OPTIMAL DESIGN OF RENOVATION SUBSIDIES FOR RESIDENTIAL BUILDINGS: A BILEVEL OPTIMIZATION APPROACH UNDER EPBD CONSTRAINTS

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Introduction

Buildings represent approximately 40% of final energy consumption and 36% of CO_2 emissions in the European Union. Two-thirds of European buildings were constructed before 1980, when energy efficiency standards were minimal or non-existent, creating an extensive renovation demand [1]. However, current renovation rates of only 1–2% annually fall far short of what is needed to achieve climate neutrality by 2050 [2]. The revised Energy Performance of Buildings Directive (EPBD 2024/1275) introduces ambitious mandatory renovation trajectories, requiring Member States to reduce average primary energy use by 16% by 2030 and 20–22% by 2035, while phasing out fossil-based heating systems by 2040 [3].

Problem Statement and Research Question

Despite the urgency of building sector decarbonization, current approaches to renovation subsidy design face two fundamental problems. First, subsidy design lacks systematic optimization. Current schemes attempt to balance competing objectives, minimizing public expenditure, ensuring equitable access across income groups, achieving building performance targets, respecting public budget limits, and meeting EPBD targets, through ad-hoc political processes rather than quantitative evidence-based approaches. Policymakers lack analytical frameworks to identify cost-effective subsidy allocations that satisfy multiple regulatory constraints simultaneously.

Second, the strategic interaction between policy design and household response is underexplored. Existing models in the literature either simulate renovation uptake at fixed, predetermined subsidy levels, or evaluate the impacts of already-defined policies ex-post. However, they rarely optimize subsidy rates while explicitly modeling how heterogeneous households respond to financial incentives. This gap is critical because subsidy effectiveness depends fundamentally on anticipating behavioral responses across different building types and income groups.

To address these problems, this study asks: *What is the cost-minimizing subsidy allocation across renovation measures, building types, and income groups that achieves EPBD compliance while satisfying equity constraints?*

Methodology

We develop a bilevel optimization framework that captures the hierarchical interaction between policymakers and households. At the upper level (leader), the policymaker minimizes discounted public expenditure by setting differentiated subsidy rates for envelope retrofits, HVAC systems (heat pumps), and photovoltaic installations across income groups. The policymaker's decisions are subject to: a public budget ceiling, EPBD energy reduction milestones (16% by 2030, 20–22% by 2035, climate neutrality by 2050), an equity rule requiring at least 30% of subsidies to flow to low-income households, and a worst-performing buildings (WPB) requirement mandating that at least 55% of energy savings originate from the least efficient 43% of the building stock.

At the lower level (follower), households minimize their discounted net private costs by deciding whether and when to adopt renovation measures over time. Household decisions are constrained by income-differentiated liquidity caps, annual renovation rate limits, and measure precedence rules. The bilevel

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structure is reformulated as a single-level mathematical program by embedding household response functions, implemented in Julia using JuMP, and solved with Gurobi.

Preliminary Results

Preliminary results using hypothetical data for 7,000 dwellings (~750,000 m²) demonstrate that the model successfully identifies subsidy configurations achieving all EPBD milestones (−16% by 2030, −21% by 2035, −53% by 2050) while minimizing public expenditure (see Figure 1). The optimal policy allocates €120 million in subsidies, with HVAC measures (heat pumps) receiving the largest share (48%) to accelerate the heating system transition before the 2040 fossil ban. Low-income households, representing 20% of the building stock, receive 40% of total subsidies through differentiated rates: 45–55% cost coverage for low-income versus 15–30% for high-income households. The model confirms that 56.9% of energy savings originate from worst-performing buildings, satisfying the EPBD requirement (≥55%).

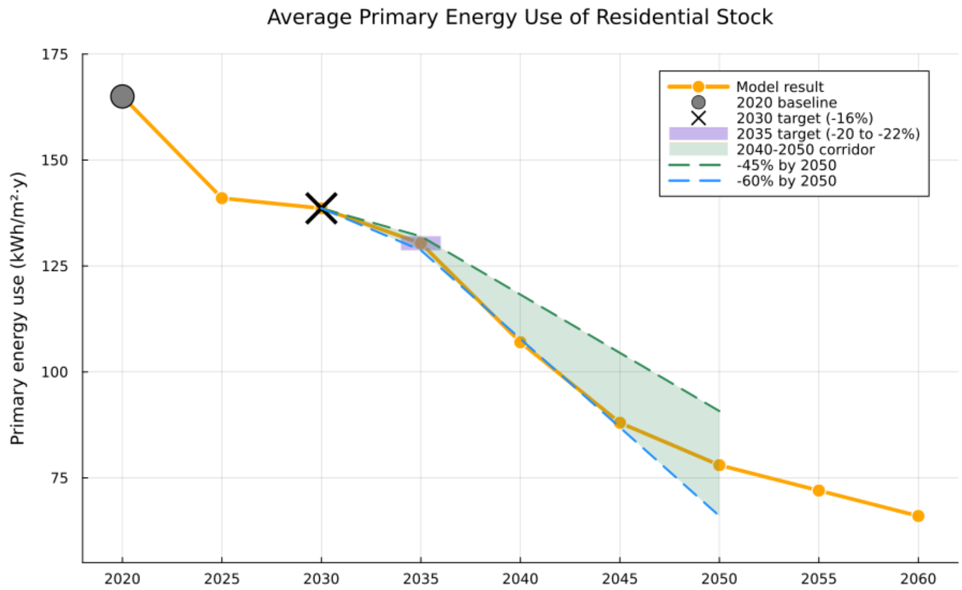

Figure 1 Average primary energy use of the building stock from 2020 to 2050

Conclusions

The bilevel optimization framework demonstrates how renovation subsidy design can be systematically optimized while accounting for household behavioral responses and regulatory constraints. Differentiated subsidy rates by income group and measure type emerge as essential policy instruments for balancing cost-effectiveness with equity objectives. Future work will calibrate the model with representative building stock data and conduct sensitivity analyses on energy prices, technology costs, and behavioral parameters.

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