Incorporating the Prebound Effect in Retrofit Policy Analysis: Distributional Results for Belgium

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Abstract

This paper compares the distributional incidence of three decarbonization instruments in the Belgian residential sector: EPC-based minimum standards, carbon pricing with an equal per-household dividend, and renovation subsidies financed by a uniform lump-sum tax. Using Woonsurvey 2018 and a dwelling-level microsimulation model that evaluates renovation profitability on observed energy use, we quantify household monetary impacts, renovation take-up, and equity (across and within income groups) for budget neutral policies calibrated to common CO_2 targets. Three results stand out. First, EPC standards concentrate burdens on low-income and low-use households and generate high dispersion because they compel renovations where realized savings are small. Second, universal subsidies are costly on average and distribute benefits unevenly, with sizable transfers to infra-marginal projects. Third, carbon pricing with revenue recycling yields the lowest and most evenly distributed household burdens, largely because it triggers heat-pump adoption in dwellings with the highest energy consumption. We further show that combining a modest carbon price with targeted heat-pump support can meet the same emissions target at lower cost and with a smaller variance of household impacts than under the carbon dividend. Results are robust to rebound, landlord–tenant limits, and reasonable variations in discounting, horizons, and costs.

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1 Introduction

Residential buildings are pivotal to Europe's decarbonization. Globally, buildings account for about 26% of greenhouse gas (GHG) emissions (International Energy Agency, 2023). Achieving the EU's Fit for 55 target and climate neutrality by 2050 requires a sustained renovation wave (European Commission, 2021). Policy design in the residential sector primarily relies on two instrument families: (i) price-based instruments (e.g., carbon pricing on fossil heating fuels) and (ii) subsidies (e.g., grants, tax credits, soft loans) that lower upfront costs for heat pumps, insulation, or photovoltaic panels. All two are already being deployed at EU level: Member states strengthened the use of subsidies as a key policy instrument to incentivize energy-efficient residential renovations, while the EU is establishing a separate Emissions Trading System for buildings and road transport (ETS2), slated to start in 2028 (European Union, 2023a, 2023b, 2024). However, existing policy instruments may prove insufficient to achieve the EU's decarbonization objectives, raising the prospect of more stringent regulatory interventions in the residential sector. In particular, minimum energy performance standards—implemented through EPC[1]-based obligations under the Energy Performance of Buildings Directive—have increasingly been discussed as a complementary policy lever. For instance, the Citizens' Convention for Climate (2020) proposed to the French government to require homeowners and landlords to achieve a minimal level of energy performance by 2040. More recently, the Brussels-Capital Region has introduced ambitious energy performance requirements for residential buildings, mandating that low-rated dwellings (e.g., classes F and G) be upgraded to at least class E by 2033, with further tightening expected in subsequent years (towards class C) (Bruxelles Environnement, 2025). Considering the rental market in other jurisdictions such as the United Kingdom and France, minimum energy efficiency standards make it illegal to rent out housing with an energy performance certificate below a specific threshold (Gouvernement français, 2023; UK Department for Energy Security and Net Zero, 2025).

In this paper, we analyze the household-level distributional impacts of three government budget neutral policy families for residential decarbonization: (i) EPC-style performance standards, (ii) carbon pricing with equal per-household lump-sum recycling (a carbon dividend), and (iii) subsidies to renovation investments. Our focus is strictly monetary for households: who bears costs, who benefits, and how burdens are distributed across and within groups. We use these comparisons to test whether climate policy entails efficiency–equity trade-offs.

[1] An Energy Performance Certificate is a standardized rating that summarizes a dwelling's energy efficiency, typically expressed as annual energy use (for heating, domestic hot water and auxiliary energy) per square meter (kWh/m^2/year) and often translated into a label (e.g., A = efficient to F = inefficient).

Distributional justice matters on normative grounds—to avoid exacerbating inequalities and protect vulnerable groups—and pragmatically, because it influences policy feasibility and public acceptability. Distributional impacts of carbon pricing are widely studied. A consistent pattern emerges: baseline carbon pricing is typically regressive; lump-sum recycling can render it progressive; and sizable within-decile dispersion underscores the importance of horizontal alongside vertical equity (Cronin et al., 2019; Fischer & Pizer, 2019; Landis et al., 2019; Rausch et al., 2011).

Subsidies and tax credits are typically found to be regressive, as they disproportionately benefit higher-income households with sufficient liquidity to undertake energy-efficiency investments (Bourgeois et al., 2021; Lekavičius et al., 2020). While much of this literature emphasizes the role of market failures—such as credit constraints or split incentives— Fernández et al. (2024) show that regressivity may persist even in their absence, since subsidies can be capitalized into housing values and thus accrue primarily to homeowners, who are on average wealthier. Beyond these vertical equity concerns, subsidies may also generate substantial horizontal inequities by conditioning transfers on heterogeneous investment opportunities across households (Bourgeois et al., 2021).

Relative to carbon pricing and subsidy-based instruments, the distributional implications of regulatory standards have received less attention. In the automotive sector, a broad consensus holds that efficiency and emissions standards tend to be regressive, as compliance costs represent a larger share of income for low-income households, while higher-income households capture a larger share of the benefits given their higher consumption of energy services (Davis & Knittel, 2019; Fullerton & Muehlegger, 2019; Levinson, 2019). On top of this, in the residential building sector, distributional concerns may be even more salient because low-income households are disproportionately concentrated in poorly insulated dwellings (Ryckewaert et al., 2019). Yet, to our knowledge, no study has quantified the distributional incidence of EPC-based standards in the residential building sector.

A wide range of modelling approaches can be used to assess the distributional impacts of climate policies (Montenegro et al., 2021). Input–output models, for instance, quantify both the direct and supply-chain (indirect) effects of carbon pricing on household expenditures (Steckel et al., 2021). Computable general equilibrium models can further capture economy-wide adjustments and evaluate the income effects of a broader set of policies (Vandyck et al., 2022).

By contrast, although they abstract from general-equilibrium feedbacks and indirect effects, microsimulation models with endogenous investment decisions are particularly well suited to measuring distributional impacts not only across groups but also within them. To account for policy impacts over time, some studies rely on dynamic microsimulation frameworks (Giraudet et al., 2021; Müller et al., 2024). However, their dynamic structure requires strong assumptions regarding stock turnover, which can constrain distributional granularity. In addition, these models often represent the housing stock through archetypal dwellings and incorporate average market frictions calibrated from external evidence. A smaller set of studies instead adopts static microsimulation approaches to provide better incidence assessments (Soubelet et al., 2024; Torné & Trutnevyte, 2024, 2026). For example, Torné and Trutnevyte (2026) use such a model to study the distributional effects of alternative policy mixes, but focus on deep (rather than partial) retrofits, do not impose budget neutrality or common abatement targets, do not consider EPC standards, and impute heating demand from archetypes and household size.

A key empirical regularity in buildings is prebound: actual pre retrofit energy use is often below theoretical consumption (Sunikka-Blank & Galvin, 2012). This reduces ex ante profitability and realized savings from renovations and can shift the abatement mix (Galvin, 2024). Ignoring prebound biases instrument comparisons and incidence: EPC style thresholds calibrated to theoretical needs can force low return renovations on low-use households, while pricing anchored in actual consumption may tilt abatement toward fuel switching (e.g., heat pumps). Because these frictions vary across households, the incidence of policies is highly sensitive to whether models are based on observed bills or theoretical consumption. Beyond correcting prebound, billing data embed otherwise unobserved behaviours (occupancy patterns, comfort/temperature preferences, attention to energy costs, environmental consciousness) that are central for exposure and thus distributional analysis. To our knowledge, no study compares the distributional incidence of policies in the residential building sector policies while anchoring energy use in observed household energy bills.

In this paper, we develop a static microsimulation model with endogenous investment for Belgium that computes renovation profitability using actual (rather than theoretical) energy consumption, explicitly capturing the prebound effect. Across the three budget neutral policy families considered, the carbon dividend consistently yields the smallest increase in households' energy spending over the next 25 years, for any environmental objective along the 0–40% CO_2

reduction range. To achieve a 20% reduction in residential emissions, the average cost borne by households is 3.7 times higher under performance standards and, under subsidies, it is 5.7 times the one under carbon dividend. The carbon dividend also performs best for low income households, generates the lowest standard deviation of impacts, and leaves a majority of households financially better off compared with the two alternative designs. Singles and households with a low ratio of actual to theoretical energy consumption are strongly penalized under standards, whereas carbon pricing distributes costs more evenly. Subsidy hurts apartments and energy-efficient dwellings owners as subsidized renovations are not profitable for them, yet, they must finance others' investments. Rebound effects have only a minor influence on realized emissions, particularly at higher ambition levels where decarbonization is driven mainly by heat pump electrification rather than envelope insulation. While quantitative magnitudes vary with modeling assumptions (discount rate, investment horizon, investment costs), the qualitative ordering of policies is robust. Finally, accounting for the prebound effect is critical: when profitability is computed from actual rather than theoretical consumption, the same carbon price yields three times more emissions reduction, a result that relies on a systematic overestimation of retrofit profitability.

Relative to the literature, our paper makes three advances. First, we exploit linked household microdata that combine actual energy bills, detailed dwelling energy characteristics, and household socio demographics to simulate the distributional incidence of building sector climate policies when households endogenously choose renovations. Computing profitability using observed energy bills allows us to internalize prebound and to recover revealed behaviours that are central to exposure and incidence but typically unobserved in surveys. Second, we deliver a microdata anchored comparison of EPC standards, carbon pricing and subsidies, allowing partial retrofit; we make policy levers directly comparable by imposing government budget neutrality and tracing continuous policy response curves over various CO_2 reduction objectives. Third, by combining microsimulation with endogenous investment, we credibly capture non linearities (profitability thresholds, complementarities between insulation and heat pumps) and isolate the investment channel from pure demand response (sobriety) effects. We preserve the individual level granularity to quantify vertical equity, horizontal equity, and incidence across fine household subgroups. This positioning clarifies why our results differ from studies that rely on representative households, archetype based theoretical consumption, or purely price elastic demand responses.

The structure of this paper is as follows. Section 2 presents the data. Section 3 details the model and scenario design. Section 4 presents the main results, and Section 5 discusses robustness.

2 Data

2.1 Woonsurvey

The Woonsurvey 2018[2] (Flanders) provides rich microdata on housing conditions with an emphasis on energy performance. It covers about 3,000 dwellings and reports: (i) Envelope quality for windows, roof, walls, and floors (three categories: poor, intermediate, good); (ii) Dwelling attributes (type, floor area, tenure, construction year, heating system); (iii) Household socio-demographics (size, income, age/education/employment of the reference person) ; and (iv) annual energy expenditures by carrier (natural gas, heating oil, electricity, wood/other solid fuels). Because end-use detail is not observed, we allocate total carrier use across services using heating technology information. If the dwelling uses a gas or oil boiler, we assume a single boiler supplies space heating and domestic hot water and split the carrier consumption in proportion to theoretical needs. Otherwise, domestic hot water is assumed to be produced by a dedicated electric boiler. Details on cleaning rules are provided in Section 1 of the technical report.[3]

2.2 Augmented Woonsurvey

We augment the Woonsurvey by (i) deriving theoretical energy consumption from building characteristics, equipment and year of construction, (ii) recovering energy quantities from observed bills. These steps are used to project bills under renovation and policy scenarios.

Theoretical energy consumption

We compute theoretical consumption as:

$$E_{\text{th}} = E_{\text{heat}} + E_{\text{dhw}} + E_{\text{aux}} - E_{\text{PV}} \tag{2.2.1}$$

where the terms reflect space heating, domestic hot water, auxiliaries (appliances), and photovoltaic panels electricity generation. By construction, E_{th} depends only on dwelling physics and equipment (household behaviour/occupancy is standardized in the EPC) and is dominated

[2] Data have been made available by Agentschap Wonen in Vlaanderen and collected by Steunpunt Wonen.
[3] The technical report is available upon request to the authors.

by space heating (about 70% on average). The details of the computation of the theoretical energy consumption is provided in Section 2 of the technical report.

Envelope performance is summarized by U-values. Following Gendebien et al. (2014), we assign U-values by construction period and insulation quality (poor/intermediate/good) for each component; the complete mapping by component and construction year is provided in Section 1 of the technical report.

Real energy consumption

Woonsurvey reports annual energy expenditures by carrier but not physical quantities. We recover quantities by dividing expenditures by carrier-specific prices (2017–2018 averages).[4]

2.3 Actual vs. theoretical energy consumption for heating

We compare billed household heating consumption with RenoBel's theoretical requirements. The ratio of actual to theoretical consumption is a standard measure of the prebound effect.

Table 1 shows that, on average, billed use is about half of theoretical needs (mean 52%; median 46%). This implies that analyses based on theoretical consumption tend to overstate bill savings from renovations and, consequently, the private profitability of such investments.

The table also reveals marked heterogeneity. The 90th-percentile ratio is roughly 5 times the 10th-percentile ratio; 25% of dwellings lie below 0.29, while another 25% exceed 0.69. These differences likely reflect variation in occupancy patterns, desired indoor temperatures, environmental attitudes, and attention to energy costs. Ignoring actual consumption therefore not only overestimates average benefits from renovation, but also masks key distributional patterns linked to household-specific composition, needs and behaviors.

Table 1: Distribution of actual-to-theoretical heating consumption ratios

	P10	P25	P50	P75	P90	Average
Ratio	20%	29%	46%	69%	97%	52%

Source: Own calculations based on Woonsurvey 2018.

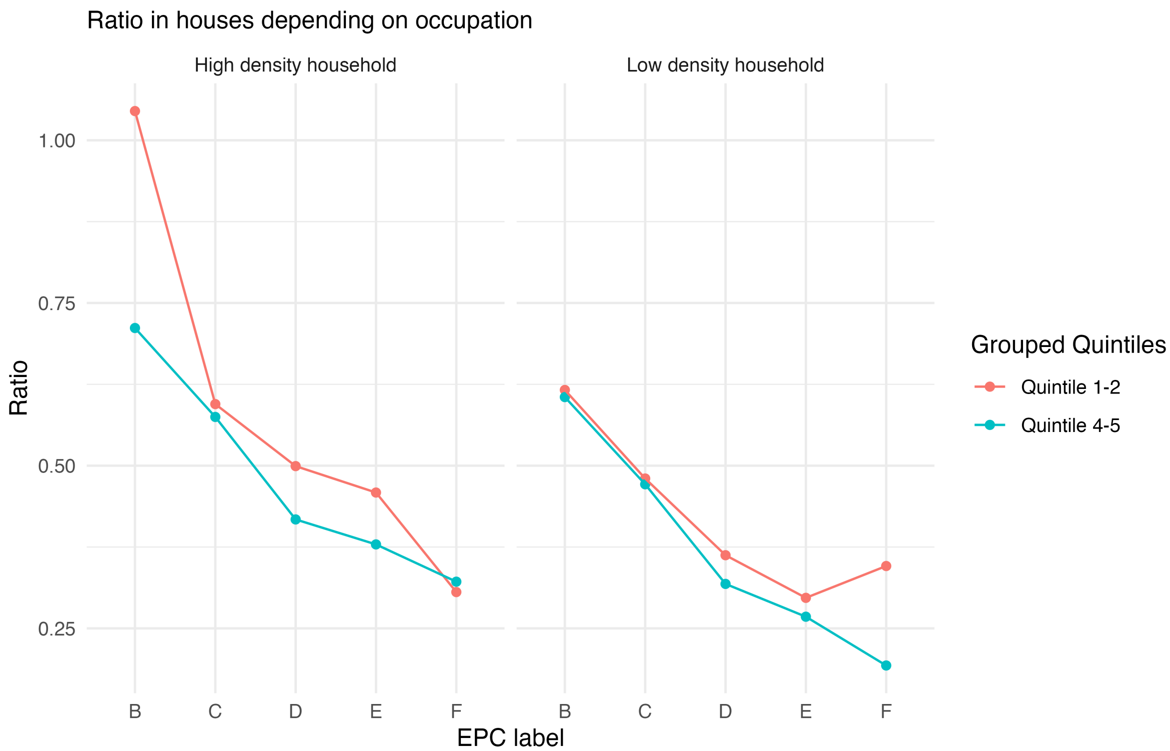
Figure 1 documents how the ratio varies with dwelling characteristics. For comparability, we restrict to houses (about 80% of the Flemish stock; see Appendix A.1). The left panel covers dwellings with living area per occupant below 75 m^2 (the median), the right panel those above

[4] Sources: CREG residential baskets 01/2017–06/2018 (gas/electricity), FPS Economy (heating oil), Valbiom (logs/pellets). See Section 1 of the technical report for values.

the median. Each horizontal axis reports the EPC rating from best (left) to worse (right), and households are split into the bottom two income quintiles (red) versus the top two quintiles (blue).

Three patterns emerge. First, conditional on energy performance and dwelling density, there is little systematic income gradient in the ratio, suggesting a low income elasticity of heating demand. Second, the ratio increases with energy performance: as dwellings become more efficient, the effective price of thermal comfort (e.g., a degree-hour of heating) falls, so households consume more heating services, narrowing the gap between actual use and theoretical needs. Third, higher occupancy density is associated with greater realized heating needs, which likewise pushes the ratio upward.

Figure 1: Actual-to-theoretical heating consumption ratios



Notes: The figure reports actual-to-theoretical heating consumption ratios for houses, by EPC rating, household income group, and dwelling density.

Source: Own calculations based on Woonsurvey 2018.

3 Methodology

This section presents the RenoBel model and the design of the counterfactual and policy scenarios.

3.1 The RenoBel model

RenoBel is a household-level microsimulation model that assesses the profitability of residential energy-renovation investments using microdata from Woonsurvey 2018. It combines detailed building characteristics with observed household energy consumption (bills).

Renovation options For each dwelling, the model enumerates technically feasible renovation options and evaluates their economic attractiveness. The option set includes upgrades to the four envelope components—roof, walls, floor, and windows—and the potential installation of a heat pump. For insulation, each component can either remain unchanged or be upgraded to "good" performance (see U-values in the technical report, Section 1). Combining four binary envelope decisions with heat pump adoption yields $2^4 \times 2 = 32$ configurations per dwelling. We restrict heat pump installation to dwellings with EPC scores below 350kWh/m^2/year (See technical report, Section 4).

Renovation costs Insulation costs are derived from Ryckewaert et al. (2019), with component-specific costs that depend on surface areas, insulation levels, location, and construction period. Heat pump installation costs depend on the required capacity, determined by dwelling heat load and standardized domestic hot water needs based on living area. Cost benchmarks come from industry sources and are updated over time using the ABEX construction price index.[5] Full cost formulas, sources, and parameters are documented in the technical report (Section 3).

Energy savings We value future energy savings at current real prices[6] discounted at fixed annual rate of 3%, consistent with standard appraisal practice (European Commission, 2014). A defining feature of RenoBel is that profitability is evaluated using households' *actual* energy consumption. Theoretical consumption reflects engineering characteristics under normative usage and typically overestimates observed use. RenoBel computes real energy savings by applying

[5] The latest values can be found here: https://abex.be/en/abex-index/

[6] We use 2023–2025 average residential prices by carrier and hold them constant in real terms throughout the horizon: natural gas and electricity from CREG residential baskets (https://www.creg.be/sites/default/files/assets/Publications/Studies/F20250514EN.pdf), heating oil from StatBel (2022), and firewood/pellets from Valbiom market reports (https://www.valbiom.be/actualites/suivi-mensuel-des-prix-des-combustibles-bois)

the ratio of observed-to-theoretical consumptions (both available ex-ante) to theoretical energy savings (projected by the EPC calculations), in line with the approach of Belaïd et al. (2021). This preserves the relative efficiency gains implied by renovations while anchoring savings in revealed behavior. By construction, this assumes no rebound effect; we assess robustness to that assumption in Section 5.1. We do not consider within-period demand response to price changes;[7] adjustments operate through investment choices rather than sobriety decision.

Life-cycle cost framework For each dwelling and renovation option i, we compute a 25-year life-cycle cost (LCC):

$$\mathrm{LCC}_i = I_i + \sum_{t=1}^{25} \frac{E_i}{(1+r)^t} \tag{3.1.1}$$

where I_i is the upfront investment and E_i the yearly energy expenditure under renovation option i, discounted at a real rate $r = 3\%$. Energy prices are held constant in real terms unless altered by a policy scenario. We assume no salvage value beyond the 25-year horizon.[8] For each dwelling, we identify the option that minimizes LCC.

Investment decision Households are assumed to be fully rational in their investment decisions and choose the renovation option that minimizes LCC. We exclude liquidity constraints: any privately profitable project can be financed.[9] For rental units, the baseline adopts a tenant-favourable limit in which renters undertake profitable renovations and retain the associated bill savings. Section 5.3 reports bounds under a landlord-surplus-capture limit.

The main modeling assumptions are summarized in table 2.

[7] In his meta-analysis, Labandeira et al. (2017) found low price elasticities for domestic energy ranging from -0.185 to -0.684 in the long run.
[8] Robustness analyses at 20-year and 30-year time horizons are conducted in section 5.2
[9] We relax that assumption in section 5.5

Table 2: Main modelling assumptions

Assumption	Description
Horizon	25-year evaluation window for life-cycle costs (LCC); no salvage value beyond the horizon.
Discount rate	Real annual discount rate of 3% (homogeneous across households).
Post-renovation behaviour	Indoor temperature held constant (no direct rebound).
Demand response	No within-period demand response to prices; adjustment operates via investment, not sobriety.
Energy savings	Relative reduction in theoretical heating needs applied to observed (billed) consumption.
Energy prices	Constant real base-year prices in the counterfactual; policy scenarios alter effective prices where relevant.
Investment choice	Households select the option with the lowest LCC.
Liquidity constraints	None: all privately profitable investments can be financed.
Landlord–tenant	Tenant-favourable limit: renters undertake profitable renovations and retain bill savings.
Heat pumps	Feasible only for dwellings with EPC < 350 kWh /m^2/ year.

3.2 Scenario design

3.2.1 No-policy counterfactual

Although many energy renovations are privately profitable, they are not systematically undertaken in practice. As a common reference, we first construct a no-policy counterfactual in which all privately profitable options are implemented. This isolates policy-induced investments from autonomous renovation behavior. In doing so, we abstract from liquidity constraints, bounded rationality, and landlord–tenant split incentives, and assume that households adopt a homogeneous discount rate and undertake all profitable investments (we discuss implications in Section 5).

A key mechanism behind unrealized "profitable" investments is the prebound effect: theoretical consumption exceeds observed use, so engineering assessments overstate savings and profitability. Once we evaluate profitability on observed consumption, some theoretically cost-effective projects are no longer profitable. In our data, 40% of dwellings would renovate if profitability were assessed on theoretical savings; this falls to 8% when based on observed consumption. Only the latter renovation cases are assumed to be undertaken in our no-policy counterfactual.

3.2.2 Policy scenarios

We compare the no-policy counterfactual to three budget-neutral policy families: Norm, carbon dividend and subsidy (see Table 3). Within each family, we vary the key parameter (norm threshold, carbon price, subsidy rate) to span emissions reductions from 0% to 40%. This design supports like-for-like comparisons at a common environmental outcome and a common public-budget stance.

Table 3: Summary of the policy scenarios

Scenario	**Description**
1. Norm	All dwellings must reach an energy score below a threshold (in kWh/m^2/year).
2. Carbon dividend	A carbon price (in €/tCO_2) is imposed on heating fuels (natural gas and heating oil). Revenues are redistributed equally to all households.
3. Subsidy	A universal subsidy rate (in %) covers a fraction of renovation investment costs, financed by an equal lump-sum tax on each household.

4 Results

This section presents results under the baseline assumptions. We proceed in two steps. First, we map response curves for each policy family by calibrating parameters to deliver any sectoral CO_2 reduction between 0% and 40% (see Section 4.1). This comprehensive exploration provides a robust, target-agnostic comparison: rather than tying conclusions to a single, potentially arbitrary target, it reveals non-linearities, and shows how outcomes evolve as ambition rises; it makes clear which findings are stable across the full range and which appear only in specific regions (e.g., at low or high emission reduction targets). By contrast, studies that compare two policies at one common target can miss these differences. Second, we fix the target at 20% and provide a granular distributional analysis at a common environmental outcome.

Throughout, the monetary impact on households, ΔLCC, is the percentage change in life-cycle cost net of transfers and taxes under the policy (LCC^{Pol}) relative to the no-policy counterfactual (LCC^{Count}). It is the additional financial burden on households due to the implementation of a given policy.

$$\Delta LCC = \frac{\text{LCC}^{Pol} - \text{LCC}^{Count}}{\text{LCC}^{Count}}, \tag{4.0.1}$$

We compute the post-policy life-cycle cost over a 25-year horizon as

$$\text{LCC}^{Pol} = (1-s)I^{Pol} + \sum_{t=1}^{25} \frac{E^{Pol} - Tr}{(1+r)^t} + T, \tag{4.0.2}$$

where I^{Pol} is the upfront renovation investment, E^{Pol} the annual energy expenditure, r the real discount rate, s the subsidy rate (with $s = 0$ in the norm and carbon-dividend scenarios), Tr the annual equal-per-household lump-sum transfer in the carbon-dividend scenario (Tr $= 0$ otherwise), and T the equal lump-sum tax used to finance subsidies in the subsidy scenario ($T = 0$ otherwise).

Relative to the counterfactual, E^{Pol} reflects three channels: (i) lower heating needs if insulation is undertaken, (ii) higher unit prices for fossil fuels when a carbon price applies, both for heating and domestic hot water consumptions, and (iii) fuel switching if a heat pump is installed (with the corresponding change in energy carrier and price).

4.1 Response curves

To obtain smooth response curves, we simulate a grid of 20 scenarios within each policy family. Norm thresholds range from 440 to 250kWh/m^2/year in steps of 10kWh/m^2/year; carbon prices range from 0 to 210 €/tCO_2 in steps of 10 €/tCO_2; subsidy rates range from 47.5% to 97.5% in steps of 2.5%. The parameterization aligns environmental outcomes and imposes government-budget neutrality for all instruments, ensuring direct comparability.

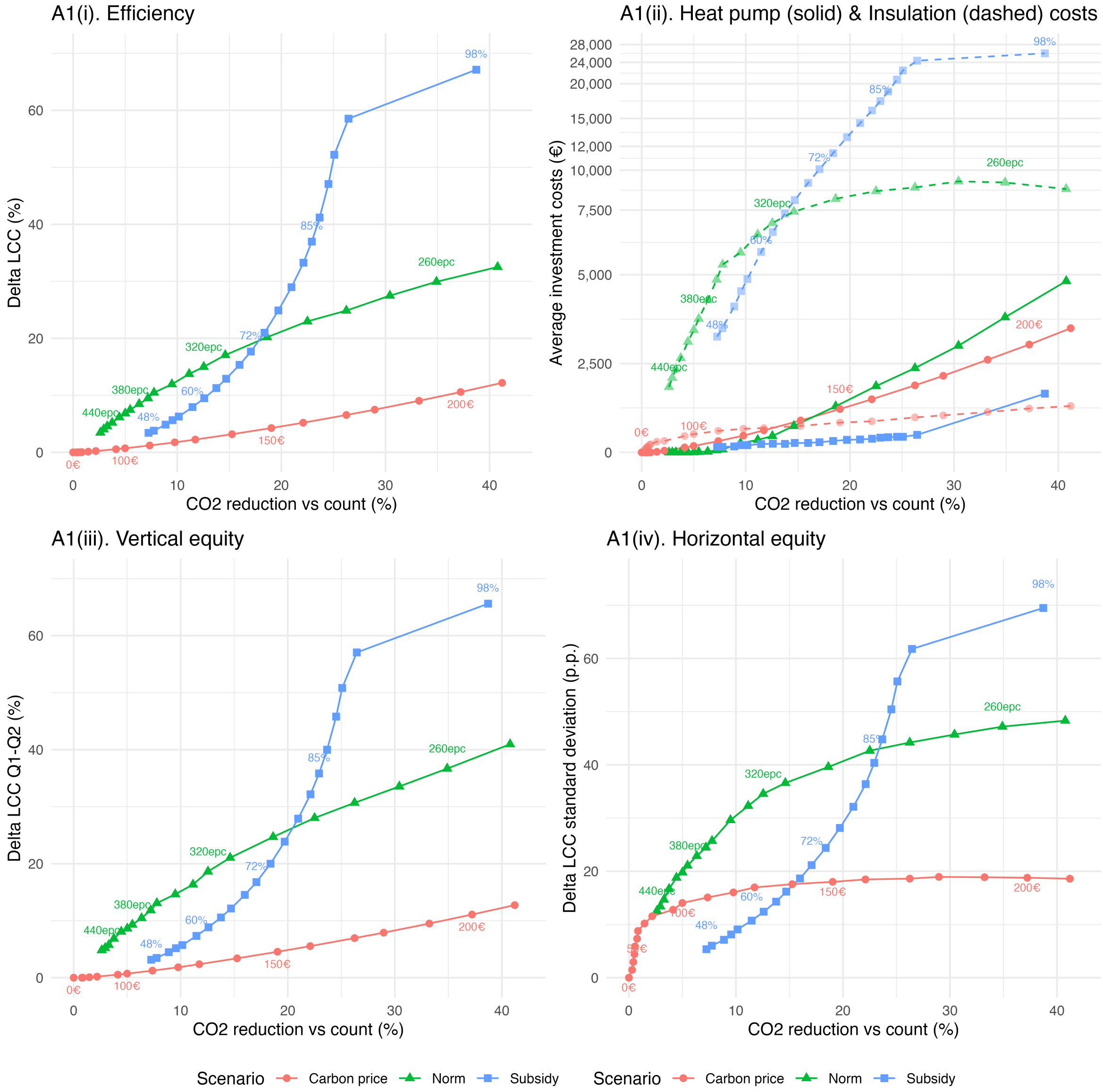
Figure 2 compares the three policy families along the 0–40% range of CO_2 reductions. The horizontal axis reports the achieved sector-wide reduction relative to the no-policy counterfactual; the vertical axis differs by panel. Panel (i) shows average ΔLCC (in %), our efficiency indicator. Panel (ii) reports the renovation mix by technology, presenting the average investment costs for heat-pump installations and for insulation measures. Panel (iii) reports average ΔLCC for the bottom two income quintiles (Q1–Q2), isolating the impact on low-income households, our measure of vertical equity. Panel (iv) presents the variance of ΔLCC across the whole population, our measure of horizontal equity: lower values indicate less dispersion in monetary impacts across households.

Three broad patterns emerge. First, efficiency and renovation composition are two sides of the same coin (panels (i) and (ii)). The carbon dividend typically delivers the lowest ΔLCC at a given environmental outcome because, once the price signal crosses a profitability threshold, heat-pump adoption scales quickly and most abatement comes from fuel switching. Given our decarbonized electricity assumption, each heat pump yields a total abatement of heating and domestic hot water emissions, implying a low cost per tonne relative to envelope retrofits. At medium to high ambition, panel (ii) also shows that average investment outlays for both heat pumps and insulation are lower under the carbon dividend than under the norm: pricing allocates electrification to dwellings with the highest private returns, whereas a uniform standard forces installations in units constrained by the norm where they are not necessarily cost-effective. Under norms, low stringency mainly induces insulation (with heat pumps still unprofitable), making costs per tonne high when many targeted dwellings have low actual energy use. As the EPC-threshold tightens, electrification-oriented bundles (sometimes paired with targeted envelope upgrades) enter the LCC-minimizing set for a growing share of dwellings, narrowing the efficiency gap compared to pricing. Subsidies outperform norms at low ambition because households self-select the insulation projects with the largest private bill savings. At higher ambition, however, electrification scarcely occurs under subsidies—heat pumps appear only at very high subsidy rates (above 90%)—so meeting the target increasingly relies on expensive envelope retrofits that deliver modest bill savings, raising the cost per abated tCO_2.

Second, the low-income profile (panel (iii)) closely tracks the efficiency ordering: average ΔLCC for Q1–Q2 moves almost one-for-one with the population average across targets, implying broadly similar rankings by instrument for low-income households. This is consistent with the observation that absolute space-heating outlays vary little across income quintiles.

Third, norms exhibit higher variance (panel (iv)) because they target a subset of dwellings with heterogeneous baseline use and may impose large costs on households with low actual consumption. Carbon pricing with a dividend displays dispersion driven by heterogeneous energy use (some households receive a transfer that exceeds their carbon payments, others the reverse), but the variance tends to shrink as high-use dwellings invest and reduce exposure. Subsidies yield low variance at very low ambition (limited gains per recipient and a uniform financing tax), but dispersion rises as uptake broadens and free-riding increases: infra-marginal households can receive sizable transfers for renovations that would have been privately profitable with only modest support, while others pay the uniform tax without investing, widening the gap in ΔLCC.

Figure 2: Response curves



Source: Own calculations based on Woonsurvey 2018.

4.2 Distributional analysis

We next fix the target at a 20% sectoral reduction and analyze the distributional outcomes in greater detail. The calibrated policy parameters that achieve this objective are: 153 €/tCO_2 in the carbon-dividend scenario, an EPC threshold of 297 kWh/m^2/year under the norm, and a subsidy rate of 77.5%.

4.2.1 Impact by subgroup

Table 4 compares the average household impact, ΔLCC (in % of LCC), for policies calibrated to a 20% reduction in residential CO_2. At the aggregate level, the carbon dividend imposes the lowest burden (+4.6%), norms are higher (+17%), and subsidy-financed packages are highest (+26%). This ranking reflects not only how many heat-pump installations occur but in which dwellings they occur. Under norms, heat pumps are more numerous but often placed in dwellings where private returns are low; under pricing, fewer heat pumps are installed overall, but they are allocated to the highest-return dwellings, lowering average costs. With a 77.5% subsidy, no heat pump is privately profitable, so the 20% target is met entirely through insulation, which raises the cost per tonne relative to electrification.

Low-income households more often occupy poorly insulated dwellings; they therefore bear larger burdens under standards, which mandate renovations in those units (see Section A.1.1). The same housing profile also makes them more likely to qualify for subsidies; however, because they typically live in smaller homes, the per-renovation subsidy is smaller, leaving the average burden under the subsidy scenario broadly balanced across income deciles. A similarly balanced pattern holds under the carbon dividend, consistent with broadly similar absolute space-heating outlays across income groups (and the equal per-capita transfer that offsets carbon payments).

Results also differ by dwelling type and efficiency. Apartments, with lower baseline heating needs, often gain under the carbon dividend (the transfer exceeds carbon payments), face small average costs under norms, and bear large burdens under subsidies when few profitable investments are undertaken but the uniform tax still applies. Houses bear higher costs across all instruments, in line with larger heating loads and greater renovation scope. By EPC, norms perform as intended—costs concentrate on D–F dwellings while A–C are largely unaffected—whereas the carbon price-and-rebate distributes costs evenly across both groups and the subsidy pushes relatively more cost onto efficient dwellings that invest little but still finance the scheme.

Finally, the prebound margin explains much of the cross-household dispersion under norms: low-use households are strongly penalized when mandated renovations yield small realized bill savings, while households whose actual use is closer to theoretical needs face much smaller costs. Pricing and subsidies align better with private incentives, which tempers dispersion in ΔLCC relative to norms. Renters gain on average under the carbon dividend, consistent with lower baseline use and smaller dwellings, so the lump-sum transfer often outweighs carbon payments; by contrast, they are hit harder by norms (compliance falls more often on the units they occupy) and under subsidies. Household composition matters primarily through heating needs and floor area: singles face particularly high costs under norms, which is concerning given they must absorb these charges on a single income, whereas larger households tend to bear somewhat higher costs under pricing in line with higher heated demand.

Table 4: Impact by categories for $\Delta^{-}CO_2 = 20\%$ (Δ LCC)

	Carbon dividend	Norm	Subsidy
Total	+4.6%	+17%	+26%
Income quintile			
1st and 2nd quintile	+4.9%	+23%	+25%
3rd quintile	+4.8%	+15%	+24%
4th and 5th quintile	+4.2%	+12%	+28%
Type of dwelling			
Apartment	-11.9%	+2.5%	+43%
House	+7.5%	+20%	+23%
Initial EPC			
A, B and C	+4.6%	+0.4%	+35%
D, E and F	+4.7%	+40%	+17%
Actual to theoretical energy consumption			
<0.5	+2.8%	+29%	+26%
$\geq$ 0.5	+6.7%	+3.8%	+26%
Tenure			
Owner-occupier	+6.5%	+15%	+24%
Renter	-3.8%	+24%	+33%
Household composition			
Couple + Children	+7.5%	+9.6%	+24%
Couple	+4.3%	+14%	+24%
Single + Children	+5.1%	+24%	+28%
Single	+1%	+28%	+30%

Source: Own calculations based on Woonsurvey 2018.

Popularity

Table 5 reports the share of households that are better off under carbon pricing relative to the norm and the subsidy scenarios, by income quintile. The table shows that 56.5% of households are financially better off under the carbon pricing than norm, and that this share is mildly decreasing across income quintiles. It also reveal that 84% of them prefer the carbon dividend to the subsidy, and that this rate is even larger among high income individuals.

Table 5: Share of households better off under carbon dividend, by income quintile

	Norm	Subsidy
Total	56.5%	84.0%
Q1	65.0%	79.2%
Q2	62.4%	83.7%
Q3	52.9%	80.3%
Q4	53.5%	90.1%
Q5	50.4%	87.6%

Source: Own calculations based on Woonsurvey 2018.

5 Discussion

In this section, we assess the robustness of the baseline findings along four dimensions. First, we incorporate a direct rebound effect and compare achieved CO_2 reductions with and without rebound. Second, we study the sensitivity of our results to key model parameters, such as the discount rate and the investment horizon. Third, we re-estimate outcomes when renovation profitability is anchored in theoretical (rather than observed) consumption, thereby quantifying how prebound affects the set of privately profitable projects and distributional incidence. Fourth, we analyze two frictions that can materially alter who invests and who benefits: the landlord–tenant dilemma (by bounding outcomes between a tenant-favourable limit and a landlord-surplus-capture limit) and liquidity constraints, which we proxy by restricting renovations to higher-income households. Together, these checks ensure that our results are stable across different modeling choices and alternative assumptions. Lastly, we compare our main results to a heat-pump targeted scenario implementing a moderate carbon price funding subsidies towards heat-pump installation.

5.1 Rebound effect

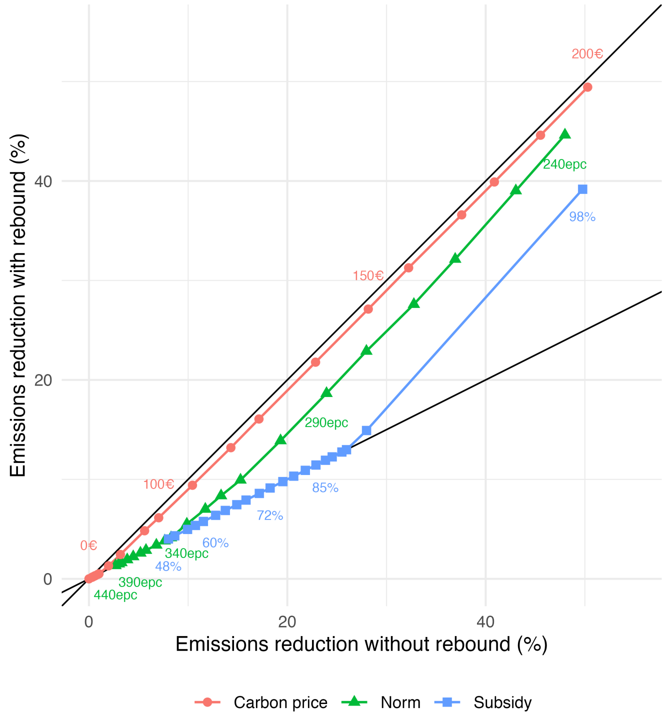
When insulation improves, households may choose higher indoor temperatures or longer heating durations because thermal comfort becomes cheaper. This behavioral response—the rebound effect—reduces realized energy savings relative to engineering predictions. The empirical literature typically finds a direct rebound for residential heating in the range of roughly 10–30% in OECD settings, with context-specific variation; reviews conclude that rebounds are meaningful but rarely large enough to erase most savings (Sorrell et al., 2009). In our data, the ratio of actual to theoretical heating consumption rises with energy performance, which is consistent with rebound: as efficiency lowers the effective "price" of thermal comfort (e.g., a degree-hour), households consume more heat services, narrowing the gap between actual consumption and theoretical needs. Our baseline scenarios abstract from rebound to keep the monetary incidence transparent. We assess below how this assumption matters:

Vertical equity We find little systematic income gradient in the actual-to-theoretical ratio once we condition on energy performance and dwelling density (Figure 1). This suggests that incorporating a rebound effect is unlikely to meaningfully alter our conclusions about vertical equity across income groups.

Household welfare Our money metric (ΔLCC) is an adequate proxy for welfare when indoor comfort is held constant: in the absence of rebound, the policy affects only energy-related expenditures and renovation outlays, so the monetary incidence aligns with welfare changes. By contrast, if renovations induce a positive rebound, households that consume more heat services enjoy additional utility (comfort gains) relative to a fixed-behaviour counterfactual. From a purely monetary perspective, ignoring rebound overstates bill savings and thus understates net costs; from a comprehensive welfare perspective, however, ignoring rebound is conservative, because it omits the comfort surplus (relative to the cost increase) households derive from higher service consumption.

Environmental effectiveness Even with a large rebound (we test 50%), the impact on achieved CO_2 reductions is limited and highly technology-dependent. In Figure 3, we plot reductions with a 50% rebound (vertical axis) against the original no-rebound reductions (horizontal axis). For low ambition, points lie on the line with slope 1/2—indicating that a 50% rebound halves the achieved reduction—up to about 2% under the carbon dividend, 8% under the norm, and 25% under the subsidy. Beyond these thresholds, the relationship switches to the 45-degree line (slope 1): additional abatement is no longer attenuated by rebound. The break in slopes mirrors the transition in the abatement mix: once electrification (heat-pump–led fuel switching) dominates, rebound no longer reduces achieved abatement because electricity is assumed decarbonized. Accordingly, incorporating a sizable rebound does not overturn our main results on environmental effectiveness; it only dampens low-ambition outcomes before electrification becomes the LCC-minimizing option.

Figure 3: Impact of a 50% rebound effect on emissions reduction



Source: Own calculations based on Woonsurvey 2018.

5.2 Sensitivity analysis

This section reports four complementary diagnostics for the carbon-dividend scenario at the 20% emissions-reduction target. In Table 6, we vary, one at a time, the heat-pump eligibility constraint, the real discount rate, the investment horizon, and investment costs. For each perturbation, the table reports (i) how counterfactual CO_2 emissions (no-policy) change relative to the augmented Woonsurvey baseline, and (ii) the carbon price required to achieve a 20% sectoral reduction under the new parameter values. We focus on the carbon-pricing scenario because these parameters do not affect investment choices under the norm and have similar qualitative effects under the subsidy as under the carbon dividend scenario.

Table 6: Sensitivity analysis – Carbon pricing

	$\Delta^- CO_2$ Counterfactual	Carbon price	Δ LCC	Heat Pump Share
Baseline scenario	-2.9%	153 €/tCO_2	4.6%	60.2%
Heat pump threshold				
300 EPC score	-2.9%	162 €/tCO_2	4.6%	57.6%
400 EPC score	-2.9%	147 €/tCO_2	4.3%	62.1%
Real discount rate				
5%	-1.9%	188 €/tCO_2	5.6%	68.8%
1%	-4.5%	118 €/tCO_2	3.3%	47.3%
Investment horizon				
30 years	-3.6%	135 €/tCO_2	3.9%	55.3%
20 years	-2.0%	178 €/tCO_2	5.3%	67.7%
Investment costs				
−20%	-4.5%	122 €/tCO_2	3.7%	50.1%
+20%	-1.9%	182 €/tCO_2	5.4%	68.0%
No discount for initial quality	-1.6%	150 €/tCO_2	4.6%	66.0%

Source: Own calculations based on Woonsurvey 2018.

For each parameter, we consider a lower and a higher value than in the baseline, remaining within empirically plausible ranges. The resulting effects are largely symmetric around the baseline. Tightening or relaxing the heat-pump feasibility threshold has no effect on counterfactual emissions and only a marginal effect on the required carbon price, consistent with the fact that heat pumps in the baseline scenario are predominantly installed in dwellings with theoretical needs below 300 kWh/m^2/year. By contrast, the discount rate, the investment horizon, and investment costs matter: a lower discount rate or a longer horizon increases the value of energy savings, raising counterfactual abatement and reducing the carbon price needed to meet the 20% target; lower investment costs similarly expand the set of prior-policy privately profitable projects and reduce the required carbon price.

Across all sensitivity checks, however, the variation in the carbon price remains moderate (within the ±25% margins), the composition of investments marginally changes, and, because carbon payments are recycled lump-sum, the impact on household LCC is minor. These results indicate that our main conclusions are not driven by any single parameter choice and are robust to reasonable alternatives.

5.3 Theoretical versus actual energy consumption

Table 7 shows that evaluating renovations with real (billed) energy use delivers markedly different conclusions than using theoretical consumption. First, the counterfactual renovation rate drops from 40% (theoretical) to 8% (real), and the implied autonomous CO_2 reduction falls from 22% to 2.9%. This indicates that many projects that look cost-effective on paper cease to be so once actual usage is considered—an assessment that better aligns with observed low adoption rates and limits the apparent pool of "profitable but unrealized" renovations. Second, under a carbon dividend of 153€/tCO_2, the distributional picture changes: with theoretical consumption, average burdens (Δ LCC) are closer across income groups (9.6% for Q1–Q2 vs. 9.1% for Q4–Q5), whereas with real consumption the burden falls proportionally more on lower-income households (4.9% for Q1–Q2 vs. 4.2% for Q4–Q5). In other words, relying on theoretical consumption masks income-related differences that emerge once actual usage is taken into account. Third, the composition of investment shifts toward electrification when using real consumption: the heat-pump share in total renovation cost rises from 37% (theoretical) to 60% (real). When actual heating consumption is roughly half of theoretical needs, insulation—which reduces demand by a percentage—yields much smaller monetary savings and thus becomes relatively less attractive. By contrast, heat-pump electrification can remain worthwhile, because prebound does not diminish domestic hot-water loads[10] and fuel switching lowers unit costs for both space heating and hot water.

[10] Domestic hot-water accounts for 25% of total energy demand using real consumption while it is only 15% when considering the theoretical approach

Table 7: Comparison of outcomes based on real versus theoretical energy consumption

	Real consumption	**Theoretical consumption**
Counterfactual		
Δ-CO_2 emissions (%)	-2.9	-22
Renovation rate (%)	8.1	39.7
Carbon dividend (Price = 153 €/tCO_2)		
Δ-CO_2 emissions (%)	-20	-59
Renovation rate (%)	14	49
Heat pump share in total renovation cost (%)	60	37
Δ LCC for Q1–Q2 households (%)	4.9	9.6
Δ LCC for Q4–Q5 households (%)	4.2	9.1

Source: Own calculations based on Woonsurvey 2018.

5.4 Landlord-tenant dilemma

In our main analysis, we adopt a tenant-favourable limit case: renters undertake privately profitable renovations and fully retain the associated bill savings. The opposite limit is one in which landlords can fully extract the surplus via rent increases equal to the value of realized energy savings. Because the landlord identity is not observed at the unit level, we cannot model capitalization directly in the population; instead, we bound renter outcomes by comparing these two limits for the norm and the carbon-pricing scenarios.

Under carbon pricing, if landlords capture the entire surplus from energy-saving renovations, a tenant's position is effectively the same as facing a higher energy price without the option to renovate. Under a standard, if the landlord is obliged to retrofit and can increase the rent by the full value of realized savings, the tenant's net position is unchanged relative to no renovation (the lower bill is exactly offset by a higher rent). Preference shares under both limits (Table 8) show that the results are very similar across these two extreme cases.

Table 8: Share of tenants better off under carbon pricing than norm

	(a) Tenant-favourable	(b) Landlord-capture
Preference: Carbon dividend > Norm	74.9%	73.6%
Δ LCC (Carbon dividend)	-3.8%	-2.9%
Δ LCC (Norm)	23.8%	23.8%

Source: Own calculations based on Woonsurvey 2018.

5.5 Liquidity constraints

A large literature documents that liquidity constraints and high implicit discount rates deter households—especially low-income—from undertaking privately profitable energy-efficiency investments. Constraints arise from limited access to credit, higher perceived borrowing costs, short planning horizons, or risk and hassle costs that effectively raise the investment hurdle rate (Allcott & Greenstone, 2012; Fowlie et al., 2018; Gillingham & Palmer, 2014). In this environment, tighter financing conditions are expected to depress renovation take-up and alter the distribution of policy impacts across income groups.

We proxy liquidity constraints with a stark bound: households in the first two income quintiles (Q1–Q2) are assumed unable to undertake any renovation in response to the policy, in line with the approach from Lekavičius et al. (2020). Holding the carbon price at its baseline value would then cause achieved abatement to fall from 20% to 13.2%. To recover the 20% emissions target under this constraint, the required carbon price rises to 187 €/tCO_2.

Table 9 shows that this recalibration only slightly increases the overall cost of the policy, but it opens a clear gap between constrained and unconstrained households. The burden for low-income households rises because they cannot invest and remain exposed to a higher carbon price; by contrast, unconstrained households invest, reduce their exposure, and benefit from a larger transfer since carbon revenues are higher at 187 €/tCO_2. As a result, average ΔLCC for Q1-Q2 increases sharply (about +50%), while ΔLCC for higher-income groups falls relative to the baseline.

Even as an extreme bound, this highlights that financing frictions can affect both efficiency and equity. If credit constraints are significant, targeted low-cost finance and grants for low-income households can ease constraints, raise take-up of high-return electrification and insulation, and improve equity.

Table 9: Liquidity constraints

	Baseline	Liquidity constraints
Carbon price (€/tCO_2)	153	187
Δ LCC Q_1–Q_2 (%)	4.9	7.5
Δ LCC Q_3–Q_5 (%)	4.4	4.0

Source: Own calculations based on Woonsurvey 2018.

5.6 Policy mix: carbon pricing and heat pump subsidy

We draw three lessons from the simulations. First, heat pumps deliver large emissions reductions at relatively low cost. Second, their adoption is highly sensitive to the relative price of gas versus electricity. Third, very high subsidy rates are typically needed to trigger widespread electrification; applying the same subsidy rate to both heat pumps and insulation is therefore expensive and inefficient. Motivated by these facts, we search for combinations of carbon price and heat-pump-only subsidy that achieve a 20% sectoral reduction. Among the feasible combinations, we retain a scenario with a 30 €/tCO_2 price funding an 80% heat-pump subsidy. Carbon revenues covers the subsidy bill and the small residual left is redistributed equally across households to ensure budget neutrality.

Table 10 shows that this heat-pump scenario is very close to the carbon-price-and-rebate benchmark in terms of average cost and distributional impacts by income, while yielding a similar overall renovation rate. Its distinguishing feature is a much higher heat-pump share in total renovation spending (76% vs. 60%), indicating that the policy primarily shifts choices within the renovation set toward electrification rather than insulation. Horizontal equity also improves relative to the dividend case because the carbon price is five times lower, which reduces cross-household dispersion in monetary impacts driven by heterogeneous energy use. Finally, the smaller impact on energy prices under a 30 €/tCO_2 signal may help with social acceptability, while targeted support ensures that electrification occurs where it is privately and socially most cost-effective.

Table 10: Comparison of calibrated scenarios vs. heat-pump targeted policy

	Carbon dividend	**Heat pump subsidy**
Carbon price (€/tCO_2)	153	30
ΔLCC (%)	4.6	4.5
ΔLCC Q1–Q2 (%)	4.9	4.6
ΔLCC Q4–Q5 (%)	4.2	4.6
Standard deviation (p.p.)	18	3
Renovation rate (%)	14	15
Heat pump share in total costs (%)	60	76

Notes: Both scenarios deliver the same environmental performance and are budget-neutral.

Source: Own calculations based on Woonsurvey 2018.

6 Conclusion

Residential buildings sit at the core of Europe's decarbonization challenge, and EU countries policy mixes increasingly combine price instruments, subsidies, and regulatory obligations. This paper asks the following question: when policies are designed to achieve the same emissions outcome under government budget neutrality, how do their household-level monetary impacts compare—both across income groups (vertical equity) and across otherwise similar households (horizontal equity)? To answer it, we built a static microsimulation model for Belgium (Reno-Bel) that endogenizes renovation choices and, crucially, anchors profitability in observed energy use from household bills. This design internalizes the prebound effect and embeds revealed behavior—occupancy, comfort preferences, attention to energy costs—that is central for exposure and distributional incidence but typically unobserved in engineering-based assessments.

Three findings stand out. First, under a common abatement target, policy instruments follow a clear ranking: carbon pricing with equal lump-sum recycling (a carbon dividend) consistently delivers the lowest average increase in life-cycle costs, while EPC-style performance standards and uniform subsidies impose substantially larger burdens. The mechanism is not merely the number of home retrofits undertaken, but the type of renovations and their allocation across dwellings. Once profitability thresholds are crossed, pricing triggers heat-pump electrification in dwellings with high private returns; by contrast, a uniform standard can force costly measures in constrained units with low realized savings, and a uniform subsidy can channel large transfers toward insulation works.

Second, the equity implications differ across instruments, and the efficiency–equity trade-off is not inevitable. With equal per-capita recycling, carbon pricing produces broadly even burdens—and for some low-use households the dividend can exceed carbon payments. Standards tend to hit low-income households hardest because they more often live in dwellings compelled to renovate. Lump-sum–financed subsidies shift costs onto households with few profitable projects (e.g., apartments, already efficient homes) while directing funds to those with many eligible, costly measures; they can therefore appear pro-poor in terms of recipients yet still generate high average burdens and sizable losses across all income groups.

Third, horizontal equity is a first-order concern with standards. For equal abatement, cost dispersion is substantially larger under norms than under the carbon dividend. Low-use households are disproportionately penalized because standards mandate renovations that deliver small realized bill savings for them. Policy evaluations that ignore observed energy use miss this channel and can therefore mis-rank instruments.

Our robustness analyses reinforce these conclusions. Incorporating rebound dampens low-ambition outcomes when abatement hinges on insulation, but the ranking of instruments is unchanged once electrification dominates. Reasonable changes to the discount rate, investment horizon, and cost parameters shift the calibrated carbon price only within moderate bounds. By contrast, valuing profitability on theoretical rather than billed consumption materially enlarges the set of "profitable" projects and alters incidence, underscoring the importance of using observed energy use. Regarding frictions behind the energy-efficiency gap, a landlord–tenant surplus-capture bound leaves our qualitative rankings essentially intact, whereas liquidity constraints may create vertical gaps. Finally, mixing instruments can be attractive: pairing a modest carbon price with targeted heat-pump support reaches the same CO_2 target at lower cost and with smaller cross-household dispersion—while requiring a much lower, more politically acceptable carbon price.

This paper is limited to partial-equilibrium and monetary in scope. We abstract from general-equilibrium feedbacks, from housing-market capitalization beyond our bounds, and from within-period demand response to prices; we also assume homogeneous discounting and no liquidity constraints. These choices preserve transparency in incidence and isolate the investment channel, but they also point to a research agenda. Future work should integrate richer behavioral heterogeneity, model landlord–tenant dilemma more precisely, and relax the decarbonized-electricity assumption to quantify how instrument rankings shift when electricity production is not fossil-free. More broadly, our results suggest that the "energy-efficiency gap" is not only about investment barriers: it is also about the *mis-measurement* of private returns when models substitute theoretical for observed consumption (prebound effect). Bringing revealed behavior into policy evaluation is therefore essential for credible distributional analysis and for designing building-sector climate policies that are both effective and publicly acceptable.

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A Descriptive Statistics and External Validity

A.1 Woonsurvey and Augmented Woonsurvey

In moving from Woonsurvey to the Augmented Woonsurvey, many observations are lost due to missing information on energy bills, reducing the sample from 2,973 to 1,332 dwellings. Table A.1 reports key descriptive statistics for the Augmented Woonsurvey and compares them with the original Woonsurvey; numbers in parentheses indicate the coverage rate, i.e., the share of observations with a non-missing entry for that variable category in Woonsurvey. Relative to the original sample, the retained sample contains (i) a somewhat higher share of houses (vs. apartments), (ii) a higher share of owner-occupiers, and (iii) a higher share of oil-heated households at the expense of gas-heated dwellings. By contrast, distributions are very similar across the two samples for envelope component performance, household income, total residential energy use, and CO_2 emissions.

To correct these composition shifts, we recalibrate the original survey weights (Woonsurvey) on the retained sample (Augmented Woonsurvey) using iterative post-stratification (raking), so that the weighted shares of dwelling type (house vs. apartment), owners (vs. tenants), and heating technology (electricity, gas, heat pump, solid fuels, oil) are closer to those observed in the full Woonsurvey. We report the so-obtained descriptive statistics under "Augm. WS (calibrated)". All other descriptive statistics and model outcomes in this paper are computed using these calibrated weights, which restores representativeness along these key margins while keeping weight dispersion moderate[11].

[11] Weight dispersion remains limited (max ≈ 5.6), and the effective sample size declines from 1,265 under the raw weights to 1,016 under the calibrated weights (about a 20% drop).

Table A.1: Treatment of Woonsurvey dataset

Variable	**WS 2018**	**Augm. WS**	**Augm. WS (cal.)**
Obs.	2973	1332	1332
Heating system			
Gas heating	71%	48%	72%
Oil/mazout	18%	35%	18%
Heat pumps	1.2%	1.7%	0.9%
Electric (other)	7.4%	11.4%	6.1%
Solid	2.5%	3.4%	2.5%
Envelope (U-values)			
U-floor (avg.)	1.65	1.61	1.61
U-roof (avg.)	0.85	0.76	0.81
U-walls (avg.)	0.92	0.90	0.93
U-window (avg.)	2.65	2.67	2.67
Energy consumption			
Gas (kWh/yr)	14 473	14 155	14 131
Oil (kWh/yr)	20 919	20 952	20 748
Solid (kWh/yr)	8 756	8 358	7 207
Fossil (avg., kWh/yr)	17 681	17 722	16 024
Elec (avg., kWh/yr)	4 143	4 170	3 692
Total (avg., kWh/yr)	18 763	19 879	18 733
Other			
Houses	74%	83%	77%
Owners	72%	82%	76%
HH income (avg., €)	2 713	2 815	2 825
Emissions (avg., tCO_2/yr)	3.36	3.79	3.48

Source: Own calculations based on Woonsurvey 2018.

A.1.1 Energy Performance Certificate

In the Augmented Woonsurvey, we impute theoretical energy consumption from responses collected in the original Woonsurvey. A key step is to infer, for each dwelling and each envelope component (walls, windows, roof, floor), a thermal performance level from the survey's reported year of construction and insulation quality (bad, intermediate, good). We then construct component-specific U-values following Gendebien et al. (2014), who distinguish five main construction periods and two insulation levels (bad, good). Since Woonsurvey includes an additional "intermediate" category, we set its U-value to the midpoint between the "bad" and "good" scenarios. For buildings constructed since 1990, we adjust the "bad" scenario from Gendebien et al. (2014) to satisfy the Flemish maximum U-values in force for the corresponding period (Vlaamse Overheid, 1991, 2018). These imputed U-values feed the heat-loss coefficients used to compute theoretical space-heating needs (and, by extension, total theoretical consumption). Full details of the theoretical-consumption calculation are provided in Section 2 of the Technical Report.

In Table A.2, we compare the distribution of EPC labels generated by our methodology with official statistics to assess consistency and external validity. In line with Table A.1, the aggregate theoretical consumption computed in the Augmented Woonsurvey closely matches what can be calculated from the original Woonsurvey. Nonetheless, relative to administrative EPC label statistics, discrepancies arise at the distributional tails: our imputation procedure yields no dwellings in EPC A and very few in EPC F, while over-representing EPC C and D. These differences plausibly reflect (i) the conversion of the "intermediate" insulation category to U-values by taking the midpoint between "bad" and "good," (ii) sample selection due to restricting to dwellings with complete billing data, and (iii) partial non-comparability with administrative series.

Table A.2: EPC label distribution by dwelling type. Shares in %.

Dwelling type	EPC label (kWh/m^2·year)	Flanders (SERV)	WS 2018	Augmented WS 2018
Apartment	A (0–100)	10	0	0
Apartment	B (101–200)	38	37.1	33.1
Apartment	C (201–300)	24	38.9	43.3
Apartment	D (301–400)	12	14.5	16.0
Apartment	E (401–500)	7	4.5	4.2
Apartment	F (>500)	9	5.0	3.5
House	A (0–100)	5	0	0
House	B (101–200)	10	19.7	19.5
House	C (201–300)	17	32.4	33.4
House	D (301–400)	17	25.5	25.2
House	E (401–500)	15	13.9	14.4
House	F (>500)	36	8.5	7.5

Notes: Official EPC statistics for 2019 are retrieved from Sociaal Economische Raad van Vlaanderen (2019), which is based on approximately one million official EPC collected by the Flemish Agency of Climate and Energy (VEKA).
Source: Own calculations based on Woonsurvey 2018.

A.1.2 Distribution of Energy Performance Certificate

Table A.3 reports the cumulative distribution of EPC labels by household income group. The income-specific distributions obtained from the original Woonsurvey and from the Augmented Woonsurvey are very similar, supporting the distributive representativeness of our working sample. The table also confirms a clear gradient: lower-income households are disproportionately located in dwellings with poorer EPC ratings. This composition effect is central for the distributional incidence of the policies we study—most notably for standards—since households in inefficient homes are more likely to be compelled to renovate and thus face higher average burdens, which contributes to the observed regressivity of norms.

Table A.3: Cumulated EPC label distribution by income group

Income group	EPC label (kWh/m^2·year)	WS 2018 (cum. %)	Augm. Woonsurvey (cum. %)
Q1–Q2	A (0–100)	0.0	0.0
Q1–Q2	B (101–200)	16.4	15.1
Q1–Q2	C (201–300)	49.7	49.4
Q1–Q2	D (301–400)	74.8	75.2
Q1–Q2	E (401–500)	89.0	89.9
Q1–Q2	F (>500)	100.1	100.0
Q4–Q5	A (0–100)	0.0	0.0
Q4–Q5	B (101–200)	32.2	31.1
Q4–Q5	C (201–300)	65.7	66.1
Q4–Q5	D (301–400)	86.4	86.3
Q4–Q5	E (401–500)	95.8	96.7
Q4–Q5	F (>500)	100.0	100.0

Notes: The table reports cumulated EPC label distributions for lower-income (Q1–Q2) and higher-income (Q4–Q5) households, comparing the Woonsurvey 2018 and the augmented Woonsurvey samples (shares in %). *Source:* Own calculations based on Woonsurvey 2018.

A.1.3 CO_2 emissions

According to the Flemish greenhouse-gas inventory, residential direct combustion emissions amounted to 8.92 MtCO_2 in 2017 in Flanders (Vlaamse Milieumaatschappij, 2017). In the same year, the Flemish Region counted about 2.77 million private households (Statbel, 2017). This implies an average of approximately 3.22 tCO_2 per household per year. Note that this covers direct fuel combustion in dwellings; it excludes electricity (accounted for in power supply) and biogenic CO_2 from biomass.

As reported in Table A.1, average direct household emissions are 3.36 tCO_2 in Woonsurvey and 3.48 tCO_2 in the Augmented Woonsurvey corrected by reweighing, i.e., slightly above the inventory benchmark.

A.2 Additional results

A.2.1 Box plots

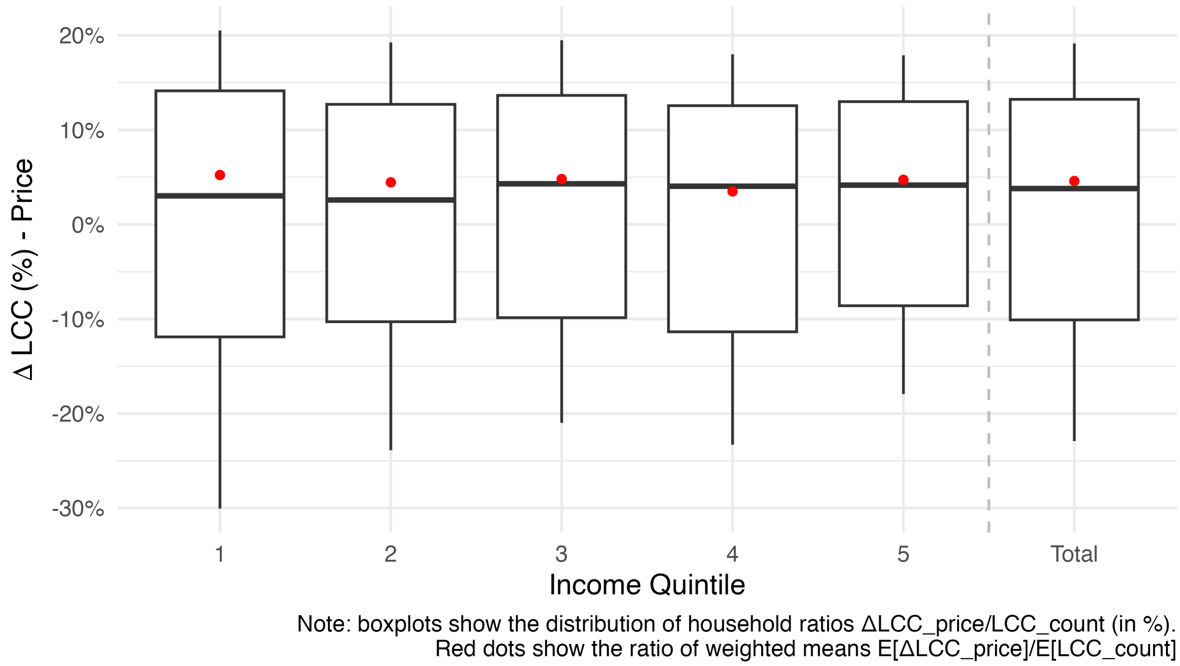
Figures A.1, A.2 and A.3 present different moments of the distribution of monetary impacts under the three policy scenarios, by income quintile. The boxplots display the 10th, 25th, 50th, 75th, and 90th percentiles of the distribution. Monetary impacts are measured as the percentage change in life-cycle cost under each policy scenario relative to the no-policy counterfactual. The red dot indicates the mean effect.

The figures show that the median impact is close to zero across all income quintiles in both scenarios. In the norm scenario, the median effect is exactly zero, reflecting the fact that fewer than half of households within each quintile are constrained by the standard. In the carbon pricing scenario, the mean impact is relatively stable across quintiles and amounts to approximately 2%. By contrast, under the norm scenario, the mean increase in life-cycle cost is about 15% in the lowest income quintile and declines steadily as income rises. This pattern indicates that the norm scenario is regressive, and that it exacerbates vertical inequality.

Horizontal distributional impacts are also markedly more unequal under the norm scenario. The most affected households within each income quintile experience very large increases in life-cycle cost, particularly in the first two quintiles. In these groups, 10% of households face an increase in life-cycle cost exceeding 45%, which is twice as high as the corresponding threshold in the fifth quintile and more than three times higher than the 90th-percentile impact observed under carbon pricing, for any quintile.

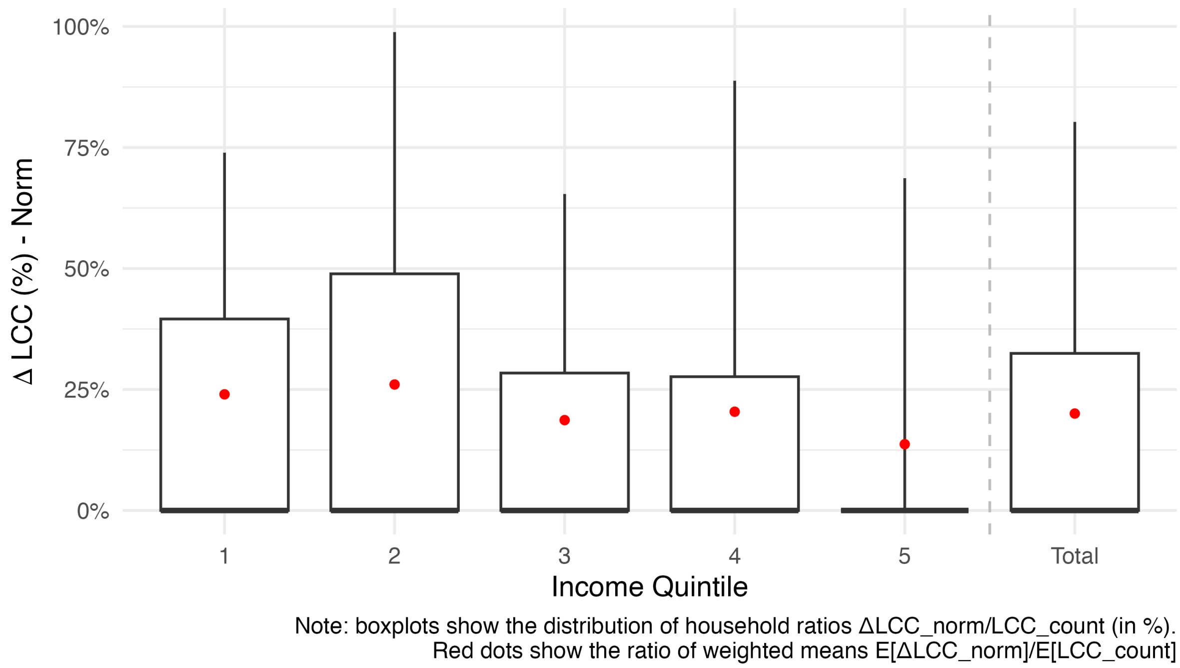
While there are no financial winners under the norm scenario, half of households experience a decrease in life-cycle cost under carbon pricing. These winners are households with below-average energy consumption, which receive more in lump-sum transfers than they pay in carbon taxes. For some households, the positive financial impact is substantial: more than 10% of households in each income quintile see their energy expenditures decline by more than 20%.

Figure A.1: Variation in LCC from the counterfactual - Price scenario



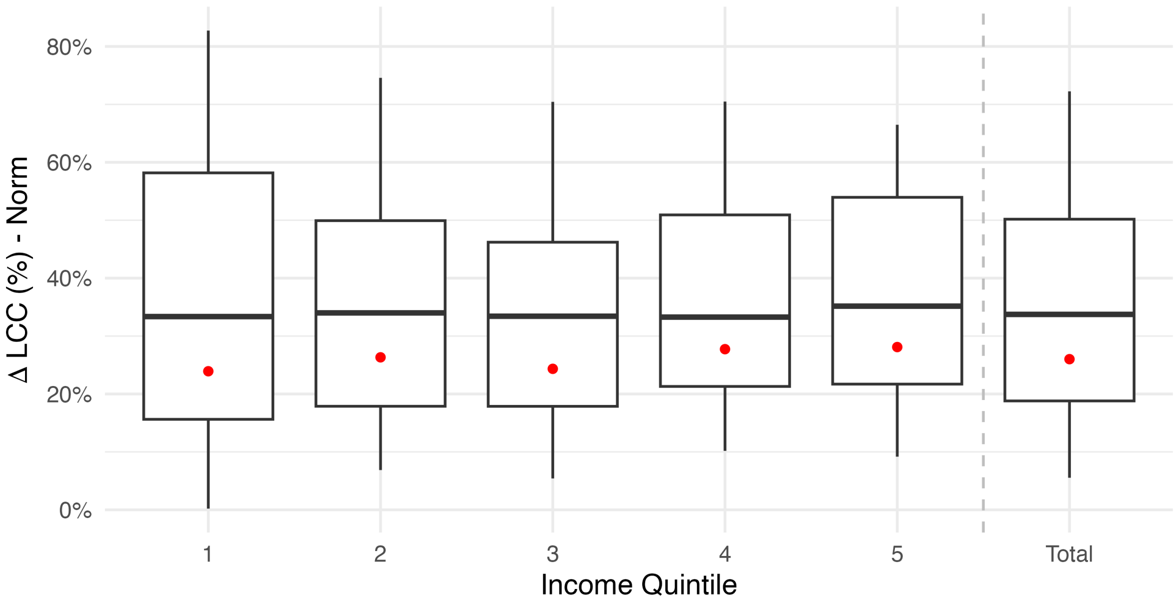
Source: Own calculations based on Woonsurvey 2018.

Figure A.2: Variation in LCC from the counterfactual - Norm scenario



Source: Own calculations based on Woonsurvey 2018.

Figure A.3: Variation in LCC from the counterfactual - Subsidy scenario



Note: boxplots show the distribution of household ratios ΔLCC_subs/LCC_count (in %).
Red dots show the ratio of weighted means E[ΔLCC_subs]/E[LCC_count]

Source: Own calculations based on Woonsurvey 2018.