 | 61.9 | 124.7 | 223.2 |
| $EP_1$ (Kwh/sqm/year) | 51.9 | 111.7 | 219.0 | 48.5 | 98.4 | 157.6 |
| $CO2_0$ (Kg/sqm/year) | 14.9 | 31.9 | 62.0 | 13.6 | 26.4 | 46.8 |
| $CO2_1$ (Kg/sqm/year) | 10.9 | 23.8 | 46.8 | 10.8 | 21.0 | 33.2 |
| Heating $\text{cost}_0$ (€) | 260.5 | 603.8 | 2079.6 | 385.3 | 471.4 | 889.3 |
| Heating $\text{cost}_1$ (€) | 189.9 | 447.9 | 1590.3 | 295.5 | 369.7 | 635.5 |
| Recommendation cost TOTAL (€) | 3500.0 | 5512.5 | 18000.0 | 5880.6 | 5115.2 | 5899.0 |
| Recommendation cost YEAR (€) | 90.5 | 176.2 | 720.0 | 233.3 | 176.2 | 165.2 |
| Recommendation value YEAR (€) | -637.1 | -56.8 | 356.5 | -167.2 | -77.5 | 40.7 |
| Recommendation useful life (Y) | 20 | 25 | 50 | 20 | 20 | 50 |

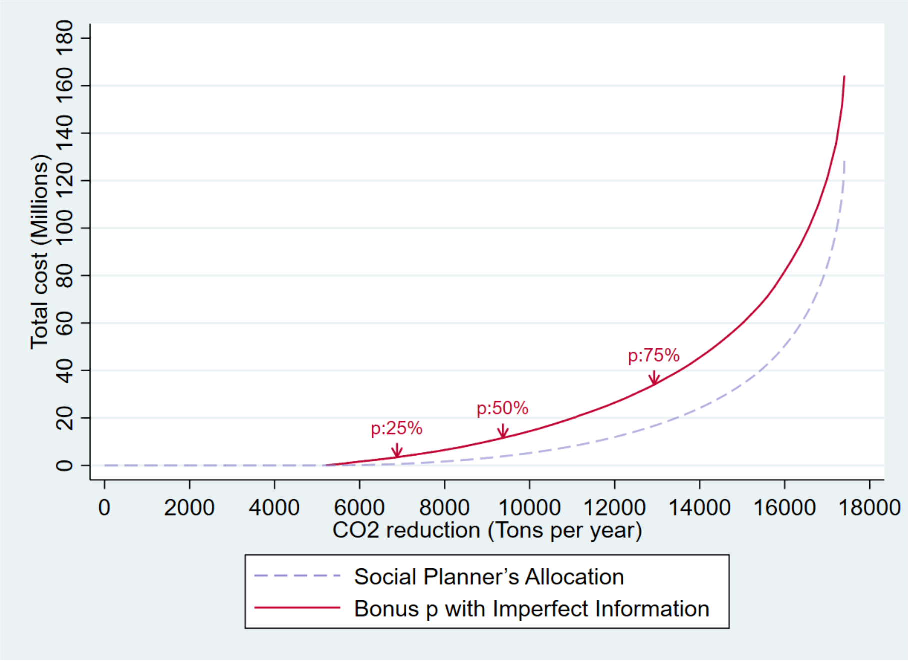
Notes. For a given variable, the subscripts 0 and 1 denote, respectively, before and after implementing the recommendation. $EP$ and $CO2$ measure, respectively, the energy required and the CO2 emitted to warm 1 sqm per year; *heating cost* measures the standardised heating cost of a dwelling; *Recommendation cost* gives the implementation cost; we include the overall (TOTAL) cost, and the overall cost divided by the useful life of the intervention (YEAR); *Recommendation value* is the difference between the reduction in the heating costs from 0 to 1 and *Recommendation cost YEAR*. *Recommendation useful life* is the expected useful life of the recommendation if implemented, in years. Unweighted sample.

**Figure A1:** *The aggregate total cost curve for CO2 emissions reduction.*

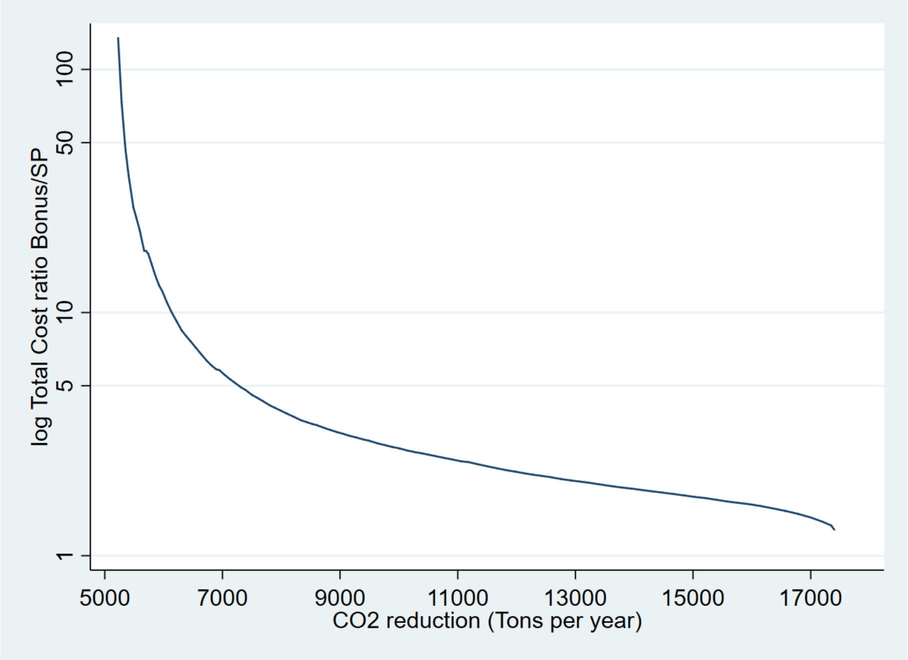


The horizontal axis indicates total CO2 reduction, in tons per year. The vertical axis shows the lowest possible total cost to achieve that emission reduction, in millions of euros. Unweighted sample.

**Figure A2:** *Policy interventions cost for CO2 emissions reduction.*



(a) Policy interventions cost



(b) Bonus inefficiency

The horizontal axis represents the total CO2 reduction, in tons per year. Panel (a) indicates the total cost of two policy interventions for different targets of CO2 reductions: social planner (dashed blue line) and bonus (solid red line). For the bonus, setting a CO2 reduction target is equivalent to setting the level of the benefit $p$. The costs for three bonus levels (25%, 50% and 75%) are highlighted. Panel (b), shows the log-ratio between the costs of the bonus and the social planner policy. The intertemporal discount rate used is 10%. Unweighted sample.

**Table A2:** Policy intervention and average characteristics of the recommendations.

| Policy level | Total cost government (MM. €) | CO2 reduction (tons/y) | Policy log-inefficiency | Share of implemented and not implemented recommendations | | Average characteristics of the recommendations | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Cost (€) | Benefit (Y €) | CO2 red. (Y kg) | Useful Life (Y) |
| 0% | 0.0 | 5175.7 | | NI | 91.47% | 8532.1 | 157.6 | 674.0 | 32.3 |
| | | | | I | 8.53% | 5381.7 | 1301.3 | 3060.7 | 43.7 |
| 25% | 3469.3 | 6888.7 | 5.843 | NI | 87.41% | 8688.8 | 143.5 | 606.6 | 31.9 |
| | | | | I | 12.59% | 5312.1 | 1029.8 | 2757.6 | 43.4 |
| 50% | 11660.1 | 9385.6 | 3.009 | NI | 79.42% | 9021.9 | 123.2 | 509.1 | 30.9 |
| | | | | I | 20.58% | 5336.1 | 764.5 | 2299.6 | 42.7 |
| 75% | 34106.2 | 12939.0 | 2.037 | NI | 60.86% | 10095.3 | 94.8 | 370.0 | 29.0 |
| | | | | I | 39.14% | 5415.8 | 504.4 | 1666.5 | 40.0 |

Notes. Column (1) lists the percentage of subsidized cost $p$ of 4 alternative policies. Columns (2) to (4) show the policy total cost to the government, the CO2 reduction, and the log-inefficiency compared to the fully informed social planner policy as in Fig. 2. Column (5) shows the proportion of recommendations implemented (I) and not implemented (NI) for each level of bonus considered; columns (6) to (9) indicate the average cost, savings on heating, CO2 reduction, years of the useful life of the implemented and not implemented recommendations. The intertemporal discount rate used is 10%. Unweighted sample.

**Table A3:** Policy intervention and average characteristics of the households.

| Policy level | Share of implemented and not implemented recommendations | | Average HH expenditure | | $(1-p)TC_r$ | $TC\ Exp$ | $AC\ Exp$ |
|---|---|---|---|---|---|---|---|
| | | | Tot. (Y €) | % heating cost | (€) | (%) | (%) |
| 0% | NI | 91.45% | 31823.0 | 5.81% | 8577.9 | 34.40% | 1.39% |
| | I | 8.55% | 33126.8 | 6.44% | 5401.7 | 21.08% | 0.52% |
| 25% | NI | 87.33% | 31818.3 | 5.79% | 6553.6 | 26.27% | 1.07% |
| | I | 12.67% | 32736.0 | 6.36% | 3996.0 | 15.76% | 0.39% |
| 50% | NI | 79.28% | 31753.5 | 5.77% | 4539.3 | 18.19% | 0.76% |
| | I | 20.72% | 32627.3 | 6.22% | 2675.2 | 10.66% | 0.27% |
| 75% | NI | 60.60% | 31638.5 | 5.74% | 2544.9 | 10.15% | 0.44% |
| | I | 39.40% | 32389.7 | 6.05% | 1356.3 | 5.49% | 0.16% |

Notes. Column (1) lists 4 different policies that vary with the level of bonus considered. Column (2) shows the proportion of recommendations implemented (I) and not implemented (NI) if such a policy is adopted. Columns (3) and (4) indicate, on average for each recommendation (implemented or not), the yearly expenditure of the household most likely to occupy the dwelling (in euros) and the heating costs as a percentage of this expenditure. Columns (5) to (7) show the average cost of the recommendation for the household net of the benefit, in euros (specifically, $(1-p)TC_r$), its incidence on total household annual expenditure $Exp$ (specifically, $TC\_Exp = (1-p)TC_r/Exp$), and its incidence on household annual expenditure when the cost of the recommendation is spread over its useful life (specifically, $AC\_Exp = (1-p)TC_r/useful\_life/Exp$). The intertemporal discount rate used is 10%. Unweighted sample.

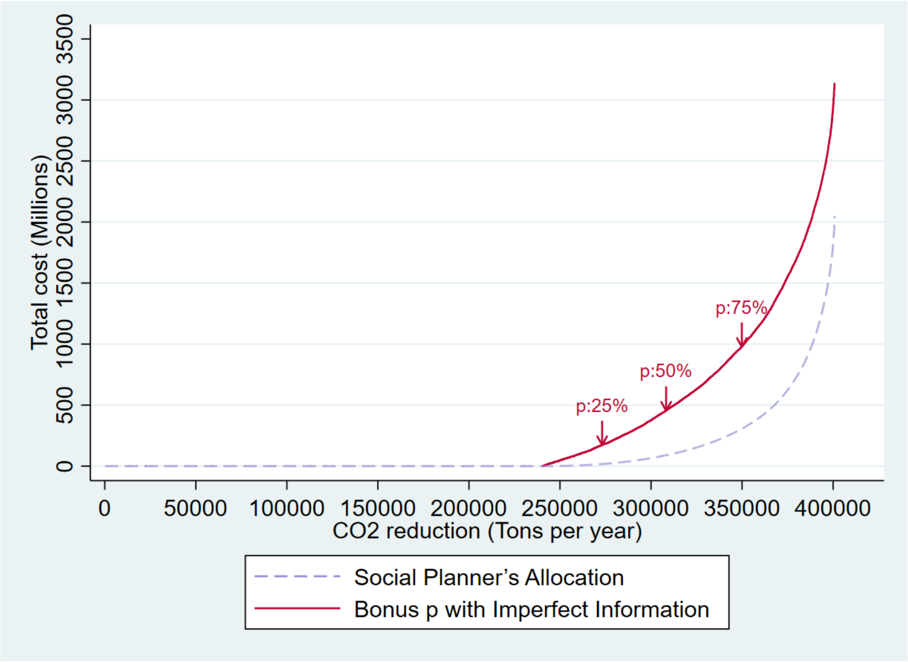
**Table A4:** Probability of implementing the recommendation. Logit models: odds ratio. Unweighted sample. Standard errors are clustered by dwelling ID and obtained by bootstrapping 100 times the entire matching procedure, the computation of the post-stratification weights and the expenditure imputation. Number of observations: 19,525. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

| Bonus | 0% | 25% | 50% | 75% |
|---|---|---|---|---|
| Ln Recommendation cost | 0.106*** | 0.093*** | 0.092*** | 0.090*** |
| | (0.006) | (0.004) | (0.004) | (0.003) |
| EPC class. Ref: A (A1 to A4) | | | | |
| B | 1.732** | 1.694** | 1.327 | 1.052 |
| | (0.438) | (0.376) | (0.238) | (0.119) |
| C | 1.600** | 1.855*** | 1.707*** | 2.113*** |
| | (0.360) | (0.382) | (0.278) | (0.230) |
| D | 4.175*** | 4.092*** | 3.287*** | 4.315*** |
| | (0.864) | (0.761) | (0.477) | (0.421) |
| E | 9.450*** | 9.318*** | 8.908*** | 9.079*** |
| | (2.003) | (1.696) | (1.274) | (0.896) |
| F | 24.386*** | 27.743*** | 23.594*** | 19.945*** |
| | (5.170) | (5.133) | (3.610) | (2.114) |
| G | 75.717*** | 92.296*** | 73.406*** | 40.854*** |
| | (16.279) | (17.167) | (11.378) | (4.249) |
| Construction period. Ref: before 1960 | | | | |
| 1960-1969 | 0.674*** | 0.694*** | 0.822*** | 0.983 |
| | (0.053) | (0.048) | (0.050) | (0.055) |
| 1970-1979 | 0.498*** | 0.613*** | 0.725*** | 0.722*** |
| | (0.038) | (0.041) | (0.043) | (0.044) |
| 1980-1989 | 0.414*** | 0.515*** | 0.576*** | 0.640*** |
| | (0.044) | (0.044) | (0.037) | (0.037) |
| 1990-1999 | 0.517*** | 0.489*** | 0.474*** | 0.480*** |
| | (0.054) | (0.042) | (0.035) | (0.027) |
| From 2000 | 0.619*** | 0.562*** | 0.490*** | 0.413*** |
| | (0.072) | (0.052) | (0.036) | (0.022) |
| Surface, sqm. Ref: ≤40 | | | | |
| 41-60 | 2.014** | 2.641*** | 3.031*** | 2.983*** |
| | (0.564) | (0.665) | (0.594) | (0.436) |
| 61-80 | 3.557*** | 4.238*** | 5.104*** | 5.546*** |
| | (0.911) | (1.064) | (0.995) | (0.787) |
| 81-100 | 7.838*** | 8.645*** | 10.623*** | 11.101*** |
| | (2.061) | (2.205) | (2.146) | (1.598) |
| 101-120 | 17.082*** | 17.957*** | 19.826*** | 17.357*** |
| | (4.715) | (4.741) | (4.144) | (2.499) |
| 121-140 | 22.021*** | 27.249*** | 27.194*** | 25.229*** |
| | (6.276) | (7.330) | (6.010) | (3.810) |
| >140 | 48.570*** | 51.009*** | 55.924*** | 49.849*** |
| | (13.842) | (13.415) | (12.136) | (7.577) |
| Primary heating fuel: natural gas | 0.113*** | 0.176*** | 0.273*** | 0.416*** |
| | (0.008) | (0.011) | (0.016) | (0.021) |
| No central heating | 1.351*** | 1.166** | 1.212*** | 1.098** |
| | (0.122) | (0.086) | (0.071) | (0.051) |
| Renewable sources | 0.564*** | 0.638** | 0.665*** | 0.894 |
| | (0.108) | (0.112) | (0.090) | (0.096) |
| Number of dwellings in the building (Ref: One) | | | | |
| 2 | 1.025 | 1.045 | 1.108 | 1.045 |
| | (0.116) | (0.104) | (0.096) | (0.077) |
| 3-4 | 0.798** | 0.861 | 0.953 | 0.957 |
| | (0.085) | (0.096) | (0.080) | (0.061) |
| 5-8 | 0.791 | 0.812* | 0.883 | 0.889* |
| | (0.123) | (0.098) | (0.095) | (0.062) |
| 9+ | 0.668*** | 0.677*** | 0.761*** | 0.750*** |
| | (0.087) | (0.078) | (0.067) | (0.053) |
| Household income quartile (Ref: first) | | | | |
| second | 1.094 | 1.022 | 1.002 | 1.019 |
| | (0.153) | (0.109) | (0.092) | (0.083) |
| third | 1.145 | 1.057 | 1.119 | 1.137 |
| | (0.164) | (0.124) | (0.106) | (0.092) |
| fourth | 1.028 | 0.998 | 1.065 | 1.181* |
| | (0.149) | (0.119) | (0.119) | (0.105) |
| Household members | 0.927 | 0.943 | 0.991 | 0.968 |
| | (0.059) | (0.051) | (0.051) | (0.039) |
| Homeowner occupied | 1.044 | 1.048 | 1.060 | 0.980 |
| | (0.119) | (0.098) | (0.077) | (0.071) |
| Household type (Ref: single) | | | | |
| Couple with children | 1.178 | 1.029 | 1.069 | 1.165** |
| | (0.194) | (0.139) | (0.122) | (0.089) |
| Couple without children | 1.353 | 1.270 | 1.091 | 1.192 |
| | (0.281) | (0.227) | (0.170) | (0.156) |
| Single parents | 0.992 | 1.168 | 1.036 | 1.097 |
| | (0.180) | (0.183) | (0.133) | (0.129) |
| Others | 1.200 | 1.354 | 1.219 | 1.077 |
| | (0.336) | (0.337) | (0.271) | (0.206) |
| At least high school | 1.075 | 1.029 | 1.064 | 0.995 |
| | (0.098) | (0.078) | (0.063) | (0.050) |
| Age class (Ref: at most 40) | | | | |
| 41-65 | 1.114 | 1.077 | 1.027 | 1.052 |
| | (0.125) | (0.107) | (0.078) | (0.070) |
| at least 65 | 1.228 | 1.223 | 1.073 | 1.004 |
| | (0.227) | (0.197) | (0.141) | (0.105) |
| Female | 0.980 | 0.963 | 1.195** | 1.129** |
| | (0.116) | (0.093) | (0.090) | (0.065) |
| Immigrants | 1.070 | 1.104 | 0.971 | 0.987 |
| | (0.160) | (0.118) | (0.096) | (0.080) |
| Occupational status (Ref: employed) | | | | |
| Retired | 0.957 | 0.925 | 0.939 | 1.045 |
| | (0.133) | (0.115) | (0.098) | (0.090) |
| Other not employed | 0.943 | 0.956 | 0.854 | 0.980 |
| | (0.147) | (0.130) | (0.096) | (0.091) |

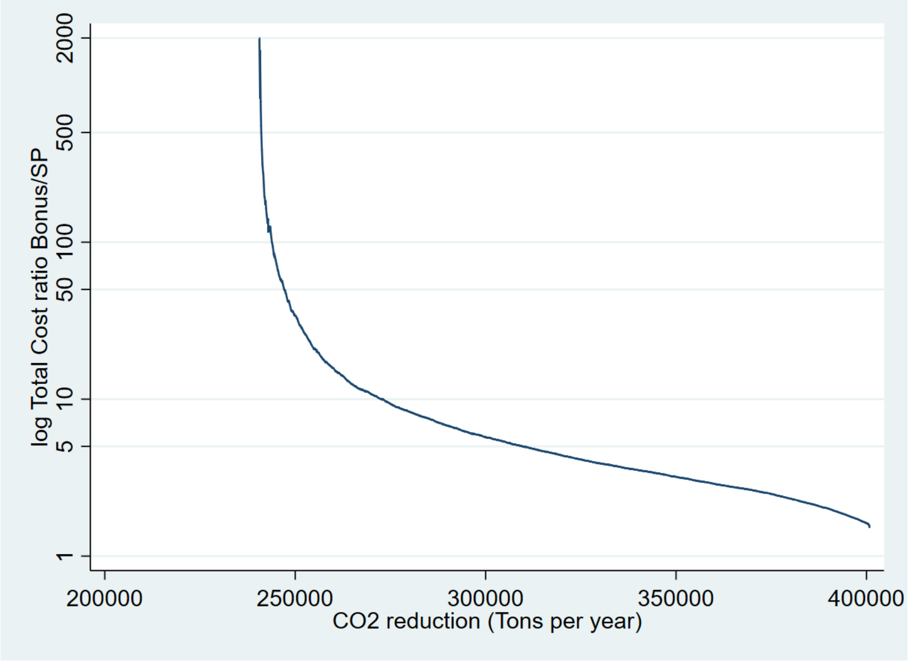
# Appendix B Discount rate 5%

All results presented in Appendix B are derived using an intertemporal discount rate of 5%.

**Figure B1:** *Policy interventions cost for CO2 emissions reduction.*



(a) Policy interventions cost



(b) Bonus inefficiency

The horizontal axis represents the total CO2 reduction, in tons per year. Panel (a) indicates the total cost of two policy interventions for different targets of CO2 reductions: social planner (dashed blue line) and bonus (solid red line). For the bonus, setting a CO2 reduction target is equivalent to setting the level of the benefit $p$. The costs for three bonus levels (25%, 50% and 75%) are highlighted. Panel (b), shows the log-ratio between the costs of the bonus and the social planner policy. The intertemporal discount rate used is 5%. Weighted sample.

**Table B1:** Policy intervention and average characteristics of the recommendations.

| Policy level | Total cost government (MM. €) | CO2 reduction (tons/y) | Policy log-inefficiency | Share of implemented and not implemented recommendations | | Average characteristics of the recommendations | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Cost (€) | Benefit (Y €) | CO2 red. (Y kg) | Useful Life (Y) |
| 0% | 0.0 | 240601.6 | | NI | 72.62% | 10749.7 | 154.1 | 663.8 | 30.7 |
| | | | | I | 27.38% | 5906.9 | 1056.5 | 2641.7 | 45.4 |
| 25% | 171409.5 | 272726.1 | 10.006 | NI | 66.04% | 11237.9 | 138.3 | 583.4 | 29.7 |
| | | | | I | 33.96% | 5896.0 | 912.4 | 2414.7 | 44.4 |
| 50% | 453266.3 | 308079.3 | 5.107 | NI | 56.52% | 12114.1 | 120.7 | 493.4 | 28.5 |
| | | | | I | 43.48% | 5926.7 | 765.8 | 2130.7 | 42.9 |
| 75% | 976442.4 | 349558.7 | 3.212 | NI | 39.91% | 14517.4 | 100.5 | 386.3 | 26.9 |
| | | | | I | 60.09% | 6040.5 | 600.9 | 1749.3 | 39.9 |

Notes. Column (1) lists the percentage of subsidized cost $p$ of 4 alternative policies. Columns (2) to (4) show the policy total cost to the government, the CO2 reduction, and the log-inefficiency compared to the fully informed social planner policy as in Fig. 2. Column (5) shows the proportion of recommendations implemented (I) and not implemented (NI) for each level of bonus considered; columns (6) to (9) indicate the average cost, savings on heating, CO2 reduction, years of the useful life of the implemented and not implemented recommendations. The intertemporal discount rate used is 5%. Weighted sample.

**Table B2:** Policy intervention and average characteristics of the households.

| Policy level | Share of implemented and not implemented recommendations | | Average HH expenditure | | $(1-p)TC_r$ | $TC\ Exp$ | $AC\ Exp$ |
|---|---|---|---|---|---|---|---|
| | | | Tot. (Y €) | % heating cost | (€) | (%) | (%) |
| 0% | NI | 72.41% | 33111.9 | 6.00% | 11318.0 | 42.65% | 1.84% |
| | I | 27.59% | 33316.7 | 6.45% | 5991.8 | 23.29% | 0.55% |
| 25% | NI | 65.86% | 32994.2 | 5.99% | 8890.4 | 33.49% | 1.47% |
| | I | 34.14% | 33504.2 | 6.39% | 4486.1 | 17.36% | 0.42% |
| 50% | NI | 56.41% | 32957.8 | 5.99% | 6411.6 | 24.10% | 1.08% |
| | I | 43.59% | 33440.8 | 6.30% | 3000.7 | 11.62% | 0.30% |
| 75% | NI | 40.28% | 32901.9 | 5.97% | 3835.9 | 14.32% | 0.66% |
| | I | 59.72% | 33347.9 | 6.23% | 1536.4 | 5.96% | 0.18% |

Notes. Column (1) lists 4 different policies that vary with the level of bonus considered. Column (2) shows the proportion of recommendations implemented (I) and not implemented (NI) if such a policy is adopted. Columns (3) and (4) indicate, on average for each recommendation (implemented or not), the yearly expenditure of the household most likely to occupy the dwelling (in euros) and the heating costs as a percentage of this expenditure. Columns (5) to (7) show the average cost of the recommendation for the household net of the benefit, in euros (specifically, $(1-p)TC_r$), its incidence on total household annual expenditure $Exp$ (specifically, $TC\_Exp = (1-p)TC_r/Exp$), and its incidence on household annual expenditure when the cost of the recommendation is spread over its useful life (specifically, $AC\_Exp = (1-p)TC_r/useful\_life/Exp$). The intertemporal discount rate used is 5%. Weighted sample.

**Table B3:** Probability of implementing the recommendation. Logit models: odds ratio. Discount rate 5%. Standard errors are clustered by dwelling ID and obtained by bootstrapping 100 times the entire matching procedure, the computation of the post-stratification weights and the expenditure imputation. Number of observations: 19,525. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

| Bonus | 0% | 25% | 50% | 75% |
|---|---|---|---|---|
| Ln Recommendation cost | 0.128*** | 0.112*** | 0.098*** | 0.068*** |
| | (0.006) | (0.006) | (0.005) | (0.003) |
| EPC class. Ref: A (A1 to A4) | | | | |
| B | 1.702** | 1.317 | 1.085 | 1.559*** |
| | (0.400) | (0.292) | (0.174) | (0.223) |
| C | 1.728** | 1.600** | 1.840*** | 2.878*** |
| | (0.394) | (0.323) | (0.283) | (0.391) |
| D | 3.908*** | 3.575*** | 3.987*** | 7.228*** |
| | (0.762) | (0.611) | (0.554) | (0.947) |
| E | 8.998*** | 9.806*** | 10.299*** | 14.541*** |
| | (1.683) | (1.608) | (1.359) | (1.789) |
| F | 21.370*** | 21.520*** | 21.434*** | 26.736*** |
| | (3.996) | (3.594) | (2.872) | (3.529) |
| G | 52.196*** | 51.728*** | 43.164*** | 49.700*** |
| | (9.552) | (8.690) | (5.870) | (6.312) |
| Construction period. Ref: before 1960 | | | | |
| 1960-1969 | 0.758*** | 0.787*** | 0.877* | 0.811*** |
| | (0.058) | (0.059) | (0.062) | (0.060) |
| 1970-1979 | 0.700*** | 0.750*** | 0.835*** | 0.789*** |
| | (0.051) | (0.049) | (0.057) | (0.056) |
| 1980-1989 | 0.542*** | 0.575*** | 0.662*** | 0.660*** |
| | (0.042) | (0.042) | (0.041) | (0.053) |
| 1990-1999 | 0.439*** | 0.417*** | 0.453*** | 0.483*** |
| | (0.035) | (0.031) | (0.031) | (0.037) |
| From 2000 | 0.401*** | 0.403*** | 0.433*** | 0.435*** |
| | (0.039) | (0.034) | (0.029) | (0.031) |
| Surface, sqm. Ref: ≤40 | | | | |
| 41-60 | 2.065** | 2.980*** | 3.177*** | 3.271*** |
| | (0.588) | (0.760) | (0.670) | (0.520) |
| 61-80 | 3.725*** | 5.479*** | 6.462*** | 7.637*** |
| | (1.028) | (1.381) | (1.325) | (1.252) |
| 81-100 | 7.973*** | 11.370*** | 13.014*** | 13.184*** |
| | (2.240) | (2.956) | (2.681) | (2.254) |
| 101-120 | 15.150*** | 20.884*** | 20.615*** | 21.824*** |
| | (4.454) | (5.513) | (4.432) | (3.906) |
| 121-140 | 18.284*** | 24.631*** | 28.050*** | 32.655*** |
| | (5.412) | (6.700) | (5.947) | (6.009) |
| >140 | 32.395*** | 47.751*** | 52.826*** | 63.118*** |
| | (9.395) | (12.797) | (11.410) | (11.929) |
| Primary heating fuel: natural gas | 0.232*** | 0.298*** | 0.358*** | 0.405*** |
| | (0.015) | (0.018) | (0.022) | (0.024) |
| No central heating | 1.221*** | 1.158** | 1.093 | 1.023 |
| | (0.092) | (0.079) | (0.071) | (0.062) |
| Renewable sources | 0.933 | 1.053 | 0.980 | 1.130 |
| | (0.149) | (0.157) | (0.141) | (0.153) |
| Number of dwellings in the building (Ref: One) | | | | |
| 2 | 1.189 | 1.207* | 1.192** | 1.023 |
| | (0.133) | (0.118) | (0.101) | (0.084) |
| 3-4 | 1.025 | 0.971 | 0.890 | 0.932 |
| | (0.099) | (0.087) | (0.074) | (0.086) |
| 5-8 | 1.013 | 0.955 | 0.917 | 0.885 |
| | (0.137) | (0.103) | (0.083) | (0.083) |
| 9+ | 0.771** | 0.797** | 0.790*** | 0.736*** |
| | (0.079) | (0.072) | (0.060) | (0.064) |
| Household income quartile (Ref: first) | | | | |
| second | 0.952 | 0.932 | 1.053 | 0.989 |
| | (0.107) | (0.090) | (0.098) | (0.091) |
| third | 1.002 | 0.972 | 1.110 | 1.083 |
| | (0.123) | (0.107) | (0.117) | (0.102) |
| fourth | 1.016 | 1.077 | 1.141 | 1.226* |
| | (0.134) | (0.137) | (0.126) | (0.140) |
| Household members | 0.945 | 0.982 | 0.971 | 0.969 |
| | (0.054) | (0.055) | (0.050) | (0.051) |
| Homeowner occupied | 1.172* | 1.081 | 0.972 | 1.028 |
| | (0.112) | (0.091) | (0.079) | (0.077) |
| Household type (Ref: single) | | | | |
| Couple with children | 1.105 | 1.170 | 1.158 | 1.218** |
| | (0.159) | (0.145) | (0.124) | (0.119) |
| Couple without children | 1.177 | 1.137 | 1.168 | 1.140 |
| | (0.227) | (0.201) | (0.194) | (0.187) |
| Single parents | 1.089 | 1.097 | 1.135 | 1.021 |
| | (0.180) | (0.155) | (0.160) | (0.140) |
| Others | 1.261 | 1.194 | 1.224 | 1.201 |
| | (0.309) | (0.296) | (0.290) | (0.255) |
| At least high school | 1.089 | 1.077 | 1.083 | 0.996 |
| | (0.079) | (0.075) | (0.068) | (0.061) |
| Age class (Ref: at most 40) | | | | |
| 41-65 | 1.133 | 1.075 | 1.079 | 1.070 |
| | (0.113) | (0.089) | (0.087) | (0.079) |
| at least 65 | 1.235 | 1.195 | 1.204 | 1.105 |
| | (0.193) | (0.171) | (0.152) | (0.135) |
| Female | 1.135 | 1.113 | 1.088 | 1.274*** |
| | (0.112) | (0.091) | (0.078) | (0.089) |
| Immigrants | 1.031 | 0.975 | 0.932 | 1.002 |
| | (0.133) | (0.101) | (0.090) | (0.093) |
| Occupational status (Ref: employed) | | | | |
| Retired | 0.868 | 0.869 | 0.888 | 0.955 |
| | (0.111) | (0.109) | (0.098) | (0.107) |
| Other not employed | 0.834 | 0.829 | 0.884 | 0.875 |
| | (0.102) | (0.097) | (0.094) | (0.094) |

# Appendix C Construction of standard heating costs

Define $v = 1, ..., V_i$ as the list of all energy vectors used for heating in dwelling $i$. The standardized measure of heating cost used in the analysis (equation 1 of the paper) is:

$$CS_i = \sum_{v=1}^{V_i} p_v C_{iv} \tag{14}$$

**Unitary prices $p_v$** We use the electricity and natural gas prices established by the Italian Regulatory Authority for Energy, Networks and the Environment (ARERA) in the enhanced protection regimen, i.e. the regulated tariff covering about 68% of the Italian retail market in the first quarter of 2015. The electricity price is based on a 3 kWh contract, the most common in Italy, and a single-hour rate tariff. For local LPG and heating oil, prices were taken from the Treviso Chamber of Commerce, year 2015. No data for wood prices in Treviso were available so 2015 data from the Bolzano Chamber of Commerce were used, a province about 100 km away. For each energy vector, the price includes all the relevant taxes.

**Consumptions $C_{iv}$** The EPC estimates are based on the assumption that dwellings are maintained at a constant temperature of 20°C, 24 hours a day. However, Italian regulation limits domestic heating in accordance with average climate conditions: for Treviso, the maximum time the heating can be left on is 14 hours a day. We correct the fuel consumption reported in the EPCs to account for this constraint and provide consistent estimates of heating costs. Specifically, we multiply the total consumption for each energy vector by a scaling factor between 0.75 and 0.9, depending on the building age. We use the residential efficiency scaling factor defined in the Veneto Regional Energy Report. (2017, p.187).[27]

**Energy vectors $v = 1, ..., V_i$ used for heating and for other needs** An EPC for a residential building considers the following primary energy uses: heating, hot water, cooling, and mechanical ventilation. All dwellings report at least one energy vector for heating and hot water. Cooling and mechanical ventilation are present in 15.7% and 1.0% of our observations, respectively. The EPCs do not break down the estimated annual quantity needed for each energy vector into these four uses. In cases where a given energy vector is used for both heating and another purpose, this leads to an overestimation of heating expenditure.

According to EPC data, 5.2% of homes use electricity for both heating and cooling. To exclude air conditioning from the standardized measure of heating costs, we set an upper limit on electricity consumption, based on homes with electric heating systems (but without cooling systems), calculating consumption per sqm. Subsequently, according to the energy efficiency class and each quartile, we calculated the median value for that ratio. We set this value as the maximum electricity consumption/sqm.

According to EPC data, most homes use the same energy vector(s) for both heating and hot water production. In this case, it is not possible to break down the quantity required for these two uses in a meaningful way. We do not see this as a problem for two reasons. Firstly, for a typical family, hot water consumption is about 10% of heating consumption.[28] Secondly, when implementing a recommendation, it is not possible to reduce hot water production costs without also reducing heating costs.

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[27] Veneto Region, 2017. Piano Energetico Regionale Fonti Rinnovabili, Risparmio Energetico ed Efficienza Energetica. Venezia: Regione Veneto.

[28] According to Italian National Regulator, a standard household requires between 120 and 480 $m^3$ of natural gas for cooking and hot water production, and between 700 and 5,000 $m^3$ of natural gas for heating. Source: `https://www.arera.it/it/operatori/stimaspesa.htm`

# Appendix D Construction of recommendation costs

For each recommendation, the EPC provides a textual description, the energy efficiency level achievable, expressed as the dwelling's new primary energy use in kWh/$m^2$/year if the recommendation is implemented, and its related energy class (from A4 to G).

Using text analysis, we classify the recommendations in the following categories: insulation (external, internal, loft, roof), windows, boiler, solar thermal panels, photovoltaic solar panels, heat pump and mechanical ventilation system. For each category, we report below how the recommendation cost was constructed.

## D.1 Insulation and windows

The EPC provides information on the useful heated surface area ($s_u$, in $m^2$), on the gross heated volume ($v_g$, in $m^3$), and whether the dwelling is a detached house or an apartment. We then make the following assumptions:

- the dwelling to have a square plan; the number of walls insulated with the outside is 4 in case of a detached house, and 2.5 in case of an apartment.
- the window/floor area ratio $w/f$ is equal to: $w/f = 0.2$ if $s_u \leq 75$, $w/f = 0.4$ if $s_u \geq 120$; $w/f$ linearly increases from 0.2 to 0.4 in $s_u$ when $75 < s_u < 120$
- the gross surface $s_g$ is equal to: $s_g = 1.2 s_u$
- the estimated ideal building height $h$ is equal to: $h = \frac{v_g}{s_g}$
- the roof has a slope of 30 degrees
- the surface required for internal insulation is 70% of the external one.

It follows that:

- the estimated floor length of the building assumed to be square is, in $m$: $l = \sqrt{s_g}$
- the estimated surface area of the external walls is, in $m^2$: $W_E = 4 \cdot l \cdot h - w/f \cdot s_u$ for a detached house, and $W_E = 2.5 \cdot l \cdot h - w/f \cdot s_u$ for an apartment.
- the estimated surface area of the roof for a detached house is, in $m^2$: $W_R = \frac{0.5l}{\cos 30} 2l$.
- The estimated surface area of the loft for a detached house is, in $m^2$: $W_L = 0.8l^2$.
- the estimated surface area of the internal walls is, in $m^2$: $W_I = 0.7 W_E$
- the surface area of the windows, not considering one main door of size 80x210cm, is, in $m^2$: $W_W = w/f \cdot s_u - 0.8 \cdot 2.1$

The unitary prices (1 $m^2$) for the insulation of the external walls, the roof, the loft and the internal walls are 80€, 90€, 50€, 55€, respectively. The useful life is 50 years.

We consider, as unitary prices for windows, a 2-pane, tilt-and-turn window, 120 × 140 cm (1.68 $m^2$) with a price (taxes included) of 1278.81€. The number of windows $N_W$ is obtained by rounding up to the nearest integer: $N_W = W_W / 1.68$. The useful life is 20 years.

## D.2 Boiler and heat pumps

We consider a boiler using natural gas as an energy vector (the price in the case of liquefied petroleum gas is similar). The power of the boiler depends (i) on the gross heated volume and, (ii) on the efficiency of the insulation. Specifically, the design thermal power (in kW) is given by: $P_b = \alpha v_g$, where the coefficient $\alpha$ is equal to 0.03, 0.05, 0.08, and 0.10 for dwellings that, after having implemented the recommendation, will reach an energy class equal to A or B, C or D, E, F or G, respectively. $P_b$ defines the size of the boiler required. We consider boilers with power equals 23.5 kW (at a cost of 3,523€), 31.5 kW (at a cost of 3,829€), and 35 kW (at a cost of 5,175€). Larger boilers (up to 150kw) have been considered where appropriate. Costs are obtained from the Official Price List of the Veneto Region (`https://www.regione.veneto.it/web/lavori-pubblici/prezzario-regionale-aggiornamento-2015-2018`). Labor, material costs and VAT have been added to the base cost of the boiler. The useful life is 20 years.

The power of the heat pump depends (i) on the useful heated surface area and, (ii), on the primary energy used for heating (variable $EP_{heat}$, in kWh/$m^2$/year). Specifically, the design thermal power (in Kw) is given by: $P_h = \frac{EP_{heat} \cdot v_g \cdot (20-T)}{D} \frac{1}{H}$, where $T = -5$ is the outdoor design temperature of the system, $D = 2378$ are the Degrees Day in Treviso, and $H = 14$ are the hours the system is operating per day. $P_h$ defines the size of the heat pump required. We consider air-to-air heat pumps with power equals to 2.1 kW (at a cost of 1,174€), 2.6 kW (1,189€), 3.5 kW (1,221€), 5.3 kW (1,382€), and water-to-air heat pumps with power equal to 6.0 kW (4,498€), 9.6 kW (5,668€), 14.2 kW (6,627€), and 21.0 kW (9,685€). Costs are obtained from the Official Price List of the Veneto Region (`https://www.regione.veneto.it/web/lavori-pubblici/prezzario-regionale-aggiornamento-2015-2018`). Labor, material costs and VAT have been added to the base cost of the heat pump. The useful life is 15 years.

## D.3 Solar thermal panels, photovoltaic solar panels, mechanical ventilation

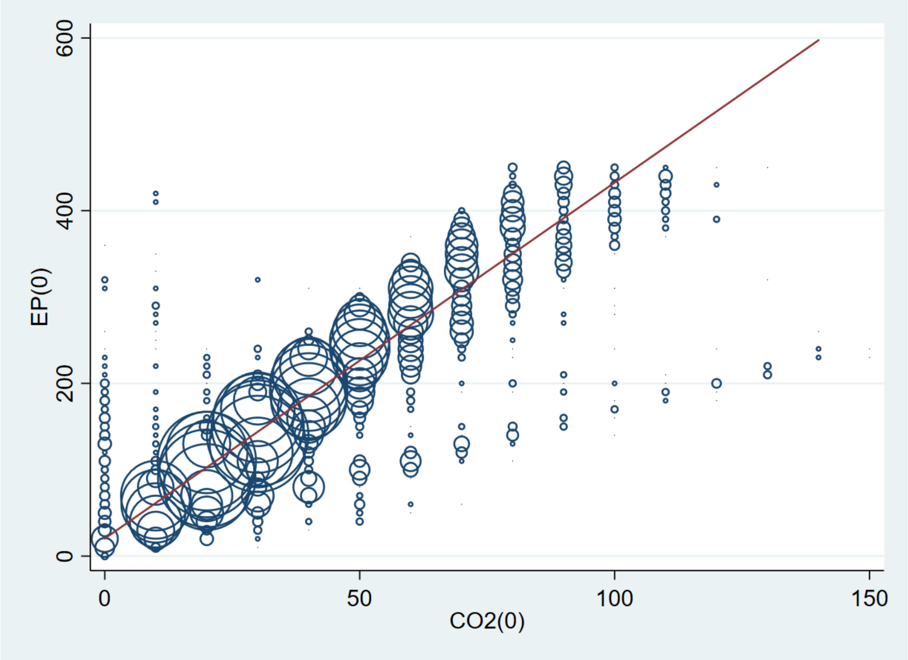
For solar thermal panels, we consider the following prices: 2,400€for a dwelling equal to or smaller than 70 $m^2$, and 3,500 for a dwelling larger than 70 $m^2$. The useful life is 15 years.

For photovoltaic solar panels, the power of the system is generally reported in the EPC. We consider the following prices: 2,000€, 4,000€, 6,000€, 10,000€, 12,000€, 18,000€, for installed powers equal to 1 Kwh, 2 Kwh, 3Kwh, 5Kwh, 6Kwh, 9Kwh, respectively. If the power is not explicitly stated in the EPC, we assume a 3 kWh system (standard in the period under consideration). The useful life is 25 years.

For mechanical ventilation systems, we consider the following prices: 6,500€, 8,500€, 10,000€, 11,500€, 15,000€, 18,000€, 21,000€, for dwellings of the size of $\leq$ 92.5$m^2$, 92.5-125$m^2$, 125-175$m^2$, 175-225$m^2$, 225-275$m^2$, 275-325$m^2$, >325$m^2$, respectively. The useful life is 15 years.

# Appendix E Relationship between energy efficiency and CO2 emissions

**Figure E1:** *Weighted scatter plot.*



EP(0) represents the energy efficiency before the implementation of recommendations, measured in kWh/$m^2$/year. CO2(0) denotes the CO2 emissions before the implementation of recommendations, expressed in kg/$m^2$/year. Both variables are rounded to the nearest integer to better illustrate their relationship. The circle sizes in the figure are proportionally weighted based on observation frequency, with a total of 308 distinct observations.