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Greenhouse Gas Payback Time of Different HVAC Systems in the Renovation of Nordic District-Heated Multifamily Buildings Considering Future Energy Production Scenarios

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Abstract: The European Union (EU) has implemented several policies to enhance energy efficiency. Among these policies is the objective of achieving energy-efficient renovations in at least 3% of EU buildings annually. The primary aim of this study was to offer a precise environmental comparison among four similar district-heated multifamily buildings that have undergone identical energy efficiency measures. The key distinguishing factor among them lies in the HVAC systems installed. The chosen systems were as follows: (1) exhaust ventilation with air pressure control; (2) mechanical ventilation with heat recovery; (3) exhaust ventilation with an exhaust air heat pump; and (4) exhaust ventilation with an exhaust air heat pump with a Photovoltaic (PV) panel. This study involved a life cycle assessment that relied on actual material data from the housing company and energy consumption measurements. This study covered a period of 50 years for thorough analysis. A sensitivity analysis was also conducted to account for various future scenarios of energy production. The findings revealed that the building with an exhaust air heat pump exhibited the lowest greenhouse gas emissions and the shortest carbon payback period (GBPT), needing only around 7 years. In contrast, the building with exhaust ventilation without heat recovery showed the highest emissions and the longest carbon payback period (GBPT), requiring approximately 11 years. Notably, the results were significantly influenced by future scenarios of energy production, emphasizing the crucial role of emission factors in determining the environmental performance of distinct renovation scenarios.

Keywords: life cycle assessment; carbon payback time; multifamily buildings; renovation; HVAC systems; future energy production scenarios

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1. Introduction

Buildings are crucial for achieving the European Union's (EUs) energy and environmental goals, as they account for a substantial 40% of total energy consumption and contribute to 33% of greenhouse gas emissions [1]. The residential building stock accounts for approximately 75% of the share, and 38% of residential buildings were built before 1970, a time when energy efficiency standards were absent in building regulations [2], while around 75% of the building stock is considered energy inefficient [3]. Concerns over energy security and the inflationary impact of higher energy prices on the world's economies have dramatically escalated [4]. It is evident that directing efforts toward enhancing energy efficiency is the most logical and effective response to address concerns related to affordability, energy supply security, and climate change objectives. To address these challenges, European Union member states are driven to formulate robust, long-term renovation strategies. These strategies are designed with the ambitious goal of achieving carbon neutrality in the national building stock by 2050, with significant milestones set for 2030, 2040, and 2050 [3]. In addition to these requirements, under the Energy Efficiency

Directive, EU countries must make energy-efficient renovations to at least 3% of the total floor area of buildings owned and occupied by central governments [3].

Swedish energy policy aims to combine security of energy supply, competitiveness, and ecological sustainability. By 2030, Sweden is targeting a remarkable 50 percent improvement in energy efficiency compared to 2005 [5]. Striving towards a building stock with a high degree of energy efficiency is essential to reaching the Swedish national energy efficiency goal by 2030 and more long-term goals of net zero emissions of greenhouse gases by 2045 and a 100 percent renewable electricity system by 2040. Sweden has made significant progress with its existing policy instruments [6]. The authorities assess that more efforts are required to achieve more ambitious goals, and one of those is that more energy-efficient renovations need to be carried out. A large part of the buildings in Sweden were built under the "Million Homes Program" between 1965 and 1974 [7]. Large shares of the Swedish million-dollar program need renovation and more efficient energy use [8]. The Million Homes Program confronts a significant dilemma: should we renovate both the exterior and interior of these multi-family buildings instead of opting for demolition? The robustness of these structures, with apartments showcasing flexibility through features like movable walls, has been affirmed by researchers [9]. Considering the social impact, Mangold's study [10] emphasizes that upcoming renovations disproportionately affect low-income individuals, leading to substantial rent increases, particularly in areas like Gothenburg. Investigations by von Platten et al. [11] reveal that small energy renovation investments in multifamily buildings result in tenant cost reductions, while large-scale energy retrofitting imposes a burdensome cost on tenants. La Fleur et al.'s life cycle cost study [12] supports the notion that deep energy renovation projects are more cost-effective than building anew. Additionally, Mangold. [13] notes that public housing companies, facing financial challenges, prioritize renovations over rent increases. This pattern underscores the importance of considering the well-being of Million Homes Program residents to prevent exacerbating social issues such as increased poverty or heightened societal divisions.

The Swedish National Board of Housing, Building, and Planning (Boverket) and the Swedish Energy Agency have developed a long-term renovation strategy since 2019. The strategy covers both public and private actors [14]. The goal is for the buildings to reach such a high degree of energy efficiency that fossil fuels are phased out by 2050 at the latest. The goal is also to facilitate a cost-effective renovation of existing buildings into near-zero-energy buildings [14]. It is feasible to renovate the houses from the million-dollar program to meet nearly the same energy standards as new homes, all the while minimizing rent increases. This was demonstrated by the EU project Cityfied, which successfully transformed the 1970s-era Linero area in Lund. Through these renovations, energy consumption can be decreased by an impressive 40 percent [15].

Numerous studies have investigated the impact of HVAC systems, uncovering issues such as performance losses, energy waste, non-compliance with regulations, and occupant discomfort that can be effectively mitigated through Fault Detection and Diagnosis techniques. Implementing these methods allows for a thorough examination and enhancement of building systems, ensuring optimal performance, energy efficiency, regulatory compliance, and improved occupant comfort [16–18].

Renovation measures have been evaluated in various literatures; however, the results have relied on simulation data [19–26]. A literature review conducted by Ma [27] has ascertained that the majority of prior studies were conducted through numerical simulations. The real-world energy savings resulting from the implementation of retrofit measures in actual buildings may deviate from the estimates, which is often called the energy gap. Further research involving practical case studies is imperative to enhance our confidence in the potential benefits of retrofitting.

In a study conducted by Kertsmik, the evaluation of residential building renovation projects were based on post-renovation measurement data. However, the primary focus of this study was on evaluation strategies rather than the examination of different HVAC systems [28]. In a review study authored by Vilches [29] about the life cycle assessment (LCA) of building refurbishment, it was found that the main focus of the LCA of building energy retrofits is on increasing insulation. Research by Galimshina [30] has concluded that the heating system is the most crucial parameter for renovation. Another study by Bilec [31] conducted a whole-building LCA for a renovation project and found that the majority of renovation impacts were due to non-structural components.

As of 1 January 2022, a requirement for a climate declaration has been established that describes a building's environmental impact [32]. This declaration is based on calculations derived from the greenhouse gas emissions associated with the entire construction process. The construction phase encompasses activities such as raw material extraction, the manufacturing of construction products, on-site construction work, and transportation. It is important to note that the climate declaration exclusively applies to new construction projects and does not encompass renovation projects. However, the Swedish Environmental Objectives Committee (Miljömålsberedningen) has officially endorsed the life cycle perspective as a foundational approach for assessing the environmental impact of new construction, rebuilding, and the management of existing buildings, including construction work [33]. Life cycle analysis (LCA) has played a central role in various studies concerning the renovation of residential buildings [28,30,34–38]. In the case of the renovation project under analysis in this study, researchers closely followed the project from its beginning, employing different assessments to select renovation measures through simulation software [39–42]. This research, part of the project's evaluation process, offers a real assessment of the chosen renovation scenarios.

As the Swedish energy system undergoes changes, numerous factors influence its developmental path, and there are many factors that influence which path the development will take. With a rapidly increasing demand for electricity in society and with new and changing patterns of electricity use, it is important to create the right conditions for extended electrification in good time [43]. A significant increase in electricity use also underlines the importance of energy efficiency and resource-efficient use of all energy. The scenarios for future energy production are designed according to the requirements contained in the Swedish regulation on climate declaration. The main advantage of these scenarios is that they are based on today's energy system and scenarios of energy use and energy demand in the future. In this study, a sensitivity analysis will be conducted across various future electricity and district heating production scenarios to mitigate result uncertainties.

Novelty and Aim

Energy-efficient renovation is a topic of extensive research, and it plays a critical role in advancing sustainability goals within the European Commission. Previous studies have primarily focused on enhancing the building envelope and exploring various renovation scenarios, often utilizing various simulation tools. However, the novelty of this study lies in its unique opportunity to assess and compare the performance of various HVAC (Heating, Ventilation, and Air Conditioning) systems implemented in separate district-heated buildings from the Million Homes Program. To achieve thiss study's aim, a life cycle analysis was conducted. This analysis used material data sourced from the housing company and on-site measurement energy data obtained from the buildings. This comprehensive approach ensured a thorough examination of the environmental impacts associated with different renovation alternatives. Based on these analyses, the greenhouse gas payback time (GPBT) for the renovation strategies was determined.

To provide a broader context and address uncertainties in the assessment, this study considered various future energy production scenarios. By considering these diverse energy production possibilities, the research yielded a more comprehensive understanding of the environmental implications of the different HVAC systems and renovation choices under varying energy supply conditions.

In essence, this study goes beyond conventional research in energy-efficient renovation by directly comparing HVAC systems in similar buildings and conducting a holistic life cycle assessment that covers 50 future years and encompasses true material data, on-site measurements, and energy production profiles of today. Such an approach will contribute valuable insights into the environmental aspects of renovation strategies, facilitating more informed decision-making towards sustainable building practices.

2. Description of the Renovation Project

The renovated buildings are located in an area called "Tjärna Ängar" in the city of Borlänge, Sweden (250 km northwest of Stockholm). During the summer months, average daytime temperatures in Borlänge typically range between 15 °C and 25 °C. Winters are cold, with temperatures often dropping below freezing, ranging from −5 °C to 0 °C. These temperature ranges provide a general overview, and actual temperatures can vary each year. The renovated buildings were built between the years 1969 and 1971, during a period in Sweden called the Million Homes Program. In 2015, the renovation project was launched with a mission: to identify and implement effective refurbishment strategies for transforming existing buildings within the area into Nearly Zero Energy Buildings. The goal was to achieve a 50% reduction in primary energy consumption. Additionally, the project aimed to improve thermal comfort and indoor air quality in the renovated units while keeping financial feasibility in mind, given that these are part of the public housing stock.

To evaluate the suitability of various refurbishment options, the project selected and executed four distinct renovation packages within the neighborhood of 40 similar buildings. The objective was to determine which of these packages could be effectively applied throughout the entire area.

Originally constructed between 1969 and 1971, these buildings each comprise three stories and house 45 apartments, with a combined heated floor area (referred to as A_{temp}) totaling 3879 square meters. The buildings have an orientation to the southeast. Initially, the buildings were heated using a district heating system and utilized exhaust ventilation without heat recovery, operating with a consistent flow rate (i.e., the exhaust fan maintained a constant rotational speed).

The renovation process involved implementing similar measures across all buildings. These measures included the following:

- Enhancing the building envelope by adding 150 mm attic insulation and 50 mm insulation to the infill walls.
- Transition from the older one-pipe heat distribution system, used for hydronic radiators, to a more efficient two-pipe system.
- Replace the old windows with new windows with a U-value of 1 W/(m^2·K).
- Install new Flow-reducing tap.

A key distinction among the various renovation packages lies in the HVAC systems, as detailed in Table 1.

Table 1. Studied HVAC systems in different buildings.

EV	MVHR	EAHP	EAHPV
Pressure-controlled fans	Mechanical ventilation with heat recovery	Pressure-controlled fans Exhaust air heat pump	Pressure-controlled fans Exhaust air heat pump PV

The first building, referred to as EV, underwent a renovation featuring an exhaust ventilation system equipped with a pressure-controlled fan. This system senses instances of over-ventilation and efficiently reduces the ventilation rate to reduce heating and electricity costs. This system is without heat recovery.

The second building, identified as MVHR, received a mechanical ventilation system with heat recovery. This setup incorporates a rotary heat exchanger to utilize the thermal energy from exhaust air and use it to warm the fresh, cold air drawn in from the outdoors.

Implementing this system involved installing supply air ducts throughout the building, including individual apartments, along with supply air fans. Additionally, outdated exhaust fans were replaced. Moreover, it necessitated an airtight building envelope to ensure optimal energy efficiency. The requirement for implementing this system makes this renovation more complex, demanding larger equipment space compared to the other systems, which can utilize existing exhaust air ducts since new supply ducts must be installed.

The third building, referred to as EAHP, underwent renovations that included an exhaust ventilation system equipped with a pressure-controlled fan, along with the addition of an exhaust air heat pump. The design of this combined District Heating (DH) and EAHP solution was informed by research conducted by the Swedish District Heating Association, specifically tailored for multi-family houses [44,45]. The exhaust air heat pump is prioritized for heating the water in radiators because it achieves a higher Coefficient of Performance (COP) when used for space heating, whereas DH heats domestic hot water.

In a previous study that examined the economic aspects of three different buildings [46], it was observed that despite the 50% energy savings in the building with the exhaust air heat pump, its overall profitability was diminished due to the high cost of electricity. Consequently, photovoltaic (PV) panels were installed on the roof of the fourth building. This decision was prompted by the building's substantial electricity consumption and the continuously rising electricity prices. This solution is referred to as 'EAHPV.' It is noteworthy that, as part of this package, the heat pump is intentionally deactivated during the months of September through February, when electricity prices reach their peak, correlating with the period of lowest PV electricity production.

3. Methods

3.1. Life Cycle Analysis (LCA)

In order to conduct an environmental assessment of various renovation scenarios, we employ a Life Cycle Analysis (LCA). LCA is a standardized method [47] used to quantify the potential environmental impacts of different solution alternatives. One of the primary strengths of LCA is its ability to consider the entire life cycle of these alternatives, from raw material production and manufacturing through their use and ultimately to final disposal and waste treatment. While LCA is mainly applied to new construction projects, it is equally essential to apply it when assessing the impacts of renovation on existing buildings. The process, as outlined in ISO 14040:2006 [48] and ISO 14044:2006 [49], consists of four essential steps: Goal and Scope definition, Life Cycle Inventory (LCI) Analysis, Life Cycle Impact Assessment (LCIA), and Interpretation of Results.

The Global Warming Potential (GWP) stands out as the most widely adopted environmental performance metric, and it is the exclusive metric utilized in Sweden's climate declarations [50]. "GWP is commonly expressed as equivalent carbon emissions (CO_2e). This metric plays a crucial role in standardizing the contributions of various greenhouse gas emissions, each having different GWP values, into a unified measure. In this study, we focus on analyzing the environmental impact category of GWP.

We employed the One Click LCA software, Version: 1.14.0, to simulate the impact of various building materials and conduct a comprehensive life cycle assessment of the building. Developed by Bionova Ltd., One Click LCA, Version: 1.14.0, compliant with the EN 15978 standard [51], provides a standardized platform for conducting Life Cycle Cost Analysis and Life Cycle Assessment. The software encompasses data from production and construction stages to in-use and end-of-life "grave" stages. One Click LCA utilizes Environmental Product Declarations (EPDs) based on ISO 14044 [48] and EN 15804 [52] standards in its database. An EPD is an externally verified, detailed, and standardized description of a product's environmental profile throughout its entire lifecycle. To offer insights into the environmental impact of building materials, the software incorporates predictions of CO_2e emissions using EPD datasets available within the tool. One Click LCA has been employed in various studies to evaluate the environmental impact of diverse projects [40,41,53–55].

3.1.1. Goal and Scope

The LCA study has the following main goals:

- Examine the influence of various renovation strategies on GHG emissions throughout the life cycle, particularly concerning materials and operational energy usage.
- Identify the distinct contributions of different life cycle stages to the overall GHG emissions associated with these renovation strategies.

3.1.2. Functional Unit

The selected functional unit for this study is 1 square meter (m^2) of heated floor area (A_{temp}). This standardized measure is utilized to assess both the energy and environmental performance of buildings. Adopting this approach allows for a precise evaluation on a per-square-meter basis, enabling effective comparisons between buildings or projects. This method assists decision-makers in making well-informed choices for sustainable building practices. Additionally, it provides a foundation for scaling up results for similar building types, enhancing the applicability and relevance of this study's findings.

The reference study period for this research extends to 50 years, aligning with the recommended building renovation period provided by the Royal Swedish Academy of Engineering Sciences (IVA) [56].

3.1.3. System Boundaries

This study covers all phases of a building's lifecycle, following the guidelines of standard EN 15978 [57]. These phases include the manufacturing of construction materials (A1–3), construction processes (A4–5), usage (B1–7), and end-of-life considerations (C1–4) (see Figure 1). The environmental benefits and impacts that extend beyond the system boundary (D) are not considered in the total results.

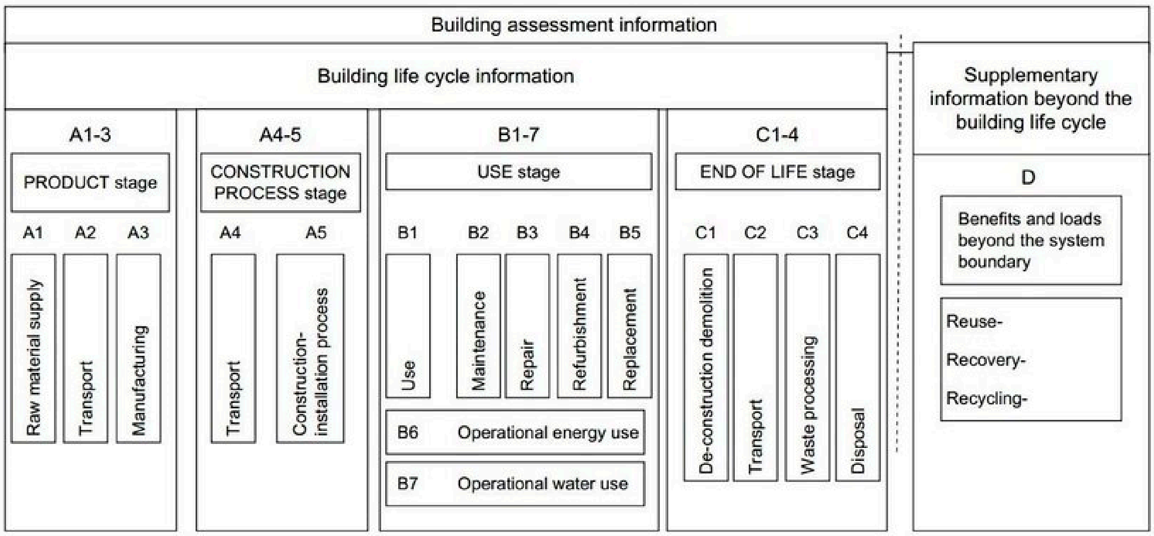

Figure 1. Building Life Cycle Assessment (EN 15978) [57].

3.1.4. Life Cycle Inventory (LCI) Analysis

Material Use

The collection of specific material data (types and quantities), including details from manufacturers, was carried out after the completion of the renovation project. Data were primarily sourced from the One Click LCA database, where the majority of the data, including EPDs, had been found. However, for certain materials, such as ventilation ducts and heating system pipes, generic data from the software were utilized based on the total heated area of the building.

To ensure accuracy, the transportation distances for each material were calculated, taking into account the unique characteristics of each item. It was assumed that a Swedish reduction diesel mix was used for transportation.

The determination of service life for various materials was based on a report from Public Housing Sweden (SABO) [58]. This comprehensive approach allowed for the gathering of precise and relevant data for this study; see Table 2.

Table 2. Material data for studied renovation packages based on data from the housing company.

	Material	Quantity	Unit	Service Life
Similar in all packages	Water circulation radiators	6570	kg	50
	District heat distribution center	300	kW	50
	Heat distribution system	3879	m^2	50
	Mineral wool insulation (150 mm)	1020	m^2	50
	Mineral wool insulation (50 mm)	400	m^2	50
	Gypsum (12 mm)	400	m^2	40
	Bricks, Facade cladding (100 mm)	400	m^2	50
	Wooden framed triple-glazed windows (1 W/(m^2·K))	82	pcs	40
	Shower tap mixer set	60	pcs	30
EV	Rooftop exhaust fan	1	pcs	20
MVHR	Air handling unit with heat recovery through a rotary heat exchanger	1	pcs	20
	Ventilation system for residential buildings (include material to install supply air ducts)	3879	m^2	20
EAHP	Rooftop exhaust fan	1	pcs	20
	Exhaust air heat pump	1	pcs	20
	Air exchanger heat recovery	1	pcs	20
EAHPV	Rooftop exhaust fan	1	pcs	20
	Exhaust air heat pump	1	pcs	20
	Air exchanger heat recovery	1	pcs	20
	Photovoltaic monocrystalline panel (include only the panel)	120	m^2	30

Energy Use

The energy use in each building was measured before and after renovation, and the energy use was adjusted to the energy use of a normal year in Borlänge, Sweden. The values of electricity use are shown in Figure 2, excluding household electricity. They include facility electricity that is used for pumps, fans, lighting in common spaces, etc. The district heating use includes energy to cover heating demand and domestic hot water (DHW), as shown in Figure 3. The energy use of the different renovation scenarios (kWh/m^2.year) for both electricity and district heating is shown in Figure 4. The DHW use was measured before and after renovation, and it is almost the same for all buildings (2 m^3/m^2·year).

The GWP-GHG value of 37 CO_2e (g/kWh) is considered the emission factor for electricity production, and it is based on an average value (Swedish mix) derived from data spanning the years 2015 to 2017, relying on the data from the Swedish National Board of Housing, Building, and Planning (Boverket) [59] and the annual statistics published by the Swedish Environmental Research Institute (IVL) [60]. The calculations comply with both EN 15804 and the methodology recommended by the Swedish Energy Agency for reporting the environmental impact associated with electricity production and the utilization of different fuels and energy carriers.

The GWP-GHG value of 56 CO_2e (g/kWh) is adopted as the emission factor for district heating production. This value serves as a representative average for district heating in Sweden and comes as a recommendation from the Swedish National Board of Housing, Building, and Planning (Boverket) [59].

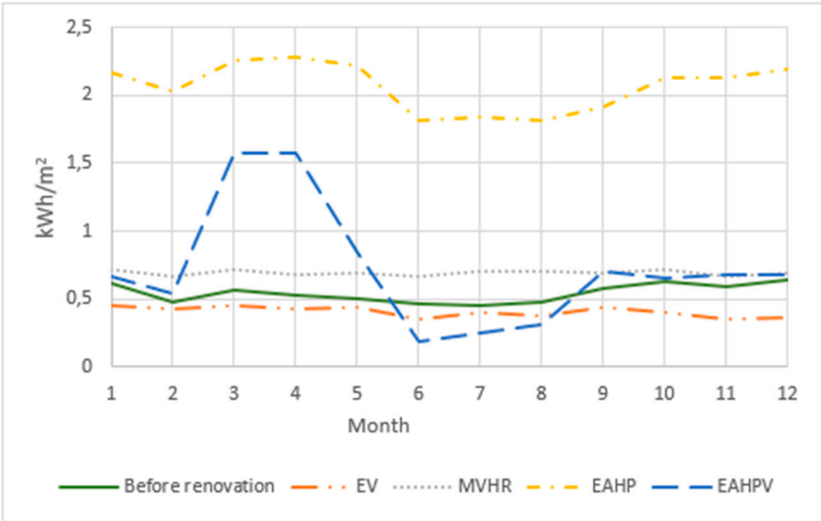

Figure 2. Measured electricity uses for heating and operation of facilities throughout the year (excluding household electricity).

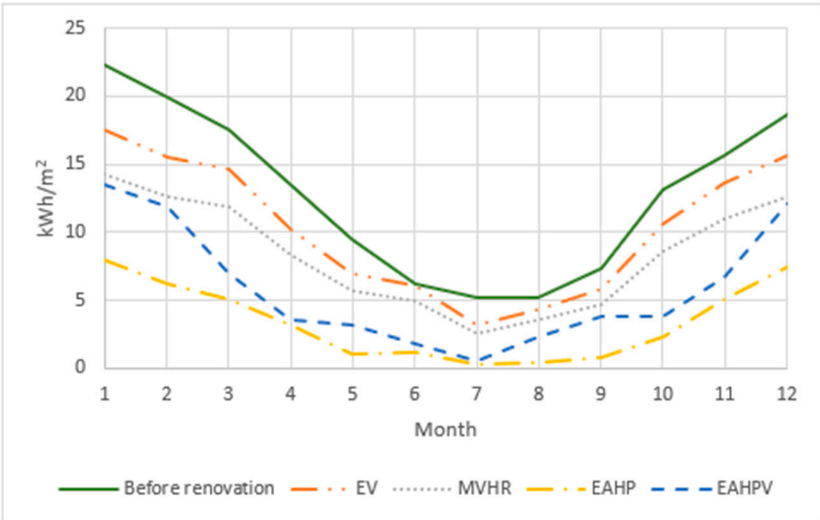

Figure 3. Measured district heating use for the renovation packages throughout the year.

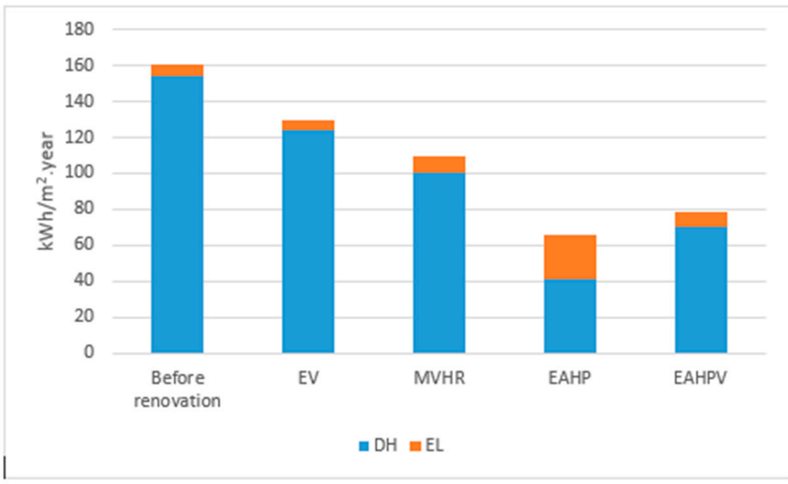

Figure 4. Total energy use in the four renovated buildings before and after the renovation (excluding household electricity).

3.2. Greenhouse-Gas Payback Time (GPBT) Estimation

The Greenhouse Gas Payback Time (GBPT) measures how long it takes for a renovation strategy to balance out its initial carbon emissions through improved energy efficiency. It guides decision-makers by comparing the environmental impact of different renovation options, favoring those with shorter payback periods. The GHG payback time (GPBT) is given by Equation (1).

$$\text{GPBT} = \frac{GHGe}{GHGs} \tag{1}$$

where GHGe is the embodied GHG associated with the renovation package (kg CO_2e), and GHGs (kg CO_2e/year) is the annual reduction in greenhouse gas emissions resulting from the renovation, specifically through decreased operational energy usage in the building.

3.3. Future Scenario for Energy Production in Sweden

The Energy Agency takes every two years long-term scenarios in connection with Sweden's reporting of Swedish climate emissions to the European Commission (2023) [43]. The agency's scenarios describe the development of the energy system based on assumptions about economic development, energy prices, sector-specific conditions, and existing and decided policy instruments. The scenarios are also used to follow up on energy policy goals and in various types of investigations where scenarios of the future are needed as a basis for decision-making. The agency, therefore, usually, in connection with this work, also produces one or more additional scenarios and sensitivity analyses in order to obtain a broad knowledge base on possible development paths in a future energy system.

The report presents three different scenarios, which are called Higher electrification, Lower electrification, and Sensitivity case industries. Total energy use in the future is projected between 470 and 643 TWh, depending on the scenario. The electricity and district heating production sources for different scenarios are shown in Figures 5 and 6 respectively. For all scenarios, the use of fossil fuels in the form of oil, coal products, and natural gas is greatly reduced by 70–77% between 2020 and2050. The Higher electrification scenario assumes extensive electrification in society as one part of the transition to reach the climate goals. Higher electrification assumes the development of electrification in the Nordic countries and in the EU to be higher than in Lower electrification. Lower electrification is based on today's policy instruments (per 30 June 2022). Electrification is not only taking place in Sweden, but at the same time, corresponding development is occurring in the Nordic countries and in the EU. Sensitive case: industry has the same conditions as in Lower electrification, with the assumption of lower electrification in industry. The scenario differs from Lower electrification in that conversion projects are shifted in time, there are fewer additional projects, or they are only partokially established as a result of obstacles around the conditions for the implementation of the projects.

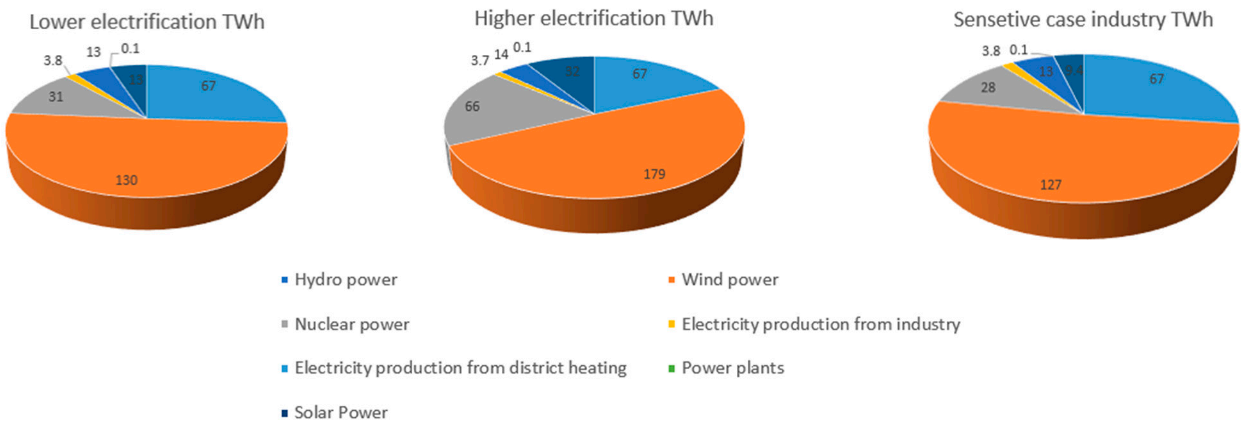

Figure 5. Electricity production sources of different future scenarios based on [43].

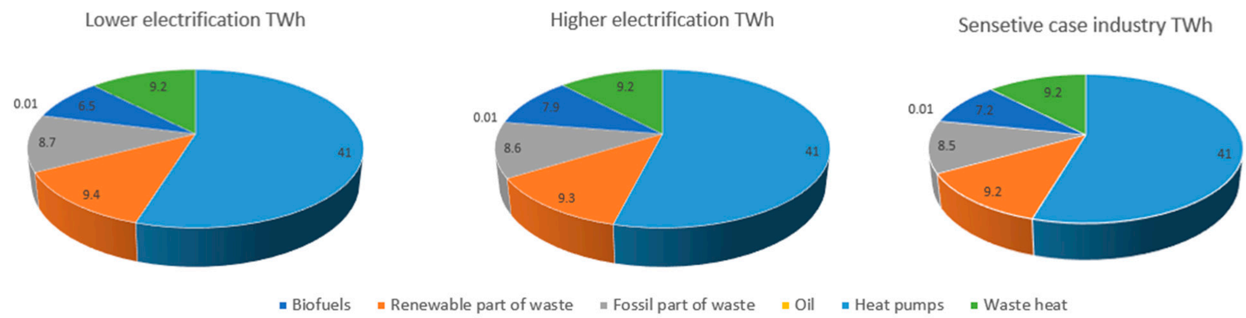

Figure 6. District heating production sources for different future scenarios based on [43].

The emission factor of electricity and district heating production for different future scenarios has been calculated based on the emission factor for each production source. The calculations of emission factors have been conducted using different references. Estimated emission factors for fuels, electricity, heat, and transport in Sweden [61–65]. The calculated emission factors for electricity production in the Lower electrification, Higher electrification, and Sensitivity case industries are 11.7 g/kWh, 12.7 g/kWh, and 11.1 g/kWh, respectively. For district heating production, the emission factors in the same scenarios are 43.1 g/kWh, 32.3 g/kWh, and 58.2 g/kWh. The values of different emission factors are used to perform a sensitivity analysis for the future energy use of the different renovation alternatives.

4. Results

The total greenhouse gas emissions of different studied renovation packages per 1 m^2 of heated area through the period of (50 years) are shown in Figure 7. Values of 37 CO_2e and 56 CO_2e (g/kWh) are considered the emission factors for electricity and district heating, respectively. Notably, GHG emissions resulting from the operation phase represent the most substantial portion of the overall greenhouse gas emissions.

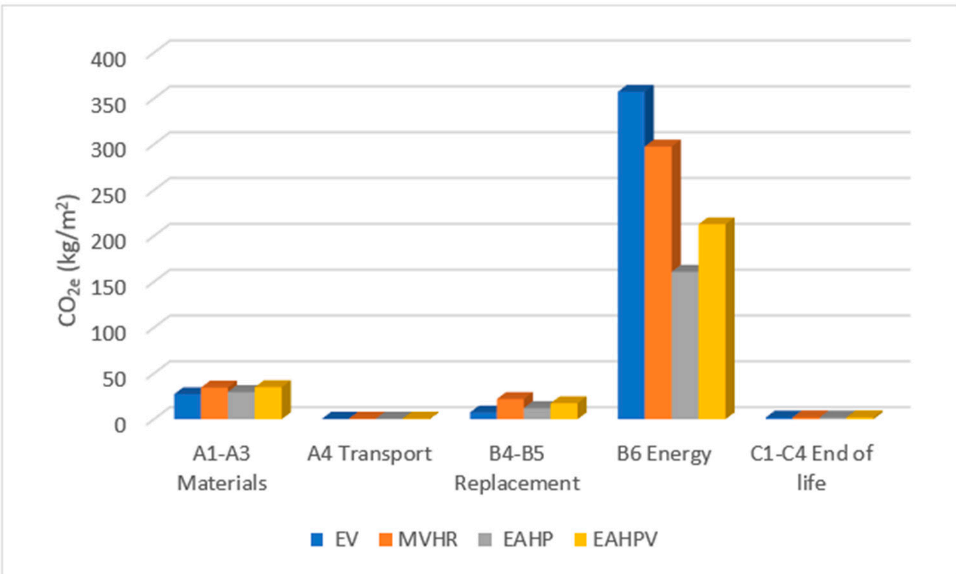

Figure 7. Greenhouse gas (GHG) emissions of the studied renovation packages at various stages of their lifecycle.

Figure 8 illustrates the Greenhouse Gas Payback Time (GPBT) for the four renovation packages. Notably, the building equipped with an exhaust air heat pump (EAHP) boasts the shortest GPBT among the options, approximately 7 years, followed by EAHPV (11 years), whereas EV and MVHR are both at about 18 years.

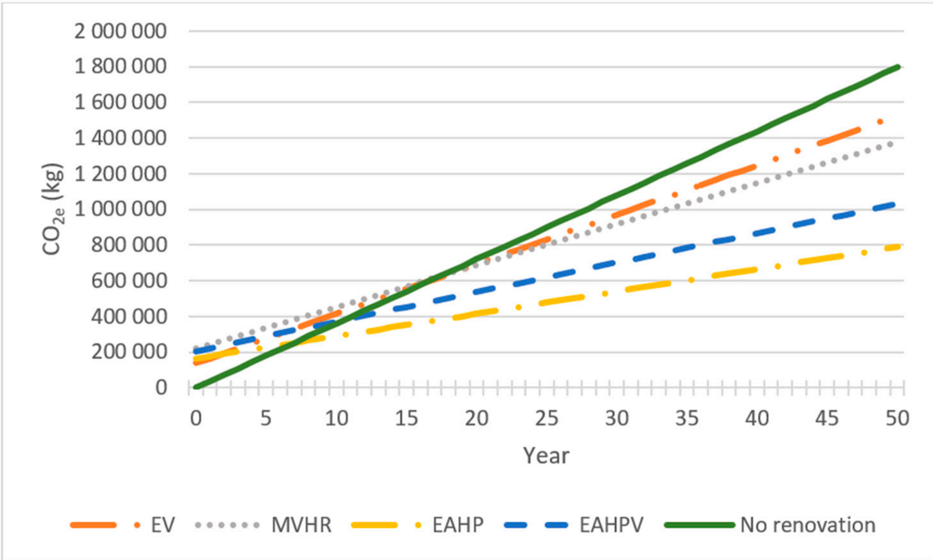

Figure 8. Accumulated GHG emissions over the years for the studied renovation packages. Greenhouse Gas Payback Time is where the renovation curves cross the "No renovation" line.

The outcomes of the sensitivity analysis conducted on the performance of various renovation packages in different future scenarios of electricity and district heating production are presented in Figure 9. Notably, in all these renovation packages, the lowest total greenhouse gas (GHG) emissions are observed in scenarios of Higher electrification. Meanwhile, the trends indicate that EVHP implies the least CO_2e emissions and EV the highest.

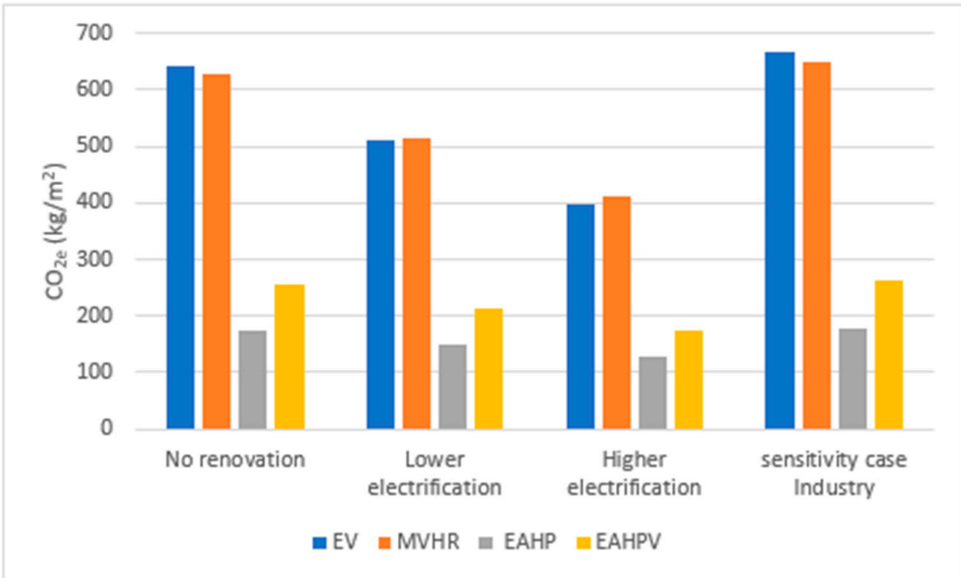

Figure 9. The total GHG emission of the studied renovation packages considering different energy production scenarios.

5. Discussion

The largest share of total greenhouse gas emissions across all renovation alternatives arises from operational energy, especially district heating, which complies with findings in other studies [30,31,66]. The minimum ratio of GHG emissions from operational energy to the total GHG emissions is 50%, which is in the building renovated with an exhaust air heat pump (EAHP), and a higher ratio of 83% in the building renovated with exhaust ventilation (EV). On the other hand, embodied greenhouse gas emissions resulting from material use (A1–A4) range from a minimum of 6.6% of the total GHG emissions in the building with exhaust ventilation (EV) to a maximum of 9.2% in the building equipped with both an Exhaust Air Heat Pump and Photovoltaics (EAHPV).

The building renovated with an exhaust heat pump (EAHP) has the lowest total CO_2e emissions, primarily due to reduced district heating usage. This is further complemented by lower emissions from electricity production as opposed to district heating production. This building boasts the shortest carbon payback period (GBPT), requiring only approximately 7 years.

The building with an exhaust air heat pump and photovoltaic panel (EAHPV) experiences higher district heating usage compared to the building with only the exhaust air heat pump (EAHP). This is mainly because the heat pump is deactivated during the winter season. Consequently, the heat pump is primarily utilized to provide domestic hot water (DHW) in the summer, during which its electricity demand is mainly covered by solar electricity production. The carbon payback period (GBPT) required for this building is almost 11 years.

The building with exhaust ventilation (EV) has the highest district heating usage, resulting in the highest total CO_2e emissions among all the buildings. However, this building has almost the same carbon payback period (GBPT) as the building with mechanical ventilation heat recovery (MVHR), which stands at 17 years. This can be attributed to the high embodied CO_2e emissions in the building (MVHR), which are not offset rapidly by the annual savings in operational CO_2e emissions, given that DH is reduced by increased electricity use mainly by fans. The extra system components needed by MVHR in comparison to EVs yield 62% higher embodied CO_2e emissions.

The renovation of the building with mechanical ventilation with heat recovery (MVHR) has led to a nearly 40% reduction in district heating usage, accompanied by a similar 40% increase in electricity consumption. Despite these changes, the renovation has only achieved a 30% reduction in total CO_2e emissions. This could be attributed to the necessity of installing a new supply duct system, as previously mentioned, which has in turn increased embodied CO_2e emissions. Additionally, it is possible that this type of ventilation system is better suited for well-insulated and airtight buildings, which may not be guaranteed in older multi-family houses. It is worth noting that in a previous study, this renovation solution was found to have a relatively high life cycle cost (LCC) [46].

The sensitivity analysis conducted for various future energy production scenarios has demonstrated that a reduction in emissions from district heating production would significantly affect the total CO_2e emissions in all buildings. Notably, in the Higher electrification scenario, the building with exhaust ventilation (EV) experiences a nearly 40% reduction in total CO_2e emissions compared to the current scenarios. This is attributed to EVs having the highest district heating use among other buildings, and the emission factor of district heating in the higher electrification scenario is the lowest among other production scenarios. However, the sensitivity analysis reveals that the building equipped with an exhaust air heat pump (EVHP) consistently maintains the lowest total CO_2e emissions across all scenarios. The findings are significantly influenced by the higher greenhouse gas (GHG) emissions from district heating (DH) compared to emissions from electricity production. Despite the notable fact that the energy carriers of the heating system in residential buildings in Sweden are nearly free of fossil resources (less than 5%), in contrast to Europe, where the heating and cooling systems of residential buildings rely on almost 60% fossil resources [67].

The results of this study rely on material data used in the renovation project provided by the housing company. The used software, One Click LCA, has a comprehensive database containing the majority of material data, which is backed by verified EPDs (Environmental Product Declarations). Nevertheless, a few data points have been sourced from the software's generic database, such as pipes for the radiator system and the ventilation supply ducts. Given that operational energy is the primary contributor to total CO_2e emissions, these specific data points are not expected to have a significant impact on the overall results.

Consideration of the time perspective is crucial. This study is grounded in an EN standard rooted in attributional LCA, which assumes a steady-state energy system. Attributional LCA provides a static snapshot of environmental impact, ignoring broader systemic effects and changes in material production and the energy system. As such, it presents a static analysis of the present situation. In this study, various future energy production scenarios have been considered.

The environmental benefits extending beyond system boundaries (D) have not been incorporated into the results of this study. This is a result of the uncertainty regarding whether future users and practitioners will recycle the various materials employed in the building's renovation.

One of the most crucial factors affecting the result of this study is the low emission factor of electricity production in Sweden, primarily resulting from the extensive use of renewable sources in the country's energy mix. The emission factor for the Nordic mix is currently around 90 g/kWh [62], whereas in the EU, the emission factor for electricity was 334 g/kWh in 2019 [68]. Utilizing this factor in the life cycle assessment can significantly impact this study's results, as demonstrated in a former study conducted by Ramirez [40]. It is important to emphasize that, both today and in all future electricity scenarios, Sweden is a net exporter of electricity [43]. Therefore, this study focuses on the Swedish electricity production mix. It reveals that utilizing electricity for heating, such as heat pumps, instead of or with district heating based on biofuels can lead to lower total CO_2e emissions in the renovation of multi-family buildings. This may seem like a contradictory result, but it is due to the low emissions of the Swedish power system. In view of the decarbonization of the future EUs power system, this kind of result will be more frequent [69–72]. However, it is important to acknowledge that recommending this solution requires a thorough consideration of various factors. An increased demand for electricity for heating buildings will necessitate a higher production and transfer capacity within the energy system. This, in turn, can lead to an uptick in marginal electricity production, potentially involving the use of fossil fuels, especially in combined heat and power (CHP) plants.

It is worth noting that in CHP plants, less district heating production translates to reduced electricity production. Moreover, the broader context presents another challenge. Scaling up electricity production in Sweden to meet increased demand, particularly for heating with technologies like heat pumps, poses several challenges. These include upgrading grid infrastructure, diversifying energy sources while maintaining low emissions, integrating renewable technologies efficiently, investing in energy storage, addressing potential opposition from communities, navigating regulatory hurdles, conducting thorough environmental impact assessments, adopting advanced technologies, fostering international cooperation, and ensuring supportive government policies and incentives. Each of these factors requires careful consideration to achieve a sustainable and low-emission energy transition [43,73,74]. In light of this, increasing electricity demand in the building sector may not be the optimal solution when considering the broader perspective, since 1 kWh_{el} may imply significant CO_2e reductions in comparison to the trade-off with DH (1 $kWh_{thermal}$).

Another important aspect to explore is the influence of fluctuations in electricity demand on both electricity production and the resulting environmental impact of renovated buildings. Local shifts in electricity demand, often encouraged by the installation of solar panels, can have a significant influence on overall energy production from a wider perspective. This study does not account for the holistic impact of changes in electricity demand driven by solar power generated from the installed panels in these buildings, nor does it consider the sale of surplus energy back to the grid.

The finding that electricity, particularly through heat pumps, can reduce CO_2 emissions in cold climates like Sweden has significant implications for integrating renewable energy, such as solar power. Future studies should explore how solar power can adapt to seasonal demand patterns, complement other renewable sources such as hydro and biofuel power, develop efficient storage solutions, enhance grid resilience, assess economic viability, drive technological innovations, consider policy implications, evaluate environmental impact, engage communities, and identify global applications. These insights will guide effective integration strategies in cold climates with peak energy demand during the winter months.

6. Conclusions

This study conducts an environmental assessment of four renovation packages with essential differences in HVAC systems implemented in multifamily buildings with district heating. Among these packages, the one with an exhaust air heat pump (EAHP) has the lowest environmental impact over its lifetime. This can be attributed to its reliance on electricity for meeting heating requirements, a source characterized by cleaner production in Sweden as compared to district heating. An interesting observation is that the installation of photovoltaic panels in this building, along with the deactivation of the heat pump during the winter due to high electricity costs, results in higher greenhouse gas (GHG) emissions due to increased utilization of district heating. The building renovated with mechanical ventilation with heat recovery (MVHR) has the third position in terms of total GHG emissions, with only a marginal difference of nearly 9% when compared to the building with exhaust ventilation (EV). Remarkably, the building employing exhaust ventilation (EV), which relies most heavily on district heating, has the highest greenhouse gas emissions among the four renovation packages.

Diverse energy production scenarios significantly influence the outcomes, but it is worth noting that the building equipped with an exhaust air heat pump (EAHP) consistently demonstrates the best environmental performance across all scenarios where electricity has low GHG emissions. Nonetheless, it is crucial to verify the satisfaction of two fundamental conditions before asserting that the EAHP (exhaust air heat pump) is the optimal solution. Firstly, the increased electricity demand generated by heat pumps must still be accommodated through fossil-free production. Secondly, the significant role of Combined Heat and Power District Heating (CHP DH) facilities in the energy system should be preserved, and their decommissioning should be avoided. Therefore, a forthcoming study is planned to evaluate these renovation packages from an energy system perspective.

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Nomenclature

HVAC	Heating, ventilation, and air conditioning
LCA	Life cycle assessment
GHG	Greenhouse gases
GPBT	Greenhouse-gas payback time
GWP	Global Warming Potential
LCI	Life cycle inventory
EPD	Environmental Product Declarations
PV	Photovoltaic
COP	Coefficient of Performance
DH	District heating
EL	Electricity
DHW	Domestic hot water.

CHP	Combined heat and power.
A_{temp}	Heated floor area (m^2).
CO_2e	Carbon dioxide equivalent.

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