energies

Article

Assessing the Economic and Environmental Dimensions of Large-Scale Energy-Efficient Renovation Decisions in District-Heated Multifamily Buildings from Both the Building and Urban Energy System Perspectives

Alaa Khadra [1,2,*], Jan Akander [2], Xingxing Zhang [1] and Jonn Are Myhren [1]

[1] Sustainable Energy Research Centre, Dalarna University, 791 31 Falun, Sweden; xza@du.se (X.Z.); jam@du.se (J.A.M.)
[2] Department of Building Engineering, Energy Systems and Sustainability Science, Faculty of Engineering and Sustainable Development, University of Gävle, 801 76 Gävle, Sweden; jan.akander@hig.se
* Correspondence: akd@du.se

Abstract: The European Union (EU) has introduced a range of policies to promote energy efficiency, including setting specific targets for energy-efficient renovations across the EU building stock. This study provides a comprehensive environmental and economic assessment of energy-efficient renovation scenarios in a large-scale multifamily building project that is district-heated, considering both the building and the broader urban energy system. A systematic framework was developed for this assessment and applied to a real case in Sweden, where emission factors from energy production are significantly lower than the EU average: 114 g CO_2e/kWh for district heating and 37 g CO_2e/kWh for electricity. The project involved the renovation of four similar district-heated multifamily buildings with comparable energy efficiency measures. The primary distinction between the measures lies in the type of HVAC system installed: (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 combined with photovoltaic (PV) panels. The study's findings show that the building with an exhaust air heat pump which operates intermittently with PV panels achieves the best environmental performance from both perspectives. A key challenge identified for future research is balancing the reduced electricity production from Combined Heat and Power (CHP) plants within the energy system.

Keywords: energy-efficient renovation; HVAC systems; urban energy system; life cycle analysis; life cycle cost analysis; district-heated multifamily buildings

Academic Editors: Kee Han Kim and Chul Kim

Received: 26 November 2024
Revised: 12 January 2025
Accepted: 21 January 2025
Published: 23 January 2025

Citation: Khadra, A.; Akander, J.; Zhang, X.; Myhren, J.A. Assessing the Economic and Environmental Dimensions of Large-Scale Energy-Efficient Renovation Decisions in District-Heated Multifamily Buildings from Both the Building and Urban Energy System Perspectives. *Energies* **2025**, *18*, 513. https://doi.org/10.3390/en18030513

1. Introduction

The buildings sector stands as a basis in the European Union's (EU) pursuit of sustainable development. The building sector plays a pivotal role in the EU's energy landscape, accounting for 40% of the entire energy use and approximately 33% of its greenhouse gas emissions [1]. Residential buildings dominate this sector, making up around 75% of the total. Built when there was little focus on energy efficiency in building regulations, almost 40% of these residential buildings were erected before 1970. Consequently, an estimated 75% of the current stock is classified as energy-inefficient [2]. The need to tackle these issues is emphasized by growing worries about energy security and the economic effects of increasing energy prices worldwide [3]. In 2020, the European Commission introduced the

"Renovation Wave for Europe" strategy, aiming to drive both energy efficiency and economic growth by doubling the annual rate of energy renovations over the next decade [4]. Aimed at reducing emissions and aligning with climate goals, this initiative addresses the environmental impact of aging structures, with clear targets set for carbon neutrality by 2050 [5].

The Swedish energy policy is committed to balancing ecological sustainability, competitiveness, and security of supply, aligning with EU legislation. A national goal is set for Sweden to achieve net-zero emissions by 2045, with at least an 85% reduction compared to 1990 levels [6]. A sub-goal involves a 50% improvement in energy efficiency by 2030 compared to 2005 [7]. Swedish authorities acknowledge the need to raise their ambition, particularly regarding energy efficiency. Notably, almost one-third of Sweden's multifamily buildings were built between 1965 and 1974 under the "Million Homes Program" during which 1,005,578 dwellings of various types were constructed across the country [8]. While Million program apartments are generally well-designed and functional, many face a great need for technical upgrades and improved energy efficiency. The extent of these needs varies based on factors such as past maintenance, construction technology, and the financial conditions of the owners for refurbishment. Estimating the scale of these needs and the required investments is challenging. Projections indicate costs may reach 500 billion Swedish crowns (roughly 50 billion Euros) [8]. It has been found that integrating energy considerations during the renovation phase offers a distinctly cost-effective approach compared to implementing separate measures afterward [9]. There is substantial potential to halve energy usage and costs, as demonstrated in the Swedish Energy Agency's "Sustainable Municipality" program. Six Swedish municipalities are actively engaged in energy efficiency measures within the "Million Homes Program", incorporating strategies such as additional insulation, new windows, and solar cells to achieve this goal [9]. The EU project "Cityfied", in which the Swedish Environmental Research Institute is actively participating, has achieved notable success in upgrading the 1970s-era Linero in Lund. Preliminary figures indicate a significant potential for a 40% reduction in energy use [10], where the district heating (DH) plays an important role in achieving that goal.

District heating is the most common energy carrier, offering substantial potential for the efficient, cost-effective, and scalable delivery of low-carbon heating solutions. However, their decarbonization potential is largely globally untapped, with 90% of heat in these networks sourced from fossil fuels, especially evident in China and Russia, the leading markets [11]. Internationally, cogeneration of heat and power (CHP) is widespread, with cogeneration representing 20.6% of electricity production within the EU in 2021 [12]. In Sweden, district heating represents nearly 20% of the total final energy consumption in the residential and service sectors in 2023 [13]. District heating remains the primary heating method for multifamily buildings, accounting for 91% of total energy use, which amounted to 25.1 TWh in 2016 [14]. There are about 170 CHP plants in Sweden, which generated 9.1% and 46.9% of the country's electricity and district heating production, respectively, in 2021. Swedish CHP achieves remarkable energy efficiency, typically 90–93%, reaching 100% with flue gas condensation. It primarily produces electricity (30–50%) and heat, employing mostly renewable or recycled biofuels like forest residues and waste. Fossil fuels, including oil, are minimally used and being gradually eliminated, with over 90% of fuels being renewable or recycled [15]. This places Sweden among the countries with one of the cleanest heating systems in Europe, given that within the EU, only 23% (year 2020) of the final energy used for heating and cooling comes from renewable energy [16].

The energy-efficient renovation of multifamily buildings, especially those connected to district heating systems, is a well-researched area. A study by Tettey and Gustavsson [17] highlighted that the primary energy savings from deep energy renovations and the risk of overheating vary significantly depending on the climate. Passive and active energy renovation measures can reduce energy use in multifamily buildings in Sweden by more than 50% without the need to install renewable energy systems [18]. Among the various energy-efficient renovation measures, improving the thermal envelope is the most effective in Sweden [19] and, for example, in the cold climate in Spain [20]. Few studies in the field consider a real-world case study like the investigation by Wrålsen et al., which conducted life cycle assessment of renovated Norwegian apartment buildings [21]. A literature review conducted by Ma et al. [22] indicated that a predominant portion of previous studies relied on numerical simulations. Recognizing the potential disparity between estimated and real-world energy savings—referred to as the energy gap—underscores the need for additional research. It is crucial to conduct practical case studies to support confidence in the actual benefits of retrofitting, especially the real economic and environmental gains.

A study by Attia et al. [23], focused on the future challenges of designing energy-efficient buildings in Eastern Europe, emphasizes the importance of the cost-optimality calculation method to ensure cost-effective market uptake. Another study, which analyzed nine exemplary renovation projects in six European countries [24], found that the drivers for district renovation extend beyond energy savings to include improving the overall quality of life, as well as the image and economic value of a district. Various studies have explored the economic feasibility of energy renovations in residential buildings and their impact on district heating systems [25,26]. Gustafsson et al. [27] concentrated on economic savings in the energy system by simulating district-heated multifamily buildings with various energy renovation measures. The research calculated the life cycle cost of the energy system, accounting not only for the purchased energy but also the costs of implementing measures. Weinberger et al. [28] investigated the economic and environmental effects of renovating residential building clusters on Gävle's district heating system in Sweden. Using simulations and optimization tools, the study assessed various renovation strategies, emphasizing the consequences of decreased district heating demand on Combined Heat and Power plants. Pohoryles et al.'s review [29] on the energy retrofitting of existing European buildings emphasized the necessity for validating integrated renovations, particularly on a large scale. However, a research gap was identified, as the majority of studies in the field focus on the environmental and economic assessment of various renovation scenarios from the building or urban energy system perspectives, hence neglecting comprehensive analysis encompassing both perspectives.

In summary, multifamily buildings in need of renovation are recognized as a significant part of today's building stock, with the majority being owned by municipal housing companies. The optimal renovation scenario for these buildings is considered critical; however, it is often assessed solely from the building perspective. This limited viewpoint fails to account for the broader implications of these renovations on the municipality's energy system. The current study offers a comprehensive assessment of the economic and environmental performance of a renovation package with four different HVAC (Heating, Ventilation, and Air Conditioning) systems installed in similar district-heated multifamily buildings. The uniqueness of this study lies in its dual assessment approach, which examines renovation measures from both the building and urban energy system perspectives. When referring to the building perspective, analyses are typically conducted by housing owners to evaluate the economic and environmental impacts of renovations. In contrast, the urban energy system perspective examines how large-scale renovations are expected to affect the municipality's energy infrastructure and overall efficiency. Additionally, this study utilizes real data from both the housing company and the energy company in the municipality. The objectives are as follows:

- Develop/suggest a framework designed for the economic and environmental assessment of various renovation scenarios, considering the perspectives of both buildings and the urban energy system, particularly in large-scale multifamily buildings renovation projects.
- Investigate the impact of various large-scale renovation scenarios on municipal energy system production, greenhouse gas emissions, and fuel costs.
- Conduct a life cycle assessment (LCA) and life cycle cost analysis (LCC) for different renovation scenarios, using real data from the housing company and emission factors from the municipal district heating system.
- Analyze and compare results from both perspectives, shedding light on any differences in the performance of renovation scenarios at both building and urban energy system levels (i.e., district heating and CHP units).

2. The Renovation Project

"Tjärna Ängar" is a neighborhood in the city of Borlänge, in which the buildings were constructed between 1964 and 1975 as part of Sweden's Million Homes Program. A pilot renovation project was initiated in 2015 to explore and implement renovation scenarios aimed at transforming existing buildings into Nearly Zero Energy Buildings (NZEBs). Four out of forty similar buildings in the neighborhood (housing approximately 12,000 people) were selected to test a standard renovation package including four different HVAC solutions. The renovation project sought to reduce the primary energy use by 50%, to enhance indoor air quality and thermal comfort, and to maintain financial feasibility. Renovation of the buildings (owned by municipal housing company Stora Tunabyggen AB) was completed in 2019.

These buildings (see Figure 1) each have 3 floors and accommodate 45 apartments. The total heated floor area, referred to as Atemp, is 3879 square meters per building. These are district-heated and, prior to renovation, used mechanical exhaust ventilation without heat recovery.

Figure 1. One of the studied buildings before (**left**) and after (**right**) renovation at Tjärna Ängar.

The energy renovation aspect of the project involved implementing uniform measures across all buildings. To reduce transmission losses, the attics were improved by additional insulation (150 mm) and external walls with 50 mm. Old, double-glazed windows were replaced by triple-glazed windows with a U-value of 1 W/(m^2·K). As for the hydronic radiator system, the one-pipe distribution system was upgraded to a two-pipe system. Moreover, low-flow water fixtures were installed.

The HVAC system differs in each renovation package. The first building (EV) underwent renovation with exhaust ventilation lacking heat recovery, where fans are pressure-controlled. The second building (MVHR) was upgraded with mechanical ventilation featuring heat recovery. In the third building (EAHP), an exhaust air heat pump was installed, while the final building (EAHPV) was renovated with both an exhaust air heat pump and photovoltaic panels.

The exhaust ventilation (EV) system with air pressure control optimizes energy usage based on ventilation needs. In each building with an exhaust air heat pump (EAHP, EAHPV), the ventilation system features a pressure-controlled exhaust fan paired with a heat exchanger unit in the attic that recovers energy from the exhaust air. This recovered energy is then utilized by a heat pump to provide heating for domestic hot water (DHW) or to supply the radiators for space heating, with priorities for space heating or DHW heating outlined below. The mechanical ventilation with a heat recovery (MVHR) system uses the heat exchanger unit to preheat incoming supply air by extraction from the exhaust air.

Both the exhaust air heat pump and the mechanical ventilation with heat recovery systems leverage heat from outgoing ventilation air, thereby reducing overall energy demand. As a result, these solutions are frequently considered effective energy renovation measures for multifamily buildings.

The exhaust air heat pump (EAHP) in the building prioritizes heating the water in the radiators for space heating, while DH supplies domestic hot water (DHW). This system operates year-round.

The other building is referred to as ‘EAHPV’. It is essential to highlight that within this setup, thanks to PV which produces most electricity during summer months, and to obtain maximum self-consumption, DHW is for PV-aided EAHP priority. The heat pump exclusively serves the purpose of supplying heat to DHW and is intentionally not utilized for space heating from September through February. This strategic decision aligns with the peak electricity prices observed during these months, coinciding with the lowest production of PV electricity.

3. Method and Data

3.1. Method Framework

A framework was developed to systematically explain the assessment conducted in this study, as illustrated in Figure 2. The primary objective was to evaluate various renovation scenarios in the context of large-scale multifamily building renovations, considering both the building (building owner) and urban energy system (local CHP and district heating system and electricity grid) perspectives.

The initial steps involved collecting data pertaining to the four buildings within the renovation project, the energy use of each building, as well as energy production from the urban energy system (i.e., DH-supplier), which could be either simulation data or measurement data. Subsequently, the second step entailed calculating greenhouse gas (GHG) emissions and fuel costs from the energy system after implementing different renovation scenarios across all buildings. The detailed method and data for calculation of GHG emissions and operation cost are displayed in Section 3.3.

Moving forward, the next step involves conducting a life cycle assessment (LCA) and life cycle cost analysis (LCC) on the building level. The final steps encompass comparing the obtained results and engaging in a comprehensive discussion on the optimal renovation scenarios, taking into consideration both building and urban energy system perspectives. The detailed tools and data for LCA and LCC analysis are illustrated in Section 3.4.

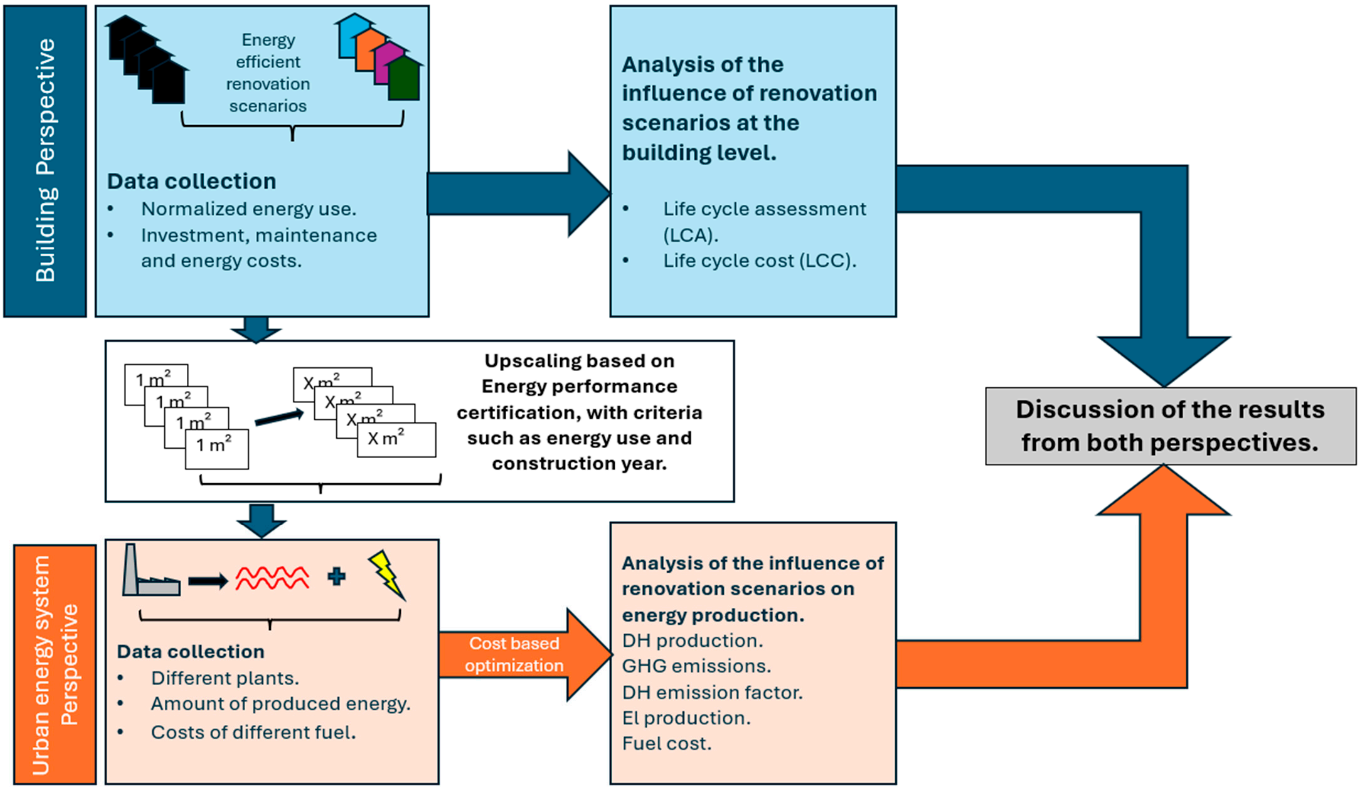


Figure 2. The framework that has been developed to fulfill the aim of this study.

3.2. Collected Data

3.2.1. Multifamily Buildings in the Municipality

According to Swedish law, all buildings are required to declare their energy consumption to the Swedish National Board of Housing, Building, and Planning (Boverket) [30]. This energy declaration should encompass general details about the building, including its type, address, and year of construction, as well as details on the heated area, energy usage for heating, domestic hot water, and facility electricity, along with information on the HVAC system within the building.

For research purposes, Boverket maintains a comprehensive database containing energy declarations for various types of buildings across all municipalities in Sweden. Leveraging this database, a subset of district-heated multifamily buildings in Borlänge municipality with specific criteria was identified. These criteria included being constructed during the Million Homes Program (1965–1974), having exhaust ventilation, and a district heating use equal to or greater than that of the renovated buildings before their renovation (150 kWh/(m^2·year)).

The analysis revealed 145 buildings, encompassing a total heated area (Atemp) of approximately 800,000 m^2, that share similar conditions with the buildings before undergoing renovation. The majority of the buildings are three-story structures, with a smaller number of two-story buildings and even fewer five-story buildings. The total heated area of all multifamily buildings in the municipality connected to the district heating system is almost 2.440 Mm^2. This makes the 800,000 m^2 account for approximately 33% of all district-heated multifamily buildings in the municipality.

The district heating reduction from each of the four renovated buildings was calculated per square meter and then scaled up to the total heated area of 800,000 m^2. To evaluate the potential influences on the municipality's energy system, the results of district heating use for various renovation scenarios were projected to cover all identified buildings.

3.2.2. The Urban Energy System in Municipality

The district heating network in Borlänge consists of four plants with annual heat deliveries totaling approximately 450 GWh. The current heat supply sources include municipal waste CHP plants, heat-only plants, and industrial excess heat, Figure 3. The municipal energy company operates waste-based CHP plants and heat-only plants fueled with waste, biofuel, and oil, as shown in Figure 4. Industrial heat deliveries originate from a specialized steel manufacturer within the municipality (thermal waste). The annual production of district heating throughout the year 2021 is shown in Figure 5.

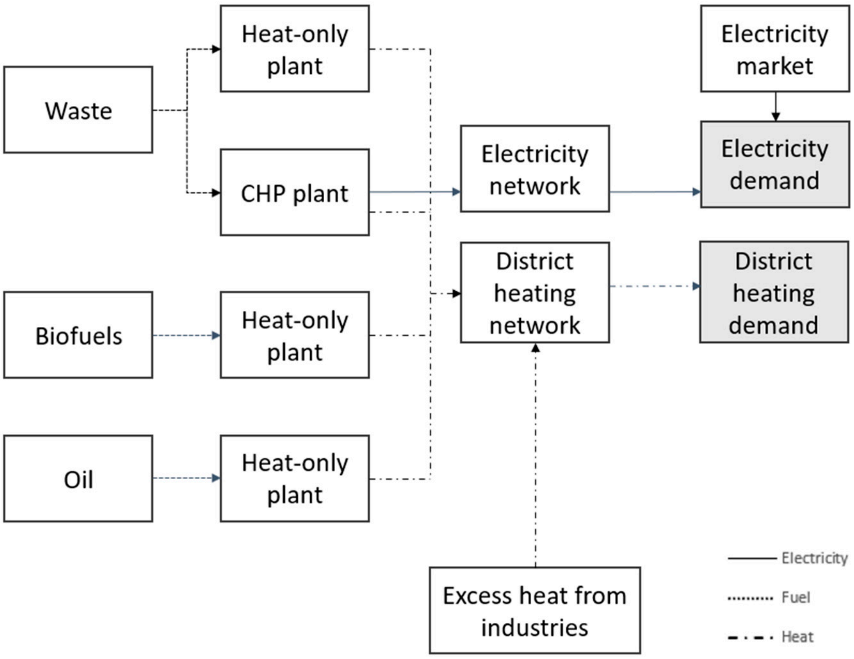


Figure 3. Fuel sources, plants and energy flows in Borlänge.

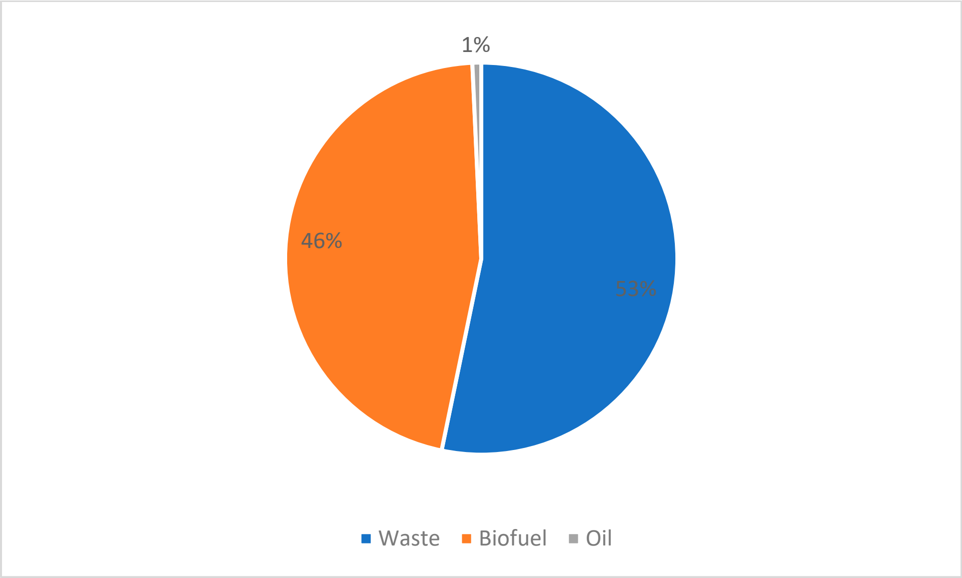


Figure 4. Percentage of different fuels in the energy system at Borlänge.

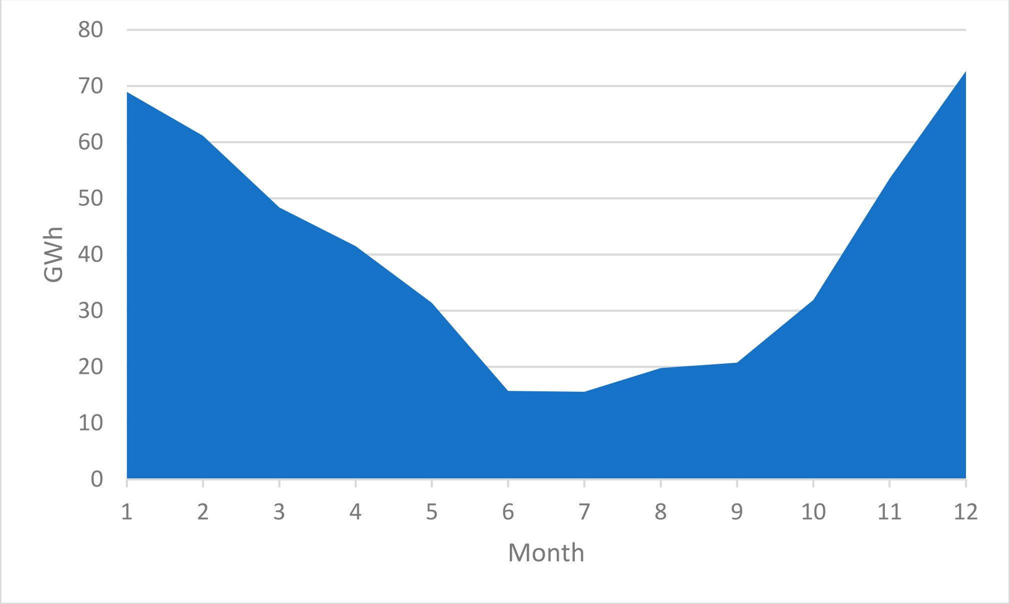


Figure 5. Production of the DH of the local energy system throughout the year (2021).

3.2.3. Data from the Renovation Project

Energy consumption in each building was recorded prior to (approximately 150 kWh/(m^2·year)) and after renovation. These values were computed to reflect on the energy consumption for a typical meteorological year in Borlänge. District heating use, which includes the energy to cover space and DHW heating demand, is shown for both before the renovation in 2015 and after the renovation in 2021 in Figure 6. The use of facility electricity, excluding household electricity, is displayed in Figure 7 for the same periods; before renovation, it corresponds to 7 kWh/(m^2·year).

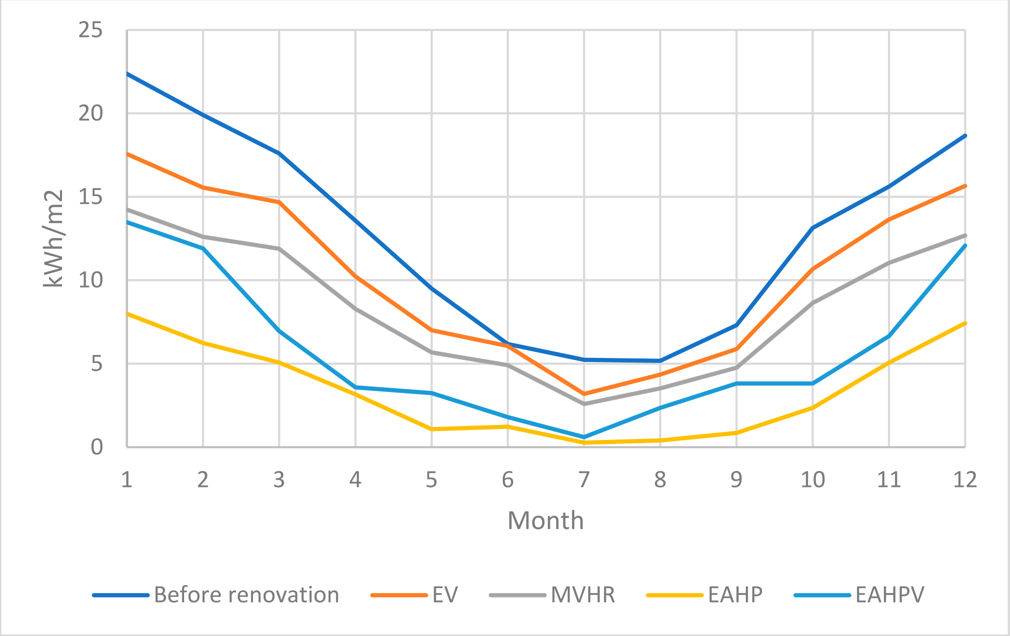


Figure 6. Month-wise normalized district heating usage for the four renovation alternatives, based on measurements (2021).

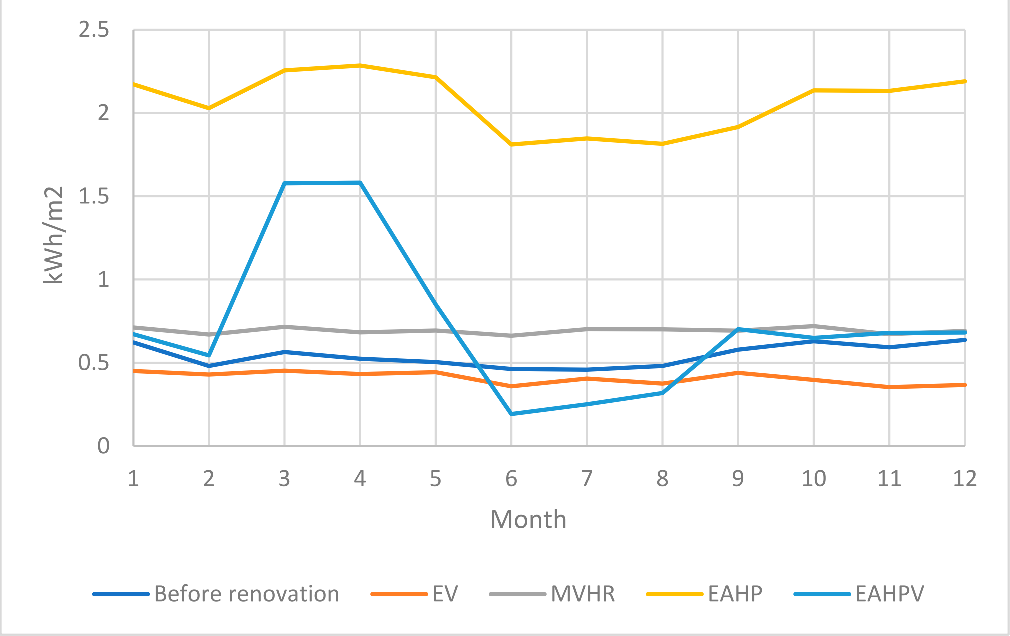


Figure 7. Electricity usage of heating and for heating and facility operations throughout the year 2021 (not including household electricity).

In terms of upscaling the renovation packages to a broader building population in Borlänge, the A_{temp} of multifamily buildings erected during the Million Homes Project using 150 kWh/(m^2·year) or more was identified through the registered energy performance certificates from National Board of Housing, Building and Planning's (Boverket) database GRIPEN. Since a detailed investigation into applying the renovation packages on archetypes within the Million Homes Project buildings is beyond the scope of this project, energy savings, GHG emissions and costs are proportionally adjusted during the upscaling process using the metric "per square meter A_{temp}".

3.3. Urban Energy System Perspective

To assess the impact of large-scale application of the renovation package's alternatives on the urban energy system, the study explored the scenarios where all buildings in the municipality, similar to the renovated buildings, underwent renovation, which was a total of 800,000 m^2 of A_{temp}. Various key aspects were considered in this analysis, including the production of district heating, greenhouse gas (GHG) emissions resulting from the operation of the energy system, emission factors associated with the production of 1 kWh of district heating, electricity generation from the CHP unit within the local system, and the fuel costs of the energy system.

The assessment of the overall change in DH production within the urban energy system was derived by analyzing the monthly district heating usage across various renovated buildings and data on monthly district heating production, which were sourced from housing and energy companies in the municipality.

To estimate the fuel consumption of various plants following the implementation of different renovation scenarios, cost-based optimization was applied. This method identifies the most economical way to meet energy demands by evaluating the costs associated with various energy sources, such as oil and biofuel. Cost-based optimization is widely used in specialized software to support decision-making, including investment selection, determining the optimal size of new installations, and managing the operation of system components. One such tool is MODEST developed by researchers at Linköping University in Sweden [31]. Modest has been extensively used in energy system analysis and optimization research, particularly for modeling complex, time-dependent energy systems [28,32]. The software can account for variations in demand, costs, and capacities over different time intervals, including seasonal, weekly, and diurnal changes. In this study, both Modest and Microsoft Excel were implemented to perform the analysis. The analysis was conducted using month-wise input data, ensuring that the specific conditions of the case under consideration were accurately reflected.

Based on the outcomes of the cost-based optimization of the energy system and the energy production alterations in CHP plant production, the consequential shifts in electricity production from these plants were estimated. This involved a careful analysis of how adjustments in the overall energy system and CHP plant operations influenced the generation of electricity within the specified scenarios

The prices of oil, waste, and biofuels were sourced from a database supplied by the Swedish Energy Agency [33]. Employing these prices, the study defined the variations in the fuel costs of the district heating system across different renovation scenarios. Fuel prices and production capacity were set as constant in future scenarios. The assessment involved calculating the cost variations based on the selected renovation options and the corresponding prices of the energy sources.

The outcomes of this optimization were then utilized to calculate both the total greenhouse gas (GHG) emissions during the operational phase of the DH production system and the emission factors of district heating across different scenarios. These calculations were conducted with reference to estimated emission factors for various fuels in Sweden [34,35].

3.4. Building Perspective

Life cycle assessment (LCA) and life cycle cost (LCC) are frequently utilized in renovation project studies to evaluate the economic and environmental impacts of various measures [36,37]. Numerous studies indicate that the LCA method is the most widely recognized and thorough approach for assessing environmental sustainability in renovation initiatives. To perform an environmental assessment of different renovation scenarios, this study utilizes life cycle analysis (LCA), a systematic and standardized approach [38] that quantifies the potential environmental impacts of alternative solutions.

For the economic assessment of sustainability in a renovation project, life cycle cost (LCC) is among the most solid and used methodologies [39–42]. LCC comprises an economic approach for assessing the total costs of products or projects during the service life of a system or component. It entails predominant influencing economic factors and discounts future costs to their present values, perceived as particularly relevant for systems with a long lifespan, such as buildings [43].

3.4.1. Life Cycle Analysis (LCA)

The LCA process, defined in ISO 14044:2006 [44] and ISO 14040:2006 [45], comprises four primary steps, which are definition of Goal and Scope, Life Cycle Inventory (LCI) Analysis, Life Cycle Impact Assessment (LCIA) and Interpretation of Results.

Global Warming Potential (GWP) is widely acknowledged as the primary metric for evaluating environmental impact and is the only measure utilized in Sweden’s climate declarations [46]. Expressed as equivalent carbon emissions (CO_2e), GWP is essential for standardizing the contributions of different greenhouse gases, each with varying GWP values, into a single measure. This study focuses on analyzing the environmental impact category of GWP.

The One Click LCA software, version: 1.14.0, developed by Bionova Ltd. Helsinki. Finland, was used to simulate the environmental impact of building materials and conduct a full life cycle analysis of the buildings [47]. Compliant with EN 15978 [48], the platform supports standardized life cycle cost analysis (LCCA) and life cycle analysis (LCA), integrating data from production, construction, in-use, and end-of-life phases. Its database is based on Environmental Product Declarations (EPDs) following EN 15804 [49] and ISO 14044 standards, enabling accurate predictions of CO_2e emissions and environmental impacts. One Click LCA has been widely applied in studies evaluating the environmental performance of diverse projects [50–55].

The primary objective of the LCA is to analyze the impact of different renovation strategies on greenhouse gas (GHG) emissions throughout the life cycle, with a particular focus on materials and operational energy consumption. The functional unit selected for this study is 1 square meter (m^2) of Atemp, which serves as the basic measurement unit for calculating specific energy use and GHG emissions associated with the building. For this study, the reference period is set at 40 years, in accordance with the recommendations for building renovations provided by the Royal Swedish Academy of Engineering Sciences (IVA) [56].

Following the renovation project, detailed material data—such as types and quantities—were sourced mainly from the One Click LCA database, which included essential information like EPDs. For materials like ventilation ducts and heating system pipes, generic data based on the building's total heated area were used. To enhance accuracy, transportation distances were calculated for each material, assuming a Swedish reduction diesel mix for transport.

The service life for different materials was derived from a report by Public Housing Sweden (SABO) [57]. This comprehensive method facilitated the collection of accurate and relevant data for the study, as detailed in Table 1.

Table 1. Material data of studied renovation scenarios, per building.

	Material	Amount	Unit	Lifespan
Similar in all packages	Hydronic radiators	6570	kg	50
	DH 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
	Triple-glazed windows with wooden frames (1 $W/(m^2{\cdot}K)$)	82	unit	40
	Shower mixer assembly	60	unit	30
MV	Roof-mounted ventilation fan	1	unit	20
MHR	Air handling unit equipped with a rotary heat exchanger for heat recovery	1	unit	20
	Residential ventilation system	3879	m^2	20
HP	Rooftop exhaust fan	1	unit	20
	Exhaust air heat pump	1	unit	20
	Air exchanger	1	unit	20
HPV	Rooftop exhaust fan	1	unit	20
	Exhaust air heat pump	1	unit	20
	Air exchanger	1	unit	20
	Monocrystalline solar panel	120	unit	30

Note. Data collected by the authors from the housing company.

The GWP-GHG value of 37 CO_2e (g/kWh) is the emission factor for electricity production, derived from an average of the Swedish mix based on data from 2015 to 2017, according to the annual statistics from the Swedish Environmental Research Institute (IVL) [58] and Boverket [59]. This value aligns with EN 15804 [49] standards and the methodology recommended by the Swedish Energy Agency for assessing the environmental impact of electricity generation and various energy carriers. It is important to highlight that Sweden's electricity production has a lower emission factor than the Nordic average (which is approximately 90 g/kWh) [60], while the EU's emission factor was 334 g/kWh in 2019 [61].

The emission factor for district heating production is established at 114 CO_2e (g/kWh), derived from the local urban energy system within the municipality. It is noteworthy that the recommended average emission factor for DH in Sweden, as suggested by Boverket, is 56 CO_2e (g/kWh) [59]. The variance between these values is attributed to the predominant use of solid waste as the primary heat source in the municipality's energy system, resulting in a higher emission factor compared to, for instance, biofuel.

3.4.2. Life Cycle Cost Analysis (LCCA)

LCCA is an economic evaluation method that accounts all costs associated with owning, operating, maintaining, and ultimately disposing of a project, considering these factors as potentially significant to the decision-making process [43]. Equation (1) gives the equation to implement LCCA, such that

$$LCC = I_0 + Repl + E + OM\&R - Res \tag{1}$$

where LCC represents the total life cycle cost of a given alternative, I_0 refers to the initial investment costs, $Repl$ denotes the present value of capital replacement costs, E represents the present value of energy costs, $OM\&R$ signifies the present value of operation, maintenance, and repair costs, and Res is the present value of residual costs.

The economic parameters required to calculate the present value of various costs were analyzed, utilizing statistics spanning from 2013 to 2023. The inflation and discount rates were sourced from the Riksbanken (Central bank) and SCB (Statistics Sweden) [62,63], while data on energy price escalation were collected from various energy companies in Sweden and SCB [64,65]. In this analysis, there is a particular emphasis on average values. Based on the outcomes, this study incorporates a 2% inflation rate and a 3% real discount rate. Additionally, nominal escalations of 4% for electricity and 2% for district heating prices were taken into consideration.

The investment costs and maintenance costs of various renovation measures were gathered from the housing company and are presented in Table 2.

Energy prices and pricing models were sourced from the local energy company, Borlänge Energi AB, based on 2021 rates. In this study, DH costs were determined by adding three components: energy use, peak demand, and the cost of flow rate. Similarly, electricity costs were determined by calculation including fixed costs, electricity consumption, and the cost of electricity transfer. In a previous study [66] within this project, detailed explanations about the pricing models of district heating and electricity were provided and presented. The total initial investment costs, along with the annual maintenance and energy costs, are summarized in Table 3. The present value of the annual costs and replacement costs will be calculated over the 40-year study period. These values will then be combined with the investment costs in accordance with Equation (1).

Table 2. Different costs of implemented renovation measures (year 2018).

Renovation Measures	**Investment Costs Including VAT (€/m^2)**			**OM&R Costs (€/m^2·year)**
	Installation Costs	**Material Costs**	**Total**	
Two-pipe heating distribution system	15	50	65	0.4
Attic insulation	-	-	5	0.0
Infill wall insulation	3	3	6	0.2
Triple-glazed windows (1 W/(m^2·K))	18	23	41	0.5
Shower tap mixer set	1	6	7	0.1
Rooftop exhaust fan	1	5	6	0.2
Exhaust air heat pump	6	28	35	0.2
Mechanical ventilation with heat recovery	-	-	95	0.2
Photovoltaic monocrystalline panel	3	7	10	0.0

Note. Data collected by the authors from the housing company.

Table 3. Different costs of different renovation scenarios.

Costs	**EV**	**MVHR**	**EAHP**	**EAHPV**
Investment cost (€/m^2)	13.3	22.5	16.8	17.8
OM&R (€/m^2·year)	0.2	0.1	0.2	0.2
Electricity (€/m^2·year)	0.1	0.1	0.4	0.1
District heating (€/m^2·year)	0.9	0.9	0.4	0.5

4. Results

The study suggests a framework for the economic and environmental assessment of different renovation scenarios, taking into account the perspectives of both buildings and the urban energy system, especially in large-scale multifamily building renovation projects. A case study based on the municipality of Borlänge in Sweden was conducted, where 800,000 m^2 of A_{temp}, representing 33% of the total heated floor area of all multifamily buildings connected to district heating in the municipality, was examined. The focus of the study was on the renovation of district-heated multifamily buildings, which were subjected to various scenarios outlined in the pilot renovation project.

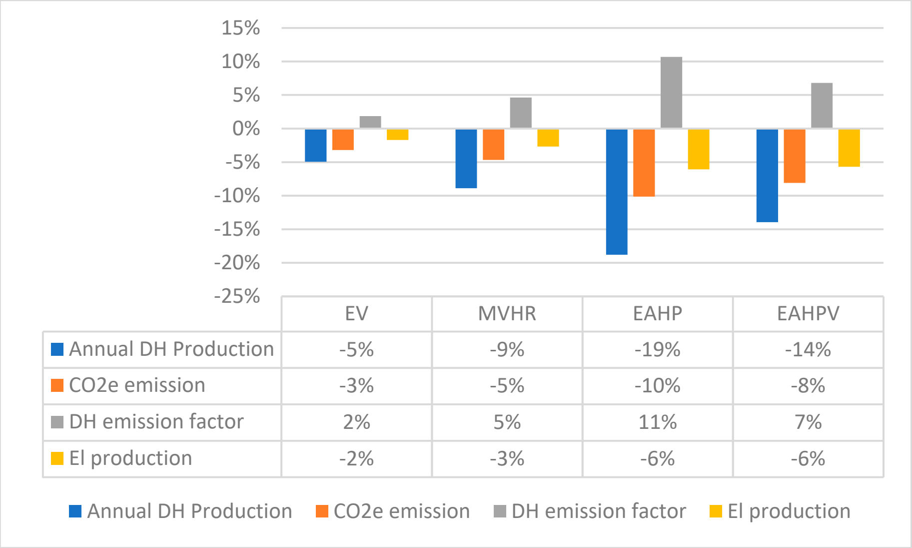
4.1. Impact on the Urban Energy System

One of the primary objectives was to assess the impact of a renovation package with four HVAC alternatives on a larger scale on the urban energy system. The key aspects analyzed include changes in annual district heating (DH) and electrical (EL) production, greenhouse gas (GHG) emissions, and the emission factor for electricity production from the CHP plant. The four different renovation scenarios are defined in Section 2. Table 4 presents the results of the impact of different renovation scenarios on the urban energy system with respect to the studied key aspects. A comparison with the baseline scenario, where no renovation occurs, is illustrated in Figure 8.

The local energy system in Borlänge, similar to many other municipalities in Sweden, has CHP plants. Consequently, a decrease in annual district heating (DH) production translates to a reduction in annual electricity production. It is crucial to note that this reduction predominantly takes place during the summer months, coinciding with the period of lowest DH demand. The reduction in annual district heating production will consequently reduce the total CO_2e emission.

Table 4. The results of different key aspects of various renovation scenarios on the urban energy system.

	No Renovation	EV	MVHR	EAHP	EAHPV
DH Production (MWh/year)	481,400	457,550	438,600	390,900	414,200
CO_2 emission (tCO_2e/year)	55,002,684,300	53,248,734,600	52,433,962,800	49,430,553,800	50,551,454,300
Emission factor (gCO_2e/kWh)	114	116	120	126	122
Fuel cost (€/year)	4,587,850	418,900	3,834,500	3,055,600	3,480,400



	EV	MVHR	EAHP	EAHPV
■ Annual DH Production	-5%	-9%	-19%	-14%
■ CO2e emission	-3%	-5%	-10%	-8%
■ DH emission factor	2%	5%	11%	7%
■ El production	-2%	-3%	-6%	-6%

Figure 8. Comparing different key aspects of various renovation scenarios to the baseline scenario with no renovation.

When implementing the large-scale renovation scenario with exhaust ventilation (EV), the least reductions in annual district heating production, CO_2e emissions, and annual electricity production compared to the baseline case with no renovation occur at 5%, 3%, and 2%, respectively. Conversely, the highest reductions in annual district heating, CO_2e emissions, and electricity production compared to the basic case with no renovation are observed in scenarios involving the exhaust air heat pump (EAHP) with 19%, 10%, and 6%, respectively. Reduced district heating demand leads to decreased operation of biofuel heat-only plants, increasing the share of solid waste in energy production. This effect is also evident with the exhaust air heat pump (EAHP), which significantly lowers district heating (DH) demand while increasing electricity (EL) demand, resulting in the greatest overall reduction in CO_2e emissions.

The results show that in any scenario, the reduction in annual DH production is greater than the reduction in CO_2e emissions, due to higher emission factors of district heating compared with the baseline with no renovation across all renovation scenarios. For example, in the EV scenario, the annual reduction in DH production is 5% higher than the reduction in CO_2e emissions, which amounts to 3%. This results in a higher emission factor of DH compared to the case with no renovation.

The comparison of the reduction in energy production from various types of fuel in different renovation scenarios to the baseline case, where no renovation occurs, is illustrated in Figure 9. The adoption of any of the renovation scenarios has effectively eliminated the use of oil in DH production. Additionally, there has been a noteworthy reduction in biofuel demand, ranging from 9% with exhaust ventilation (EV) to 33% with the exhaust air heat pump (EAHP). It is worth noting that the EAHPV achieves lower reductions compared to the EAHP, primarily because the heat pump remains inactive during the coldest winter months. However, despite this operational difference, the reductions achieved by EAHPV are still greater than those achieved by MVHR.

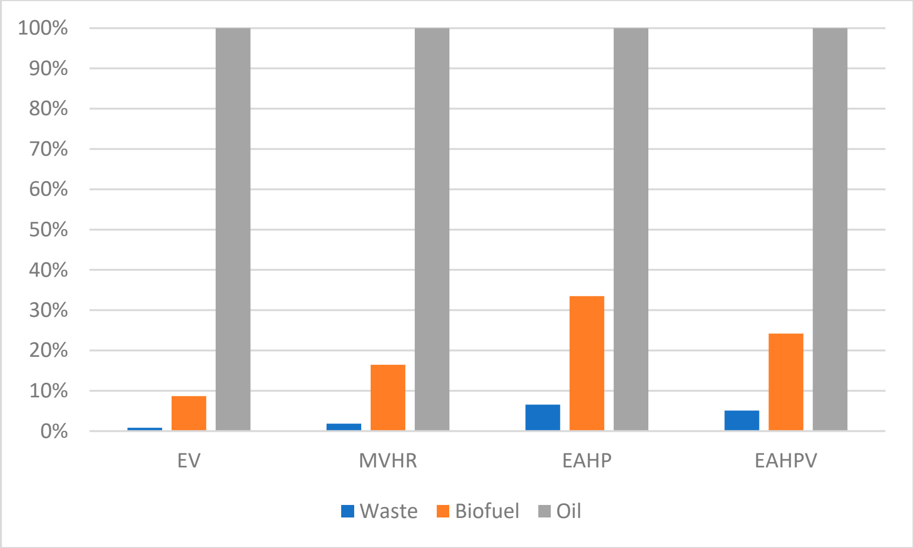


Figure 9. Comparing the reduction in energy production from various types of fuel in different renovation scenarios to the baseline with no renovation.

The comparison of the reduction in fuel costs of the urban energy system in different renovation scenarios to the basic case, where no renovation occurs, is shown in Figure 10. The annual fuel cost of DH production has also experienced a decrease, ranging from 9% with exhaust ventilation (EV) to 33% with the exhaust air heat pump (EAHP). This reduction is primarily attributed to the decrease in demand for oil and biofuel, since burning waste is prioritized.

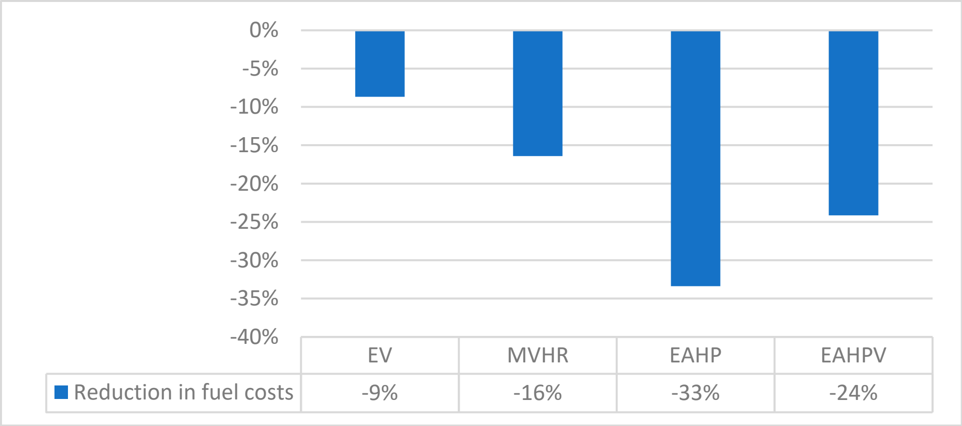


Figure 10. Comparing the reduction in annual fuel costs of the district heating system across different renovation scenarios.

4.2. Impact on Buildings

Another primary objective of this study was to carry out an environmental and economic assessment of the four renovation scenarios from the building perspective. To achieve this, a life cycle assessment (LCA) was conducted to calculate GHG emissions over a 40-year period, considering various stages in the building's life cycle, and the results of the assessment are shown in Figure 11. As displayed, it is the 40 years of operation of the buildings that dominate GHG emissions, even though emissions are low for Swedish energy systems. Additionally, a life cycle cost analysis (LCCA) was undertaken to calculate the total cost of different renovation scenarios across various stages in the life of the buildings. The results of this analysis are presented in Figure 12. Notably, the operational costs (electricity and district heating) are lowest for EAHPV but highest for EAHP, closely followed by EV. As a whole, EAHPV has the lowest present value costs. The high investment cost of MVHR implies that this is an expensive alternative.

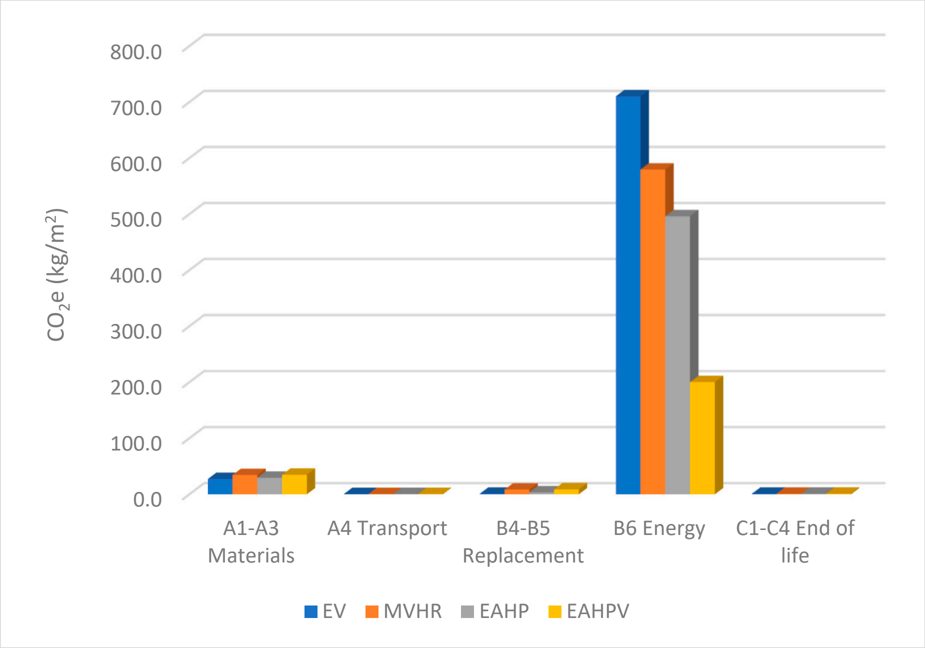


Figure 11. GHG emissions of the four renovation scenarios at stages of their life cycle.

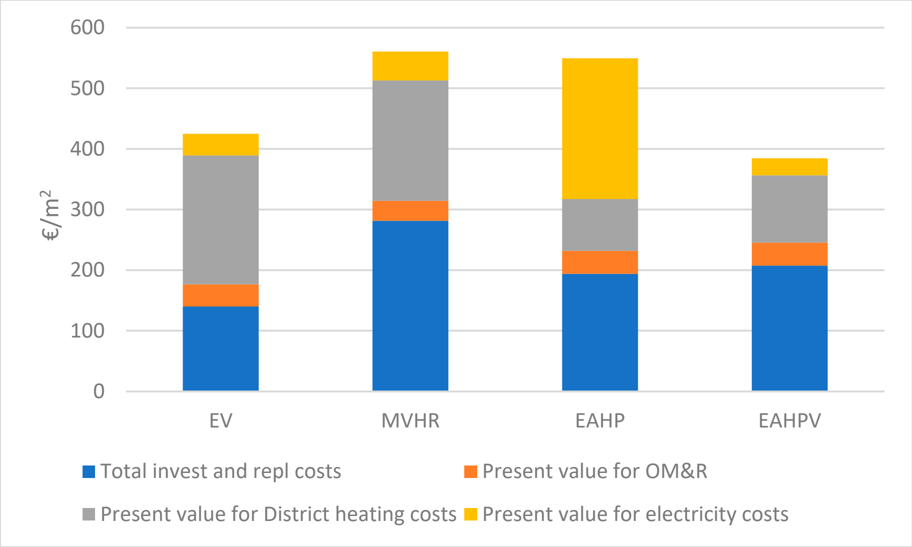


Figure 12. LCC for the four renovation scenarios.

5. Discussion

The framework developed in this study provides a systematic method for evaluating the economic and environmental aspects of large-scale energy renovation projects. This framework was applied in a case study conducted in Borlänge, Sweden, where the energy system consists of low-emission electricity compared to other Nordic countries and Europe, coupled with high-emission district heating (DH) compared to the national average in Sweden. It is important to note that urban energy systems in other municipalities in Sweden may have lower or higher emission factors for thermal energy, which influences the generality of this study in a Swedish perspective. However, the results illustrate the types of results and trade-offs that are associated with energy systems that generally approach fossil-free transition.

The results of this study highlight the significant impact of using various HVAC systems in an energy-efficient renovation package for district-heated multifamily buildings, not only affecting their individual energy usage but also exerting a noteworthy influence on the broader local and urban energy system. Four distinct HVAC systems were examined in existing buildings, each showing varied district heating and electricity use. One building relied entirely on district heating for both heated spaces and domestic hot water (EV scenario), while others incorporated heat pumps and mechanical ventilation with or without heat recovery, utilizing electricity for heating spaces and/or domestic water.

Even though the overall GHG emissions from DH production have decreased, the emission factor has increased after renovation for all cases, as seen in Figure 8. This is attributed to the reduction in annual DH production; thus, the share of solid waste as fuel increases, consequently increasing emissions per produced unit of energy. This change will significantly influence the total GHG emissions of district-heated buildings in the future. It is important to note that the calculation does not account for the increase in DH demand due to construction of new buildings. Currently, waste used as fuel for CHP plants often contains a certain proportion of fossil-based materials. This content is liable to decrease in the future due to new regulations on sorting household waste [67]. Whereas the energy-saving solutions lead to increased emission factors, the absolute emissions are reduced. Moreover, what to do with the waste is beyond the scope of this paper.

The results of life cycle assessment from building perspective have shown that the emission from operational energy accounts for the biggest share of total GHG emissions compared to the other life stages of the renovation projects. The building with the exhaust air heat pump (EAHP) has the lowest total GHG emission, while the building with exhaust ventilation has the highest GHG emission. This could be explained by the fact that the building with higher DH use will have higher emission as the emission factor of DH, which is 114 CO_2e (g/kWh), is almost double the emission factor of El, which is 37 CO_2e (g/kWh).

The life cycle cost analysis (LCCA) reveals that the building with mechanical ventilation with heat recovery (MVHR) has the highest life cycle cost. This is primarily due to the substantial investment cost associated with this system, which could not be offset sufficiently by energy savings. The increase in investment cost is due to the need for installing supply air ventilation ducts. Following this, the building (EAHP) ranks next, largely influenced by its high electricity use compared to the other buildings and the elevated electricity prices in contrast to district heating prices. Subsequently, the building with exhaust ventilation (EV) emerges as an economically advantageous scenario, despite having the highest energy use. The lower electricity use and low district heating prices contribute to its positive economic standing compared to the EAHP and MVHR scenarios. Remarkably, the building (EAHPV) exhibits the lowest life cycle cost. This is attributed to reduced purchased electricity, arising from the partial disabling of the heat pump in winter (higher electricity prices) and the utilization of solar energy to meet a portion of the electricity demand. Consequently, the EAHPV scenario stands out as the most economically beneficial option from a life cycle cost perspective for the building owner. In a former study that primarily focused on the economic assessment of the renovation project from the building owner perspective [66], a sensitivity analysis was conducted for different discount rates and energy price escalations. The analysis revealed that various economic parameters do impact the results; however, they do not alter the primary conclusion regarding which renovation alternative is the most economically efficient.

In terms of the environmental aspect from both the urban energy system and building perspectives, this study shows that a building (EAHP) can exhibit the lowest GHG emissions due to the very low electricity emission factor. However, it is noteworthy that this building has the highest electricity consumption compared to the other buildings under examination. Simultaneously, it leads to the most significant reduction in electricity production from the Combined Heat and Power (CHP) plant of the system due to reduced demand of DH. This raises a critical question regarding the large-scale adoption of this scenario—how can the reduction in electricity production be compensated by other renewable sources without increasing the emission factor of electricity?

In terms of the economic aspect from the energy system perspective, this study reveals that the building (EAHP) boasts the lowest operational cost for district heating production, primarily due to its significant reduction in annual district heating production. However, from the building perspective, this building exhibits a relatively high life cycle cost when compared to other scenarios studied. On the other hand, the building with both an exhaust air heat pump and photovoltaic panels (EAHPV) not only has the lowest life cycle cost but also contributes to additional solar electricity that can be sold to the electric grid. Moreover, in comparison to EAHP, the operation strategy of EAHPV, involving the heat pump being shut off during the coldest winter months, increases DH demand during the winter, which in turn allows more electricity production at the CHP plant.

One limitation of this study lies in the calculation of GHG emissions, which is solely based on average steady-state values. This approach overlooks the dynamic interactions present in real urban energy systems, where factors like weather and occupancy cause energy usage and emissions to fluctuate over time. In this study, the total CO_2e emissions were calculated without consideration of these dynamic complexities.

The measured energy use of 150 kWh/(m^2·year), which was recorded from the buildings prior to renovation, serves as one of the criteria for scaling up the renovation. This value is also defined as the average energy use for buildings from the Million Homes Program, as reported in the published "Energy Statistics for Multi-Family Buildings" by the Swedish Energy Agency [68]. Building owners are required to submit energy declarations for their buildings every 10 years. However, the actual energy performance may differ from the data recorded in the energy declaration database.

Additionally, the cost analysis in this study is based on the municipality's pricing model for specific years. Since energy prices fluctuate over time, and municipalities apply different pricing models, this can influence the cost estimates. Furthermore, electricity prices in Sweden vary by region. The country is divided into four electricity regions, with Borlänge located in region 3 (elområde 3), where electricity prices tend to be higher compared to regions 1 and 2.

The upscaling of energy use from the studied buildings to the total heated area in the municipality was based on district heating savings and electricity use per square meter as the functional unit. While the selected multifamily buildings in the municipality exhibit comparable or higher district heating usage, which enhances the credibility of the analysis, there remains uncertainty in estimating reductions in district heating production due to variations in the technical and geometric characteristics of different buildings.

To address this uncertainty, a simplified equation for estimating energy use was developed, relying on a minimal set of input parameters. This equation was applied to evaluate the impact of geometry and U-values in non-renovated buildings within the Million Homes Program. The use of a functional unit of 1 m^2 A_{temp} allows for proportional upscaling. The uncertainty in energy use for different renovation scenarios, considering variations in geometry and U-values, is approximately ±4% (see Supplementary Materials). The "degree-hour" method, which calculates energy demand based on heat losses through various building components, was employed to conduct the analyses.

6. Conclusions

This study has developed a framework to conduct a comprehensive analysis aimed at assessing the environmental and economic impact of large-scale renovation, taking into account both urban energy systems and building perspectives. The research proposed a systematic approach for conducting in-depth analyses within the context of large-scale renovation projects. The case study involved a pilot renovation project where four renovation scenarios were implemented on four multifamily buildings from the Million Homes Program. While these scenarios share similar measures aimed at improving the thermal envelope of the buildings, the key difference lies in the HVAC systems, resulting in variations in electricity and district heating use across the different buildings.

The building with the lowest district heating use, namely the one with an exhaust air heat pump (EAHP), shows the lowest total district heating production, fuel cost, and greenhouse gas (GHG) emissions from an urban energy system perspective. Consequently, it also has the highest emission factor. This building, characterized by its high electricity use, simultaneously induces the most significant reduction in electricity production from the Combined Heat and Power (CHP) plant. This building also has the lowest total GHG emissions due to the low emission factor of electricity. However, it does not have the lowest life cycle cost due to higher electricity prices compared to district heating.

The EAHP system has become increasingly popular among building owners, despite not providing the lowest life cycle cost because of higher electricity prices compared to district heating. However, when a building with an EAHP is paired with photovoltaic panels (EAHPV), the dynamics change. By generating solar energy, these buildings can reduce their electricity consumption. Additionally, deactivating the heat pump during winter months—when heating demand is typically higher—can further improve cost-effectiveness. This scenario (EAHPV) can achieve a lower life cycle cost while also contributing to the use of solar electricity on a larger scale.

One of the primary challenges highlighted in this study is managing electricity production with a low emission factor in the face of increasing electricity demand. This issue is compounded by the reduction in electricity generation from Combined Heat and Power (CHP) plants, which often occurs alongside a decrease in district heating production. It is essential to develop strategies that meet growing electricity demand sustainably while addressing the decline in traditional electricity sources.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en18030513/s1, Figure S1: schematic picture of a building. Figure S2: results from measurements (meas.) and simulations (sim.). Figure S3: simulated total specific energy use as function of the length/width-ratio of the building (γ) and number of stories (N). The reference point (red) illustrates measured energy use of the non-renovated building. Table S1: inputs for the actual buildings, before and after renovation. Table S2: the percentage (%) of specific energy savings of the three renovation scenarios in relation to the non-renovated building. N depicts number of stories. Refs. [69–75] are cited in Supplementary Materials.

Author Contributions: Conceptualization, A.K., J.A., X.Z. and J.A.M.; Methodology, A.K.; Software, A.K.; Validation, J.A.; Formal analysis, A.K.; Data curation, A.K.; Writing—original draft, A.K.; Writing—review & editing, A.K., J.A., X.Z. and J.A.M.; Visualization, A.K. and J.A.; Supervision, J.A. and J.A.M.; Project administration, J.A.M.; Funding acquisition, J.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: The research leading to these results has received funding from the Swedish Energy Agency under grant agreement No 40811-2 and from Sustainable Integrated Renovation (SIRen). The authors would like to appreciate the financial support from the Swedish Energy Agency through the Viable Cities' international program (ENVISION CHANGE project P2023-01559), which is part of the ERA-NET Cofund Urban Transformation Capacities (ENUTC) framework: Building Transformation 681 Capacity Through Arts and Design (BTC-ENUTC).

Data Availability Statement: The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author(s).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Why Buildings Are the Foundation of an Energy-Efficient Future. World Economic Forum. 22 February 2021. Available online: https://www.weforum.org/agenda/2021/02/why-the-buildings-of-the-future-are-key-to-an-efficient-energy-ecosystem/ (accessed on 29 March 2023).
2. Energy Performance of Buildings Directive. European Commission. 2018. Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed on 29 March 2023).
3. Energy Efficiency. The First Fuel of a Sustainable Global Energy System. Iea. 2022. Available online: https://www.iea.org/energy-system/energy-efficiency-and-demand/energy-efficiency/ (accessed on 29 March 2023).
4. European Commission. *Communication from The Commission to the European Parliament, The Council, The European Economic and Social Committee and The Committee of the Regions*; European Commission: Brussels, Belgium, 2020.
5. Renovation Wave—European Green Deal. EU Funding Overview. 1 February 2023. Available online: https://eufundingoverview.be/funding/renovation-wave-european-green-deal (accessed on 5 December 2023).
6. Sveriges Klimatmål och Klimatpolitiska Ramverk. Naturvårdsverket. Available online: https://www.naturvardsverket.se/amnesomraden/klimatomstallningen/sveriges-klimatarbete/sveriges-klimatmal-och-klimatpolitiska-ramverk/ (accessed on 5 December 2023).
7. Sveriges Energi- och Klimatmål. Energimyndigheten. 21 June 2023. Available online: https://www.energimyndigheten.se/klimat/klimat/sveriges-energi--och-klimatmal/ (accessed on 5 December 2023).
8. Under Miljonprogrammet Byggdes en Miljon Bostäder. Boverket. Available online: https://www.boverket.se/sv/samhallsplanering/stadsutveckling/miljonprogrammet/ (accessed on 11 January 2024).
9. Råberger, C.; Berggren, T. Stora vinster med energieffektiv renovering av miljonprogrammen. Energimyndigheten. 2 October 2015. Available online: https://www.energimyndigheten.se/arkiv-for-resultat/Resultat/stora-vinster-med-energieffektiv-renovering-av-miljonprogrammen/ (accessed on 5 December 2023).
10. Lunds Kommun: Cityfied—Prisat Energiprojekt på Linero. Future by Lund. 5 April 2024. Available online: https://www.futurebylund.se/project/energiprojekt-pa-linero-prisas (accessed on 11 May 2024).
11. District Heating. Iea. 11 July 2023. Available online: https://www.iea.org/energy-system/buildings/district-heating (accessed on 8 December 2023).
12. Hur Fungerar Kraftvärme? Elfakta. 25 August 2023. Available online: https://www.ekonomifakta.se/Fakta/elfakta/om-kraftslagen/hur-fungerar-kraftvarme/ (accessed on 8 December 2023).
13. Yacoub, L.L. *Energy in Sweden Facts and Figures 2023*; Energimyndigheten: Stockholm, Sweden, 2023.
14. Eriksson, E.; Nilsson, L. *Energistatistik för Flerbostadshus 2016*; Statens Energimyndighet: Eskilstuna, Sweden, 2017.
15. Rydegran, E. Kraftvärme. Energi Företag. 3 December 2018. Available online: https://www.energiforetagen.se/energifakta/elsystemet/produktion/kraftvarme/ (accessed on 24 February 2024).
16. Decarbonisation Heating and Cooling—A Climate Imperative. 23 February 2023. Available online: https://www.eea.europa.eu/publications/decarbonisation-heating-and-cooling/decarbonising-heating-and-cooling/folder_contents (accessed on 11 August 2024).
17. Tettey, U.; Gustavsson, L. Energy savings and overheating risk of deep energy renovation of a multi-storey residential building in a cold climate under climate change. *Energy* **2020**, *202*, 117578. [CrossRef]

18. Boussaa, Y.; Dodoo, A.; Nguyen, T.; Gadd, K. Comprehensive renovation of a multi-apartment building in Sweden: Techno-economic analysis with respect to different economic scenarios. *Build. Res. Inf.* **2023**, *52*, 463–478. [CrossRef]
19. López-Ochoa, L.M.; Las-Heras-Casas, J.; López-González, L.M.; García-Lozano, C. Energy Renovation of Residential Buildings in Cold Mediterranean Zones Using Optimized Thermal Envelope Insulation Thicknesses: The Case of Spain. *Sustainability* **2020**, *12*, 2287. [CrossRef]
20. Asdrubali, F.; Ballarini, I.; Corrado, V.; Evangelisti, L.; Grazieschi, G.; Guattari, C. Energy and environmental payback times for an NZEB retrofit. *Build. Environ.* **2019**, *147*, 461–472. [CrossRef]
21. Wrålsen, B.; O'Born, R.; Skaar, C. Life cycle assessment of an ambitious renovation of a Norwegian apartment building to nZEB standard. *Energy Build.* **2018**, *177*, 197–206. [CrossRef]
22. Ma, Z.; Cooper, P.; Daly, D.; Ledo, L. Existing building retrofits: Methodology and state-of-the-art. *Energy Build.* **2012**, *55*, 889–902. [CrossRef]
23. Attia, S.; Kurnitski, J.; Kosiński, P.; Borodiņecs, A.; Belafi, Z.D.; István, K.; Krstić, H.; Moldovan, M.; Visa, I.; Mihailov, N.; et al. Overview and future challenges of nearly zero-energy building (nZEB) design in Eastern Europe. *Energy Build.* **2022**, *267*, 112165. [CrossRef]
24. Rose, J.; Thomsen, K.E.; Irigoyen, S.; Bolliger, R.; Venus, D.; Konstantinou, T.; Mlecnik, E.; Almeida, M.; Barbosa, R.; Terés-Zubiaga, J.; et al. Building renovation at district level–Lessons learned from international case studies. *Sustain. Cities Soc.* **2021**, *72*, 103037. [CrossRef]
25. Bogdanovics, R.; Zemitis, J.; Zajacs, A.; Borodinecs, A. Small-scale district heating system as heat storage for decentralized solar thermal collectors during non-heating period. *Energy* **2024**, *298*, 131260. [CrossRef]
26. Belaïd, F.; Ranjbar, Z.; Massié, C. Exploring the cost-effectiveness of energy efficiency implementation measures in the residential sector. *Energy Policy* **2021**, *150*, 112122. [CrossRef]
27. Gustafsson, M.S.; Myhren, J.A.; Dotzauer, E.; Gustafsson, M. Life Cycle Cost of Building Energy Renovation Measures, Considering Future Energy Production Scenarios. *Energies* **2019**, *12*, 2719. [CrossRef]
28. Weinberger, G.; Amiri, S.; Moshfegh, B. Investigating techno-economic effects and environmental impacts of energy renovation of residential building clusters on a district heating system. *Energy Build.* **2021**, *251*, 111327. [CrossRef]
29. Pohoryles, D.; Bournas, D.; Porto, F.D.; Caprino, A.; Santarsiero, G.; Triantafillou, T. Integrated seismic and energy retrofitting of existing buildings: A state-of-the-art review. *J. Build. Eng.* **2022**, *61*, 105274. [CrossRef]
30. Boverket—the Swedish National Board of Housing, Building and Planning. Boverket. Available online: https://www.boverket.se/en/start/ (accessed on 28 December 2023).
31. Henning, D. MODEST—An energy-system optimisation model applicable to local utilities and countries. *Energy* **1997**, *22*, 1135–1150. [CrossRef]
32. Henning, D.; Amiri, S.; Holmgren, K. Modelling and optimisation of electricity, steam and district heating production for a local Swedish utility. *Eur. J. Oper. Res.* **2006**, *175*, 1224–1247. [CrossRef]
33. Vinterbäck, J. Trädbränsle-, torv- och avfallspriser. Energimyndighet. 5 December 2023. Available online: https://www.energimyndigheten.se/statistik/officiell-energistatistik/prisutveckling-inom-energiomradet/tradbransle--och-torvpriser/ (accessed on 30 December 2023).
34. Gode, J.; Martinsson, F.; Hagberg, L.; Öman, A.; Höglund, J.; Palm, D. *Miljöfaktaboken 2011*; VÄRMEFORSK Service AB: Stockholm, Sweden, 2011.
35. *Emissionsfaktorer och Värmevärden Submission 2023*; Naturvårdsverket: Stockholm, Sweden, 2022.
36. Gluch, P.; Baumann, H. The life cycle costing (LCC) approach: A conceptual discussion of its usefulness for environmental decision-making. *Build. Environ.* **2004**, *39*, 571–580. [CrossRef]
37. Pombo, O.; Allacker, K.; Rivela, B.; Neila, J. Sustainability assessment of energy saving measures: A multi-criteria approach for residential buildings retrofitting—A case study of the Spanish housing stock. *Energy Build.* **2016**, *116*, 384–394. [CrossRef]
38. Baumann, H.; Tillman, A. *The Hitch Hiker's Guide to LCA*; Studentlitteratur AB: Lund, Sweden, 2015.
39. Pombo, O.; Rivela, B.; Neila, J. The challenge of sustainable building renovation: Assessment of current criteria and future outlook. *J. Clean. Prod.* **2016**, *123*, 88–100. [CrossRef]
40. Chidiac, S.; Marjaba, G. Sustainability and resiliency metrics for buildings-Critical review. *Build. Environ.* **2016**, *101*, 116–125.
41. Ingrao, C.; Messineo, A.; Beltramo, R.; Yigitcanlar, T.; Ioppolo, G. How can life cycle thinking support sustainability of buildings? Investigating life cycle assessment applications for energy efficiency and environmental performance. *J. Clean. Prod.* **2018**, *201*, 556–569. [CrossRef]
42. Pinheiro, M.D.; Ferreira, J.; Brito, J.D. Refurbishment decision support tools review—Energy and life cycle as key aspects to sustainable refurbishment projects. *Energy Policy* **2013**, *62*, 1453–1460.
43. Fuller, S.K.; Petersen, S.R. *Life Cycle Cosing Manual for the Federal Energy Management Program*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 1995.

44. *ISO 14044:2006*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. ISO: Geneve, Switzerland, 2006.
45. *ISO 14040:2006*; Environmental Management—Life Cycle Assessment—Principles and Framework. ISO: Geneve, Switzerland, 2006.
46. Klimatdeklaration-en Digital Handbok från Boverket. Boverket. 2022. Available online: https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/klimatdeklaration/ (accessed on 3 October 2023).
47. One Click LCA. 2015. Available online: https://www.oneclicklca.com/ (accessed on 3 January 2022).
48. *EN 15978:2011*; Sustainability of Construction Works—Assessment of Environmental Performance of Buildings – Calculation Method. European Committee for Standardization (CEN): Brussels, Belgium, 2011.
49. *EN 15804:2012+A2:2019*; Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products. European Committee for Standardization (CEN): Brussels, Belgium, 2022.
50. Opher, T.; Duhamel, M.; Posen, I.D.; Panesar, D.K.; Brugmann, R.; Roy, A.; Zizzo, R.; Sequeira, L.; Anvari, A.; MacLean, H.L. Life cycle GHG assessment of a building restoration: Case study of a heritage industrial building in Toronto, Canada. *J. Clean. Prod.* **2021**, *279*, 123819. [CrossRef]
51. Felicioni, L.; Gaspari, J.; Veselka, J.; Malík, Z. A comparative cradle-to-grave life cycle approach for addressing construction design choices: An applicative case study for a residential tower in Aalborg, Denmark. *Energy Build.* **2023**, *298*, 113557. [CrossRef]
52. Petrovic, B.; Myhren, J.; Zhang, X.; Wallhagen, M.; Eriksson, O. Life cycle assessment of a wooden single-family house in Sweden. *Appl. Energy* **2019**, *251*, 113253. [CrossRef]
53. Ramirez-Villegas, R.; Eriksson, O.; Olofsson, T. Life Cycle Assessment of Building Renovation Measures–Trade-off between Building Materials and Energy. *Energies* **2019**, *12*, 344. [CrossRef]
54. Villegas, R.R.; Eriksson, O.; Olofsson, T. Environmental Payback of Renovation Strategies in a Northern Climate—the Impact of Nuclear Power and Fossil Fuels in the Electricity Supply. *Energies* **2020**, *1*, 13.
55. Khadra, A.; Akander, J.; Myhren, J.A. Greenhouse Gas Payback Time of Different HVAC Systems in the Renovation of Nordic District-Heated Multifamily Buildings Considering Future Energy Production Scenarios. *Buildings* **2024**, *14*, 413. [CrossRef]
56. IVA. *Energieffektivisering av Sveriges flerbostadshus—Hinder och möjligheter att nå en halverad energianvändning till 2050*; Kungl. IngenjörsVetenskapsAkademien IVA: Stockholm, Sweden, 2012.
57. *Nyckeltal för Underhåll av Bostäder*; Sveriges allmännyttiga bostadsföretag: Stockholm, Sweden, 2013.
58. Erlandsson, M. *Modell för Bedömning av Svenska Byggnaders Klimatpåverkan*; Svenska miljöinstitutet (IVL): Stockholm, Sweden, 2020.
59. Boverket—The Swedish National Board of Housing. In *Climate Data Base, Version 02.03.000*; Boverket: Stockholm, Sweden, 2023.
60. Sandgren, A.; Nilsson, J. *Emissionsfaktor för Nordisk Elmix med Hänsyn Till Import och Export*; VL Svenska Miljöinstitutet: Stockholm, Sweden, 2021.
61. Scarlat, N.; Prussi, M.; Padella, M. Quantification of the carbon intensity of electricity produced and used in Europe. *Appl. Energy* **2022**, *305*, 117901. [CrossRef]
62. The Reference Rate. Svergies Riksbank. 1 December 2023. Available online: https://www.riksbank.se/en-gb/statistics/interest-rates-and-exchange-rates/reference-rate/ (accessed on 28 December 2023).
63. Konsumentprisindex, 12-Månadersförändring, Procent (Inflationstakten). Statistikmyndigheten. 14 December 2023. Available online: https://www.scb.se/hitta-statistik/statistik-efter-amne/priser-och-ekonomiska-tendenser/priser/konsumentprisindex-kpi/ (accessed on 28 December 2023).
64. Lindholm, K. Fjärrvärmepriser. Energi Företag. 29 June 2023. Available online: https://www.energiforetagen.se/statistik/fjarrvarmestatistik/fjarrvarmepriser/ (accessed on 28 December 2023).
65. Electricity Prices and Electricity Contracts. SCB Statistics Sweden. 22 December 2023. Available online: https://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__EN__EN0301/SSDManadElhandelpris/ (accessed on 28 December 2023).
66. Khadra, A.; Hugosson, M.; Akander, J.; Myhren, J.A. Economic performance assessment of three renovated multi-family buildings with different HVAC systems. *Energy Build.* **2020**, *224*, 110275. [CrossRef]
67. Nya Regler för Avfallsförebyggande, och Återvinning—Från Avfall Till Resurs. Naturvårdsverket. Available online: https://www.naturvardsverket.se/amnesomraden/avfall/hander-pa-omradet/nya-regler-for-avfallshantering-och-atervinning--fran-avfall-till-resurs/ (accessed on 27 February 2024).
68. Energimyndighet. Energistatistik för Flerbostadshus. 14 June 2024. Available online: https://www.energimyndigheten.se/statistik/officiell-energistatistik/tillforsel-och-anvandning/energistatistik-for-flerbostadshus/ (accessed on 7 January 2025).
69. Planverk, S. *Svensk Byggorn 67-Föreskrifter, råd och Anvisningar till Byggnadsstadgan BABS 1976*; Statens planverk: Stockholm, Sweden, 1967.
70. Boverket. *Handbok för Energihushållning Enligt Boverkets Byggregler—Utgåva 2*; Edita Västra Aros AB: Karlskrona, Sweden, 2012.
71. Boverket. *Så mår våra hus - Redovisning av Regeringsuppdrag Beträffande Byggnaders Tekniska Utformning m.m.*; Boverket: Stockholm, Sweden, 2009.

72. *ISO 15927-6:2007*; Hygrothermal Performance of Buildings—Calculation and Presentation of Climatic Data. Part 6: Accumulated Temperature Differences (Degree-Days). ISO: Geneve, Switzerland, 2007.
73. Elmarsson, B.; Nevander, L.E. *Fukthandbok: Praktik och Teori*; Svensk Byggtjänst: Stockholm, Sweden, 2006.
74. Sveby. *Brukarindata Bostäder, Version 1.0*; Svebyprogrammet: Eskilstuna, Sweden, 2012.
75. Björk, C.; Kallstenius, P.; Reppen, L. *Så byggdes Husen 1880–2000: Arkitektur, Konstruktion och Material i våra Flerbostadshus Under 120 år*; Svensk Byggtjänst: Stockholm, Sweden, 2013.