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Optimization of energy efficiency renovations in buildings: Unlocking multiple benefits across environmental, economic, and social dimensions

COLLECTION: BUILDINGS AND APPLIANCES

PEER-REVIEWED PAPER

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ABSTRACT

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Residential renovation policy is still too often assessed through narrow cost-efficiency and operational-energy metrics, despite growing pressure on governments to deliver decarbonization, affordability, resilience and social justice at the same time. This paper asks what is gained – and what is lost – when public renovation programs are designed around different policy rationales rather than around a single economic-efficiency criterion. Using the Portuguese residential stock as a case study, it combines Hybrid Rectangular Input–Output Lifecycle Assessment, building energy simulation and multi-objective optimization to evaluate renovation portfolios across 60 residential archetypes under realistic budgetary, technical and regulatory constraints. The analysis compares portfolios through total primary energy savings, greenhouse-gas payback time, savings-to-investment ratio and health impacts, while also examining broader societal effects. The results show that the trade-offs are structural. Portfolios that maximize stock transformation, Zero-Emission Buildings uptake and aggregate co-benefits do not maximize economic efficiency per euro invested, whereas high-return portfolios remain too limited in scale to support broad decarbonization of the housing stock. Balanced portfolios emerge as more credible program compromises, retaining substantial benefits while avoiding the steep efficiency losses of the most expansive options. The results also show that high energy and climate performance do not automatically imply better societal outcomes, since some high-ZEB pathways perform poorly in health terms due to PM2.5-related effects associated with biomass uptake. The paper therefore argues that renovation policy should move beyond cost-efficiency alone and adopt multi-criteria, climate-sensitive and health-aware program design.

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INTRODUCTION

Buildings sit at the center of several challenges that European policymakers are being compelled to address simultaneously, such as decarbonization targets, affordability restriction, energy security, indoor quality, and social vulnerability. In the EU, buildings account for about 40% of energy consumption and 36% of energy-related GHG emissions, while residential buildings alone represented more than one quarter of final energy use in 2022. Moreover, a large share of the European stock is old and inefficient, which makes the transformation of existing dwellings central to climate policy rather than a secondary technical issue (Bertoldi et al. 2025). This pressure is particularly acute in countries such as Portugal, where many households still cannot maintain adequate indoor comfort, and where the high upfront cost of deep renovation makes public support not only an energy policy instrument but also a form of social protection (Presidency of the Council of Ministers 2021; Carvalho et al. 2022). In this context, the revised Energy Performance of Buildings Directive (EPBD) and Energy Efficiency Directive (EED), together with the Energy Efficiency First (EE1st) raise a broader question than how to save energy at least cost: what kind of building energy transition should public policy actually prioritize? (European Commission 2021).

In practice, renovation policy still relies too heavily on cost-optimal or cost-efficient reasoning. The cost-optimal framework plays an important role in European building funding policy by comparing alternative energy performance levels through lifecycle cost logic, but it remains poorly suited to capture the wider societal value now expected from renovation programs (Thema et al. 2019; Russell et al. 2015; European Parliament and of the Council 2010). This limitation has become more consequential as policy framework has evolved. The revised EPBD no longer treats buildings only as units of energy consumption to be improved incrementally; it places growing weight on decarbonization, renewable integration, comfort, health and energy poverty, while the broader European policy agenda increasingly frames renovation as a strategic lever for resilience, competitiveness and fairness (European Parliament and of the Council 2024). Evidence on multiple benefits reinforces this shift, showing that the value of energy efficiency (EE) extends well beyond operational savings and include substantial environmental, economic and social benefits (IEA 2025; BPIE 2024b; Ürge-Vorsatz et al. 2016; Zhang et al. 2016). This means that the solutions that perform best per euro are not necessarily those that perform best as public programs. A renovation strategy that maximizes economic return or cost-efficiency may still be weak in scale, limited in Zero-Emission Building (ZEB) uptake, socially regressive in its distributional effects, or blind to health-related trade-offs. Conversely, program that drive broader stock transformation and deeper decarbonization may appear less attractive on ratio-based metrics precisely because they pursue more demanding public objectives. This is especially relevant in a context where current renovation rates remain far below what is needed to meet European climate and energy goals, and where a narrow private cost-benefit logic is increasingly insufficient for public decision-making (BPIE 2024a; Bertoldi et al. 2025). In this context, the real issue is therefore not only which renovation packages are technically efficient, but which program logics are most compatible with climate neutrality and social equity objectives (European Commission 2021; Rosso et al. 2020).

This paper addresses that question for the Portuguese residential sector. Rather than searching for a single best renovation solution, it asks what types of programs profiles emerge when renovation choices are assessed jointly through total primary energy savings (TPES), greenhouse-gas payback time (GPBT), savings-to-investment ratio (SIR), and health impacts (HI). Portugal provides a relevant case for this discussion because it combines an ageing and heterogeneous building stock with strong climatic variation, persistent affordability constraints and a policy need to design renovation support schemes that are both effective and socially defensible (Presidency of the Council of Ministers 2021; Carvalho et al. 2022). These characteristics make it a useful setting in which to evaluate how different policy priorities generate different EE portfolios and different distributions of benefits, costs and trade-offs.

By integrating Hybrid Rectangular Input–Output Lifecycle Assessment (HRIO-LCA), building energy simulation, and multi-objective optimization to design and evaluate EE renovation portfolios across 60 residential archetypes, the framework identifies Pareto-efficient portfolios

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under realistic budgetary, technical, and policy constraints. Previous work has already shown that the best-performing renovation packages vary depending on which energy, environmental, economic and social (E3S) indicators are prioritized (Tenente et al. 2025). Building on that insight, this paper expands the focus from package selection to program design at stock level. In doing so, it argues that renovation policy should not be guided by cost-efficiency alone, but by an explicit comparison of what different program logics deliver in terms of decarbonization, affordability, health and broader public value.

METHODS

This section presents the analytical framework used to compare alternative renovation programs for the Portuguese residential stock. The objective is not to identify a single universally optimal solution, but to examine how different public priorities translate into different renovation portfolios and different distributions of benefits, costs and trade-offs. The method combines a stock-based representation of Portuguese dwellings, a package-level assessment of multiple benefits, and a multi-objective optimization model able to compare competing program objectives under realistic technical, budgetary and regulatory constraints.

Figure 1 summarizes the workflow.

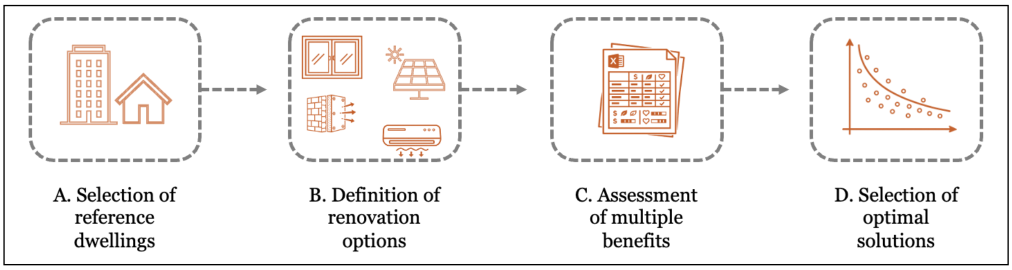

Figure 1 Schematic representation of the multi-objective optimization of retrofit portfolios for Portugal's building stock.

WHY A PORTFOLIO OPTIMIZATION IS NEEDED

Designing public renovation programs is not a single-objective problem. Once renovation policy moves beyond narrow cost-efficiency reasoning, renovation choices must be assessed across several competing dimensions, including energy savings, decarbonization, economic performance, health effects and program feasibility. In this context, multi-objective optimization is useful not because it identifies one universally optimal solution, but because it makes visible the trade-offs between competing priorities and reveals which types of renovation portfolios emerge under different public objectives (Rosso et al. 2020; Costa-Carrapiço et al. 2020).

This is particularly relevant for residential renovation, where envelope upgrades, HVAC and domestic hot water (DHW) systems, and renewable integration interact within a large and highly constrained decision space (Shao et al. 2014; Bonamente et al. 2018). In literature Genetic algorithms (GAs), and particularly Non-dominated Sorting Genetic Algorithm II (NSGA-II) (Deb et al. 2002), are widely used for multi-objective optimization because they can approximate a diverse set of non-dominated trade-offs in a single run, without collapsing conflicting objectives into a single scalar criterion. However, in very large-scale discrete decision spaces, NSGA-II should be regarded as a heuristic whose performance is strongly problem- and configuration-dependent, rather than as a method that guarantees global optimality (Alexakis et al. 2025; Azevedo et al. 2021).

The relevance of this approach has expanded from individual buildings to portfolios of buildings and renovation schedules. Studies in Canada, Switzerland and France show that NSGA-II-based portfolio optimization can be used to compare retrofit strategies under lifecycle, uncertainty and multi-year budget constraints (Galimshina et al. 2024; Zhang et al. 2021; Pannier et al. 2021). In Portugal, however, this type of portfolio-based optimization remains limited, particularly when broader E3S indicators are considered simultaneously. Existing Portuguese studies have addressed selected aspects of retrofit optimization, eco-efficiency or employment effects, but have not framed the problem as a national program-design exercise comparing competing public-value objectives across the residential stock (Asadi et al. 2014; Oliveira et al. 2014; Tadeu et al. 2022; Tenente et al. 2025).

PORTUGUESE RESIDENTIAL STOCK AND REFERENCE ARCHETYPES

Portuguese residential buildings range from pre-1960 stone-masonry structures to recent constructions that comply with the Regulation on the Energy Performance of Residential Buildings (REH 2013), reflecting the historical evolution of construction practices and insulation standards. For existing building stock, construction solutions were determined primarily by construction period rather than by climate zone, which makes period-based archetyping particularly relevant for stock-level analysis (Directorate General for Energy and Geology 2014).

This study focuses on deep renovation pathways consistent with at least Nearly Zero-Energy Buildings (nZEB) performance while also creating the conditions for a transition to ZEB. In practice, attaining nZEB category requires a minimum energy class of A, which is associated with the following thresholds: $R_{nt} \leq 0.50$, representing the ratio between actual and reference nominal primary energy needs, and $Ren_{hab} \geq 0.50$, representing the share of total primary energy demand supplied by renewable sources (e.g., solar, wind, biomass). To further reach the ZEB category, the building must also cumulatively achieve $CO_{2,op}$ = 0.0 CO_2eq., corresponding to operational carbon emissions locally produced (Directorate General for Energy and Geology 2020; European Parliament and of the Council 2024).

Following the scope of Portuguese Long-Term Renovation Strategy (LTRS), the analysis covers 3,821,099 dwellings, representing more than 99% of the current residential stock, excluding vacant dwellings and secondary or seasonal residences (Presidency of the Council of Ministers 2021). Dwellings built from 2014 onward are not included, since they generally do not require deep renovation to meet nZEB levels, although we acknowledge the fact that they will require further intervention before 2050. The total program budget is set at €110,078 million, in line with the LTRS estimate (Presidency of the Council of Ministers 2021).

To represent this stock, the analysis used 60 archetypes combining four construction periods, five climate zones and three dwelling types: single-family dwellings, multi-family dwellings with roof, and multi-family intermediate dwellings. The resulting stock distribution is presented in Table A.1 in the Supplementary Material, while climate zones definition is reported in Table A.3 in the Supplementary Material. This adaptation extends the LTRS logic by distinguishing five climate zones rather than only heating-based categories, so that cooling-related conditions are increasingly relevant for selecting EE measures under climate change (Presidency of the Council of Ministers 2021). The physical and thermal characteristics of the reference dwellings are summarized in Table A.2 in the Supplementary Material.

For single-family buildings, the representation assumes one dwelling per building. For multi-family buildings in the climate zones represented by Coimbra, Faro, Guarda, and Tomar, the stock is represented through one dwelling with roof and one intermediate dwelling. In the climate zone represented by Lisbon, where large metropolitan multifamily buildings are prevalent as the representation assumes one roof dwelling and two intermediate dwellings (INE 2020; Pinto and Fragoso 2018). Ground-floor units are excluded based on three main considerations. First, the selected roof and intermediate dwellings capture the most relevant energy-demand extremes for simulation purposes. Second, ground-floors are often used for non-residential functions in urban contexts. Third, renovation is prioritized for the worst-performing dwelling, typically the roof unit, and because façade insulation and window upgrades must be uniform across all units in multifamily buildings. Thus, that unit determines the building-wide façade and window specifications. This simplification reduces computational burden while remaining consistent with the intervention rationale assessed in the paper.

RENOVATION PACKAGES AND PROGRAM LOGIC

The baseline configuration assumes electric resistance heating for space heating and gas-fired water heaters for DHW, consistent with common patterns in Portuguese households (National Statistics Institute and Directorate General for Energy and Geology 2021). Space cooling is assumed to rely predominantly on natural ventilation, which represents a limited share of final energy consumption in Portugal, despite increasing cooling relevance in newer buildings and in warmer southern regions (Reis et al. 2023).

Renovation options were defined as integrated packages rather than isolated measures. The package combines façade and roof insulation, windows replacement, space-heating/cooling (SHC) and DHW systems, and photovoltaic (PV) generation. The full set of measures is reported

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in Table A.4 in Supplementary Material. Insulation thickness was capped at 120 mm due data limitations for thicker solutions, although this upper bound exceeds the minimum regulatory thermal-performance requirements (REH 2013). For PV, the annual generation values by climate zone were taken from PVGIS and are reported in Table A.5 in the Supplementary Material.

The measures used to build the EE packages reflect the structure of Portuguese EE financing programs (Presidency of the Council of Ministers 2021; Presidency of the Council of Ministers 2020). EE packages were prioritized over isolated measures because integrated interventions generally deliver larger energy savings, lower installation costs, and fewer disruptions during implementation. In addition, substantial climate-zone-related differences in space-heating requirements, reinforce the importance of weather conditions in residential energy use and argue against a one-size-fits-all retrofit strategy (Tenente et al. 2025).

Overall, the analysis evaluates 7,177,195 possible EE packages across the considered archetypes, providing technological basis for the portfolio optimization stage.

ASSESSMENT OF MULTIPLE BENEFITS

Each renovation package was assessed relative to a business-as-usual baseline using a HRIO-LCA framework. The purpose of this stage is not only to quantify operational energy savings but also capturing both embodied impacts generating a broader evidence base on the E3S effects of renovation packages before they enter the optimization model.

The assessment follows four main steps. In step 01 system boundaries are defined by identifying business-as-usual technologies, best available EE alternatives (BAT), the reference archetypes representative of the national residential stock for final and primary energy assessments, and the EE solutions' lifecycle stages considered: manufacturing, packaging, installation and maintenance (MPIM), and operation. In step 02 investment, installation, and maintenance costs are compiled, disaggregated by component and activity, and linked to domestic output through a rectangular Input–Output model to estimate the total E3S effects associated with the MPIM phases. In Step 03, pre- and post-renovation operational energy needs are assessed using the Portuguese building energy certification system's steady-state seasonal method (Decree-Law 101-D/2020 2020), which enables efficient and reliable simulation of a very large number of package combinations without the computational burden of dynamic simulation. Finally, in step 04, post-renovation impacts are compared with the baseline scenario to estimate TPES, GPBT, GHG savings, employment, gross value added (GVA), SIR, Net Present Value (NPV), household budget impacts, and reductions in premature deaths associated with PM2.5 emissions (HI).

The economic assumptions used to derive SIR, NPV and household-related effects are reported in Table 1. Employment and GVA are restricted to MPIM-phase. Because EE packages combine technologies with different lifespans, the analysis avoids a single common time horizon that would artificially impose premature replacement of some technologies. Instead, costs are depreciated over the lifetime of each technology for NPV and SIR, while embodied energy and embodied GHG emissions are annualized. All benefits are ultimately expressed on an annual basis.

Table 1 Economic parameters.

ECONOMIC PARAMETERS		VALUES	REFERENCES:
Energy prices for consumers	Electricity	€0.2284/kWh	(Presidency of the Council of Ministers 2021; Eurostat 2022a; Eurostat 2022b)
	Biomass	€0.05/kWh	
Avoided costs of energy supply	Electricity	€0.1144/kWh	(Eurostat, 2022b, 2022c; Presidency of the Council of Ministers, 2021)
	Biomass	€0.0469/kWh	
Discount rate		5%	(Presidency of the Council of Ministers 2021)

Further technical details on the HRIO-LCA framework and the underlying E3S calculations are provided in Tenente et al. (2025).

Once calculated at package level for each archetype, TPES, GPBT, SIR and HI are used as optimization objectives, while the remaining indicators are used to interpret the broader societal value of the resulting portfolios.

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PORTFOLIO OPTIMIZATION MODEL

The portfolio-design problem is combinatorial and involves multiple conflicting objectives. To identify non-dominated renovation portfolios for the Portuguese residential sector, the NSGA-II was applied. The algorithm was run for 30,000 generations with a population size of 300, a crossover rate of 0.85, and a mutation rate of 0.15.

Each chromosome represents a renovation portfolio across residential archetypes. In this encoding, genes identify the EE packages assigned to each archetype, while alleles define the corresponding number of dwellings receiving each package. To reflect the structure of public renovation programs, implementation was modelled in discrete blocks of 300 dwellings rather than as a continuous dwelling-by-dwelling allocation to reflect the implementation logic of large-scale public renovation programs.

The optimization problem was formulated with four objectives: maximizing TPES, SIR and HI, while minimizing GPBT. These objectives jointly represent the main energy, economic, environmental, and social dimensions of residential renovation policy, including embodied-carbon recovery and PM2.5-related health effects. The feasible solution space was further constrained by budget limits, stock availability, technical eligibility criteria, and archetype-coupling rules.

The complete mathematical formulation of the model, including decision variables, objective functions, and constraints, is provided in the Supplementary Material.

RESULTS AND DISCUSSION

This section examines the Pareto-efficient renovation portfolios as alternative programmatic approaches for the Portuguese residential stock, emphasizing the trade-offs among the different objectives. Figure 2 illustrates the trade-offs among the objectives across 294 non-dominated portfolios, indicating that portfolios with higher energy savings tend to exhibit lower economic efficiency and longer GPBT. HI peaks in an intermediate region rather than at the extremes, indicating that health co-benefits do not increase monotonically with TPES.

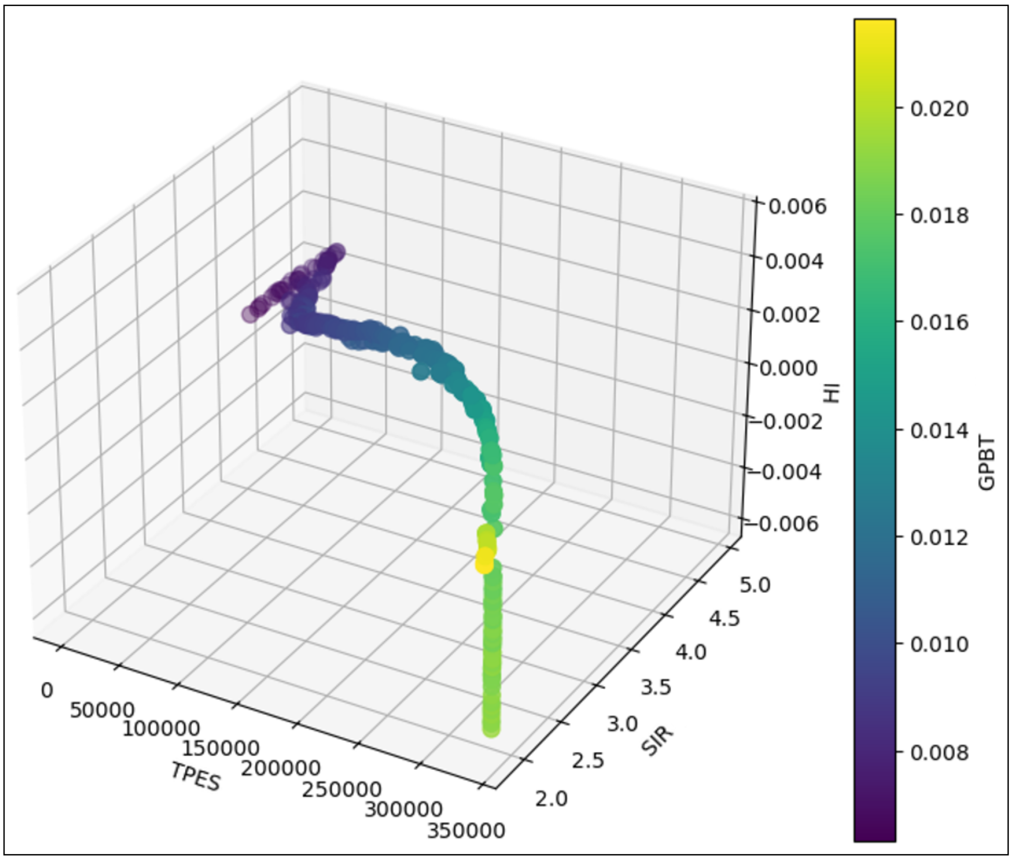

Figure 2 3D objective space defined by TPES (x-axis, TJ), SIR (y-axis), and HI (z-axis, number of potential premature deaths), with the minimization objective GPBT expressed in years.

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On the other hand, Figure 3 compares a reduced set of representative program options identified using k-medoid clustering technique. Detailed indicators for representative portfolios remain reported in Table 2 in the Appendix.

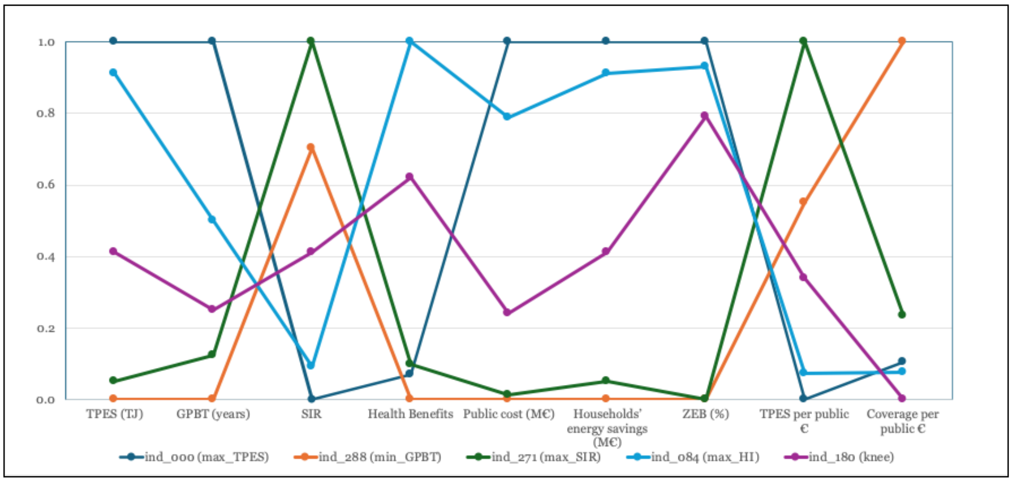

Figure 3 Policy scorecard for representative portfolios.

THREE RENOVATION PROGRAM LOGICS EMERGE

Three broad program profiles emerge from the non-dominated solution set. First, large-scale, high-ZEB portfolios renovate approximately 3.31 to 3.80 million dwellings at high public cost, typically around €30.0–€35.6 billion, while achieving ZEB shares above 80% in the most ambitious cases. These portfolios dominate aggregate outcomes, including avoided supply costs, household energy savings, operational GHG reductions, GVA and employment. Second, high-return, low-coverage portfolios require comparatively limited public expenditure and perform best on ratio-based metrics such as SIR and GPBT, but they cover only a small share of the stock and often deliver little or no ZEB penetration. Third, balanced compromise portfolios occupy the intermediate region of the solution space: they renovate roughly 0.50 to 1.62 million dwellings, achieve intermediate ZEB shares, and retain substantial aggregate benefits while avoiding the steep efficiency losses of the largest-scale options. This threefold structure is visible and detailed in Table 2 in the Appendix.

This pattern is not incidental. Because the feasible solution space already enforces at least nZEB-level eligibility, nZEB compliance is effectively saturated across the representative portfolios. Differentiation is therefore driven mainly by how far portfolios push dwellings beyond minimum eligibility and toward ZEB, and by the cost of doing so. In practice, the dominant tension is between scale and depth of transformation, on the one hand, and cost-effectiveness and administrative simplicity, on the other. This makes the optimization results directly relevant for policy design: the main question is not whether the portfolios are compliant, but what kind of public program they imply once broader policy goals are considered together.

WHAT EACH PROGRAM PROFILE DELIVERS AND WHAT IT SACRIFICES

The large-scale, high-ZEB portfolios are the most transformative program type. The TPES-maximizing portfolio, ind_000, illustrates this logic most clearly. It renovates 99.5% of the dwellings, delivers 335,889.51 TJ of primary energy savings, and achieves a ZEB share of 83.37%, while also generating the largest aggregate co-benefits in avoided supply costs, household savings, operational GHG savings, GVA and employment. Similar portfolios, such as ind_014, ind_027, and ind_084, confirm that large-scale transformation can generate very large system-level gains. However, these portfolios also perform less favorably on ratio-based indicators: ind_000 has the lowest SIR and the worst GPBT, showing that deep stock transformation comes at the cost of lower economic performance, lower energy savings per euro invested and slower recovery of embodied emissions. From a policy perspective, these program designs are highly effective, but they place significant demands on public budgets.

At the opposite extreme, niche portfolios such as ind_288 and ind_271 maximize ratio-based performance. They achieve the best SIR and GPBT values in the representative set and deliver

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very high benefits per dwelling or per euro invested. Yet they cover less than 2.5% of the Portuguese dwellings, respectively, and achieve no ZEB penetration. Their aggregate co-benefits therefore remain modest in absolute terms. These portfolios are economically efficient, but they are weak as stock-transformation programs. For public policy, this is a crucial distinction: a program can look highly attractive when judged through efficiency metrics alone and still be too limited in scale to contribute meaningfully to broad decarbonization, resilience or social protection.

The intermediate region is represented by balanced portfolios such as ind_180, ind_212, ind_197, ind_157 and ind_137. These solutions retain a large share of the aggregate benefits of the most expansive programs while reducing the penalty in SIR and GPBT. The knee representative, ind_180, is especially important from a program-design perspective. It renovates about 23% of dwellings, achieves a ZEB share of 66.01%, and combines substantial total co-benefits with stronger per-dwelling and per-public-euro performance than the largest portfolios. This makes the balanced region particularly relevant for policymakers who must reconcile decarbonization ambition with fiscal constraints, political acceptability and implementation realism, positioning it as a plausible program compromise.

Figure 3 shows the benchmark results for the anchor portfolios, and Table 2 in the Appendix reports the detailed values for the representative portfolios.

WHY COST-EFFICIENCY ALONE IS AN INADEQUATE GUIDE FOR PUBLIC RENOVATION POLICY

Taken together, the results challenge the idea that renovation policy can be guided mainly through cost-efficiency or return-per-euro reasoning. The solution set shows a clear trade-off between TPES and SIR: portfolios that deliver the highest aggregate energy savings and the broadest stock transformation generally perform worse in economic-efficiency terms and display longer GPBT. This reflects a structural policy reality. Once the most attractive measures and archetypes have been exploited, further expansion of renovation coverage and deeper movement toward ZEB requires more public investment and often more material- and technology-intensive interventions. A narrow cost-efficiency lens may therefore favor micro-programs with high returns but low transformative capacity.

This result is particularly important because all feasible portfolios already satisfy the technical conditions associated with high energy performance. What differentiates them is not basic eligibility, but how much public value they generate beyond it. In that sense, choosing between portfolios is not a neutral technical exercise. It amounts to choosing what public renovation policy is meant to optimize for: stock-wide transformation, ZEB uptake, budget efficiency, health outcomes, or some explicit balance among them. The present results therefore support evaluating renovation programs through a structured comparison of alternative program profiles rather than through a single scalar metric.

THE TECHNOLOGY MIX REVEALS THE TYPE OF TRANSITION BEING FUNDED

Across representative portfolios, the technology profile is relatively stable. The solutions are strongly dominated by wall and roof insulation, DHW electrification and near-universal PV, while high-performance glazing remains much less prominent. This suggests that compliance is driven mainly by a combination of envelope upgrades, electrification and on-site renewables, with PV acting almost as a feasibility condition in the solution space. At the same time, some economically efficient niche portfolios remain associated with gas-based DHW solutions, which helps explain why good ratio-based performance does not necessarily coincide with high ZEB penetration.

This technology pattern has two implications. First, it suggests that the transition favored by the model is not based on a uniform upgrade package, but rather on a relatively narrow core of measures that repeatedly prove effective across archetypes. These facts support the point made in Reis et al. (2023), that commercially available solutions in Portugal can reduce building energy needs by approximately 90–99%, with the potential to approach a zero-carbon level. Second, it exposes a regulatory and policy nuance: although the selected

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packages comply with the nZEB/ZEB-oriented criteria used in the model, they do not satisfy RNV because the baseline configuration does not include cooling technologies. This does not imply formal legislative non-compliance in the way the model is framed, but it does reveal an area where regulatory interpretation and program design may diverge. In a policy context increasingly shaped by climate adaptation and summer overheating, that gap deserves more attention than a purely technical optimization paper would normally give it.

The complete dataset and supporting materials of this analysis are available in the Data Availability Statement.

HEALTH AND BIOMASS INTRODUCE A POLITICALLY RELEVANT TENSION

An important finding of this study is that health co-benefits do not improve monotonically with energy savings or ZEB uptake. Several large, high-ZEB portfolios, including ind_014, ind_027, ind_034 and ind_044, display negative HI values. In these cases, increased biomass boiler uptake appears to worsen PM2.5-related health outcomes even while the portfolios remain strong in decarbonization, ZEB penetration and aggregate economic indicators. This is a politically significant warning. Technologies that remain compatible with renewable-energy requirements and ZEB thresholds are not automatically socially desirable once local air-pollution effects are considered. In other words, “renewable-compatible” is not equivalent to “health-optimal”.

This finding strengthens the case for including explicit health metrics in renovation policy appraisal, especially when public funding is used to scale technologies that may affect local air quality. This point is of great relevance because it shows that the transition to an energy-efficient and decarbonized building stock cannot be assessed only in terms of operational energy and carbon. A program that performs well on climate and coverage may still generate socially problematic side-effects if the technology mix is not scrutinized. Health therefore needs to be treated as a core program-design criterion rather than as a secondary co-benefit.

HETEROGENEITY MATTERS: DEEP DECARBONIZATION IS NOT A ONE-SIZE-FITS-ALL PROGRAM

The results also show that broad decarbonization requires intervention across heterogeneous archetypes and climate contexts, not only in the most favorable parts of the stock. Archetype-level variation in ZEB implementation intensity and public investment intensity is substantial. The highest ZEB implementation intensity occurs for single-family dwellings built between 1961 and 1990 in the climate region represented by Coimbra in ind_000, whereas the lowest occurs for multifamily dwellings built between 1991 and 2005 in the climate region represented by Lisbon in ind_088. Public investment intensity per ZEB dwelling also varies strongly across archetypes, with high values observed, for example, in Guarda and much lower values in some Lisbon multifamily cases. This variation indicates that uniform funding rules are unlikely to be efficient or equitable across the whole stock. Instead, climate-sensitive and archetype-sensitive support rules are likely to be necessary if programs are meant to combine fairness with effectiveness. Detailed values remain in Table 2 in the Appendix.

This heterogeneity also reinforces a broader policy point: large-scale stock transformation is not achieved simply by funding the easiest or cheapest cases first. The most transformative portfolios distribute interventions across a wide range of archetypes, including cases with less attractive unit economics. For public policy, this means that the question is not only how to maximize return per euro, but how to design differentiated support structures that can bring more difficult parts of the stock into the transition without collapsing program efficiency.

POLICY IMPLICATION: THE RELEVANT CHOICE IS NOT THE BEST PORTFOLIO, BUT THE PUBLIC OBJECTIVE

The main implication of the results is that renovation policy should not be framed as a search for one best portfolio. The optimization shows that different objectives generate different program profiles, each with distinct strengths, weaknesses and political implications. Large-scale portfolios are strongest on transformation and aggregate co-benefits; niche portfolios are

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strongest on economic efficiency; balanced portfolios are strongest as compromise options. The relevant policy question is therefore not which portfolio is mathematically superior in abstract terms, but what type of public value should be prioritized under real budgetary, social and political constraints.

For building policy and program design, this means that cost-efficiency should be treated as one criterion among several, not as the default public objective. If the aim is to align renovation program with climate neutrality, affordability, resilience and social welfare, decision-makers need frameworks that make those trade-offs explicit. This is precisely what the present results make visible. The choice between portfolio types is ultimately a choice between competing visions of what a just and effective building transition should look like.

CONCLUSIONS

This paper has argued that residential renovation policy should not be guided by cost-efficiency alone. Using the Portuguese residential stock as a case study, it showed that once renovation programs are evaluated simultaneously through E3S dimensions, the trade-offs are structural rather than marginal. The portfolios that deliver the broadest stock transformation, the highest ZEB uptake and the largest aggregate co-benefits are not those that perform best on ratio-based metrics such as SIR or GPBT. Conversely, the portfolios with the strongest return per euro remain too limited in scale to support a broad transformation of the housing stock.

This is the central policy lesson of the paper. Choosing a renovation program based on cost-efficiency alone is not a neutral technical decision; it is a normative choice that privileges a particular program logic over others. The results show that different objectives generate different renovation strategies, with different implications for decarbonization, affordability, health, territorial balance and public value. In that sense, the relevant policy question is not which portfolio is universally optimal, but what kind of building transition public policy is trying to fund.

The results also show that deep decarbonization requires intervention across heterogeneous archetypes and climate contexts, which limits the relevance of uniform funding rules. At the same time, high energy and climate performance do not automatically guarantee better societal outcomes. Some high-TPES, high-ZEB portfolios perform poorly in health terms because biomass-based pathways can increase PM2.5-related harm. This means that public renovation program should be assessed not only against energy and carbon targets, but also against explicit health and equity criteria. Climate-sensitive, archetype-sensitive and multi-criteria support design is therefore more appropriate than one-size-fits-all program structures.

More broadly, the paper suggests that the debate on building renovation should move beyond the search for the cheapest savings and toward a more explicit discussion of program priorities. Balanced portfolios may be especially relevant in this respect, because they retain substantial aggregate benefits while avoiding the steep efficiency losses of the most expansive options and the limited transformative value of narrow high-return programs. For policymakers facing simultaneous pressure to decarbonize, protect households and justify public expenditure, the challenge is not only to optimize renovation, but to define what public objective should be optimized for.

Several limitations remain. The results depend on the assumptions used to estimate techno-economic, environmental and health effects, including embodied impacts, operational savings and valuation methods. In addition, the optimization does not capture all real-world barriers to implementation, such as behavioral resistance, supply-chain bottlenecks, administrative delays, financing frictions or local institutional inequalities. These constraints may limit the practical scalability of the portfolios identified here. Even so, the analytical framework remains useful because it makes visible the trade-offs that policymakers will have to confront regardless of the final program design.

APPENDIX

Table 2 Performance and cost indicators for representative portfolios by cluster (anchors and representatives).

PORTFOLIO PROFILE	ID	TPES (TJ)	GPBT (YEARS)	SIR	HI (NO.)	PUBLIC COST (M€)	BUILDINGS (No.)	AVOIDED SUPPLY COSTS (M€)	NPV (M€)	TOTAL GHG SAVINGS OPERATION (MTCO2EQ.)	GVA (M€)	JOBS (x1000.)	HOUSEHOLDS' ENERGY SAVINGS (M€)	ZEB (%)
Large-scale/ high ZEB	ind_000	335 889.51	0.022	1.85	0.0005	35,647.30	3,801,300	4,418.25	2024.54	11.88	441.62	12.82	8,347.20	83.37
	ind_014	334 658.50	0.019	1.99	−0.00538	32,869.08	3,783,900	4,395.57	2182.2	11.86	411.16	11.94	8,317.54	84.25
	ind_027	333 778.74	0.019	2	−0.0037	32,761.83	3,741,900	4,381.96	2186.59	11.83	408.65	11.84	8,294.12	84.07
	ind_034	333 456.84	0.019	2.01	−0.00262	32,425.19	3,719,100	4,377.08	2197.44	11.81	403.28	11.73	8,286.02	83.98
	ind_044	332 509.28	0.018	2.02	−0.00093	32,305.38	3,674,100	4,362.47	2201.87	11.77	400.6	11.62	8,261.01	83.78
	ind_054	331 035.06	0.018	2.04	0.00207	31,830.52	3,604,800	4,340.23	2215.41	11.7	391.98	11.38	8,222.54	83.43
	ind_068	322 900.29	0.016	2.12	0.00372	30,013.75	3,312,600	4,224.18	2229.82	11.37	363.31	10.58	8,023.73	82.81
	ind_084	307 017.33	0.014	2.14	0.00535	28,190.36	2,950,500	4,003.73	2132.05	10.76	343.66	9.76	7,633.02	77.52
	ind_088	300 676.95	0.015	2.33	0.00456	25,474.59	2,625,600	3,916.85	2232.8	10.51	302.31	8.82	7,479.06	83.16
	ind_112	267 036.00	0.013	2.44	0.00495	21,572.72	2,130,900	3,470.98	2047.02	9.31	253	7.44	6,643.42	81.16
Balanced compromise	ind_137	224 958.38	0.012	2.75	0.00465	15,813.10	1,620,900	2,912.77	1854.65	7.78	183.85	5.5	5,603.89	72.92
	ind_157	181 354.61	0.011	2.92	0.00411	12,104.80	1,215,600	2,344.85	1540.82	6.26	138.5	4.2	4,518.02	71.54
	ind_180	140 750.19	0.01	3.12	0.00337	8,730.98	863,100	1,816.48	1234.1	4.85	95.78	2.94	3,508.03	66.01
	ind_197	111 297.54	0.009	3.27	0.00282	6,554.39	633,300	1,434.03	995.03	3.82	70.94	2.19	2,775.32	62.43
	ind_212	89 513.68	0.009	3.44	0.00221	4,956.61	503,700	1,150.69	816.35	3.05	55.27	1.7	2,234.98	46.28
High-return/ low-coverage	ind_236	60 523.79	0.009	3.86	0.00155	2,969.55	323,100	774.37	573.83	2.04	34.3	1.03	1,514.26	21.26
	ind_257	38 363.27	0.008	4.35	0.00114	1,587.42	179,100	490.62	377.81	1.3	18.7	0.56	959.42	23.95
	ind_271	20 741.61	0.008	4.94	0.00065	713.11	83,100	264.63	211.09	0.7	8.28	0.24	519.14	0
	ind_283	6 102.59	0.007	4.49	0.00019	249.64	36,600	77.84	60.52	0.2	2.72	0.08	152.75	0
	ind_288	4 162.08	0.006	4.02	0.00013	205.45	35,700	53.07	39.87	0.14	2.11	0.07	104.19	0

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author(s) used Grammarly and ChatGPT to improve readability and to detect spelling/grammar mistakes. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

DATA ACCESSIBILITY STATEMENT

The dataset supporting the findings of this study is openly available in Zenodo, DOI: 10.5281/zenodo.18896314.

ADDITIONAL FILES

The additional files for this article can be found as follows:

- **Supplementary Material.** Input data and mathematical formulation of the multi-objective optimization model, including residential building archetypes, climate classifications, energy-efficiency measures, photovoltaic energy production, objective functions, and constraints. URI: https://eceeeproceedings.org/articles/8/files/6a5dfc68a15c6.pdf
- **PowerPoint Slides.** PowerPoint Slides relating to this article. URI: https://eceeeproceedings.org/articles/8/files/6a5dfc8355a6b.pptx

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COMPETING INTERESTS

The authors have no competing interests to declare.

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REFERENCES

Alexakis, K, Benekis, V, Kokkinakos, P and **Askounis, D.** 2025. 'Genetic algorithm-based multi-objective optimisation for energy-efficient building retrofitting: A systematic review'. *Energy and Buildings*, 328: 115216. DOI: https://doi.org/10.1016/j.enbuild.2024.115216

Asadi, E, da Silva, MG, Antunes, CH, Dias, L and **Glicksman, L.** 2014. 'Multi-objective optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application'. *Energy and Buildings*, 81: 444–456. DOI: https://doi.org/10.1016/j.enbuild.2014.06.009

Azevedo, L, Gomes, R and **Silva, C.** 2021. 'Influence of model calibration and optimization techniques on the evaluation of thermal comfort and retrofit measures of a Lisbon household using building energy simulation'. *Advances in Building Energy Research*, 15(5): 630–661. DOI: https://doi.org/10.1080/17512549.2019.1654916

Bertoldi, P, et al. 2025. 'Transformative investment strategy for carbon–neutral residential buildings in the European Union'. *Energy and Buildings*, 347: 116232. DOI: https://doi.org/10.1016/j.enbuild.2025.116232

Bonamente, E, et al. 2018. 'A life-cycle approach for multi-objective optimisation in building design: methodology and application to a case study'. *Civil Engineering and Environmental Systems*, 35(1–4): 158–179. DOI: https://doi.org/10.1080/10286608.2019.1576646

BPIE (Buildings Performance Institute Europe). 2024a. *Accelerating deep renovation in the EU with Renovation Passports*. Available at: https://www.bpie.eu/wp-content/uploads/2024/09/iBRoad2EPC-D5-5-EU-roadmap-for-uptake-of-iBRoad2EPC-schemes-2024-07-BPIE-1.pdf.

BPIE (Buildings Performance Institute Europe). 2024b. *From cost savings to societal gains: rethinking the cost-optimal methodology*. Available at: https://www.bpie.eu/publication/from-cost-savings-to-societal-gains-rethinking-the-cost-optimal-methodology/ [Accessed February 10, 2025].

Carvalho, A, et al. 2022. *Energy and Socioeconomic Characterization of the Residential Sector in Portugal*. APE – Associação Portuguesa de Energia.

Costa-Carrapiço, I, Raslan, R and **González, JN.** 2020. 'A systematic review of genetic algorithm-based multi-objective optimisation for building retrofitting strategies towards energy efficiency'. *Energy and Buildings*, 210: 109690. DOI: https://doi.org/10.1016/j.enbuild.2019.109690

Deb, K, Pratap, A, Agarwal, S and **Meyarivan, T.** 2002. 'A fast and elitist multiobjective genetic algorithm: NSGA-II'. *IEEE Transactions on Evolutionary Computation*, 6(2): 182–197. DOI: https://doi.org/10.1109/4235.996017

Decree-Law 101-D/2020. 2020. *Requirements for buildings to improve their energy performance and regulates the Energy Certification System for Buildings (2020)*.

Directorate General for Energy and Geology. 2014. *Cost Optimum Levels*. Annex C: Residential buildings. Lisbon.

Directorate General for Energy and Geology. 2020. *Order no. 6476-E/2021- Approval of the minimum requirements for thermal comfort and energy performance applicable to the design and renovation of buildings*. Available at: https://diariodarepublica.pt/dr/detalhe/despacho/6476-e-2021-166302786.

European Commission. 2021. *Commission Recommendation (EU) 2021/1749 of 28 September 2021 on Energy Efficiency First: from principles to practice — Guidelines and examples for its implementation in decision-making in the energy sector and beyond*.

European Parliament and of the Council. 2010. *Directive 2010/31/EU of 19 May 2010 on the Energy Performance of Buildings (recast)*.

European Parliament and of the Council. 2024. *Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast)*.

Eurostat. 2022a. *Electricity prices by type of user*. Available at: https://ec.europa.eu/eurostat/databrowser/product/view/NRG_PC_204.

Eurostat. 2022b. *Gas prices by type of user*. Available at: https://ec.europa.eu/eurostat/databrowser/product/view/NRG_PC_202.

Eurostat. 2022c. *Greenhouse gas emission statistics - air emissions accounts*. Available at: https://ec.europa.eu/eurostat/statisticsexplained/.

Galimshina, A, et al. 2024. 'Strategies for robust renovation of residential buildings in Switzerland'. *Nature Communications*, 15(1): 2227. DOI: https://doi.org/10.1038/s41467-024-46305-9

IEA. 2025. *Multiple Benefits of Energy Efficiency*. Paris. Available at: https://www.iea.org/reports/multiple-benefits-of-energy-efficiency.

INE. 2020. *Construction and Housing Statistics –2019*. Lisbon. Available at: https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_publicacoes&PUBLICACOESpub_boui=443821545&PUBLICACOESmodo=2.

National Statistics Institute and Directorate General for Energy and Geology. 2021. *Survey on Energy Consumption in Households 2020 National Statistics Institut & Directorate General for Energy and Geology (eds). Lisbon*. Available at: https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_publicacoes&PUBLICACOESpub_boui=48433981&PUBLICACOESmodo=2.

Oliveira, C, Coelho, D and **da Silva, PP.** 2014. 'A prospective analysis of the employment impacts of energy efficiency retrofit investment in the Portuguese building stock by 2020'. *International Journal of Sustainable Energy Planning and Management*, 2: 81–92.

Pannier, M-L, et al. 2021. 'Identifying optimal renovation schedules for building portfolios: Application in a social housing context under multi-year funding constraints'. *Energy and Buildings*, 250: 111290. DOI: https://doi.org/10.1016/j.enbuild.2021.111290

Pinto, A and **Fragoso, R.** 2018. 'Indicador de comportamento térmico solar passivo de habitações – Estação de aquecimento'. *LNEC – Laboratório Nacional de Engenharia Civil*. Available at: www.lnec.pt.

Presidency of the Council of Ministers. 2020. *Resolution of the Council of Ministers no. 53/2020 – National Energy and Climate Plan 2030 (NECP 2030)*. Diário da República n.o 133/2020, Série I de 2020-07-10: 2–158.

Presidency of the Council of Ministers. 2021. *Resolution of the Council of Ministers No. 8-A/2021 – Long Term Strategy for the Renovation of Buildings*. Diário da República n.o 23/2021, 1o Suplemento, Série I de 2021-02-03: 16-(2)–16-(105).

REH. 2013. *Regulation of Energy Performance of Residential Buildings – Design requirements for new buildings and interventions*. Portaria no 349B-2013, amended by Ordinance n.o 379-A/2015, of October 22 and Ordinance no 319/2016 of 15 December.

Reis, DC, De Domenico, AT, Lopes, L and **Almeida, M.** 2023. 'Strategies and Actions for Achieving Carbon Neutrality in Portuguese Residential Buildings by 2050'. *Sustainability*, 15(21): 15626. DOI: https://doi.org/10.3390/su152115626

Rosso, F, Ciancio, V, Dell'Olmo, J and **Salata, F.** 2020. 'Multi-objective optimization of building retrofit in the Mediterranean climate by means of genetic algorithm application'. *Energy and Buildings*, 216: 109945. DOI: https://doi.org/10.1016/j.enbuild.2020.109945

Russell, C, Baatz, B, Cluett, R and **Amann, J.** 2015. 'Recognizing the Value of Energy Efficiency's Multiple Benefits. ACEEE Report IE1502'. *American Council for an Energy-Efficient Economy (aceee)*.

Shao, Y, Geyer, P and **Lang, W.** 2014. 'Integrating requirement analysis and multi-objective optimization for office building energy retrofit strategies'. *Energy and Buildings*, 82: 356–368. DOI: https://doi.org/10.1016/j.enbuild.2014.07.030

Tadeu, S, Rodrigues, C, Marques, P and **Freire, F.** 2022. 'Eco-efficiency to support selection of energy conservation measures for buildings: A life-cycle approach'. *Journal of Building Engineering*, 61: 105142. DOI: https://doi.org/10.1016/j.jobe.2022.105142

Tenente, M, Henriques, C, Gomes, Á and **da Silva, PP.** 2025. 'A comprehensive framework for evaluating energy efficiency solutions'. *Energy and Buildings*, 344: 115997. DOI: https://doi.org/10.1016/j.enbuild.2025.115997

Thema, J, et al. 2019. 'The multiple benefits of the 2030 EU energy efficiency potential'. *Energies*, 12(14): 2798. DOI: https://doi.org/10.3390/en12142798

Ürge-Vorsatz, D, et al. 2016. 'Measuring multiple impacts of low-carbon energy options in a green economy context'. *Applied Energy*, 179: 1409–1426. DOI: https://doi.org/10.1016/j.apenergy.2016.07.027

Zhang, H, Hewage, K, Prabatha, T and **Sadiq, R.** 2021. 'Life cycle thinking-based energy retrofits evaluation framework for Canadian residences: A Pareto optimization approach'. *Building and Environment*, 204: 108115. DOI: https://doi.org/10.1016/j.buildenv.2021.108115

Zhang, S, et al. 2016. 'Modeling energy efficiency to improve air quality and health effects of China's cement industry'. *Applied energy*, 184: 574–593. DOI: https://doi.org/10.1016/j.apenergy.2016.10.030

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