15TH IEA HEAT PUMP CONFERENCE
MAY 26–29, 2026 | HOFBURG
VIENNA 2026
DECARBONISATION THROUGH INNOVATION

Toward optimal retrofit levels for heat pump installation in residential buildings.

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Abstract

Whereas the installation of a heat pump (HP) in new buildings is becoming rather common, electrifying the existing building stock remains a significant challenge. In particular, implementing low-temperature heating via HPs is often not feasible in dwellings with limited insulation and existing emitter systems. However, the growing market penetration of high-temperature heat pumps is reducing the stringency of insulation requirements. Previous studies have attempted to define the insulation threshold at which a dwelling can be considered 'HP-ready,' typically focusing on technical feasibility and energy cost. Yet, even when a dwelling meets these criteria, additional insulation may still be beneficial to reduce heat demand and optimize overall performance. This paper presents a multi-criteria analysis aimed at identifying optimal renovation strategies by examining the interplay between the building envelope and heating system, based on standardized calculations. Two representative Belgian dwellings are used as case studies, with varying initial conditions. For each initial state, suitable envelope renovation scenarios are developed, alongside detailed HP system designs. No alternative system variants, such as different heat pump models or photovoltaic panels, are considered. Both financial and CO_2 indicators are calculated. Using Monte Carlo analyses, a robust set of insulation scenarios minimizing both financial and CO_2 costs is identified, providing insights into cost effective and low-carbon renovation pathways for existing buildings.

Keywords: heat pump, renovation, cost effectiveness, low-carbon

1. Introduction

Historically, high insulation levels were considered essential for heat pump efficiency, as they minimize heat losses and allow operation at lower, more efficient supply temperatures. Williams and Thomson [1] explicitly link heat pump deployment to deep insulation, assuming that in the absence of such measures, direct electric heating is the only viable long-term option. Recent developments, however - such as high-temperature heat pumps- reduce the technical necessity for deep retrofits in all cases. Guire et al. [2] show that Ireland's "fabric-first" approach, requiring extensive thermal retrofitting for heat pump subsidies, is not cost-optimal. Lämmle et al. [3] confirm the link between seasonal performance factor (SPF) and supply temperature based on field data and identify alternative methods to lower supply temperatures, such as targeted replacement of undersized radiators.

Guidelines for making dwellings *"heat pump ready"* are provided by the Flemish Government, based on a study conducted by VITO [4]. That study defines a dwelling as "heat pump ready" when a heat pump operates at a lower energy cost than a gas boiler for more than 70% of the annual heating demand. Based on this

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15th IEA Heat Pump Conference 2026 - BRE1.4 - https://doi.org/10.23697/2nyf-bq28

criterion, the corresponding minimum insulation level was found to yield a specific heat load of approximately 70 W/m². However, this study does not address whether it remains beneficial to insulate beyond this minimum level. That question can be approached from a broader, societal perspective, considering the impact of large-scale heat pump deployment on the electricity system. Several studies address the risk of increased grid stress and higher system costs associated with large-scale deployment of heat pumps. For example, Sarevet et al. [5] assess to what extent extensive insulation can mitigate the rise in electricity demand and peak loads resulting from widespread heat pump adoption. Lingard et al. [6] analyse, at the building level, the impact of different insulation scenarios and their influence on heat pump input power and grid loading. Pena-Bello et al. [7] illustrate that peak-load mitigation can be pursued not only through insulation but also through energy-storage strategies.

In this paper, the optimal insulation level is determined based on building-level criteria, namely the total financial cost and the total CO_2-equivalent emissions. For the financial analyses the cost assumptions and methodological framework are based on a series of cost-optimal studies commissioned by the Flemish Government and published through its official energy performance portal [8]. In these studies gas boilers were often identified as part of the most cost-effective retrofit solution. However, given the current transition towards electrification, this paper adopts the premise that a heat pump is mandatory used as the heating system.

For the CO2 analysis, the TOTEM tool [9] is used, based on generic European environmental data from the Ecoinvent 3.9 "cutoff" database. Although the embodied carbon of heat pump installations is not elaborated in sufficient detail in TOTEM, it can be neglected in this study especially because all compared scenarios include a heat pump and only differ in the size of the HP, while the existing distribution/emission system is retained. Furthermore, according to [10], embodied emissions of a heat pump installation account for 5–20% of total emissions depending on the electricity mix, and assuming a low GWP refrigerant only 15% of this corresponds to the newly installed heat producer. This results in a negligible contribution of 0.75–3% of the total carbon emissions associated with the heating system.

2. Methods

2.1. General

Two reference buildings are considered: a typical Flemish terraced house and a freestanding house. For each building type, three initial conditions are defined based on construction years 1970, 1990, and 2005, as specified in the TABULA database [12]. This results in six initial cases, with key parameters summarized in Table 1.

Table 1. Key parameters of 6 reference cases

Building type	Heated volume (m³)	Heat loss area (m²)	construct year	Uroof/wall/windows/floor (W/m²K)	Airtightness v50 (m³/hm²)
Terraced (T)	521	243	1970	2.04/1.7/4.72/0.87	11
			1990	0.85/0.95/2.92/0.87	11
			2005	0.54/0.51/2.9/0.47	6
Freestanding (FS)	872	566	1970	2.04/1.7/4.72/0.75	11
			1990	0.85/0.95/2.92/0.75	11
			2005	0.54/0.51/2.9/0.5	6

For these six initial cases, the optimal renovation level with heat pump installation is determined according to two criteria: (1) the financial total cost for the building owner and (2) the CO_2 - equivalent (CO_2eq) cost. To this end, cost-efficient insulation scenarios for the building envelope are defined. Subsequently, for each insulation scenario, the total cost is calculated for the retrofitted reference building equipped with a correctly dimensioned heat pump. No alternative system variants, such as different heat pump models or photovoltaic panels, are considered. A Monte Carlo analysis is then applied to identify, for each criterion, a robust set of low-cost scenarios that achieve near-minimal total costs across most parameter samples. The different steps are elaborated in the following paragraphs.

2.2. Selection and cost of building envelope retrofit scenarios

For each building envelope component (wall, roof, windows, floor), a set of insulation measures and levels with corresponding financial and CO_2eq costs, is defined. The corresponding improvements in component air tightness are also taken into account. Both internal and external insulation options are considered. Low-cost finishing layers are assumed, and the existing load-bearing structure is preserved wherever possible. For the financial analyses, a distinction is made between *intrusive* and *non-intrusive* insulation scenarios. The latter include only measures that can be implemented while the dwelling is occupied, thus excluding interior insulation and floor replacement. For the CO_2 criterion, a distinction is made between *standard* and *low-carbon* insulation scenarios. In the low-carbon scenarios, cellulose is used instead of PUR or EPS, wood is used in place of plaster for external wall finishing or aluminium for window frames, and roof and floor tiles are reused where applicable.

Investment costs for the financial analysis are based on studies of cost-optimal energy performance conducted by the Flemish Government [8] and on EPC (Energy Performance Certificate)-reported costs for the recommended insulation measures, all indexed using the ABEX index. The CO_2eq costs for the climate impact analysis are derived following the TOTEM approach [9]. The embodied CO_2eq comprises the following life cycle stages over a period of 60 years: product (A1–3), construction (A4–5), replacement (B4), and end-of-life (C1–4) stage.

For all possible combinations of the preselected insulation measures, the building's net energy demand is calculated according to the methodology used in the Belgian Energy Performance of Buildings (EPB) regulations. From these results, the combinations with the lowest total cost and net energy demand—representing the Pareto front—are selected for further analysis. This approach results in 24 Pareto fronts in total: for each of the six initial cases, two variants are defined for the financial analysis (intrusive and non-intrusive) and two for the CO_2eq analysis (standard and low-carbon insulation scenarios).

2.3. Total cost of retrofit scenarios with heat pump

The total financial and CO_2eq cost of the selected building envelope scenarios is calculated under the assumption that a new air-to-water heat pump (heat generation efficiency 147%) is installed, while the existing heat emission system is retained. The electricity consumption of the heat pump is determined according to the EPB calculation method, which accounts for the impact of lower supply temperatures on the system efficiency.

For the financial analysis, the total actual cost is evaluated over a lifespan of 30 years. This includes the investment cost of insulation, as calculated in Section 2.2, as well as replacement costs and the residual value at the end of the 30-year period. For the heat pump, both (re)investment and residual value are also included. The investment cost of the heat pump was based on a recent VEKA study [8]. Units with a nominal capacity of up to 20 kW are considered, but with a marked increase in cost above 12–14 kW. Furthermore, energy and maintenance costs over the 30-year period were included, assuming an electricity price of €0.32 /kWh. All costs were discounted at a rate of 3%.

The total CO_2-equivalent (CO_2eq) cost accounts for the full lifecycle impact of the building renovation scenarios, following the TOTEM methodology. It includes the embodied CO_2eq cost of the insulation measures (as calculated in Section 2.2) combined with the operational CO_2eq emissions related to electricity consumption for space heating over a period of 60 years. The operational CO_2eq emissions are calculated using an emission factor of 0.250 kg CO_2eq/kWh, consistent with TOTEM [9]. This factor is sourced from Ecoinvent v3.6, taking into account the average electricity mix in Belgium. Compared to other European countries, the climate impact of electricity in Belgium is relatively low due to the high share of nuclear power in the national energy mix. The embodied CO_2eq emissions of the heat pump are not included in the life cycle analysis, as this simplification is consistent with previous studies (see Section 1).

2.4. Parameter analyses to define robust set of low cost retrofit scenarios

A Monte Carlo analysis is applied to account for uncertainties in key input parameters, including investment costs, embodied CO_2, energy use, radiator sizing, energy prices, and the discount rate. Parameter values are sampled within experience or literature-based ranges using appropriate probability distributions. For each case study, 10,000 samples are generated to ensure statistical robustness.

Energy use is a key parameter in the analysis, as it strongly affects both the total financial and CO_2eq costs, while being subject to substantial uncertainty. In particular, the EPB methodology has been shown to systematically overestimate the energy use in relation to actual measured values. Decorte et al. [11] derived rebound factors to adjust calculated primary energy for space heating and domestic hot water (DHW) in order to better reflect real consumption. However, these correction factors were based on gas-heated dwellings and EPC certificates, which often include default values when input data are missing. For heat pump systems—where night setback is generally not applied—and for theoretical EPB calculations with complete building data, the actual energy use is expected to correspond more closely to the calculated value. Therefore, a uniform distribution is assumed between the calculated and corrected energy use.

For each simulation run, total financial and CO_2eq costs were calculated. Scenarios in which the total cost did not exceed 10% above the minimum were classified as *low-cost* scenarios. Finally, scenarios that consistently (in more than 80% of the samples) achieved near-minimal total costs across the parameter space were identified as *robust low-cost solutions*.

3. Results and discussion

The results are structured in two parts: the economic analyses are presented first, followed by the CO_2eq analyses. For both, the Pareto front illustrating the selected envelope renovation scenarios is presented. The robust low-cost scenarios are subsequently examined for the different dwelling cases and boundary conditions. In the financial analyses, intermediate results are presented and discussed in greater detail for one representative case as this provides additional insight that helps to interpret the results of the other cases, which follow the same principles. Finally the section ends with a general discussion of the results.

3.1. Pareto front with selected envelope renovation scenarios (economic analyses)

For the freestanding house built in 1970, Figure 1 shows the net energy demand and the total investment cost for all possible combinations of the defined insulation measures. To reduce the computational time of the Monte Carlo analysis, not all combinations on the Pareto front were further evaluated. The figure presents both the complete Pareto front and the selected combinations, which still provide a good representation of the overall front.

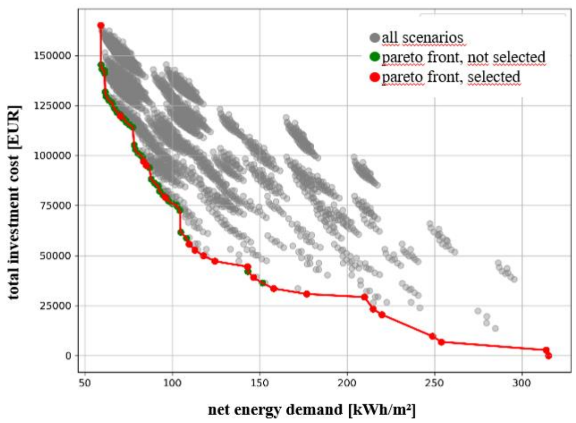

Figure 1. Total investment cost and net energy demand of renovation scenarios, the renovation scenarios on the pareto front selected for further analysis are indicated in red (the green scenarios on the pareto front are not further analysed)

For each of the six initial cases, a subset of envelope renovation scenarios was selected, following the same procedure, to represent the Pareto front. In addition, an alternative Pareto front was generated considering only non-intrusive measures, thereby excluding interventions such as interior insulation of the roof and façade, or the replacement of the floor surface. The resulting Pareto fronts are shown in the figure below. For a given net energy demand non-intrusive scenarios result in higher investment costs. The fact that investment costs are sometimes higher for the 1990 dwelling than for the 1970 dwelling is primarily due to the low cost of injecting insulation into the empty cavity of the 1970 building. This option was not considered for the more recent dwellings, which already contain a (limited) amount of cavity insulation.

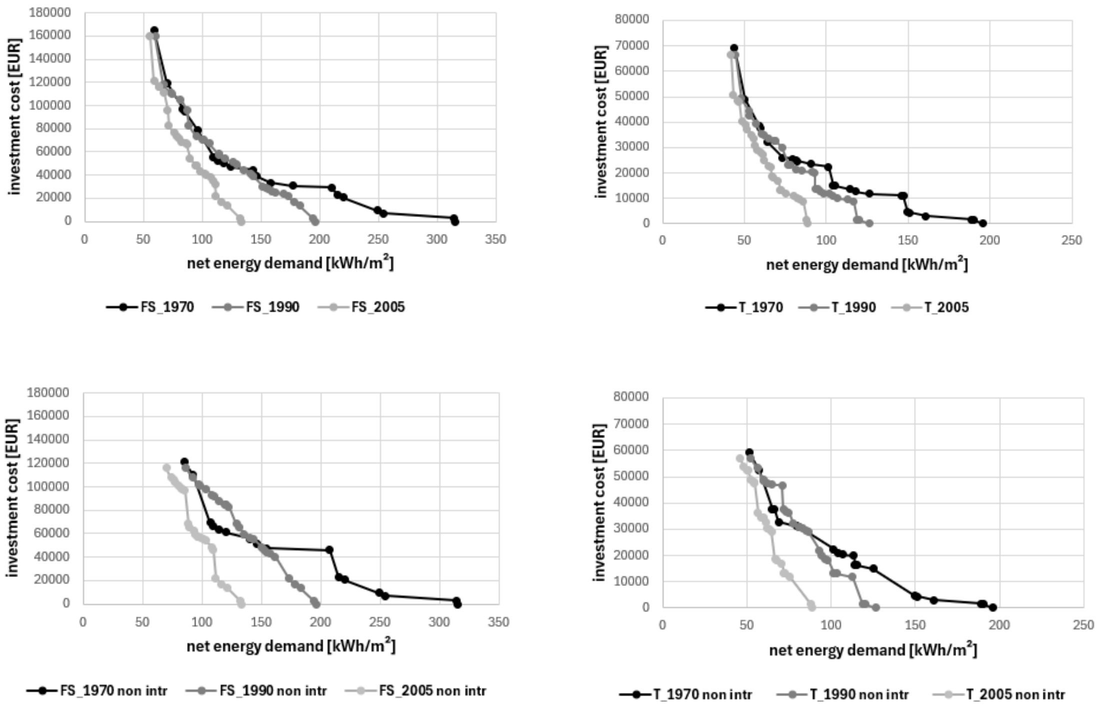

Figure 2. Selection of insulation scenarios on pareto front for freestanding (FS) and terraced (T) dwelling (construction year 1970,1990,2005), intrusive (-) and non-intrusive (non intr) scenarios

3.2. Detailed analyses for representative case study (economic analyses)

Figure 3 presents the evolution of the total present cost (TPC) as a function of the net energy demand (NED), for the selected insulation scenarios of the freestanding dwelling built in 1970. The figure also includes several intermediate cost components (1) - (5).

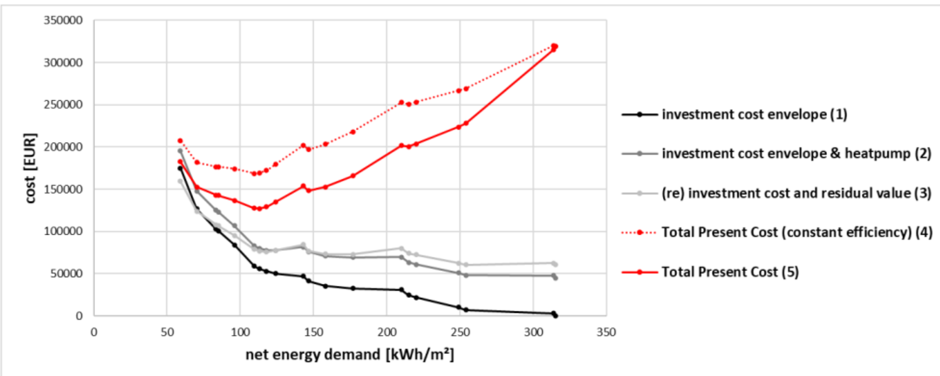

Figure 3. Total present cost (solid red line) as a function of net energy demand, for the selected insulation scenarios, together with some intermediate cost components (freestanding dwelling, 1970 case)

The first curve (1) represents the Pareto front of the investment costs for the building envelope insulation. Adding the heat pump investment cost (2) shows a clear cost reduction with decreasing NED, as smaller heat pump capacities can be installed. When reinvestment costs and residual values are included (3), the more advanced insulation packages become relatively more favourable, due to the long life span (and thus high residual values) of insulation measures, flattening the cost curve and showing a distinct inflection around 120 kWh/m².

Finally, when energy costs are added, the curve representing the total present cost shows a minimum around 120 kWh/m². In fact two effects occur: the energy demand decreases with improved insulation, while the heat pump efficiency increases due to lower supply temperatures. The fourth curve illustrates the total cost assuming constant efficiency, and the final curve represents the full result including the efficiency gain. Although the reduced supply temperature contributes to lower costs, it is mainly the decreasing NED that determines the insulation level corresponding to the minimum total cost.

It is evident that energy consumption constitutes a major component of the total cost. Consequently, Figure 4 investigates the influence of incorporating the rebound effect, as described in [11]. Scenarios in which the total cost remains within 10% of the minimum value are indicated as *low-cost* scenarios. The figure demonstrates, on the one hand, that lower energy consumption has a pronounced effect on the total cost, thereby reducing the incentive to invest in insulation. On the other hand, scenarios with a NEB between 110 and 125 kWh/m² consistently remain within the *low-cost* range, despite the large difference in energy consumption.

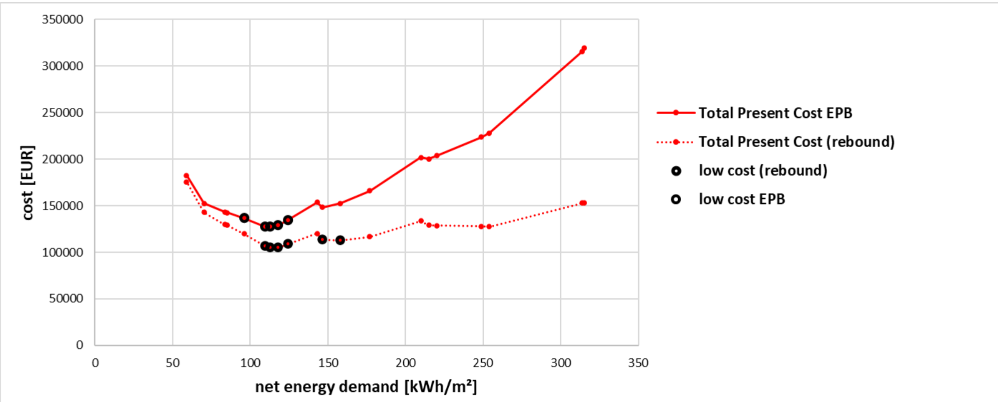

Figure 4. Total present cost as a function of net energy demand, calculated for energy use according to EPB (solid line) and considering the rebound effect (dashed line), with indication of low cost scenarios (freestanding dwelling, 1970)

This initial parameter analysis suggests that it is possible to define a robust optimal insulation level, despite the fact that certain parameters clearly have a significant impact on the total cost on its own.

3.3. Robust low cost scenarios (economic analyses)

Figure 5 presents the results of the Monte Carlo simulations for the different building cases, highlighting the range of solutions identified as *robust low-cost scenarios* (as defined in 2.4). The bounds of the robust low-cost region are plotted on the Y-axis, while the building cases are shown on the X-axis. The results are expressed in terms of the net energy demand (NED). For the detached house, 110–120 kWh/(m²·year) can be identified as an indicative cost-optimal insulation level, independent of the building age or the potential insulation measures. At this insulation level, the detached house requires a heating capacity of 12 kW or 50 W/m², and the existing radiators operate at 50-55 °C (depending on the initial building state and radiator sizing). For the terraced house, an indicative cost-optimal level of about 90 kWh/(m²·year) was obtained, primarily reflecting the higher compactness of this building type. This corresponds to a required heating capacity of 7 kW or 40 W/m². The existing radiators operate at 55-60 °C. For both dwellings, the EPC label corresponding to their cost-optimal insulation level and equipped with a low-temperature heat pump lies roughly between 100 and 150 kWh/(m²·year). This indicates that further insulation towards achieving label A is no longer economically justified. However, by adding a demand-controlled ventilation system and/or photovoltaic panels, label A can be easily achieved.

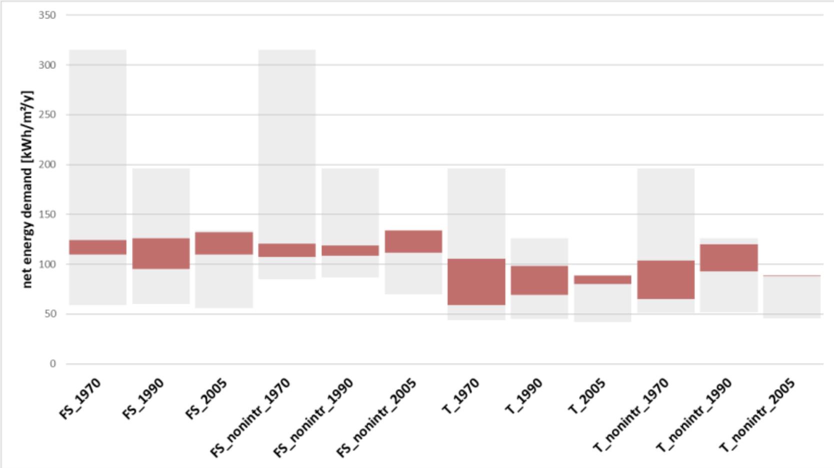

Figure 5. Results of Monte Carlo analyses for variants of freestanding (FS) and terraced (T) dwelling, with intrusive (-) and non-intrusive (nonintr) scenarios and for different construction years (1970, 1990, 2005). The shaded area represents the net energy demand -range of all the considered renovation scenarios, while the darker region contains the robust low cost combinations.

Overall, the results demonstrate that the robust low-cost regions remain relatively stable across the different cases with the building type -specifically its compactness- being the most influential parameter. This suggests that it is possible to define design recommendations that balance investment and operational costs while maintaining robustness against uncertainty.

To translate these recommendations into concrete renovation actions, two straightforward measures can be identified: adding insulation to the basement ceiling and installing an insulated garage door. Beyond these, the recommended insulation measures corresponding to the defined target values are as follows: roof insulation, cavity wall insulation, and new windows with high-performance double glazing for the 1970 dwelling; façade insulation for the 1990 dwelling combined with roof insulation (or with high-performance glazing for the terraced house when no intrusive measures are allowed); interior roof insulation where feasible for the 2005 dwelling, with new HR-glazed windows for the freestanding one. For most building components, it is generally not necessary to insulate beyond a U-value of 0.24 W/m²K. Only for the roof do U-values as low as 0.18 W/m²K occasionally fall within the identified optimal range.

3.4. Pareto front with selected envelope renovation scenarios (CO_2eq analyses)

The Pareto front representing the relationship between the total CO_2eq cost (embodied CO_2eq) and the net energy demand for the envelope renovation scenarios is constructed in the same manner as described in Section 3.1 and is presented in Figure 6. The total CO_2eq cost includes all embodied emissions related to the envelope renovation measures, excluding the operational CO_2eq cost. The figure also illustrates variants that incorporate low carbon insulation measures, as outlined in Section 2.2.

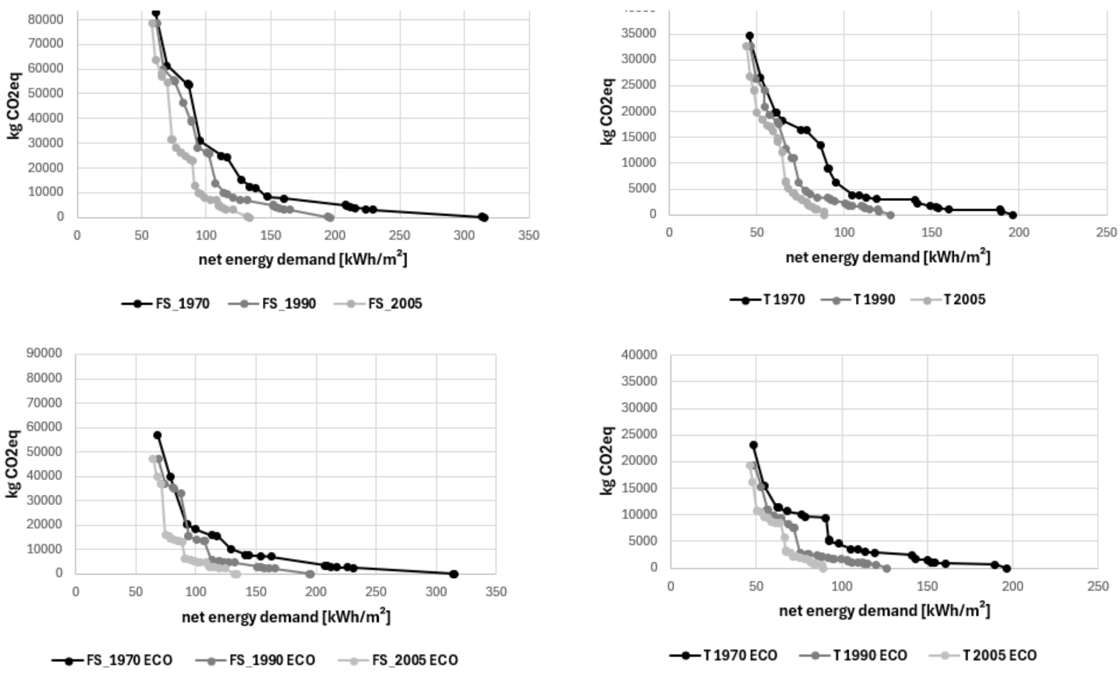

Figure 6. Selection of insulation scenarios on pareto front for freestanding (FS) and terraced (T) dwelling (construction year 1970,1990,2005), standard (-) and low-carbon (ECO) insulation variants.

3.5. Robust low cost scenarios (CO_2eq analyses)

Figure 7 presents the results of the Monte Carlo simulations for the different building cases, constructed in the same way as Figure 3.3 for the financial analyses. In general, the results show that from a CO_2eq perspective, it is worthwhile to insulate further than what is financially optimal. For the freestanding dwelling, a net energy demand (NED) of around 100 kWh/m² can be considered a robust target value. For the 2005 dwelling, this 100 kWh/m² threshold can even be exceeded when low-carbon insulation measures are used. For the terraced house, a NED of approximately 55 kWh/m² emerges as a consistent target level, independent of the initial condition and the choice of insulation materials.

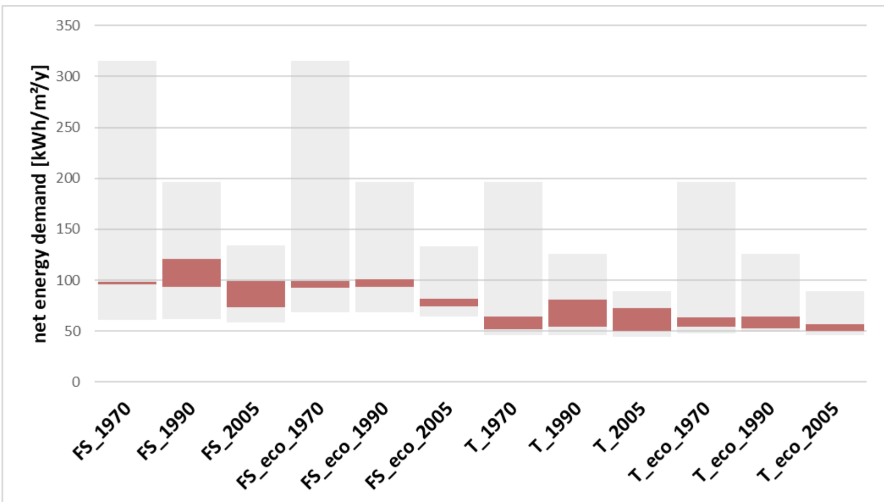

Figure 7. Results of Monte Carlo analyses for variants of freestanding (FS) and terraced (T) dwelling with standard (-) and low carbon (eco) insulation variants and for different construction years (1970, 1990, 2005). The shaded area represents the net energy demand-range of the considered renovation scenarios, while the darker region indicates the robust low cost region.

Concretely, this means that the insulation measures added beyond the financially optimal scenarios include façade insulation (rather than cavity wall insulation alone) for the 1970 dwelling, the installation of new windows with at least high-performance glazing for the 1990 dwelling, and both roof and façade insulation for the 2005 dwelling combined with new windows for the terraced house.

3.6. General discussion.

The results presented in section 3 identify cost-optimal insulation levels for residential buildings equipped with heat pumps, evaluated from both financial and CO_2eq perspectives. These results are derived from a set of standardized assumptions regarding energy performance calculations, cost data and life-cycle emission factors. While absolute cost levels depend on these assumptions, the applied Monte Carlo analysis shows that the identification of low-cost regions is robust across the considered parameter ranges.

From the results, a few general insights emerge. (1) Cost-optimal insulation levels differ depending on whether financial costs or CO_2eq emissions are prioritized, with CO_2eq -optimal scenarios generally favouring higher insulation levels. (2) From a financial perspective, the results suggest that insulation up to roughly the level of a 2005 building (or slightly higher) is generally sufficient, and it is not necessary to reach the full insulation standard of newly built dwellings. (3) For the different variants per building type (based on construction year and renovation assumptions), the analysis identifies a range of robust low cost solutions rather than a single value (Figure 5 and Figure 7). These ranges do not coincide but do overlap, making it possible to derive a single indicative value per building type that falls within the low cost range for all variants (Table 2).

4. Conclusion

This study presents a multi-criteria analysis to identify optimal insulation levels for residential buildings equipped with heat pumps, considering both financial costs and CO_2-equivalent emissions. Two representative Belgian dwellings with varying initial conditions were used as case studies. For each case, a range of envelope renovation scenarios was evaluated, and robust low-cost solutions were identified using Monte Carlo analyses that accounted for uncertainties in energy use, costs, and other key parameters.

The results demonstrate that, from a financial perspective, a clear range of cost-optimal insulation levels exists for each building type, with the detached house showing an indicative net energy demand (NED) of 110–120 kWh/(m²·year) and the terraced house around 90 kWh/(m²·year). From a CO_2 perspective, higher insulation levels are beneficial, particularly when low-carbon materials are employed. The resulting design recommendations are summarized in Table2.

Table 2. cost-optimal insulation levels for typical residential buildings with a heat pump, from a financial and CO_2 perspective

Building type	Evaluation perspective	Net energy demand [kWh/(m².year)]	Heating capacity [W/m²]
Terraced (T)	financial	90	40
	CO_2	55	25
Freestanding (FS)	financial	120	50
	CO_2	100	45

This study relies on standardized calculation frameworks to assess energy performance, financial costs and CO_2eq emissions, including the Belgian EPB-methodology for energy demand, cost-optimal assumptions derived from governmental studies and life-cycle emission factors from the TOTEM/Ecoinvent database. While these approaches ensure internal consistency and enable systematic comparison across renovation scenarios, the results are derived from generalized, standardized models rather than from operational data of individual buildings. The identified cost-optimal insulation levels should therefore be interpreted as robust, model-based design targets intended to inform generic renovation strategies rather than case-specific performance outcomes.

Overall, the study shows that robust design recommendations can be formulated that balance investment and operational costs while reducing carbon emissions. The methodology provides a framework for systematically assessing retrofit strategies for heat pump installations, supporting cost effective and low-carbon pathways for electrifying the existing building stock.

Acknowledgements

This research was conducted in the framework of the COOCK+ project Recover funded by the Flemish government (www.vlaio.be) and a user group of Flemish companies.

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