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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

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

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

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

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1 Introduction

Residential buildings have a significant carbon footprint (IEA, 2022), amounting to about 10.9% of all CO2 emissions in Europe in 2018 (EU, 2020). According to the EU Commission, roughly 75% of the EU building stock is energy inefficient, highlighting the need for emissions reduction in that sector. However, renovating existing buildings requires an upfront investment that not all households can afford: given the large and positive externalities from CO2 emissions reduction, a government's intervention is desirable in the aim to support cost-effective improvements for the energy performance of housing. And indeed, different forms of financial and fiscal mechanisms are used by governments to support the energy renovation of buildings in many EU Member States and in the US.[1]

This paper investigates the efficiency of a mechanism, i.e. a bonus, whereby the government pays part of the cost of improvements to anyone who applies for them, resulting in an overall reduction in CO2 emissions from the housing sector. Efficiency is assessed by comparing the cost to the government of this mechanism with the cost of individually tailored subsidies that a fully informed social planner would have paid to achieve the same CO2 reduction.

We use micro-level data from the archives of the Energy Performance Certificates (EPCs) for homes in a specific territory, the Treviso Province in Italy.[2] For each dwelling, the certificate provides data on energy efficiency, CO2 emissions, an estimate of standardized energy consumption as well as recommendations for improving the energy performance of the building. These recommendations inform the household of the type of the improvement suggested, as well as the benefits in terms of increased energy efficiency. EPCs are not available for all dwellings: to ensure that our data are statistically representative, we construct sample weights using information from the Census, which is less detailed than EPCs, but covers all dwellings. Note that both the EPCs and census data are available for all European countries: thus, our analysis can be easily replicated for any territory in the European Union and can inform local, regional and national policymakers in the design of policies to support building renovation and to reduce CO2.

Our empirical analysis on the Treviso Province shows that, with no government support, only about 15% of the recommendations proposed in the EPCs are likely to be implemented. In the same setting, if the government pays a percentage (i.e. a bonus) of the energy renovation cost, the number of recommendations implemented can increase and lead to lower emissions: for example, with a bonus of 50%, the reduction in CO2 emissions is 55.8% more than in the baseline scenario of no support and the cost to the government is around 300 million euros (341 euros per inhabitant). As the bonus increases, so does the total amount of CO2 emissions reduced and the cost to the government: the policymaker can therefore set a specific CO2 reduction target, design the appropriate level of bonus to achieve that target, and meet the cost of that policy. However, this is not the most cost-effective way of achieving the goal: a policymaker who is fully informed about building characteristics can tailor individual bonuses to selected households so that it makes no difference to the household if the recommendation is implemented or not, and hence can achieve the same goal at a lower cost. Comparing the bonus with this latter policy allows the assessment about the efficiency of the bonus.

Our empirical analysis shows that low levels of bonus are particularly inefficient. For example, a bonus covering 25% of the cost to implement the EPCs' recommendation for energy

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

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

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

As yet, our analysis does not provide information on the characteristics of the households potentially receiving the bonus. For this purpose, we match each dwelling for which we have the EPC with information - from the Italian census and the Household Budget Survey (HBS) - on the socio-economic characteristics of the household most likely to occupy it. Our analysis shows that the average upfront costs of implementing the EPCs' recommendations are in the range of 10%-30% of the annual household expenditure, when medium to low levels of bonuses are in place. Note that these costs become affordable when spread over the useful life of the intervention, thus suggesting that any support for improving the efficiency of dwellings should be complemented by measures to facilitate access to credit.

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

We contribute to the three main strands of literature using micro-level data to study investments' cost in improving energy efficiency of residential properties and, in turn, in reducing CO2 emissions. A first strand of this literature has focussed on the role of housing prices. Brounen and Kok (2011), using a large dataset on transaction prices in the Dutch housing market, show that homebuyers are willing to pay a premium for dwellings labeled as more energy efficient. The relationship between EPCs and house prices has also been studied in Cerin et al. (2014), Fuerst et al. (2016), and −for commercial property assets− in Fuerst and McAllister (2011).[3] We add to this literature original results on the effects of government's bonuses supporting investments in the dwelling's energy efficiency improvements (and increasing the dwelling's price).

A second strand of literature looks at CO2 emissions from residential buildings and related policies for their reduction. Goldstein et al. (2020) use building-level data from the US to compare greenhouse gas emissions from neighborhoods differing in income and urban density. They propose using home retrofits to reduce energy demand and model different greenhouse gas emissions reduction scenarios depending on the level of government intervention. Differently from these authors, which focus on the aggregate outcome of the policy, in our paper we investigate its design and relative efficiency. In this literature, engineers usually use EPCs to derive optimization models to be adopted in identifying the best combination of retrofit options (see, among others, Fan and Xia (2018), Delmastro et al. (2016), and Ali et al. (2020),) and to design the energy planning at local/regional scales (Dall'O' et al., 2012, 2015). We add to this literature the investigation of a policy to reduce CO2 emission based on EPCs' recommendation (i.e. on improvements for the energy performance of housing), and investigating its efficient design.

Finally, we contribute to the strand of literature on the methodological exploitation of EPCs dataset. [4]Curtis et al. (2015), for example, use EPCs to show that the location and occupancy

[3]Broberg and Egüez (2018) study the impact of ownership type on households' decisions about the energy efficiency level of the dwelling they live in.

[4]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

type of energy inefficient buildings can be derived using census and other commonly available data. Differently from Curtis et al. (2015), in this paper, we propose a novel approach: starting from a subset of houses for which EPC data are available, we use appropriate weights to make the data representative of the entire housing stock of the area under study. Camboni et al. (2021) link each EPC to the characteristics of the household (from the census) most likely to live there, using a non-parametric micro approach called (conditional) random hotdeck. We borrow their approach, originally developed to study fuel poverty, and adopt it for the present analysis.

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

2 Data and descriptive statistics

In this Section we present datasets our analysis relies on. The first source of information is on CO2 emissions and standardized heating costs, derived from EPCs (2.1). The second source of information is about the residential building stock: we collect it from the ten-year population and building Census (2.2). Finally, we present related descriptive statistics (2.3).

2.1 Energy Performance Certificates, EPCs

EPCs were introduced in the European Union Member States by the 2002 Energy Performance of Buildings Directive (EPBD) and, since then, have been amended several times, most recently by the EPBD 2018/844. These directives aim to improve the energy performance of buildings by informing owners, tenants and potential buyers of a dwelling of its energy efficiency expressed by the primary energy use in kWh/m^2/year. The information contained in EPCs is the same for all EU Member States,[5] and several countries currently provide open access to their local EPC registers.[6]

We accessed the EPCs of around 25,000 homes located in the province of Treviso. The certificates were issued between September 2015 and December 2017 in the format adopted in Italy from Q4-2015. Each EPC contains information on the surface area and volume of the home, its date of construction, its geo-location (latitude and longitude) and the characteristics of the building. In particular, EPCs provide information on the type(s) of energy sources available, separately, for heating, cooling, hot water, and mechanical ventilation; the use of renewable energy sources; insulation; and the orientation of the home/building (north, south, etc.). Based on this information, each certificate provides an estimate of the energy required to meet the various needs associated with what the regulation considers a standard use of the home over a year and the associated level of CO2 emissions. The estimates of the energy requirements are

mandates the monitoring of a statistically significant random sample of EPCs issued annually, starting in 2015.

[5] *"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).

[6] 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.

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.[7]

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:[8]

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

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

We use textual analysis to classify the type of improvement recommended in 7 different categories: insulation (external, internal, loft, roof), doors & 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.[9]

The new level of energy efficiency after the implementation of each recommendation is expressed in kwh/m^2/year and is also shown in the EPC. We assume that the associated reductions in CO2 levels and heating costs are proportional to the increase in energy efficiency due to the recommendation. Specifically, CO2 emissions after implementing the recommendation are set equal to:

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

where EP_1 and EP_0 measure the energy required (in Kwh-equivalent/sqm/year) and $CO2_0$ and $CO2_1$ measure CO2 emissions (in Kg/sqm/year) for a given dwelling i, 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.[10]

After cleaning the data, we were left with 19,838 recommendations for 17,017 different dwellings.[11] When multiple recommendations are proposed for the same dwelling, it is difficult to determine exactly in which sequence the recommendations should be implemented. In our analyses, we assume that each recommendation can be implemented independently of the others and that the CO2 emission reduction associated with a recommendation does not depend on the sequence in which the recommendations for a given dwelling are implemented. In other words, we assume that an intervention has the same effect regardless of whether or not another intervention has previously been carried out in the same dwelling. In our opinion, the measurement

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

[8] 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).

[9] Appendix D provides a detailed description of the methodology used to construct the recommendation costs.

[10] 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.

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

error is negligible since 86% of our recommendations refer to single interventions associated with separate dwellings, and only 2% of dwellings have more than two recommendations.

2.2 Census Data

We use the 2011 General Population and Housing Census data to compute the weights necessary to reduce the "distance" between our sample of dwellings and the reference population. 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.[12] Specifically, the Census provides micro data on a total of 347,883 households and 399,815 homes in the Treviso province in 2011.[13]

In our exercise, we focus on inhabited homes and on records that have all the information needed to associate the houses in the Census with the EPCs records. This reduces the number of useful homes in the Census dataset to 279,964 which we consider our reference population from now on. Our EPC data covers only 6.3% of the housing stock considered in the province of Treviso,[14] and the characteristics of certified accommodation are different from those of the overall housing stock (see Table 1a). We calculate weights for EPCs relying on Census data and defining strata based on the date of construction of the houses, their size, the main heating fuel (natural gas or other), and the degree of urbanization (below/above 500 inhabitants/km2). Weighting the EPC data renders them representative of the housing stock of the province and improves the external validity of our exercise.

2.3 Descriptive statistics

Table 1a shows the characteristics of the homes, Treviso Province, from Q4 2015 to Q4 2017, comparing our unweighted EPC dataset (Column 2) with the characteristics of the homes from Census data (Column 1); it then presents the EPC data weighted (Column 3). Table 1a highlights two important features. First, homes in the EPC data look substantially different from homes in the Census data: homes with an EPC are, on average, more recent, smaller, more likely to use natural gas and more likely to be located in an urbanized area (above 500 inhabitants/km2). Once weighted, as expected, the marginal distributions of the variables used to define the weights are equivalent between EPC and Census samples. Second, using weighted statistics allows us to effectively reduce the difference between EPC and Census samples in relation to the size of the dwelling, less for the degree of urbanization. In the analysis which follows, all the statistics are computed using EPC weighted data.

Table 1b shows the descriptive statistics of the energy requirements, CO2 emissions, and heating costs (where *subscript 0* and *subscript 1* refer cost before and after implementing the recommendation). *EP* and *CO2* represent the energy required and the CO2 emitted to heat 1 sqm per year, respectively. The variable *heating cost* measures the standard heating cost of a dwelling (see Appendix C). Statistics for the recommendations are also set out, including the total cost (variable *Recommendation cost TOTAL*), and the variable *Recommendation value YEAR* which defines the average value of implementing a recommendation. *Recommendation value YEAR* is calculated as the difference between the reduction in the heating costs before and after implementing the recommendation and the yearly cost of the recommendation (*Recommendation cost YEAR*, i.e., the total cost of the recommendation divided by its useful life).

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

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

[14] An EPC is required for every new, renovated, purchased or rented home.

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

Table 1b includes three interesting empirical statistics. First, more than half of the recommendations have a negative *Recommendation value YEAR* and therefore would not be implemented without an external incentive. Second, the total recommendation cost largely exceeds the reduction in the heating costs for one year ($Heating\ cost_1 - Heating\ cost_0$). Any energy efficiency intervention requires a large upfront payment, whilst producing benefits over a much longer period. Median useful life for a recommendation is 25 years (a minimum of 15 and maximum of 50 years). Therefore, even if it is optimal to implement a recommendation, a household needs either access to credit or the availability of sufficient savings. Third, recommendation values vary between homes with different energy performances: recommendations in the least efficient houses (EPC classes F-G) produce the largest benefits on average.

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

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

Notes. For a given variable, the subscripts 0 and 1 denote, respectively, before and after implementing the recommendation. *EP* and *CO*2 measure, respectively, the energy required and the CO2 emitted to warm 1 sqm per year; *heating cost* measures the standardised heating cost of a dwelling; *Recommendation cost* gives the implementation cost; we include the overall (TOTAL) cost, and the overall cost divided by the useful life of the intervention (YEAR); *Recommendation value* is the difference between the reduction in the heating costs from 0 to 1 and *Recommendation cost YEAR*. *Recommendation useful life* is the expected useful life of the recommendation if implemented, in years. Weighted sample.

3 Methodology

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

The efficient choice depends on the policymaker's objectives and the information available. We begin with the simplest case, where the government pays the full implementation cost and has all the information on the characteristics of each dwelling. We then relax both these assumptions. First, we allow for the implementation costs to be shared between the government and private households. This is akin to the optimum policy of a social planner with full information. Second, we use the social planner's optimum decision as a benchmark for evaluating the efficiency of a policy where the government - under imperfect information, being unable to provide tailored bonuses - simply covers a certain percentage of the cost to implement an EPC recommendation for anyone who requests it.

3.1 The aggregate total cost curve for CO2 emissions reduction

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

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

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

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

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

Following this intuition, publicly available information from EPCs can be used to construct a total cost curve for CO2 emissions reduction relating every feasible target $\mathcal{T}$ (on the horizontal axis) with the lowest total cost $C(\mathcal{T})$ that has to be paid to achieve it (on the vertical axis).[15] In symbols:

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

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

[15]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 social planner

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

$$NPV = \sum_{t=0}^{T} \frac{\left|h_r^1 - h_r^0\right|}{(1+\delta)^t} - C_r \tag{6}$$

where h_r^0 and h_r^1 are, respectively, the heating costs before and after implementing recommendation r, λ is the inter-temporal discount factor and T is the useful life of the intervention (i.e., the useful working life of a new heater).[16]

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

$$c_r^P = \begin{cases} \frac{C_r - B_r}{E_r} & if\ C_r \geq B_r \\ 0 & if\ C_r < B_r \end{cases} \tag{7}$$

where $B_r = \sum_{t=0}^{T} \frac{\left|h_r^1 - h_r^0\right|}{(1+\delta)^t}$ is the actual value of the future private benefit. Equation 7 informs the social planner on the level of subsidy per Kg of reduced CO2 each recommendation should receive if funded. The total subsidy for r is simply $S_r = c_r^P E_r$.

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

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

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

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

[16] Note that future heating costs are known only in expectation, as they depend on the future costs of the energy vector used and future weather conditions and temperatures. This is a problem with a risk-averse household. In this case, we would need to incorporate its risk aversion into equation 6 using an additional parameter. Failing this, we allow δ to capture both effects, the intertemporal preferences as well as the risk aversion.

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

3.3 A real-world policy intervention: the implementation bonus

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

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

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

Or:

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

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 s.t. $p > \frac{C_r - B_r}{C_r}$. Note that, if a recommendation is implemented with a bonus p, then it is implemented for any bonus $p' \in [p, 1]$. As a result, each value of p corresponds to an emissions reduction $E^B(p)$ and a total subsidy cost $C^B(p)$, both increasing in p.

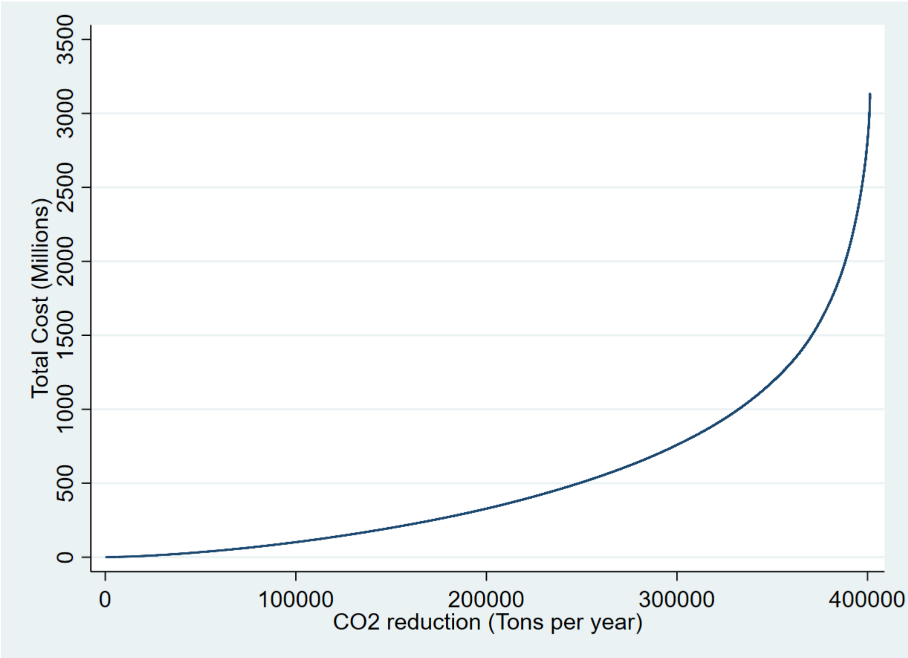
Note also that the relationship between p and $E^B(p)$ can be inverted: that is, for a given emission reduction target $\mathcal{T}$, it is possible to derive the level of bonus p required to achieve $\mathcal{T}$, and the associated costs to the state. This cost can be compared to what a fully informed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

4 Results and policy simulation

We now turn to empirical analysis. Our goal is to estimate the three cost curves for CO2 emissions reduction from the use of fossil fuels in residential buildings: these curves refer to total cost, costs for a fully informed social planner, and the cost of an implementation bonus.

To assess these cost, we use micro-level data from EPCs, weighted using census information.[17] We carry out our simulations for the Province of Treviso, but the exercise can be replicated in other areas with similar data available. Note that temperatures in the Treviso Province (13.1°C on average) are comparable to those of other large western cities (e.g., Baltimore): thus, our results on the need for building insulation and heating costs can be useful also for other urban areas.

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



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

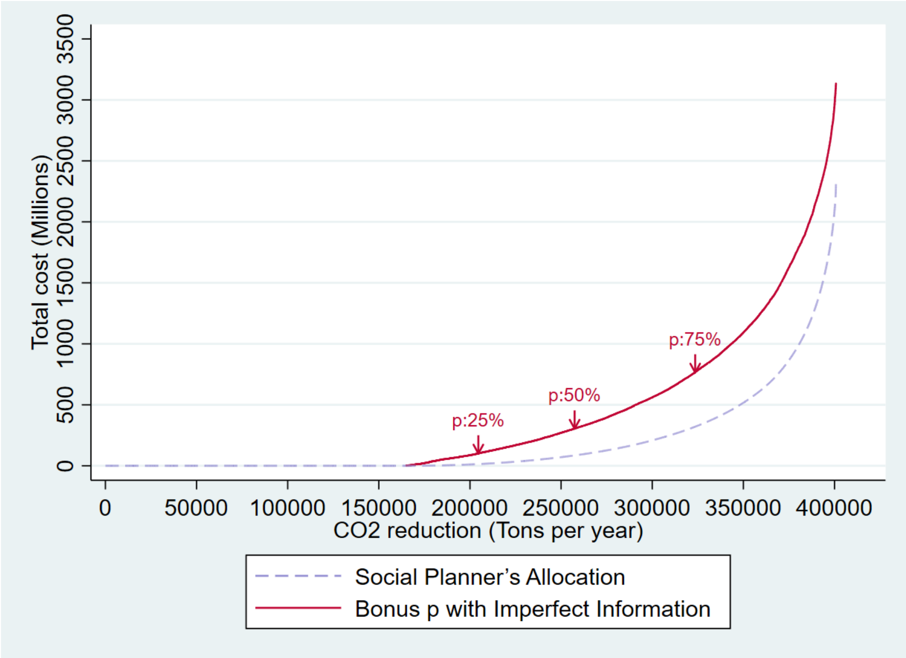
Figure 1 shows the aggregate total cost curve for CO2 emissions reduction. The horizontal axis indicates the total CO2 reduction in tons per year. The vertical axis shows the lowest total cost to achieve each level of emission reduction, in millions of euros. It is interesting to highlight that, on the one hand, net zero CO2 emissions would not be achieved even if all the recommendations were implemented. On the other hand, the highest feasible reduction - 401,083 tons per year - is significant and represents a 31.88% cut in current emissions (equivalent to 1,258,275 tons per year). This maximum reduction comes at a very high price, 3,134 million euros (i.e., more than 3,400 euros per inhabitant in the province), because costs increase exponentially with CO2 reduction. Indeed, CO2 emissions reduction targets of 100,000, 200,000, and 300,000 tons per year (i.e., about one, two, and three quarters of the maximum reduction, respectively) can be achieved at a cost of 101 million euros (about 1/32 of the maximum reduction costs), 329 million euros (about 1/10), and 761 million euros (about 1/4), respectively.

When the total cost of reducing CO2 emissions is shared by the government and private households, an additional parameter, δ, is required to estimate the cost curve for the government alone (see equations 6 and 10 above). The two cases of a fully informed social planner and of an implementation bonus are presented in Figure 2, which is constructed setting $\delta = 0.1$.[18] Our choice on the value for δ is motivated by the fact that it can capture both the intertemporal preferences of households as well as their risk aversion (see footnote 16).

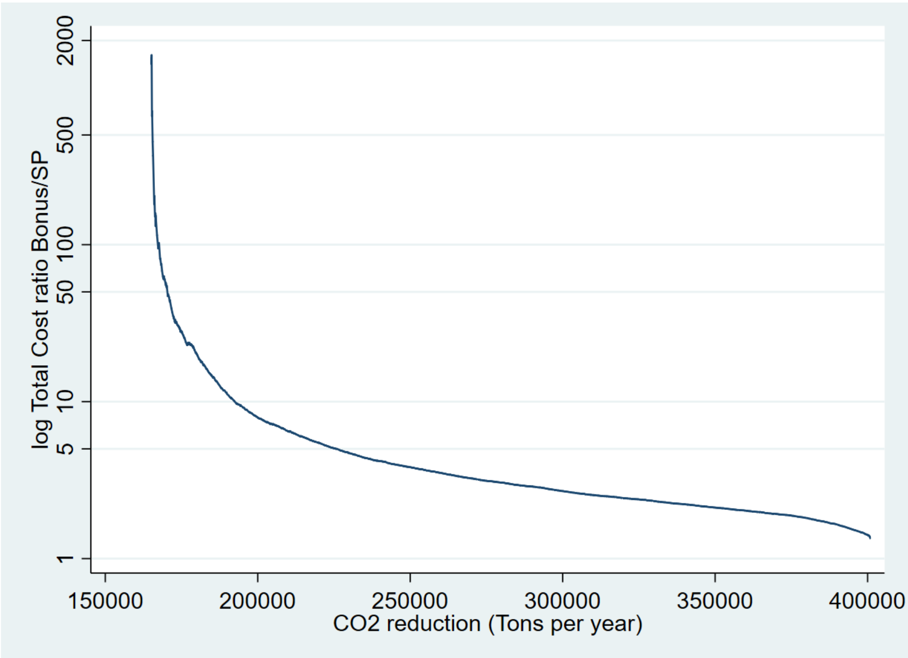
[17] Appendix A repeats all the estimates using unweighted data. The aim is to show that, qualitatively, our results are unaffected by the weighting methodology used.

[18] 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) Bonus inefficiency

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

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

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

Although the increase in the bonus level leads to a greater reduction in CO2 emissions, this policy is always inefficient compared to the allocation of a fully informed social planner: given a CO2 reduction target (i.e. 300,000 tons per year), the required bonus $p = 0.66$ (not depicted in the figure) generates higher costs for the state (561 million euros) than those incurred by a fully informed social planner (208 million euros).[19] Graphically, the vertical distance between the solid red and dashed blue lines in Figure 2, panel (a), indicates the magnitude of this inefficiency. Figure 2, panel (b), shows the log-ratio between the costs of the two policies for every CO2 reduction target. Implementing a bonus of 25% of the recommendation cost is 7.21 times more expensive than the cost a social planner with full information would have sustained to obtain the same CO2 emissions reduction. This proportion falls to 3.60 and 2.39 for a bonus equal to, respectively, 50% and 75% of the cost to implement recommendation. Overall, increasing bonus levels are associated with a decrease in policy inefficiency. This is unsurprising: low bonuses are extremely inefficient because the government is mostly subsidizing recommendations that would be implemented even without its intervention.[20]

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

With the aim of investigating this trade-off, Table 2a shows the effects of three different levels of bonus: 25%, 50%, and 75%, compared to the baseline scenario of no government intervention. A bonus of 25% increases CO2 reduction by 23.9% from the baseline scenario, at a cost of around 100 million euros (about 114 euros per inhabitant of the province). An increase of CO2 emissions reductions of 55.9% and 96% from the baseline can be achieved with bonus levels of 50% and 75%, respectively. These reductions come with a significantly higher cost: 3

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

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

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 Cost (€)	(7) Benefit (Y €)	(8) CO2 red. (Y kg)	(9) Useful Life (Y)
0%	0	164,984		NI	85.04%	10069.9	199.2	834.2	33.0
				I	14.96%	5757.0	1547.3	3311.6	44.6
25%	100.38	204450.5	7.211	NI	79.83%	10353.5	178.9	739.9	32.3
				I	20.17%	5749.3	1279.6	3044.7	44.4
50%	304.15	257269.4	3.600	NI	70.28%	10969.0	151.9	614.7	31.0
				I	29.72%	5775.1	989.9	2599.9	43.6
75%	764.38	323355.6	2.393	NI	52.08%	12638.9	118.4	447.3	28.8
				I	47.92%	5930.6	708.4	2028.9	41.2

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

and 7.6 times more than a 25% bonus, respectively (i.e., 341 and 864 euros per inhabitant). There is also an increase in the proportion of recommendations implemented from 15% in the absence of government intervention to 48% with a bonus of 75%.

In terms of average recommendation costs, we do not see substantial differences across levels of bonus: for the implemented recommendation, the average cost ranges between 5,700 and 5,900 euros, whereas for non implemented recommendations the average costs are between 10,000 and 11,000 euros. Inspection of the types of recommendations implemented shows that the mix of recommendations does not change substantially moving from low to high levels of subsidies. A more generous policy tends to increase the number of houses with at least one recommendation implemented, rather than increasing the number of interventions per house [21]. On the contrary, as the bonus increases, both the average private (lower heating costs) and average public (lower CO2 emissions) benefits of the implemented recommendation decrease. The former falls from 1,547 to 708 euros/year, while the latter from 3,312 to 2,029 kg of CO2/year.

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

5 Household Characteristics

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

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

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

5.1 EPC-Census matching

The census data include information on the dwellings and the demographic characteristics of their occupants for the entire population of the Treviso province. Among dwelling characteristics, we identify those in common with the EPC data, which we call background variables, i.e., variables present in both the EPC and the census, allowing us to link these two datasets. They relate to the year of construction, the size of the dwelling, the main heating fuel (natural gas or other), the main heating system (central heating for the whole building, central heating per dwelling, or independent appliances), the domestic hot water system (natural gas, electricity or other), and renewable energy sources (with or without). In addition, the census data include census tracts, i.e. the geographical location of small contiguous areas in which each dwelling is located. In the Treviso province, a census tract has 75 households on average. Census tracts can be used as background variables because the EPC register provides georeferenced zero-dimensional information (i.e. point data) on the location of each certified dwelling.[22]

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

5.2 Imputation of expenditure from the HBS

To retrieve household economic information, we rely on the Italian Household Budget Survey (HBS, `https://www.istat.it/en/archivio/180353`). The HBS collects detailed information on the expenditures incurred by households to purchase goods and services intended for household consumption. The survey is representative at the (NUTS-2) regional level; we use the subsample of 1,155 households surveyed in 2015 for the Veneto region.[23]

In addition to expenditure information, the HBS includes socio-demographic and housing descriptors that are consistent with census data, which allows us to integrate the previously matched EPC-census dataset with the household expenditure information available from the HBS data. To do so, we again follow Camboni et al. (2021) and impute the total monthly

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

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

expenditure from the HBS to our dataset using a parametric micro approach called *stochastic regression imputation* (see, for example, D'Orazio et al. (2006)). First, we estimate a total family expenditure function from the HBS data based on dwelling and household characteristics. We then use the estimated function and the distribution of its stochastic term to impute the total family expenditure to the records in the matched EPC-census dataset.

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

5.3 Policy intervention and household characteristics

The matched EPC-Census-HBS dataset allows us to investigate the characteristics of the households most likely to occupy dwellings associated with given recommendations. Table 2b presents the average household characteristics for four different levels of policy bonuses, i.e., no bonus, bonus at 25%, 50%, and 75%, distinguishing between households that occupy dwellings where recommendations are implemented from households in dwellings where recommendations are not implemented[24]. Column (3) of Table 2b shows that the average total annual household expenditure of households with and without implemented recommendations is similar, regardless of the level of the policy bonus. The only exception is that expenditure is slightly higher for families living in dwellings with implemented recommendations when $p > 50\%$. Column (4) also shows that there is little variation in the cost of heating for households, expressed as a percentage of their total expenditure. Column (5) shows the average cost incurred by households to implement a recommendation, net of the bonus received as partial refund from the government, i.e., $(1-p)TC_r$; column (6) sets out the average incidence of this cost on household total expenditure, $(1-p)TC_r/Exp$.

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

Table 3 presents the maximum likelihood estimates of logit models for the probability of implementing a recommendation, i.e., the probability that the recommendation has a positive recommendation value. Such a probability is a function of the characteristics of both the home and the household associated with the recommendation. It is estimated for four levels of policy bonuses, and the estimated coefficients are expressed as odds ratios. The energy class of the home and its surface area are crucial factors determining the implementation of a recommendation, for any level of bonus. Indeed, in the absence of a bonus, $p = 0\%$, the

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

odds of positive recommendations for homes with energy class G is 66.72 times that of the recommendations for class A homes, all else being equal. This odds ratio falls when p increases, but still remains at 49.95 when $p = 75\%$. Regarding the surface area, when $p = 0\%$, the odds of implementing the recommendations in homes larger than 140 sqm is 45.99 times that of homes smaller than 41 sqm. In this case, the odds ratio increases with p, reaching 66.54 when $p = 75\%$. There are two additional interesting results. First, recommendations are less likely to be implemented in buildings with 9 or more dwellings, for every level of bonus. For instance, when there is no bonus, the odds of implementing recommendations in buildings with at least 9 dwellings are 0.674 times the odds for implementing recommendations in buildings with a single dwelling, i.e., in a detached house. Second, when the bonus reaches $p = 75\%$, the odds of implementing a recommendation for households belonging to the 3rd (4th) quartile of the expenditure distribution are 1.166 (1.268) times the odds for the households in the first quartile. The latter finding is in line with Table 2b: the gap in household expenditure between those who implement a recommendation and those who do not increases with p.

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

(1) 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	84.74%	33157.5	6.05%	10573.1	39.95%	1.66%
	I	15.26%	33229.2	6.55%	5824.0	22.63%	0.55%
25%	NI	79.48%	33139.3	6.03%	8163.2	30.81%	1.30%
	I	20.52%	33281.1	6.49%	4377.5	17.00%	0.41%
50%	NI	70.04%	32998.2	6.00%	5776.6	21.79%	0.94%
	I	29.96%	33566.1	6.40%	2932.6	11.32%	0.28%
75%	NI	52.05%	32828.2	6.00%	3346.9	12.57%	0.56%
	I	47.95%	33537.4	6.26%	1502.2	5.80%	0.16%

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

Table 3: Probability of implementing the recommendation

Bonus	0%	25%	50%	75%
Ln Recommendation cost	0.108***	0.103***	0.096***	0.081***
	(0.009)	(0.007)	(0.006)	(0.004)
EPC class. Ref: A (A1 to A4)				
B	2.008*	1.997**	1.403	1.063
	(0.755)	(0.655)	(0.351)	(0.212)
C	1.750	1.910**	1.744**	2.029***
	(0.635)	(0.570)	(0.386)	(0.347)
D	4.539***	4.267***	3.403***	4.533***
	(1.346)	(1.096)	(0.653)	(0.708)
E	9.208***	9.571***	9.250***	10.59***
	(2.702)	(2.434)	(1.751)	(1.669)
F	24.01***	26.96***	21.96***	23.12***
	(7.137)	(6.967)	(4.266)	(3.754)
G	66.72***	75.73***	61.83***	49.95***
	(20.14)	(19.94)	(12.26)	(8.339)
Construction period. Ref: before 1960				
1960-1969	0.621***	0.663***	0.819**	0.918
	(0.071)	(0.067)	(0.073)	(0.077)
1970-1979	0.484***	0.594***	0.743***	0.794***
	(0.056)	(0.060)	(0.065)	(0.067)
1980-1989	0.392***	0.488***	0.573***	0.682***
	(0.055)	(0.058)	(0.056)	(0.062)
1990-1999	0.478***	0.453***	0.459***	0.489***
	(0.069)	(0.055)	(0.046)	(0.044)
From 2000	0.517***	0.494***	0.457***	0.457***
	(0.077)	(0.062)	(0.047)	(0.043)
Surface, sqm. Ref: ≤40				
41-60	2.266*	2.669***	2.605***	3.391***
	(1.034)	(0.846)	(0.720)	(0.685)
61-80	3.310***	4.184***	4.859***	7.307***
	(1.478)	(1.302)	(1.330)	(1.471)
81-100	8.606***	9.305***	9.930***	14.66***
	(3.811)	(2.886)	(2.735)	(2.989)
101-120	17.30***	18.15***	18.25***	23.02***
	(7.688)	(5.668)	(5.097)	(4.795)
121-140	22.46***	27.39***	24.36***	32.99***
	(10.16)	(8.782)	(7.006)	(7.218)
>140	45.99***	47.95***	47.09***	66.51***
	(20.75)	(15.37)	(13.56)	(14.34)
Primary heating fuel: natural gas	0.118***	0.192***	0.284***	0.390***
	(0.010)	(0.012)	(0.022)	(0.028)
No central heating	1.174	1.029	1.152*	1.060
	(0.132)	(0.098)	(0.091)	(0.072)
Renewable sources	0.773	0.848	0.903	0.939
	(0.186)	(0.188)	(0.166)	(0.152)
Number of dwellings in the building (Ref: One)				
2	0.999	1.050	1.148*	1.038
	(0.101)	(0.093)	(0.090)	(0.076)
3-4	0.765**	0.860	0.951	0.868*
	(0.095)	(0.092)	(0.086)	(0.071)
5-8	0.898	0.928	0.925	0.867*
	(0.117)	(0.099)	(0.082)	(0.067)
9+	0.674***	0.680***	0.734***	0.683***
	(0.089)	(0.073)	(0.064)	(0.050)
Household income quartile (Ref: first)				
second	1.131	1.071	1.027	1.055
	(0.143)	(0.114)	(0.090)	(0.078)
third	1.173	1.131	1.136	1.166**
	(0.154)	(0.127)	(0.104)	(0.090)
fourth	1.094	1.039	1.141	1.268***
	(0.154)	(0.125)	(0.113)	(0.108)
Household members	0.897*	0.918*	0.969	0.943*
	(0.051)	(0.044)	(0.038)	(0.032)
Homeowner occupied	1.180	1.109	1.093	0.925
	(0.127)	(0.100)	(0.079)	(0.055)
Household type (Ref: single)				
Couple with children	1.140	1.005	1.096	1.193**
	(0.162)	(0.121)	(0.109)	(0.098)
Couple without children	1.373*	1.254	1.074	1.204*
	(0.256)	(0.196)	(0.137)	(0.134)
Single parents	0.933	1.140	1.000	1.102
	(0.170)	(0.169)	(0.118)	(0.115)
Others	1.238	1.323	1.157	1.234
	(0.314)	(0.302)	(0.218)	(0.191)
At least high school	1.123	1.061	1.099	1.019
	(0.096)	(0.076)	(0.066)	(0.052)
Age class (Ref: at most 40)				
41-65	0.965	0.998	1.051	1.109*
	(0.100)	(0.088)	(0.075)	(0.067)
at least 65	1.098	1.170	1.138	1.042
	(0.174)	(0.163)	(0.135)	(0.110)
Female	1.031	0.941	1.224***	1.148**
	(0.112)	(0.084)	(0.088)	(0.070)
Immigrants	1.067	1.079	0.954	0.980
	(0.155)	(0.130)	(0.095)	(0.077)
Occupational status (Ref: employed)				
Retired	0.908	0.904	0.871	0.995
	(0.118)	(0.103)	(0.088)	(0.089)
Other not employed	0.834	0.858	0.773**	0.881
	(0.125)	(0.105)	(0.078)	(0.078)
Observations	19525	19525	19525	19525

Logit models: odds ratio. Discount rate 10%, weighted sample. Standard errors, clustered by dwelling ID, in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

6 Conclusions

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

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

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

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

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

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Appendix A Unweighted results

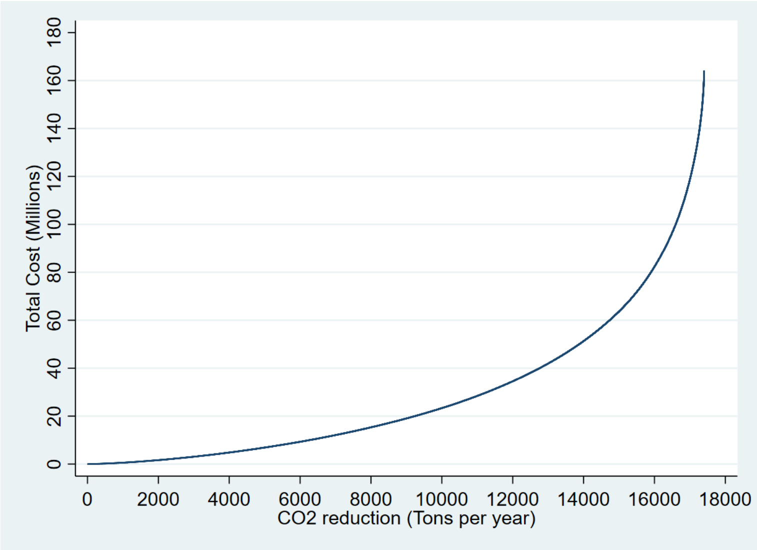
All results presented in Appendix A are derived from EPC micro-level data that are NOT weighted with census information.

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

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

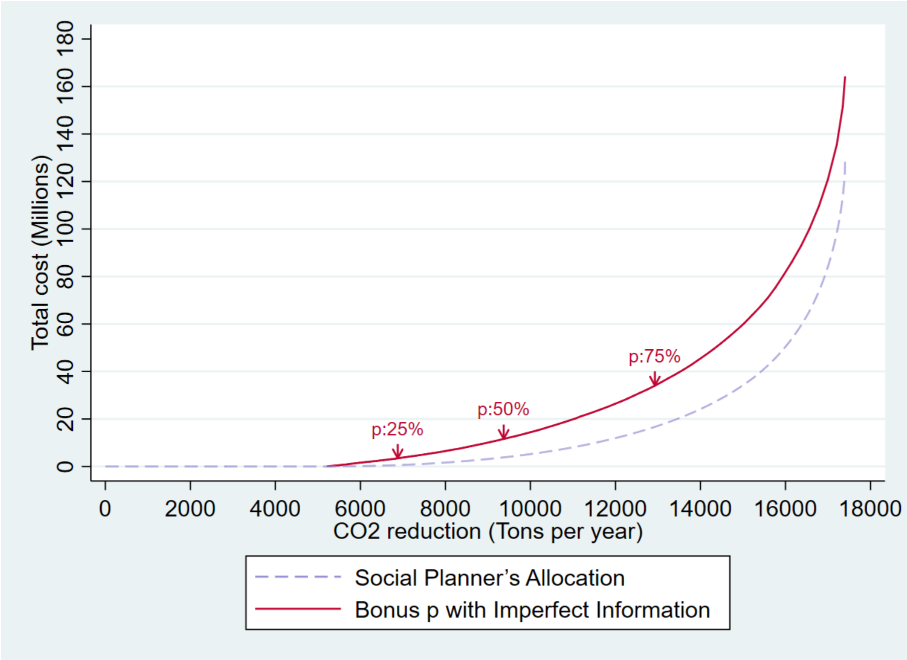
Notes. For a given variable, the subscripts 0 and 1 denote, respectively, before and after implementing the recommendation. *EP* and *CO2* measure, respectively, the energy required and the CO2 emitted to warm 1 sqm per year; *heating cost* measures the standardised heating cost of a dwelling; *Recommendation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

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

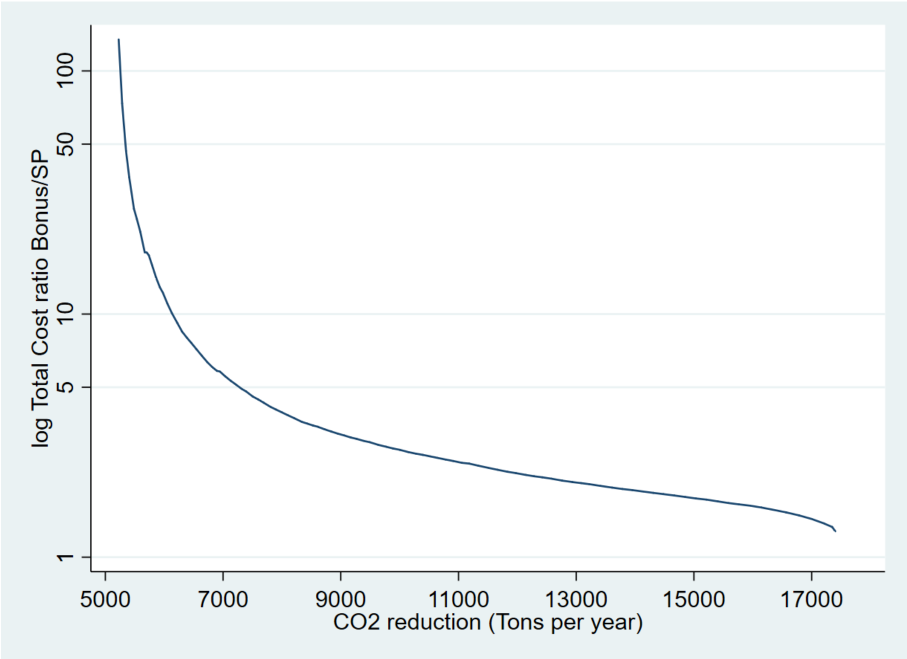


The horizontal axis indicates total CO2 reduction, in tons per year. The vertical axis shows the lowest possible total cost to achieve that emission reduction, in millions of euros. Unweighted sample.

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



(a) Policy interventions cost



(b) Bonus inefficiency

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

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

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

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

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

Policy level	Share of implemented and not implemented recommendations		Average HH expenditure Tot. (Y €)	% heating cost	$(1-p)TC_r$ (€)	$TC\ Exp$ (%)	$AC\ Exp$ (%)
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%

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

Table A4: Probability of implementing the recommendation

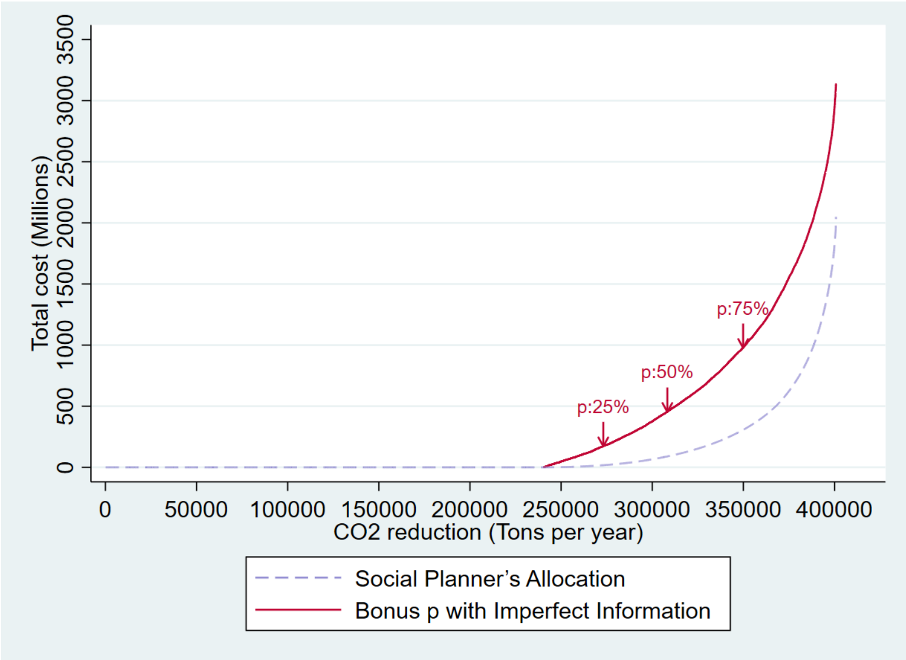
Bonus	0%	25%	50%	75%
Ln Recommendation cost	0.106***	0.093***	0.091***	0.090***
	(0.008)	(0.006)	(0.005)	(0.004)
EPC class. Ref: A				
B	1.731*	1.694**	1.327	1.052
	(0.541)	(0.454)	(0.279)	(0.165)
C	1.600*	1.855***	1.707***	2.112***
	(0.456)	(0.441)	(0.313)	(0.279)
D	4.176***	4.091***	3.288***	4.314***
	(0.993)	(0.840)	(0.527)	(0.519)
E	9.449***	9.319***	8.911***	9.078***
	(2.197)	(1.882)	(1.417)	(1.108)
F	24.38***	27.74***	23.60***	19.94***
	(5.828)	(5.736)	(3.850)	(2.515)
G	75.70***	92.34***	73.40***	40.86***
	(18.37)	(19.52)	(12.31)	(5.301)
Construction period. Ref: before 1960				
1960-1969	0.674***	0.693***	0.822***	0.983
	(0.064)	(0.059)	(0.0560)	(0.066)
1970-1979	0.498***	0.613***	0.726***	0.722***
	(0.049)	(0.051)	(0.052)	(0.048)
1980-1989	0.414***	0.515***	0.577***	0.640***
	(0.050)	(0.052)	(0.049)	(0.048)
1990-1999	0.517***	0.488***	0.474***	0.479***
	(0.068)	(0.053)	(0.042)	(0.036)
From 2000	0.619***	0.562***	0.490***	0.413***
	(0.089)	(0.061)	(0.044)	(0.031)
Surface, sqm. Ref: $\leq$40				
41-60	2.014**	2.641***	3.033***	2.984***
	(0.657)	(0.656)	(0.583)	(0.418)
61-80	3.557***	4.236***	5.102***	5.547***
	(1.128)	(1.031)	(0.967)	(0.771)
81-100	7.835***	8.643***	10.62***	11.11***
	(2.477)	(2.118)	(2.036)	(1.584)
101-120	17.07***	17.96***	19.82***	17.35***
	(5.437)	(4.447)	(3.880)	(2.556)
121-140	22.03***	27.25***	27.18***	25.23***
	(7.182)	(6.976)	(5.552)	(3.952)
>140	48.59***	50.99***	55.95***	49.83***
	(15.78)	(12.97)	(11.34)	(7.663)
Primary heating fuel: natural gas	0.113***	0.176***	0.273***	0.416***
	(0.009)	(0.013)	(0.019)	(0.026)
No central heating	1.352***	1.167**	1.211***	1.098*
	(0.126)	(0.090)	(0.076)	(0.059)
Renewable sources	0.564***	0.637**	0.665***	0.894
	(0.122)	(0.121)	(0.104)	(0.117)
Number of dwellings in the building (Ref: One)				
2	1.025	1.045	1.108	1.045
	(0.088)	(0.080)	(0.074)	(0.063)
3-4	0.798**	0.860*	0.953	0.957
	(0.083)	(0.076)	(0.072)	(0.063)
5-8	0.791**	0.812**	0.884	0.889*
	(0.093)	(0.078)	(0.070)	(0.059)
9+	0.668***	0.677***	0.761***	0.750***
	(0.076)	(0.062)	(0.057)	(0.047)
Household income quartile (Ref: first)				
second	1.094	1.021	1.002	1.019
	(0.115)	(0.089)	(0.070)	(0.058)
third	1.144	1.057	1.118	1.137**
	(0.125)	(0.097)	(0.083)	(0.070)
fourth	1.028	0.998	1.065	1.181**
	(0.122)	(0.098)	(0.086)	(0.080)
Household members	0.927	0.943	0.991	0.968
	(0.044)	(0.038)	(0.034)	(0.029)
Homeowner occupied	1.044	1.048	1.059	0.980
	(0.094)	(0.077)	(0.063)	(0.047)
Household type (Ref: single)				
Couple with children	1.178	1.029	1.069	1.165**
	(0.137)	(0.100)	(0.087)	(0.078)
Couple without children	1.353*	1.270*	1.091	1.193*
	(0.209)	(0.166)	(0.122)	(0.114)
Single parents	0.992	1.167	1.035	1.097
	(0.149)	(0.146)	(0.105)	(0.093)
Others	1.200	1.354*	1.219	1.077
	(0.247)	(0.240)	(0.185)	(0.135)
At least high school	1.075	1.029	1.064	0.995
	(0.078)	(0.063)	(0.054)	(0.042)
Age class (Ref: at most 40)				
41-65	1.114	1.077	1.027	1.052
	(0.101)	(0.081)	(0.063)	(0.052)
at least 65	1.227	1.223*	1.073	1.004
	(0.163)	(0.139)	(0.104)	(0.082)
Female	0.980	0.963	1.195***	1.129**
	(0.088)	(0.071)	(0.071)	(0.055)
Immigrants	1.070	1.104	0.971	0.987
	(0.129)	(0.108)	(0.079)	(0.064)
Occupational status (Ref: employed)				
Retired	0.957	0.925	0.939	1.045
	(0.102)	(0.087)	(0.076)	(0.072)
Other not employed	0.943	0.956	0.854*	0.980
	(0.124)	(0.101)	(0.074)	(0.069)
Observations	19525	19525	19525	19525

Logit models: odds ratio. Discount rate 10%, unweighted sample. Standard errors, clustered by dwelling ID, in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

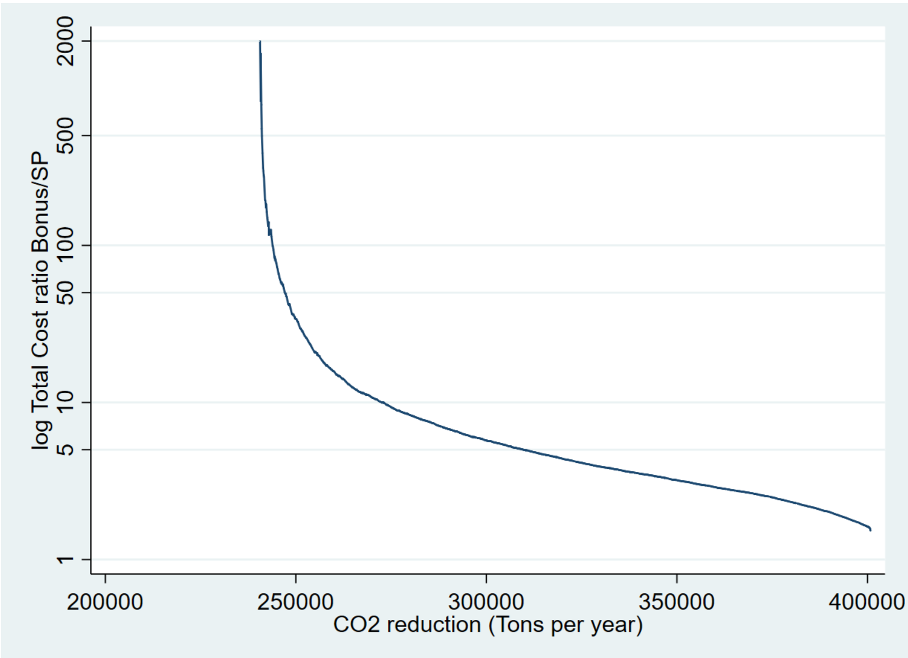
Appendix B Discount rate 5%

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

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



(a) Policy interventions cost



(b) Bonus inefficiency

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

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

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

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

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

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

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

Table B3: Probability of implementing the recommendation

Bonus	0%	25%	50%	75%
Ln Recommendation cost	0.128***	0.112***	0.098***	0.068***
	(0.007)	(0.006)	(0.005)	(0.004)
EPC class. Ref: A (A1 to A4)				
B	1.702*	1.316	1.085	1.559**
	(0.486)	(0.326)	(0.229)	(0.282)
C	1.728**	1.599**	1.840***	2.878***
	(0.469)	(0.364)	(0.339)	(0.457)
D	3.906***	3.575***	3.988***	7.226***
	(0.909)	(0.694)	(0.652)	(1.076)
E	8.994***	9.809***	10.30***	14.54***
	(2.064)	(1.873)	(1.663)	(2.201)
F	21.36***	21.53***	21.43***	26.74***
	(4.994)	(4.215)	(3.566)	(4.164)
G	52.18***	51.74***	43.16***	49.72***
	(12.43)	(10.30)	(7.369)	(7.901)
Construction period. Ref: before 1960				
1960-1969	0.758***	0.788***	0.878	0.811**
	(0.067)	(0.067)	(0.073)	(0.071)
1970-1979	0.700***	0.750***	0.835**	0.789***
	(0.063)	(0.063)	(0.068)	(0.069)
1980-1989	0.542***	0.575***	0.662***	0.660***
	(0.056)	(0.054)	(0.060)	(0.063)
1990-1999	0.439***	0.417***	0.453***	0.483***
	(0.045)	(0.039)	(0.040)	(0.044)
From 2000	0.401***	0.403***	0.433***	0.435***
	(0.044)	(0.040)	(0.041)	(0.041)
Surface, sqm. Ref: $\leq$40				
41-60	2.065**	2.981***	3.179***	3.271***
	(0.583)	(0.771)	(0.672)	(0.543)
61-80	3.724***	5.481***	6.462***	7.635***
	(1.036)	(1.410)	(1.360)	(1.261)
81-100	7.971***	11.37***	13.02***	13.18***
	(2.225)	(2.935)	(2.762)	(2.238)
101-120	15.15***	20.89***	20.62***	21.83***
	(4.278)	(5.477)	(4.457)	(3.850)
121-140	18.29***	24.63***	28.05***	32.67***
	(5.316)	(6.678)	(6.338)	(6.195)
>140	32.40***	47.77***	52.81***	63.11***
	(9.415)	(12.94)	(11.83)	(11.69)
Primary heating fuel: natural gas	0.232***	0.298***	0.358***	0.404***
	(0.018)	(0.022)	(0.025)	(0.030)
No central heating	1.221**	1.158*	1.093	1.023
	(0.103)	(0.087)	(0.077)	(0.070)
Renewable sources	0.933	1.053	0.980	1.130
	(0.189)	(0.189)	(0.168)	(0.174)
Number of dwellings in the building (Ref: One)				
2	1.189**	1.206**	1.192**	1.023
	(0.095)	(0.091)	(0.085)	(0.076)
3-4	1.025	0.971	0.890	0.932
	(0.094)	(0.083)	(0.074)	(0.076)
5-8	1.013	0.955	0.917	0.885
	(0.094)	(0.080)	(0.072)	(0.069)
9+	0.771***	0.797***	0.790***	0.736***
	(0.070)	(0.064)	(0.059)	(0.053)
Household income quartile (Ref: first)				
second	0.952	0.932	1.053	0.989
	(0.087)	(0.078)	(0.081)	(0.071)
third	1.002	0.971	1.110	1.083
	(0.096)	(0.086)	(0.088)	(0.082)
fourth	1.016	1.077	1.141	1.226**
	(0.105)	(0.102)	(0.098)	(0.102)
Household members	0.945	0.982	0.971	0.969
	(0.038)	(0.037)	(0.033)	(0.035)
Homeowner occupied	1.172**	1.081	0.972	1.028
	(0.090)	(0.074)	(0.060)	(0.059)
Household type (Ref: single)				
Couple with children	1.105	1.170*	1.158*	1.218**
	(0.115)	(0.111)	(0.097)	(0.098)
Couple without children	1.177	1.136	1.167	1.140
	(0.157)	(0.142)	(0.131)	(0.128)
Single parents	1.089	1.097	1.135	1.021
	(0.135)	(0.125)	(0.118)	(0.105)
Others	1.261	1.194	1.224	1.200
	(0.245)	(0.216)	(0.203)	(0.196)
At least high school	1.089	1.077	1.083	0.996
	(0.067)	(0.062)	(0.056)	(0.050)
Age class (Ref: at most 40)				
41-65	1.133*	1.075	1.079	1.070
	(0.084)	(0.073)	(0.067)	(0.062)
at least 65	1.235*	1.195	1.204*	1.105
	(0.151)	(0.138)	(0.126)	(0.116)
Female	1.136*	1.113	1.088	1.274***
	(0.086)	(0.078)	(0.068)	(0.077)
Immigrants	1.031	0.975	0.932	1.002
	(0.102)	(0.089)	(0.075)	(0.076)
Occupational status (Ref: employed)				
Retired	0.868	0.869	0.888	0.955
	(0.089)	(0.085)	(0.078)	(0.085)
Other not employed	0.834*	0.829*	0.884	0.874
	(0.088)	(0.079)	(0.079)	(0.082)
Observations	19525	19525	19525	19525

Logit models: odds ratio. Discount rate 5%, weighted sample. Standard errors, clustered by dwelling ID, in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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).[25]

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

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

[26] According to the 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: $W_I = 0.7W_E$
- 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.