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CO2 EMISSIONS REDUCTION FROM RESIDENTIAL BUILDINGS: COST ESTIMATE AND POLICY DESIGN

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

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Abstract

Relying on microdata from Energy Performance Certificates (EPCs) for the Treviso province (Italy), which include information on the energy use of buildings and detailed recommendations on renovations to increase energy performance and the corresponding achievable energy efficiency, we first assess the cost of improving building energy efficiency for a given CO2 abatement. To our EPC dataset we add information on household characteristics (from the Census) and expenditure (from the Households Budget Survey) using a probabilistic matching technique. We then investigate the optimality of a subsidy financed by the policy maker covering a percentage of the renovation cost.

Our results show that the cost of reducing carbon emissions increases exponentially with CO2 abatement. Moreover, without any subsidy, only 15% of the recommended energy efficiency enhancing investments result in a positive private net present value (NPV) and are likely to be implemented: these investments represent an average upfront cost of about 22% of annual household spending. The adoption of a subsidy covering 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%. Finally, in determining the likelihood of a recommendation being implemented, our empirical findings further show that household characteristics play a far less important role than dwelling characteristics.

JEL: H23, Q48; Q54.

KEYWORDS: CO2 emission reduction; residential building energy efficiency; energy performance certificates (EPCs); housing renovation; Energy: government housing policy; distributional impact.

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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 the sector.[2] However, renovating existing buildings requires an upfront investment that not all households can afford: given the large and positive externalities from CO2 emissions reduction, government intervention is desirable aiming 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.[3]

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 assessed here by comparing the cost to the government of this mechanism with the cost of individually tailored subsidies that a fully informed policymaker would have paid to achieve the same CO2 reduction.

We use micro-level data from the archives of Energy Performance Certificates (EPCs) for homes in a specific territory, the Treviso Province in Italy.[4] For each dwelling, depending on the characteristics of the building and the energy technology used, the certificate provides energy efficiency data, including an estimate of standardized energy consumption, the associated CO2 emissions and recommendations for improving 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, where the data are less detailed than for EPCs, but cover all dwellings. Note that both 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.[5]

Our empirical analysis for the Treviso Province shows that, with no government support, only about 15% of the recommendations proposed in EPCs have a positive private Net Present Value (NPV) and, therefore, are likely to be implemented. These recommendations would result in a reduction of standardized CO2 emissions of approximately 165,000 tonnes per year compared to the *status quo* (i.e., about 13.1% of the overall emissions from the residential building sector). In the same setting, if the government pays a subsidy covering a percentage of the energy renovation cost, the number of recommendations potentially implemented can increase and lead to lower emissions: for example, with a subsidy of 50%, the reduction in standardized CO2 emissions is 55.8% more than in the baseline scenario of no support (i.e. leading to a

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

[2] EU has recently ramped up its climate ambition, with the introduction i) of a new emissions trading system named ETS2 - separate from the existing EU ETS - to address the CO2 emissions from fuel combustion in buildings, road transport and additional sectors (Kalsbach and Rausch, 2024), and ii) of a Carbon Border Adjustment Mechanism (CBAM) to mitigate the risk of carbon leakage (Ambec et al., 2024).

[3] The most common mechanisms used in EU Member States fall into two categories: non-repayable reward (grants, subsidies, tax incentives) and debt financing (loans, leasing). 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 of these policies and their effects, see Wiese et al. (2018).

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

[5] Similar certification programs providing energy ratings for dwellings are adopted in the USA (ENERGY STAR), and in Australia (NatHERS): in principle, the related registers of data on certifications, with the appropriate adaptations, can be exploited to replicate our analysis.

reduction of about 257 million tonnes per year), with a cost to the government of about 300 million euros (341 euros per inhabitant). The greater the subsidy, the more CO2 emissions fall and the higher the cost to the government: policymakers can, therefore, set a specific CO2 reduction target, design the appropriate level of subsidy to achieve that target, and meet the cost of that policy. However, by setting the same reimbursement percentage for everyone, the government inevitably also finances families that would have carried out energy restructuring even in the absence of public intervention. A policymaker fully informed of building characteristics could adopt a more cost-effective strategy by paying dwelling-based subsidies to make the implementation of the recommendations only marginally convenient for the households and hence achieve the same goal at a lower cost. Comparing the flat subsidy (i.e., a constant percentage of the implementation cost) with this latter policy - targeting household support based on the characteristics of the dwelling where they live - allows efficiency to be assessed.

Our empirical analysis shows that low levels of flat subsidies are particularly inefficient. For example, a subsidy covering 25% of the cost of implementing EPC recommendations for the energy efficiency of housing is 6.02 times more expensive than individual specific subsidies with the same CO2 target reduction. This is because low subsidy levels do little to induce households to adopt EPC recommendations, and the government ends up subsidizing interventions that would have been carried out anyway. In contrast, a high level of flat subsidy (i.e., 75%) is more efficient (only 2.18 times more expensive than individual subsidies), but is 7 times more expensive for the government than a 25% subsidy.

By matching each dwelling for which we have an EPC to 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 the incidence of dwelling renovation costs on household budgets. Our analysis shows that in the period 2015-2017 the average upfront costs of implementing EPC recommendations are in the range of 10%-30% of 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, 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, are related to the probability that the suggested renovation, if subsidized, is worth implementing. We find no evidence of this relationship: once building characteristics are controlled for, household ones do not matter, except at very high subsidy levels (i.e. 75%). This result - on the one hand - highlights the need of policies encouraging investments by the able-to-pay, also empowering them to understand costs and benefits of renovation by promoting - for instance - the adoption of smart meter technologies (Gazze, 2023; Gosnell and McCoy, 2023). On the other hand, it suggests that a subsidy based on building characteristics alone has no regressive effects. Note that this result can also be particularly interesting from a political economy perspective: if - even in the absence of liquidity and credit constraints - subsidies were more likely to benefit the wealthiest households, political support for this publicly funded intervention would have waned.

This paper contributes to three main strands of literature which use micro-level data to investigate the cost of investment in energy efficiency improvements in residential buildings and the related reduction of CO2 emissions. The first strand focuses on the role of housing prices. These studies have 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 the positive impact of energy efficiency on 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 strong effect.[6] 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), because the engineering models predicting higher expected savings are flawed. Christensen et al. (2022) show that targeting public subsidies on homes with specific characteristics dramatically improves the effectiveness of investment in energy efficiency. Our paper adds novel results to this literature by showing the effects of government subsidies supporting energy efficiency improvements in buildings (increasing their value).

A second strand of the literature looks at energy efficiency and CO2 emissions from residential building renovation and related policies. Peñasco and Anadón (2023) investigate changes in residential gas consumption from energy efficiency programmes in England and Wales between 2005 and 2017. (Liang et al., 2018) estimate energy savings for different types of retrofits on residential (and commercial) buildings from the Energize Phoenix program in Arizona. Goldstein et al. (2020) use building-level data from the US to compare greenhouse gas emissions from neighbourhoods 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. Unlike Goldstein et al. (2020) who focus on the aggregate outcome of the policy, and similarly to Peñasco and Anadón (2023) and to (Liang et al., 2018), our paper investigates policy design and relative efficiency. In this literature, engineers usually use EPCs to derive optimization models to identify 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 policymakers are not always fully informed, and are limited in the set of policies they can implement.

Finally, our research relates to the strand of literature on the methodological exploitation of EPC datasets.[7] Curtis et al. (2015), for example, use EPCs to show that the location and occupancy type of energy inefficient buildings can be derived from census and other commonly available data. Unlike Curtis et al. (2015), we propose a novel approach: starting from a subset of dwellings 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. A recent paper (Camboni et al., 2021) links each EPC to the characteristics of the household (from the census) most likely to live in that certified building, using a non-parametric micro approach called (conditional) random Hot Deck. In this paper, we borrow the matching approach developed in Camboni et al. (2021) -used to investigate fuel poverty-, and adapt it for the present analysis.

The remainder of the paper is organized as follows. Section 2 illustrates our data and presents descriptive statistics guiding subsequent analyses. Section 3 discusses how the micro-level data can be used to assess the efficiency of a policy subsidizing 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. Section 6 concludes with policy implications.

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[6] The relationship between EPCs and house prices was 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).

[7] 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.

2 Data and descriptive statistics

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

2.1 Energy Performance Certificates, EPCs

EPCs were introduced in European Union Member States by the 2002 Energy Performance of Buildings Directive (EPBD) and, since then, have been amended several times, most recently by the EPBD 2018/844. These directives aim to improve the energy performance of buildings by informing owners, tenants and the 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,[8] and several countries currently provide open access to their local EPC registers.[9]

We accessed the EPCs of around 25,000 dwellings 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, 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 dwelling/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.[10]

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:[11]

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

EPCs are also issued to suggest ways to reduce energy consumption (Pérez-Lombard et al., 2009) by providing recommendations with suggested improvement(s) and the related level of

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[8] *"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).

[9] 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.

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

[11] 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).

energy efficiency it contributes (they contribute) to achieving.

We use textual analysis to classify the type of improvement recommended in 7 different categories: insulation (external, internal, loft, roof), doors & windows, boiler, 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.[12]

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 energy demand are proportional to the increase in energy efficiency according to the recommendation.[13] Specifically, CO2 emissions of home i after implementing the 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.[14]

After cleaning the data, we were left with 19,838 recommendations for 17,017 different dwellings.[15] 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. Note that the related measurement error should be negligible as 86% of the dwellings considered here have only one recommended intervention proposed and only 2% of dwellings have three or more recommendations proposed.

2.2 Census Data

Under Italian legislation, an EPC is required for every dwelling on the housing market, whether for sale or for rent, with 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 for 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.[16] Specifically, we had access to Census micro data

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[12] 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.

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

[14] 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.

[15] Starting from the original 25,182 recommendations retrieved from EPCs, we classify 20,610 recommendations for 17,506 different dwellings in the 7 categories listed above. 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.

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

on 347,883 households and 399,815 homes in the Treviso province in 2011.[17]

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 EPC 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 cover only 6.3% of the housing stock considered in the province of Treviso, and, unsurprisingly, the characteristics of certified dwellings 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 construction date, 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 province's housing stock and improves the external validity of our exercise.

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 urban area (above 500 inhabitants/km2). Once weighted, as expected, the marginal distributions of the variables used to define the strata are equivalent between EPCs and census data. Second, the weighting allows us to effectively narrow the gap between the home sizes based on EPC and Census data, less so for the average population density. In the following analysis, all the statistics are computed using EPC-weighted data.

Table 1b shows the descriptive statistics for energy requirements, CO2 emissions, and heating costs (where subscript *0* and subscript *1* refer to before and after implementing one given 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 future useful 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 pieces of empirical evidence. First, the total recommendation cost significantly exceeds the reduction in heating costs for one year ($Heating\ cost_0 - Heating\ cost_1$). Even when spreading the initial costs over the entire future working life, more than half of the recommendations have a negative *Recommendation value* and therefore would not be implemented without an incentive. Second, any energy efficiency intervention requires a large upfront 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 savings set aside or they need access to credit to finance the intervention. Third, recommendation values vary between homes with different energy performances: recommendations for the least efficient houses (EPC classes F-G) produce the largest median benefits.

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[17] 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.

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

	CENSUS %	**EPC data unweighted** %	**EPC data weighted** %
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 indicating the decade in which the building was constructed and its total size, respectively. *Heating fuel* is a dummy variable equal to one if the main energy vector used for heating is natural gas. *500+ inhabitants / km2* indicates the share of dwellings in municipalities with a density above 500 inhabitants / km2. Note that we also include the average surface area of the dwellings and the average degree of urbanization for the two datasets.

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

	All recommendations (19,838)			by EPC class		
				A-B (2,067)	C-E (9,656)	F-G (8,115)
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 cost$_0$ (€)	315.2	847.9	3147.2	447.3	612.0	1241.3
Heating cost$_1$ (€)	226.9	626.0	2354.1	350.3	473.5	841.9
Recommendation total cost (€)	3500.0	5830.1	18000.0	6000.0	5390.4	6193.0
Recommendation annual 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 (year)	20	25	50	20	20	50

Notes. For a given variable, subscripts 0 and 1 denote before and after implementation of the recommendation, respectively. *EP* and *CO2* measure the energy required and the CO2 emitted to warm 1 sqm per year, respectively. *Heating cost* measures the standardized heating cost of a dwelling, while *Recommendation cost* indicates the cost of implementing a recommendation. We include the total cost (*total*) of a recommendation and the total cost divided by the useful life of the recommendation (*annual*). *Recommendation value* is the difference between the reduction in the heating cost from 0 to 1 and *Recommendation annual cost*. *Recommendation useful life* is the potential useful life of the recommendations if implemented, in years. Weighted sample.

3 Methodology

Given that the aim is to reduce CO2 emissions from residential buildings, the government's choice of which energy efficiency recommendation to support with a subsidy becomes crucial. Indeed, a poor choice would lead to a waste of public resources and more CO2 in the atmosphere than would otherwise be the case. The *optimal* government choice largely depends on the information and the resources available.

We begin with the simplest case, where we assume the government is (i) fully informed of the characteristics of the dwellings and the related recommendation(s) to improve their energy efficiency and (ii) pays all the implementation costs. We then relax both these assumptions. First, the government exploits its full information and covers only a fraction of the costs needed to make the renovation cost effective for the homeowner: this can be considered the optimal policy of a policymaker with full information. Second, we use this policymaker's optimal policy as a benchmark to evaluate a policy chosen by the government to support EPC recommendations when information is imperfect and, thus, the government cannot provide tailored subsidies.

3.1 The aggregate total cost curve for CO2 emissions reduction

Denote with C_r the total implementation cost of a dwelling-specific recommendation $r \in \{1, ..., R\}$, and E_r the related reduction in 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 costs C_r 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.

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

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, to the recommendation with the unit 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 to every feasible target $\mathcal{T}$ with the lowest total cost $C(\mathcal{T})$ that has to be paid to achieve it.[18] In symbols:

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

Based on this curve, policymakers can establish a given CO2 emissions reduction policy and target recommendations where energy improvements need to be supported with subsidies.

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[18] 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 $\mathcal{T}$.

3.2 A fully informed policy maker

Implementing EPC recommendations - which increase a dwelling's energy efficiency - has, on the one hand, a private benefit (i.e., lower heating costs) and, on the other, a positive externality (i.e., lower CO2 emissions). Accordingly, a fully informed policymaker should design a policy intervention where the owner of the dwelling pays part of the total cost required to achieve an emissions reduction target $\mathcal{T}$. In this framework, the policymaker's problem is twofold: deciding *which* recommendations to subsidize and by *how much*, i.e., establishing a subsidy tailored for each dwelling. Intuitively, this subsidy should be designed so the household is indifferent to whether 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 $B_r = \sum_{t=0}^{T} \frac{|CS_r^0 - CS_r^1|}{(1+\delta)^t}$ is the actual value of the future private benefit; CS_r^0 and CS_r^1 are, respectively, the heating costs before and after implementing recommendation r, δ is the inter-temporal discount factor and T is the useful life of the intervention (e.g., the useful working life of a new heater).

Note that future heating costs can only be estimated in advance, as they depend on the future cost of the energy vector used. This uncertainty weighs differently according to household attitudes to risk and, to consider it, we would need to include an additional risk aversion parameter in equation (6). Unfortunately, we do not have separate information on household risk attitudes and intertemporal preferences: therefore, we allow δ to capture both effects.[19]

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

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

Equation 7 informs the policymaker 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 policymaker:

$$c_1^P = c_2^P = ... c_Z^P < c_{Z+1}^P \leq ... c_r^P \leq ... \leq c_{R-1}^P \leq c_R^P, \tag{8}$$

where all recommendations $r \in [1, Z]$ have no cost to the policymaker (i.e., $c_r^P = 0$), and all recommendations $r \in [Z+1, R]$ have a strictly positive cost to the policymaker (i.e., $c_r^P > 0$).

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[19] Equation 6 abstracts from two additional factors that could potentially alter the NPV of a recommendation. First, for a rented dwelling, $CS_r^0 - CS_r^1$ represents the increase in rent the owner could 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 dwelling value as a result of implementing the recommendation, where the house is sold before time T.

Therefore, the minimum cost for the policymaker 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 $\sum_{r=1}^{X} E_r \geq \mathcal{T}$.

Ranking all the recommendations from most to least cost-effective, we can therefore construct a total subsidy curve that relates a given level of CO2 emission reduction $\mathcal{T}$ (on the horizontal axis) to the lowest possible amount of public money $C^P(T)$ required to achieve this policy intervention (on the vertical axis). In symbols:

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

3.3 A real-world policy intervention in the absence of full information

So far, we have relied on policymakers having complete information about the technological characteristics of all dwellings. More realistically, when this information is not available, second-best policies need to be designed. Typically, governments commit to paying a percentage of the implementation cost, i.e. a flat subsidy, to those who can demonstrate that the costs incurred are for energy efficiency improvements (and emissions reductions). This subsidy 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 fully informed policymakers.

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:

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

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 subsidy is such as to compensate for any negative NPV. Note that, if a recommendation is implemented for $p \in [0, 1]$, then it will be implemented for any larger subsidy $p' \in [p, 1]$. 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 subsidy p required to achieve

$\mathcal{T}$, and the associated costs to the state. This cost can be compared to what a fully informed policymaker 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 compared to the benchmark case of the fully informed policymaker.

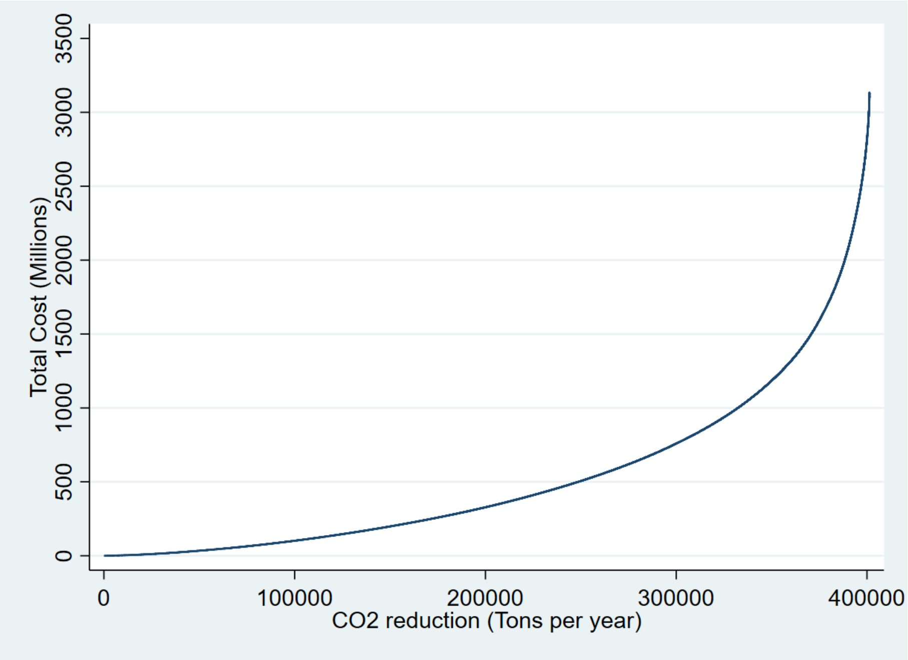
4 Results and policy simulation

We now turn to the empirical analysis. Our aim is to estimate the cost of reducing CO2 emissions from residential buildings. The methodology used to construct heating costs is illustrated in Appendix C. Intuitively, we multiply the quantity consumed for each energy vector (such as natural gas or electricity) by its unit price. Similarly, the methodology used to construct recommendation costs is discussed in Annex D. Again intuitively, we use the EPC information on the size of the dwelling, its insulation, and its heating system to assign a standardized cost to this recommendation.

For each target reduction, we estimate the aggregate total cost $C(\mathcal{T})$ (Figure 1) and the cost of two separate policy interventions (Figure 2), the first, $C^P(\mathcal{T})$ implemented by fully informed policymakers and the second, $C^B(p)$ comprising a subsidy based on recommendation costs included in EPCs. These three measures are described in equations (5), (9), and (12), respectively.

To assess these costs, we use micro-level data from EPCs, weighted using census information. Appendix A provides all the estimates using unweighted data. Qualitatively, our results are unaffected by the weighting methodology used. The simulations carried out for the province of Treviso 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), and our results are thus potentially of interest elsewhere.

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



The horizontal axis indicates the target total CO2 reduction, in tonnes 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 $C(\mathcal{T})$ for different targets of CO2 emissions reduction $\mathcal{T}$ or, in other words, the cost to a policymaker of paying all implementation costs. The horizontal axis indicates the total standardized CO2 reduction in tonnes 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 tonnes per year when implementing all the 19,838 recommendations, weighted using census information - is significant and represents a 31.88% cut[20] in current emissions of the building in the province considered in this analysis (equivalent to 1,258,275 tonnes per year).[21] This maximum feasible reduction comes at a cost of 3,134 million euros, corresponding to about 3,400 euros per inhabitant in the province considered. Note that costs to reduce CO2 increase exponentially with CO2 abatement: indeed, according to our simulations, CO2 emissions reduction targets of 100,000, 200,000, and 300,000 tonnes per year[22] can be achieved at the cost of 101 million euros (about 1/32 of the maximum reduction cost), 329 million euros (about 1/10), and 761 million euros (about 1/4), respectively.

We now consider the setting where the total cost of reducing CO2 emissions is shared between the government and homeowners: accordingly, this cost curve can be estimated using equation (9), for the case of fully informed policymakers and equation (12) for the case of partially informed policymakers. These curves are presented in Figure 2, and are constructed setting $\delta = 0.1$.[23] As discussed in Section 3.2 above, δ captures both household intertemporal preferences and risk aversion.

In Figure 2, panel (a), the dashed blue line shows the costs incurred by fully informed policymakers to achieve a given CO2 emissions reduction. For levels up to 164,984 tonnes per year, policymakers incur no cost. In fact, these targets can be achieved by implementing recommendations with a positive NPV for households, where government intervention is unnecessary. Above this threshold, the cost function for policymakers grows exponentially, and monetary transfers to selected households − with negative NPV − are required to incentivize implementation. In all cases, the policymaker pays less than the total cost (plotted in Figure 1). For example, targeting a CO2 reduction of 300,000 tonnes per year corresponds to a total cost of 761 million euros (see Figure 1). Following our analysis, of this cost, only 208 million euros need to be paid by the policymaker, while the rest would be covered by households who enjoy the private benefit of reduced heating costs from implementing EPC recommendations.

In Figure 2, panel (a), the solid red line shows the results of a policy where the government pays a certain percentage p (or 'flat subsidy') of the recommendation cost to anyone who implements it. Once the subsidy is set, all recommendations from EPCs with a positive NPV, that is, recommendations satisfying equation 10, are implemented. Each generates a cost to the government (which finances a portion) and a benefit (reduction of CO2 emissions). The sum of all costs and benefits for three subsidy levels (25%, 50%, and 75%) is highlighted above the solid red line, and the corresponding data are shown in Table 2a. The higher the flat subsidy, the greater both the cost to the government and the CO2 reduction, for two reasons. The condition in equation (10) becomes less stringent because the costs for the household are reduced while future benefits remain the same. Therefore, additional recommendations are

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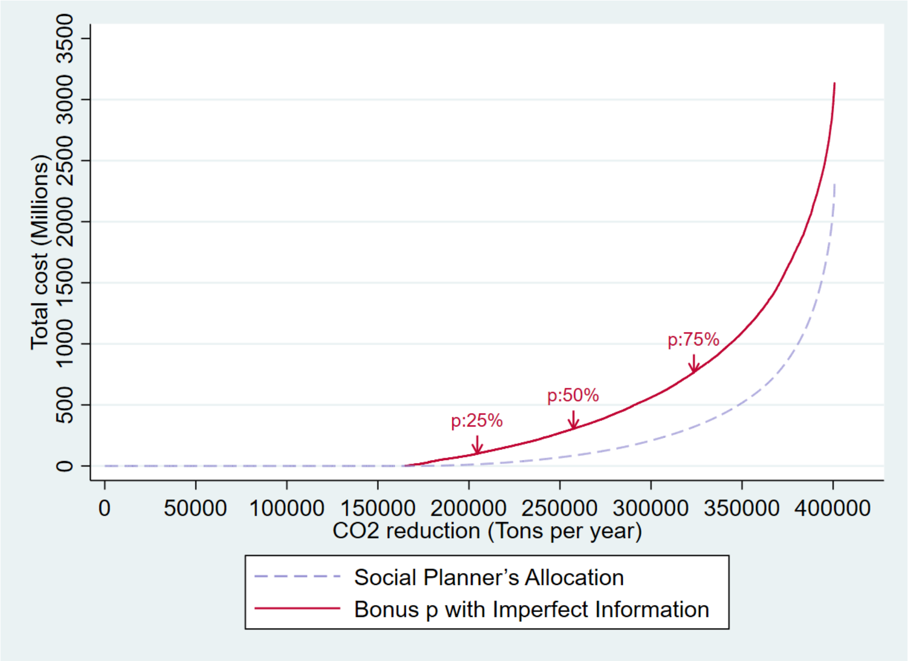
[20] For comparison, we note that, the Italian Integrated National Energy and Climate Plan 2019 sets a CO2 emissions reduction target for 2030 of 30% below 2005 levels for all non-ETS sectors (i.e. all sectors - including the residential sector - not covered by the EU Emissions Trading Scheme).

[21] Data are available on actual CO2 emissions from natural gas, LPG and diesel boilers in the residential sector in the province of Treviso. For the period 2013-2017, these emissions range from 776.4 to 853.7 thousand tonnes per year (source: INEMAR and Veneto Region). Restricting our sample to dwellings that use only natural gas, LPG and diesel as energy vectors, we arrive at estimated annual emissions of 1066.2 thousand tonnes per year. Thus, our standardised energy consumption from EPCs and census data compares reasonably well with actual data.

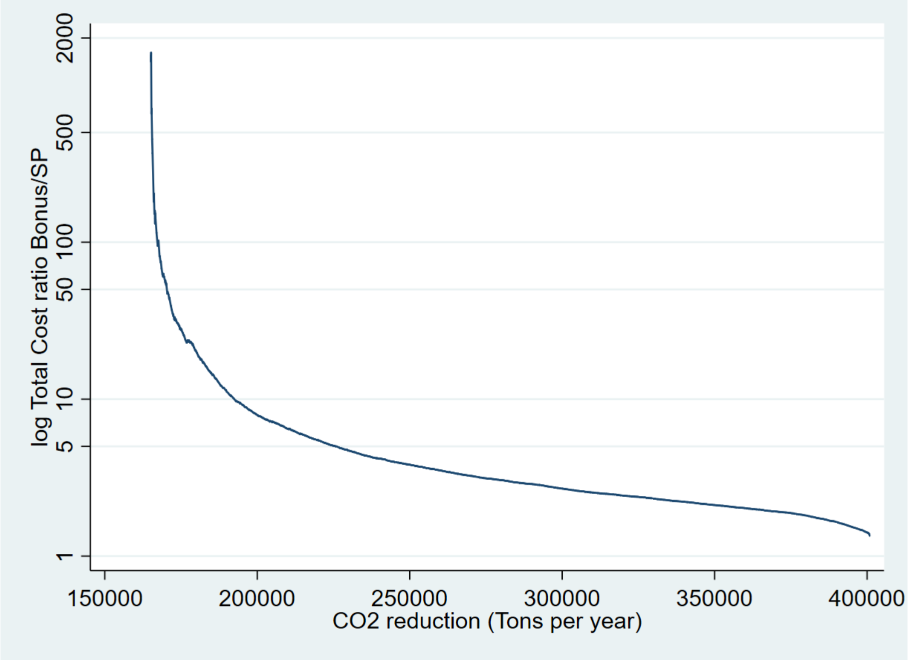
[22] These targets correspond respectively to about one, two, and three quarters of the maximum feasible reduction in the setting considered.

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

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



(a) Policy interventions cost



(b) subsidy inefficiency

In both panels, the horizontal axis represents the total target CO2 reduction, in tonnes per year. In Panel (a), the vertical axis indicates the total cost of two policy interventions for different targets of CO2 reductions: one by fully informed policymakers via tailored subsidies (dashed blue line), and the other by partially informed policymakers via a flat subsidy (solid red line). According to our analysis, in the case of imperfectly informed policymakers, setting a CO2 reduction target is equivalent to setting the level of the flat subsidy p. The costs for three subsidy levels (25%, 50% and 75%) are highlighted. Panel (b) shows the log-ratio between the costs of the flat vs the tailored subsidies. The intertemporal discount rate used is 10%. Weighted sample.

likely to be implemented. Furthermore, the government share of the cost for each implemented recommendation also increases.

Although the increase in the flat subsidy value leads to a greater reduction in CO2 emissions, this policy is always inefficient compared to the intervention of a fully informed policymaker. Indeed, consider for example a CO2 reduction target of 300,000 tonnes per year: according to our analysis, the required subsidy corresponds to $p = 0.66$ and generates a cost for policymakers of 561 million euros, which is much larger than the one incurred by a fully informed policymaker (208 million euros). 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 flat subsidy of 25% of the recommendation cost is 7.21 times more expensive than the cost a policymaker with full information would have sustained to obtain the same CO2 emissions reduction. This proportion falls to 3.60 and 2.39 for a flat subsidy equal to, respectively, 50% and 75% of the cost of implementing the recommendation. Overall, the increase in subsidy value is associated with a decrease in policy inefficiency. This is unsurprising: low subsidies are extremely inefficient because the government is mostly subsidizing recommendations that would be implemented without its intervention.[24] These results highlight the fundamental trade-off that each partially informed policymaker faces when setting the flat subsidy value: on the one hand, a low subsidy value – corresponding to a small reduction in CO2 emissions – is inefficient (Figure 2(b)); on the other hand, a high subsidy value – corresponding to a large reduction in CO2 emissions – is very expensive in terms of public resources (Figure 2(a)).

To investigate this trade-off, Table 2a shows the effects of three different levels of flat subsidies: 25%, 50%, and 75%, compared to the baseline scenario of no government intervention. According to our analysis, a subsidy 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 in the province for our dataset). An increase of CO2 emissions reductions of 55.9% and 96% from the baseline can be achieved with subsidy levels of 50% and 75%, respectively. These reductions have a significantly higher cost: 3 and 7.6 times more than a 25% subsidy, respectively (i.e., 341 and 864 euros per inhabitant). Moving from no government intervention to government intervention by subsidy leads to an increase in the proportion of recommendations implemented: specifically an increase from 15% in the absence of government intervention to 48% with a subsidy of 75%.

In terms of the average costs of implementing EPC recommendations, we do not observe substantial differences between levels of flat subsidies: for the implemented recommendation, the average cost ranges between 5,700 and 5,900 euros, and 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 shifting from low to high subsidy values. A more generous policy tends to increase the number of houses with at least one implemented recommendation, rather than increasing the number of interventions per house.[25] Conversely, the higher the subsidy, the lower both the average private (reduced heating costs) and average public (less CO2 emissions) benefits of the implemented recommendation. The former falls from 1,547 to 708 euros/year and the latter from 3,312 to 2,029 kg of CO2/year.

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[24] Note that for CO2 emissions reduction targets below 164,984 tonnes per year (see Figure 1), a flat subsidy makes no sense; indeed, such a policy would have infinite inefficiency, since those targets can be achieved by implementing only recommendations from EPCs with a positive NPV that households would have adopted without a subsidy. Hence, the red line is shown only for strictly positive levels of subsidy, starting with a CO2 reduction or more than 164,984 tonnes per year.

[25] Non-implemented recommendations become approximately 15% more expensive at a subsidy level of 75% compared to a subsidy level of 50%.

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

(1) Policy level	(2) Total cost government (MM. €)	(3) CO2 reduction (tons/y)	(4) Policy log-inefficiency	(5) Share of implemented and not implemented recommendations		(6) Average characteristics of the recommendations	(7)	(8)	(9)
						Cost (€)	Benefit (Y €)	CO2 red. (Y kg)	Useful Life (Y)
0%	0	164984		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 total policy cost to the government, the CO2 reduction, and the log-inefficiency compared to the fully informed policymaker policy as in Fig. 2. Column (5) shows the proportion of recommendations implemented (I) and not implemented (NI) for each level of subsidy considered. Columns (6) to (9) report the average characteristics of the recommendations: average cost, heating savings benefit, CO2 reduction, and years of potential useful life. The intertemporal discount rate used is 10%. Weighted sample.

5 Household Characteristics

The policy simulations presented in the previous section assess the level of public investment required to achieve a targeted abatement in CO2 emissions from residential buildings, based on the information available and under the assumption that all implementable recommendations with a positive NPV (subsidized or not) are actually implemented. However, those simulations do not provide information on the distributional impacts of the investigated policies, i.e. on the type of households affected by the interventions. In this section, we aim to address this insufficiency. In doing so, we link our EPC dataset to two additional data sources: the census data already introduced in Section 3.2 (where it was used to define 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, draws on Camboni et al. (2021).

The following subsections describe the information provided by the Census and HBS data, how we link it to our EPC dataset (in 5.1 and 5.2, respectively), and the results obtained (5.3).

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 the dwelling characteristics, we identify those in common with the EPC data, which we call ″background variables″, and which allow us to link the two datasets. They include the year of construction, the size of the dwelling, the main heating system (central heating for the whole building, central heating per dwelling, or independent appliances), the main heating fuel (natural gas or other), 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 records 75 households on average. Census tracts can be used as background variables because the EPC register provides geo-referenced zero-dimensional information (i.e. point data) on the location of each certified dwelling.[26]

We therefore match EPC and Census data records to obtain a synthetic matched EPC-Census dataset enriching 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 (D'Orazio et al. (2006)).

5.2 Imputation of expenditure from the Italian Household Budget Survey

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 expenditure incurred by households in purchasing goods and services for 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.[27]

In addition to expenditure information, the HBS includes socio-demographic and housing descriptors 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* (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 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 by policies aimed at reducing CO2 emissions from residential buildings. The matching and imputation procedures reduce the sample from the 17,017 houses in 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 by adding family type (single, couples, couples with children, single parents, other) as a stratification criterion. Below, all the statistics are computed using these weights.

5.3 Policy interventions 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 policies, i.e., no subsidy, flat subsidies at 25%, 50%, and 75%. We distinguish between two groups of households: those living in dwellings where EPC recommendations have positive NPV and are thus likely to be adopted and those living in dwellings where EPC recommendations have negative NPV and are likely not to be implemented.[28] Column (3) of Table 2b shows that the average total annual expenditure of

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

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

[28] The share of implemented and non-implemented recommendations is slightly lower than as presented in Table 2a due to sample reduction after matching.

households living in dwellings where EPC recommendations have a positive or negative NPV is similar, regardless of the level of the flat subsidy. The only exception is for $p > 50\%$ where expenditure is slightly higher for households living in dwellings recording recommendations with positive NPV. Column (4) also shows that there is little variation in the cost of heating for households, expressed as a percentage of total expenditure. Column (5) shows the average cost incurred by households to implement a recommendation, net of the subsidy 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, $(1-p)TC_r/Exp$.

Unsurprisingly, these statistics show that the cost and its incidence on household budgets decreases as the subsidy level increases. This is because the type of recommendation implemented does not vary with the level of the policy, p, nor its useful life or related cost. Therefore, the cost to households falls solely 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 flat subsidy; the average incidence for implemented recommendations ranges from 22.63% (with no government intervention) to 5.80% (with a subsidy 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 1% of total annual household expenditures, Exp, for implemented recommendations for each level of subsidy. 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. For households in the lowest 10% of income distribution, the average incidence for implemented recommendations is higher and ranges from 1.52% (with no government intervention) to 0.44% (with a subsidy level of 75%) when the recommendation cost is spread over its useful life.

Table 3 presents maximum likelihood estimates of logit models for the probability of a recommendation having a positive NPV. Such a probability is a function of the characteristics of both the dwelling and the household associated with the recommendation. It is estimated for four levels of policy subsidies, 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 imputation of expenditure.

The energy class of the dwelling and its surface area are crucial factors for the implementation of a recommendation, at any level of flat subsidy. Indeed, in the absence of a subsidy, $p = 0\%$, the odds of positive recommendations for a dwelling in energy class G is 66.75 times that of the recommendations for a dwelling in class A, all else being equal. This odds ratio falls when p increases, but remains at 49.95 when $p = 75\%$. Regarding the surface area, when $p = 0\%$, the odds of implementing the recommendations in a dwelling 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 interesting additional results. First, recommendations are less likely to be implemented in buildings including 9 or more dwellings, for any subsidy value. For instance, when there is no subsidy, the odds of implementing recommendations in buildings with at least 9 dwellings are 0.674 times the odds of implementing recommendations in buildings with a single dwelling, i.e., in a detached house. Second, when the subsidy reaches $p = 75\%$, the odds of implementing a recommendation for households in the 4th quartile of expenditure distribution are 1.267 times the odds for 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 the percentage of subsidized cost p of 4 alternative policies. Column (2) shows the proportion of recommendations implemented (I) and not implemented (NI) for each level of subsidy considered. Columns (3) and (4) indicate the average total annual expenditure (in euros) of the households most likely to occupy the dwellings where the recommendations are implemented or not, given the level of subsidy, and their heating costs as a percentage of this expenditure. Columns (5) to (7) show the average cost (in euros) of the recommendations net of the subsidy received (specifically, $(1-p)TC_r$), its incidence on total annual household expenditure Exp (specifically, $TC\_Exp = (1-p)TC_r/Exp$), and its incidence on total annual household expenditure when the cost of the recommendations is spread over their 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. Discount rate 10%. Standard errors are clustered by dwelling ID and obtained by bootstrapping 100 times the entire matching procedure, the computation of 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 Concluding remarks

The residential building sector has a large carbon footprint and its rapid energy efficiency improvement is needed to meet the specific EU target of reducing greenhouse gas emissions by at least 55% below 1990 levels by 2030. The improvement in energy efficiency of residential buildings has both a positive externality for society in terms of reduced CO2 emissions, and private benefits for households in terms of reduced energy costs. However, the upfront cost of these interventions to improve the energy efficiency of buildings is generally high and usually requires households to have sufficient savings or access to credit to carry them out. The access to monetary resources can determine an issue of affordability - in particular for vulnerable households - limiting the implementation of energy efficiency measures. Note that the 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).

The significant benefit from reduced CO2 emissions due to the improved energy efficiency of buildings and the potential affordability issue in financing such renovations suggest that national governments should intervene to support the process. Coherently, several policies have been introduced in European countries to encourage the energy renovation of buildings.

In this paper, we first assess the cost of improving the energy efficiency of buildings, and then investigate the optimality of a flat subsidy financed by the government, covering a percentage of the cost. We use micro data from Energy Performance Certificates (EPCs) for the province of Treviso, Italy, containing information on dwelling characteristics, as well as detailed recommendations on renovations to increase energy performance. We weight the observations from the EPC dataset using Census data: this ensures that our database is representative of the provincial housing stock we focus on.

We find that governments face an important trade-off when setting the policy in the form of a flat subsidy, i.e. a percentage of the cost - financed with public funds - to households that improve the energy efficiency of their buildings. On the one hand, our results show that a low subsidy value set by the government proves to be i) barely effective because it ends up subsidizing recommendations included in EPCs that households would have implemented anyway; and ii) relatively inefficient compared to the intervention of fully informed policymakers seeking the same CO2 reduction target and minimizing the amount of public money used to achieve it. On the other hand, a high subsidy can be very expensive for the government, as documented in our analysis: indeed, the cost of this policy grows exponentially with the related CO2 reduction.

We then add to our EPC data information on household characteristics (derived from the census) and their expenditure (derived from the HBS) using probabilistic matching techniques. Our empirical findings further show that household characteristics play a far less important role than dwelling characteristics in determining the likelihood of a recommendation being implemented. Moreover, our analysis highlights that the costs of implementing recommendations included in EPCs are a significant proportion of annual household expenditure for all but the highest subsidy levels: this evidence underscores i) the importance of spreading these costs over several years; ii) the relevance of household access to credit, in particular, to implement the large number of EPC recommendations with a positive NPV. Conversely, subsidies by the government should focus on recommendations with a slightly negative NPV, which are the most cost-effective in terms of reducing CO2 emissions.

The implications of our analysis are relevant to both national and regional policymakers as to how policy for CO2 emissions reduction for residential buildings should be carried out. Since EPC data, Census and Household Budget Survey are widely available for all countries in the European Union, our analysis can be replicated and used to support policymakers in designing locally tailored policies for cost-effective improvements in the energy performance of buildings.

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Appendix A Unweighted results

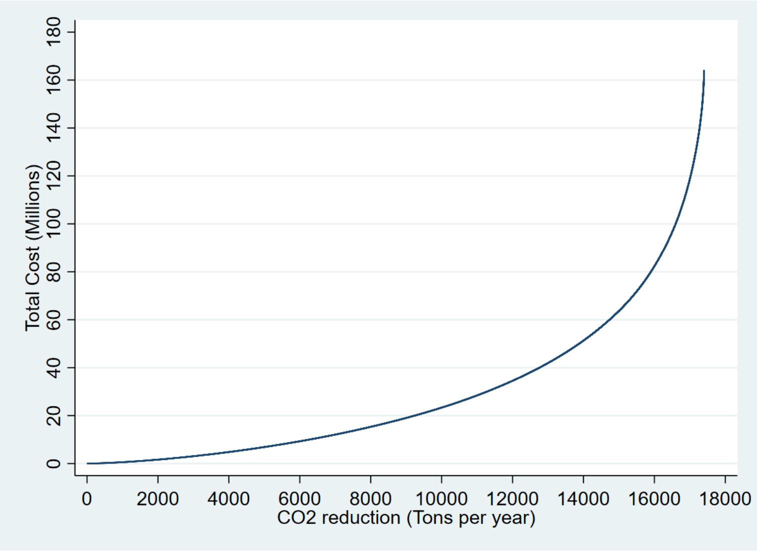
All results presented in Appendix A are derived from EPC micro-level data that are NOT weighted with census information.

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

	All recommendations (19,838)			by EPC class		
				A-B (2,067)	C-E (9,656)	F-G (8,115)
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 cost$_0$ (€)	260.5	603.8	2079.6	385.3	471.4	889.3
Heating cost$_1$ (€)	189.9	447.9	1590.3	295.5	369.7	635.5
Recommendation total cost (€)	3500.0	5512.5	18000.0	5880.6	5115.2	5899.0
Recommendation annual 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 (year)	20	25	50	20	20	50

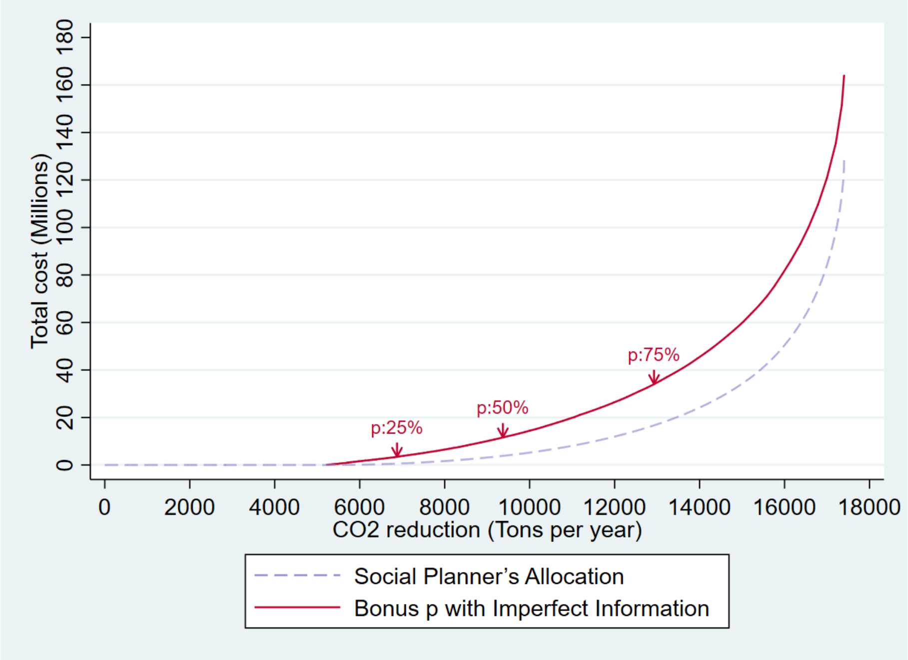
Notes. For a given variable, subscripts 0 and 1 denote before and after implementation of the recommendation, respectively. EP and $CO2$ measure the energy required and the CO2 emitted to warm 1 sqm per year, respectively. *Heating cost* measures the standardized heating cost of a dwelling, while *Recommendation cost* indicates the cost of implementing a recommendation. We include the total cost (*total*) of a recommendation and the total cost divided by the useful life of the recommendation (*annual*). *Recommendation value* is the difference between the reduction in the heating cost from 0 to 1 and *Recommendation annual cost. Recommendation useful life* is the potential useful life of the recommendations if implemented, in years. Unweighted sample.

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

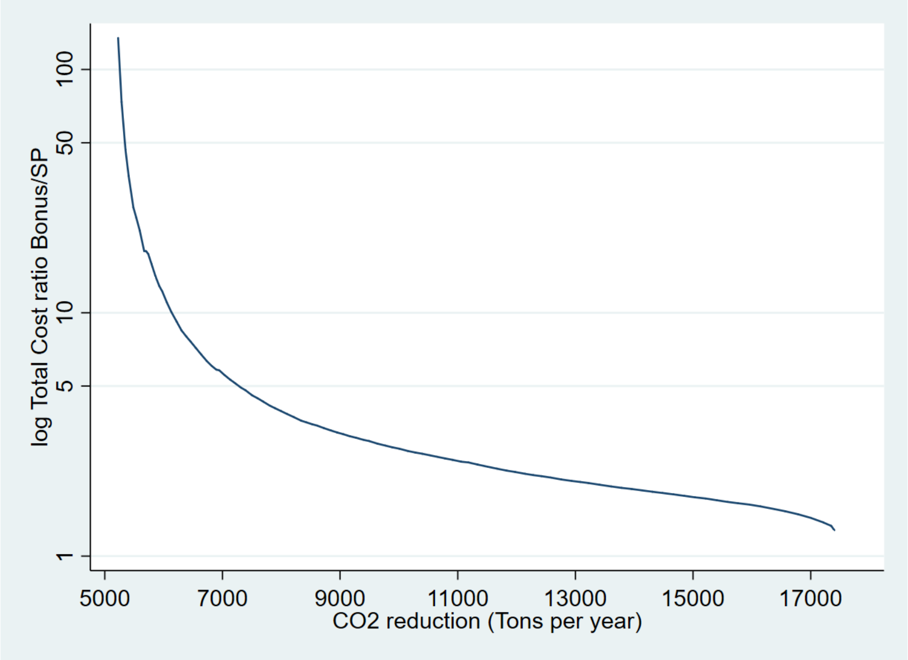


The horizontal axis indicates the target total CO2 reduction, in tonnes per year. The vertical axis shows the lowest possible total cost to achieve that emission reduction, in millions of euros.

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



(a) Policy interventions cost



(b) subsidy inefficiency

In both panels, the horizontal axis represents the total target CO2 reduction, in tonnes per year. In Panel (a), the vertical axis indicates the total cost of two policy interventions for different targets of CO2 reductions: one by fully informed policymakers via tailored subsidies (dashed blue line), and the other by partially informed policymakers via a flat subsidy (solid red line). According to our analysis, in the case of imperfectly informed policymakers, setting a CO2 reduction target is equivalent to setting the level of the flat subsidy p. The costs for three subsidy levels (25%, 50% and 75%) are highlighted. Panel (b) shows the log-ratio between the costs of the flat vs the tailored subsidies. The intertemporal discount rate used is 10%. Unweighted sample.

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

(1) Policy level	(2) Total cost government (MM. €)	(3) CO2 reduction (tons/y)	(4) Policy log-inefficiency	(5) Share of implemented and not implemented recommendations		(6) Average characteristics of the recommendations	(7)	(8)	(9)
						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 total policy cost to the government, the CO2 reduction, and the log-inefficiency compared to the fully informed policymaker policy as in Fig. A2. Column (5) shows the proportion of recommendations implemented (I) and not implemented (NI) for each level of subsidy considered. Columns (6) to (9) report the average characteristics of the recommendations: average cost, heating savings benefit, CO2 reduction, and years of potential useful life. The intertemporal discount rate used is 10%. Unweighted sample.

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

(1) Policy level	(2) Share of implemented and not implemented recommendations		(3) Average HH expenditure Tot. (Y €)	(4) % heating cost	(5) $(1-p)TC_r$ (€)	(6) *TC Exp* (%)	(7) *AC Exp* (%)
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%

Column (1) lists the percentage of subsidized cost p of 4 alternative policies. Column (2) shows the proportion of recommendations implemented (I) and not implemented (NI) for each level of subsidy considered. Columns (3) and (4) indicate the average total annual expenditure (in euros) of the households most likely to occupy the dwellings where the recommendations are implemented or not, given the level of subsidy, and their heating costs as a percentage of this expenditure. Columns (5) to (7) show the average cost (in euros) of the recommendations net of the subsidy received (specifically, $(1-p)TC_r$), its incidence on total annual household expenditure Exp (specifically, $TC\_Exp = (1-p)TC_r/Exp$), and its incidence on total annual household expenditure when the cost of the recommendations is spread over their useful life (specifically, $AC\_Exp = (1-p)TC_r/useful\_life/Exp$). The intertemporal discount rate used is 10%. Unweighted sample.

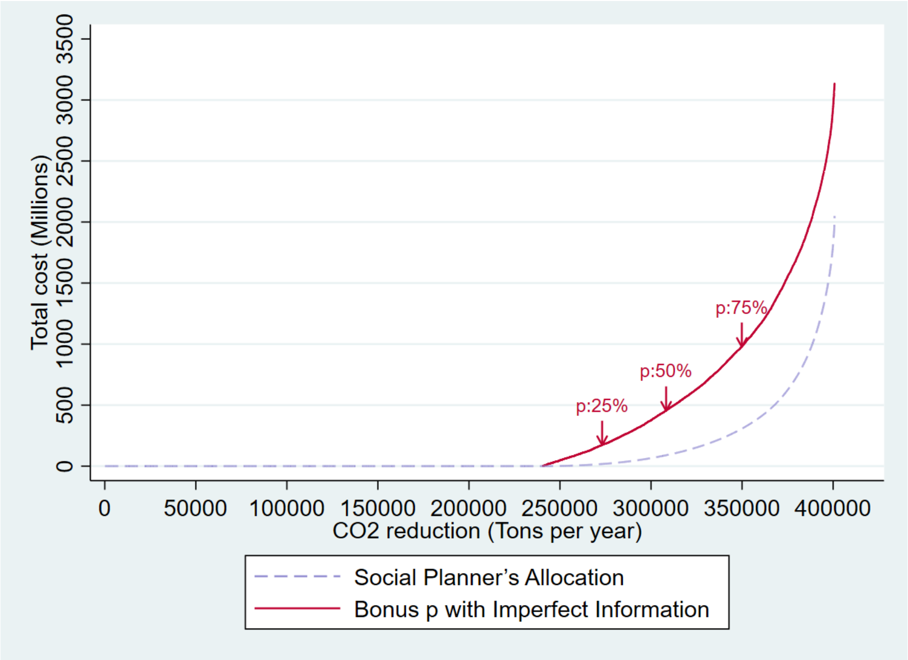
Table A4: Probability of implementing the recommendation. Logit models: odds ratio. Unweighted sample. Discount rate 10%. Standard errors are clustered by dwelling ID and obtained by bootstrapping 100 times the entire matching procedure and the expenditure imputation. Number of observations: 19,525. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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)

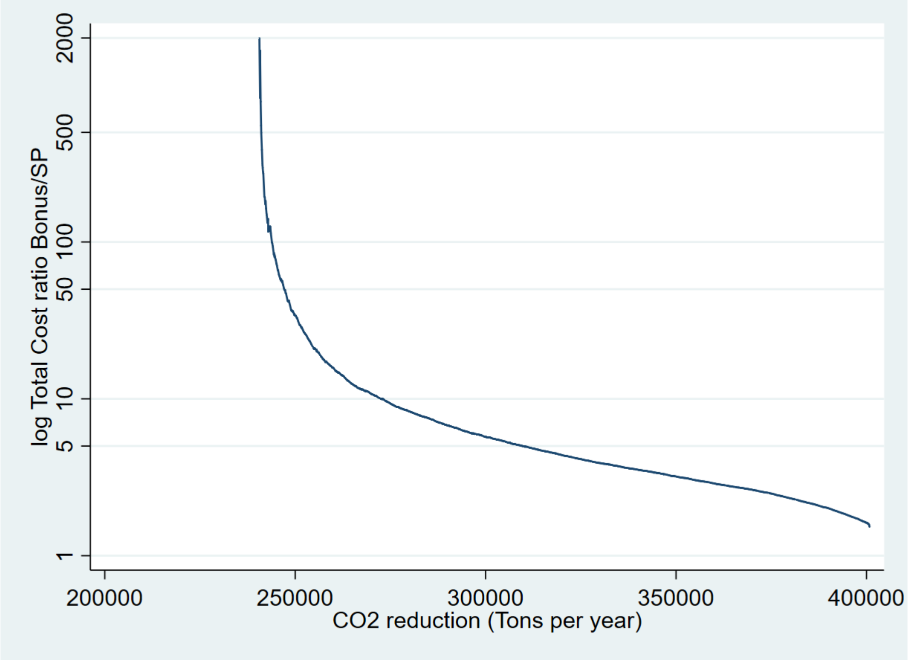
Appendix B Discount rate 5%

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) subsidy inefficiency

In both panels, the horizontal axis represents the total target CO2 reduction, in tonnes per year. In Panel (a), the vertical axis indicates the total cost of two policy interventions for different targets of CO2 reductions: one by fully informed policymakers via tailored subsidies (dashed blue line), and the other by partially informed policymakers via a flat subsidy (solid red line). According to our analysis, in the case of imperfectly informed policymakers, setting a CO2 reduction target is equivalent to setting the level of the flat subsidy p. The costs for three subsidy levels (25%, 50% and 75%) are highlighted. Panel (b) shows the log-ratio between the costs of the flat vs the tailored subsidies. The intertemporal discount rate used is 5%. Weighted sample.

Table B1: 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%	0.0	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 total policy cost to the government, the CO2 reduction, and the log-inefficiency compared to the fully informed policymaker policy as in Fig. B1. Column (5) shows the proportion of recommendations implemented (I) and not implemented (NI) for each level of subsidy considered. Columns (6) to (9) report the average characteristics of the recommendations: average cost, heating savings benefit, CO2 reduction, and years of potential useful life. The intertemporal discount rate used is 5%. Weighted sample.

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

(1) Policy level	(2) Share of implemented and not implemented recommendations		(3) Average HH expenditure Tot. (Y €)	(4) % heating cost	(5) $(1-p)TC_r$ (€)	(6) *TC Exp* (%)	(7) *AC Exp* (%)
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%

Column (1) lists the percentage of subsidized cost p of 4 alternative policies. Column (2) shows the proportion of recommendations implemented (I) and not implemented (NI) for each level of subsidy considered. Columns (3) and (4) indicate the average total annual expenditure (in euros) of the households most likely to occupy the dwellings where the recommendations are implemented or not, given the level of subsidy, and their heating costs as a percentage of this expenditure. Columns (5) to (7) show the average cost (in euros) of the recommendations net of the subsidy received (specifically, $(1-p)TC_r$), its incidence on total annual household expenditure Exp (specifically, $TC\_Exp = (1-p)TC_r/Exp$), and its incidence on total annual household expenditure when the cost of the recommendations is spread over their 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 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).[29]

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.[30] Secondly, when implementing a recommendation, it is not possible to reduce hot water production costs without also reducing heating costs.

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

[30] 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 α 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

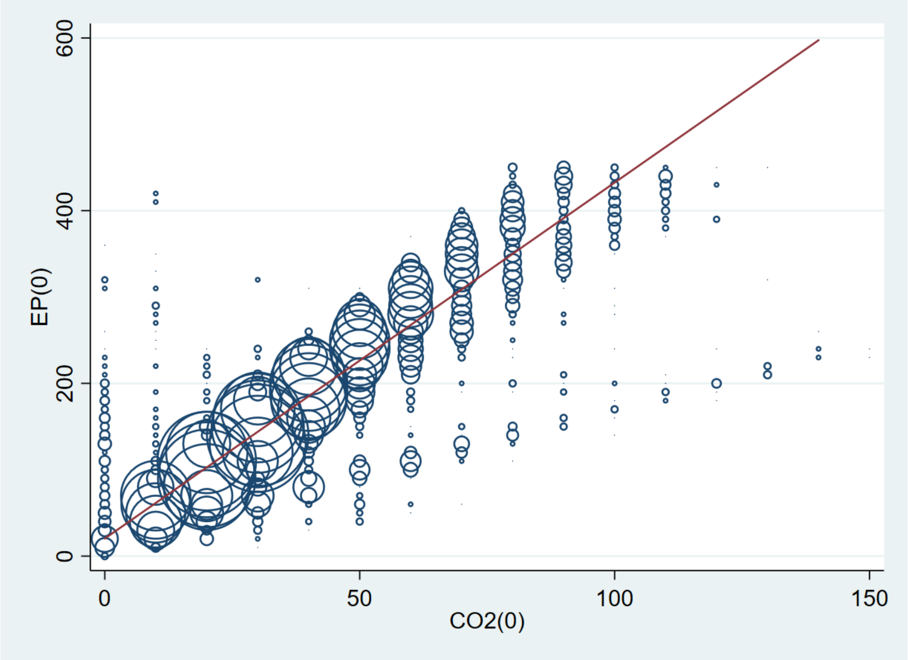
For solar thermal panels, we consider the following prices: 2,400€for a dwelling equal to or smaller than 70 m^2, and 3,500 for a dwelling larger than 70 m^2. The useful life is 15 years.

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 $\leq$ 92.5m^2, 92.5-125m^2, 125-175m^2, 175-225m^2, 225-275m^2, 275-325m^2, >325m^2, respectively. The useful life is 15 years.

Appendix E Relationship between energy efficiency and CO2 emissions

Figure E1: *Weighted scatter plot.*



EP(0) indicates 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.