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Energy Renovation in Apartment Buildings Through Heat Recovery: A Comparative Case Study of HRV and EAHP

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ABSTRACT

Renovation measures aimed at recovering heat from exhaust air were assessed for their energy performance and economic feasibility in three Swedish apartment buildings. Case Building $1_{\text{C-HRV}}$ (Växjö) implemented a central heat recovery ventilation system, achieving the largest improvement: a 23% reduction in primary energy use (22 kWh/m²/year). Case Building $2_{\text{DE-HRV}}$ (Ljungby) installed decentralised HRV units, which increased energy consumption by 2 kWh/m²/year and incurred the highest annual service costs (SEK 14,000). Case Building 3_{EAHP} (Växjö) integrated an exhaust air heat pump in one building, reducing primary energy use by 15% (12 kWh/m²/year) while supplying heat to three buildings on the premises. Despite the energy savings, none of the renovation measures were economically feasible under current conditions; the shortest payback period was 19 years for the exhaust air heat pump. Future integration of smart controls and photovoltaic panels could improve economic viability, particularly for Case Building 3_{EAHP}, where operational patterns favour complementary technologies.

KEYWORDS

Energy renovation, Economic profitability, Heat recovery ventilation, Exhaust air heat pump, Multi-family buildings, District heating.

INTRODUCTION

Buildings play a crucial role in global energy consumption and its environmental impact. A full 40% of the world's energy use is attributed to the building sector, underlining its importance for sustainability. In addition, buildings account for 36% of energy-related greenhouse gas emissions [1]. The energy efficiency of buildings is not at the level required. In fact, 75% of buildings in the EU are not energy efficient, leading to unnecessary energy use and increased environmental impact. This category includes buildings from the Swedish Million Programme, implemented between 1965 and 1974 to provide affordable, high-quality housing nationwide. Today, much of this building stock requires renovation due to material degradation and reduced performance.

The current building stock also has a long-term impact. Between 85% and 95% of today's buildings in the EU are expected to remain in use until 2050. This highlights the importance of integrating sustainability measures into both current and future building projects to reduce energy consumption and carbon emissions in line with global climate goals [1]. The EU has

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recognised the need for a reliable and transparent tool to support businesses in their transition towards climate neutrality and long-term economic sustainability. To meet this need, the EU has developed the Green Taxonomy, which translates overarching climate and environmental objectives into clear criteria. Its aim is to create common definitions of what constitutes sustainable activities. The Regulation on the Taxonomy was adopted in June 2020 [2].

The Energy Performance of Buildings Directive (EPBD) provides the legislative framework for improving the energy performance of buildings across the EU. To strengthen its impact, the Commission has proposed a revision requiring upgrades of 15% of the EU building stock. This proposal was adopted in March 2023 [3]. The revision aims to increase renovation rates and reduce energy use, with a specific focus on buildings with the lowest performance, class G. These buildings should reach at least class F by 2030 and class E by 2033. The target also applies to residential buildings currently in class G [1], [4].

The overarching objective for 2050 is a climate-neutral construction sector. New buildings must be net-zero from 2028, and those owned, used or managed by public bodies must reach this target by 2026. Solar panels are to be installed on new buildings from 2028 where technically and economically feasible. For existing residential buildings undergoing major renovation, solar panels should be installed by 2032. Each EU country is responsible for defining and implementing national renovation plans to meet these targets [3]. To reduce the performance gap between predicted and actual energy use, EU guidelines emphasise the need to calibrate real-life performance of heating, ventilation and air-conditioning systems against calculated values [5].

Deep renovation strategies for multi-family buildings typically require modernisation of Heating, Ventilation and Air Conditioning (HVAC) systems alongside improvements to the building envelope. To meet EU climate targets, current regulations strongly promote high-efficiency heating solutions, such as district heating networks and exhaust air heat pumps, as integral components of renovation projects [6]. Exhaust ventilation with heat recovery (HRV) and exhaust air heat pumps (EAHP) are two main energy-efficiency options for renovated apartment buildings in cold climates [7], while deficiencies in existing natural ventilation systems can often be addressed by centralised mechanical balanced ventilation with heat recovery (C-HRV) or decentralised balanced ventilation with heat recovery (DE-HRV) [8]. The implementation of decentralised heat-recovery units in apartment buildings can lead to significant thermal energy savings and reduced CO_2 emissions [9]. Multi-family buildings equipped with hybrid heating systems, where district heating and mechanical exhaust ventilation are complemented by an EAHP, have shown reductions in space-heating energy costs of 23–31% [10]. Previous research has highlighted substantial discrepancies between calculated and measured energy savings in renovation projects, where current methods often overestimate savings by a factor of two [11]. This reinforces the need for reliable real-world performance data when evaluating energy-renovation measures, as demonstrated in studies such as [12], and calls for further empirical research to bridge this gap.

Three energy systems for heat recovery from exhaust air have been analysed using real-world data to compare their impact on economic profitability and energy performance in Swedish apartment buildings. Given the significant need for energy efficiency in the residential sector, it is crucial to select renovation measures that optimise both technical performance and long-term cost effectiveness. Ventilation losses are the main source of heat losses in buildings with mechanical exhaust ventilation (MEV) [6], which was the case for two of the properties in this study before renovation. For existing apartment buildings with district heating and exhaust-air ducts, common renovation options include installing heat recovery ventilation (HRV) systems or exhaust air heat pumps (EAHP), both intended to reduce delivered heat demand.

The present study evaluates the energy savings and economic outcomes of these measures in three case buildings: heat recovery ventilation with a central unit in Case Building $1_{\text{C-HRV}}$ in Växjö, heat recovery ventilation with apartment-level units in Case Building $2_{\text{DE-HRV}}$ in

Ljungby, and an exhaust air heat pump installed in one building supplying heat to three buildings on the premises of Case Building 3_{EAHP} in Växjö.

The novelty of this study lies in the combined use of measured post-renovation energy-performance data and tariff-sensitive economic modelling to evaluate three fundamentally different heat-recovery strategies in real Swedish apartment buildings. Unlike previous research, this work compares C-HRV, DE-HRV and EAHP systems under both Växjö and Ljungby tariff structures, providing new empirical insights into how local energy-price conditions influence the profitability of renovation measures.

METHOD

The aim is to compare three renovation measures intended to reduce energy use in three case study apartment buildings. The renovation measures were: heat recovery ventilation with a central unit, C-HRV, heat recovery ventilation with an apartment unit, DE-HRV and an exhaust air heat pump, EAHP. The comparison was made using measured consumption data, investment costs and electricity and district heating costs.

Energy savings are reported through an energy declaration carried out by a certified independent energy expert for each property before and after the measure. This introduces an uncertainty in the pre-renovation baseline, as design values do not fully reflect measured operational conditions. The goal of the present study is to compare the three different measures from an economic and energy technology perspective to be able to determine:

i. Energy use before and after the measure and how the primary energy ratio is affected.
ii. Investment costs for HRV and EAHP.
iii. Payback period and profitability of the investments.
iv. The difference in power tariffs for electricity and district heating in the cities Växjö and Ljungby.

Description of Case Buildings

The apartment buildings for the current study were selected with the requirement that measured consumption values were available. The apartment buildings that have been energy renovated in Växjö and Ljungby are presented in **Table 1**.

<u>Case Building $1_{C\text{-}HRV}$.</u> The multi-family Case Building $1_{C\text{-}HRV}$ in Växjö, underwent an energy renovation between mid-October 2021 and mid-January 2022. The property is owned by the municipal company Vidingehem AB. The multi-family house has three floors with 12 rental apartments and an Atemp of 1 128 m².

The renovation is part of a larger renovation project where Case Building $1_{C\text{-}HRV}$ is one of a total of nine buildings. The ventilation systems on all nine buildings were exhaust ventilation. Measures in the project include window replacement, additional insulation of the attic, pipe replacements, installation of individual metering and billing (IMD) for cold and hot water, installation of room sensors and energy-efficient mixer faucets. There is also reconstruction of substations and parts of distribution pipes and conversion from exhaust ventilation to C-HRV ventilation, to improve the indoor climate. The larger renovation project began in 2021 and was completed in 2025. For more information about the renovation project, see report **[13]**. In the current study, the aim is to isolate the impact of the HRV measure, while the effects of the other measures have been minimized or set to zero. Pre-renovation energy consumption is based on the design value, while post-renovation district heating consumption is based on measured operational data. The thermostats in the apartments are limited to 22°C, preventing occupants from increasing the indoor temperature above this level.

Table 1. Comparison of the three Case Buildings

Building	Municipality	Ownership	Base Heating	Heated area	Ventilation	Construction year
 1 C-HRV	Växjö	Municipal rental apartments	District heating	1 128 m^2	Central HRV	1963
 2 DE-HRV	Ljungby	Municipal rental apartments	District heating (old unit)	1 671 m^2	Decentralized HRV	1959
 3 EAHP	Växjö	Condominium apartments	District heating (new unit)	5 914 m^2	Exhaust air heat pump	1996

Case Building 2$_{\text{DE-HRV}}$. The multi-family Case Building 2$_{\text{DE-HRV}}$ in Ljungby is owned by the municipal company Ljungbybostäder AB. The building is a late 1950s house and is divided into 68% residential, the remaining 32% is a shop and warehouse. Ventilation is provided by natural ventilation, and the heat requirement is met by district heating from Ljungby Energi. The 16 rental apartments required renovation due to moisture problems and poor indoor conditions, such as black mould in bathrooms. Doors and windows without fresh air valves had previously been replaced. The thermostats in the apartments are not limited, enabling participants to freely adjust and increase the indoor temperature. The renovation measure that was chosen was HRV with apartment units, on the grounds that it is a relatively simple installation that is quick and does not require any major interventions. The renovation was carried out primarily to improve comfort levels. No measured ventilation-flow or indoor air-quality (IAQ) data were available for Case Building 2$_{\text{DE-HRV}}$. This limits the ability to quantify changes in ventilation rates and should be considered when interpreting the results.

Case Building 3$_{\text{EAHP}}$. The Case Building 3$_{\text{EAHP}}$ in Växjö has 76 condominiums spread over three buildings and is managed by HSB Riksförbund. They were built in 1996 with a total Atemp of 5,914 m^2 and have exhaust air ventilation and district heating as heating systems. The thermostats in the apartments are limited to 22°C. For Case Building 3$_{\text{EAHP}}$, the energy renovation involved installing an exhaust air heat pump in one of the three buildings on the premises, with heat recovery occurring solely from that building's exhaust air. The heat pump supplies heat for domestic hot water and the radiator system to all three buildings. The ventilation unit is an EcoHeater (0.86 m^3/s) from Company A, with an SFP of 0.48 kW/(m^3/s), and the heat pump has a heating output of 29.3 kW [14].

Comparability of the Case Buildings

Although the case buildings differ in construction year, ventilation systems and ownership, they remain comparable for the purpose of this study because each renovation measure targets the same underlying issue: ventilation-related heat losses in multi-family buildings with district heating. The analysis focuses on relative improvements before and after each measure rather than on absolute performance levels. This enables meaningful comparison of the energy and economic impacts of C-HRV, DE-HRV and EAHP solutions across different building contexts.

Calculations

The energy declarations were carried out by a certified independent energy expert in the Swedish National Board of Housing, Building and Planning's programme Gripen according to BBR29. For normalized energy consumption for domestic hot water, 22.5 $\mathrm{kWh/A_{temp}/year}$ has been used, which is a 10% reduction from 25 $\mathrm{kWh/A_{temp}/year}$. The reduction has been made because the properties have efficient mixer taps. [15] The primary energy use for each case building was calculated according to the BBR29 methodology, following the formulation in:

$$PE = \frac{(E_{el} * f_{el} + E_{dh} * f_{dh})}{A_{\mathrm{temp}}} \tag{1}$$

where:
E_{el} (kWh): delivered electricity to the building,
f_{el} (–): primary energy factor for electricity,
E_{dh} (kWh): delivered district heating for space heating and domestic hot water,
f_{dh} (–): primary energy factor for district heating,
A_{temp} (m²): heated floor area.

The equation expresses the total primary energy use as the sum of electricity and district heating, each weighted by their respective primary energy factors, divided by the building's heated area. This allows comparison of energy performance across buildings and renovation measures on a common, normalised basis.

Input data has been for 2022 consumption, except before measures for Case Building $2_{\mathrm{DE\text{-}HRV}}$. Regarding Case Building $2_{\mathrm{DE\text{-}HRV}}$, district heating consumption includes another building, consumption is distributed with 59% to Case Building $2_{\mathrm{DE\text{-}HRV}}$. For Case Building $2_{\mathrm{DE\text{-}HRV}}$ consumption after the measure, measured values were used from March to December 2022 and January and February 2023. Consumption before the measure were values from 2021.

The district heating consumption at Case Building $1_{\mathrm{C\text{-}HRV}}$ after the measure was 67,262 kWh, which then included all renovation measures at the block. According to the design calculations, the HRV measure was estimated to reduce the primary energy figure by 20 kWh/Atemp/year. Before the measure was implemented, the primary energy use was estimated at 139,504 kWh. The total reduction in the primary energy number for all measures combined, according to the design, was 37.7 $\mathrm{kWh/A_{temp}/year}$.

The property electricity at Case Building $1_{\mathrm{C\text{-}HRV}}$ before the measure was based on projected values and included electricity for fans before the measure and electricity for pumps. To ensure that the new, more efficient pumps did not influence the results, their electricity use was included in the property electricity both before and after the measure. Interior and exterior lighting were unchanged before and after the measure and are included in the property electricity.

Total consumption for the three apartment buildings at the premises of Case Building 3_{EAHP} in 2022 was consumption after the measure. Combined with information on the heat pump production and electricity to the compressor, the district heating requirement before the measure could be determined. It would also have been possible to estimate the district heating requirement before the measure based on the 2021 consumption.

TMF Energi is an Excel program developed by Research Institutes of Sweden (RISE) on behalf of the Swedish Wood and Furniture Companies (TMF) [16]. For Case Building 3_{EAHP}, TMF Energi has been used to investigate the difference between heat recovery from exhaust air from one of the buildings compared to all three. It has also been used to see how the primary energy figures change when installing solar cells.

Energivision is a program used for energy declarations and energy analyses [17]. In this Excel-based program, proposed measures can be added to see how they affect the energy declaration, energy needs and the profitability of the investment. Climate data and energy prices are available in Energivision. In the present study, Energivision has been used to determine energy needs/energy losses before measures Case Building $1_{C\text{-}HRV}$, Case Building $2_{DE\text{-}HRV}$ and Case Building 3_{EAHP}.

Electricity and District Heating

No consideration has been given to whether the measure resulted in increased electricity supply security for the properties. Consideration of increased electricity demand due to charging was included only for Case Building 3_{EAHP} with the exhaust air heat pump and was only relevant for prices regarding Växjö. The power price for the highest average electricity output was 102.5 SEK/kW/month (incl. VAT) [18]. District heating tariffs and electricity network fees for Ljungby were obtained from Ljungby Energi [23], [24] and were used in the economic calculations wherever Ljungby price conditions were applied, including for Case Building $2_{DE\text{-}HRV}$ and in the comparative scenarios for Case Building $1_{C\text{-}HRV}$ and Case Building 3_{EAHP}.

The increased electricity output was based on an average value between two methods for estimating the output. One was based on the exhaust air heat pump's COP which was 4.89 and that the district heating output decreased by 20 kW according to invoices, which gave an electricity output of 4.09 kW.

The second method was to take the compressor output of 39,970 kWh and divide by the year's 8,760 hours, which gave 4.56 kW. The average value was thus 4.33 kW as a result of increased power output from the exhaust air heat pump operation at Case Building 3_{EAHP}. Reduced charged district heating output for Case Building $1_{C\text{-}HRV}$ and Case Building $2_{DE\text{-}HRV}$ was estimated at 10 kW, half of what Case Building 3_{EAHP} reduced according to costs from Växjö Energi AB.

The reduced district heating consumption for the properties has been distributed in percentage terms based on the previous distribution over the year. As a result of this assumption, the HRV units at Case Building $1_{C\text{-}HRV}$ and Case Building $2_{DE\text{-}HRV}$ reduces the district heating demand during the summer months of June, July and August, when the only remaining load is domestic hot water.

The power cost for Växjö Municipality was based on the so-called signature power of Växjö Energi AB. Daily average power measurements are taken for weekdays between November and March, if the outdoor temperature is below 10℃. These data points build up characteristic power consumption at different outdoor temperatures. Billing is done for characteristic consumption at -10℃, which is based on the expected power drawn at -10℃. [19]

Economic Performance Model

The economic analysis was based on simple payback period (SPB)(Eq. (2)), detailed payback period (DPB) (Eq.(5)), annual energy-cost savings, and annual electricity-cost increases. Annual net savings consist of reduced district-heating energy cost, reduced district-heating power charges (where applicable), increased electricity cost due to operation of the HRV or EAHP systems, and annual service costs. A rent increase was also included for Case Building $1_{C\text{-}HRV}$.

The simple payback period (SPB) is defined as:

$$SPB = \frac{I}{B_{net}} \tag{2}$$

where the annual net savings are:

$$B_{\text{net}} = B_{\text{dhw+sh}} + B_{\text{eff}} + B_{\text{rent}} - C_{\text{el}} - C_{\text{serv}} \tag{3}$$

The detailed payback method accounts for monthly variations in electricity and district-heating prices, as well as monthly distribution of heat savings. Monthly savings are expressed as:

$$B_m = B_{\text{dhw+sh},m} + B_{\text{eff},m} - C_{\text{el},m} \tag{4}$$

The detailed payback period (DPB) is then defined as:

$$\text{DPB} = \frac{I}{\sum_{m=1}^{12} B_m} \tag{5}$$

In Eqs. (3–5), B-terms denote annual or monthly benefits, including savings from reduced district heating demand for domestic hot water and space heating ($B_{\text{dhw+sh}}$), reductions in district heating power charges (B_{eff}), and additional income from rent adjustments (B_{rent}). C-terms represent annual or monthly costs, comprising electricity use associated with the HRV or EAHP system (C_{el}) and service and maintenance costs (C_{serv}).

Economic Analysis

The economic analysis was based on collected investment costs and electricity and district heating prices. The electricity price consists of two parts, electricity grid and electricity trading costs. The electricity grid and district heating prices were supplemented with spot prices from Vattenfall [20]. Spot prices for 2021 were used to avoid including the record high prices for 2022. However, the price for electricity grid and district heating has been based on the 2023 prices.

Payback periods for the renovation measures were evaluated using both simple and detailed type, in accordance with Eq. (2) and Eq. (5). The two simple payback periods were based on a representative electricity and district heating price derived from data from [21] and [22]. The two detailed payback periods, for Växjö and Ljungby municipalities, were implemented with a higher level of methodological detail. The method accounts for monthly electricity and district heating prices, the monthly distribution of annual district heating reductions, increased electricity consumption, and the reduced delivered district heating output, where the monthly savings are computed according to Eq. (4). Increases in rent or fees have also been considered in both the simple and detailed payback period calculations, where the annual net savings follow the formulation in Eq. (3).

RESULTS

This section presents the results of the current study with respect to energy performance and economic outcomes.

Energy Calculations and Energy Declarations

The energy performance of the properties before and after the measures is presented in Figure 1. All values are normalized to a standard year and weighed using primary energy factors. Case Building $1_{C\text{-}HRV}$ had the largest percentage reduction with 22.7%, as the improvement was 22 kWh/m²/year. Case Building $2_{DE\text{-}HRV}$ increased its primary energy number by 2 kWh/m²/year, corresponding to an increase of 2.1%, while Case Building 3_{EAHP} decreased by 12 kWh/m²/year, corresponding to a reduction of 15%.

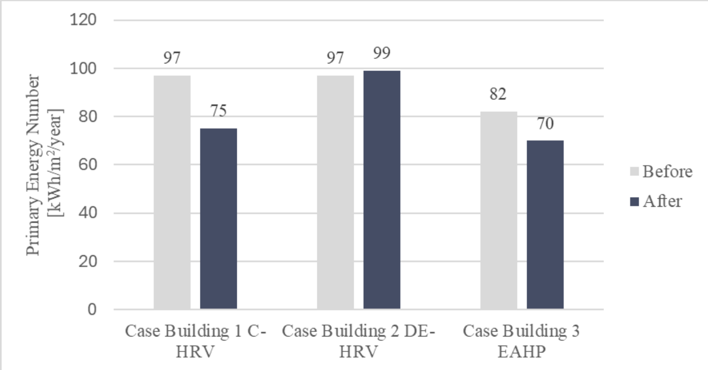

Figure 1. Summary of the properties' primary energy numbers before and after the measures based on the energy declarations

In Figure 2, the consumption before and after the measures is indicated in terms of specific energy use, meaning that the consumption is unweighted and uncorrected. This means that 1 kWh of electricity is equated with 1 kWh of district heating. The energy for domestic hot water is normalized. Case Building $1_{C\text{-}HRV}$ reduces energy use from 125.5 to 93.5 kWh/m²/year, which corresponds to a 25.5% reduction and 32 kWh/m²/year. Case Building $2_{DE\text{-}HRV}$ reduces energy use by 24.3% and 25.6 kWh/m²/year, from 106.5 to 80.6 kWh/m²/year. Case Building 3_{EAHP} reduces its specific energy use by 10 kWh/m²/year, from 134.5 to 124.5 kWh/m²/year, compared to the increase in primary energy number shown in Figure 1. The increase is mainly due to the weighing of electricity and district heating consumption. Normal year correction can also be a contributing factor depending on the year.

To perform a detailed payback period that follows monthly price variations, the district heating savings of the measures need to be distributed per month, the distribution is shown in Figure 3. The data are based on measurements from 2020–2022 for Case Building $2_{DE\text{-}HRV}$ and Case Building 3_{EAHP} for the years 2020 to 2022, and the Figure 3 displays the averaged percentage distribution.

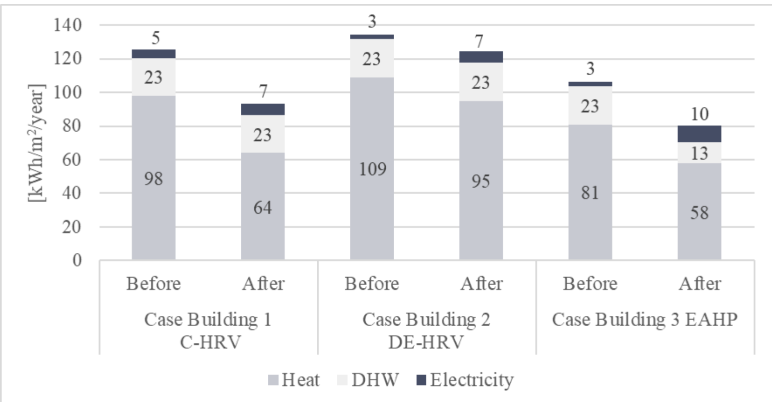

Figure 2. Summary of specific energy use for each of the Case Buildings, separated into heat, DHW and Electricity, before and after the measures

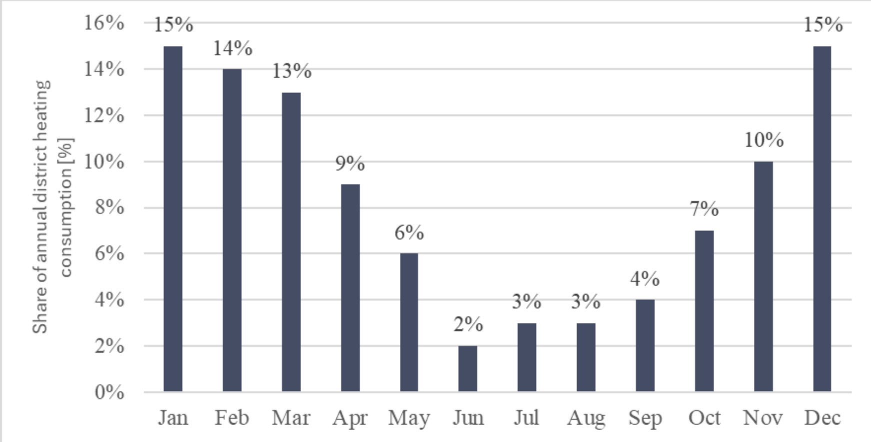

Figure 3. Monthly percentage distribution of annual district heating consumption

Figure 4 shows the amount of kWh per m³ of district heating. The values were used for detailed payback period to estimate the reduced amount of district heating flow after the renovation measures. Flow savings are relevant for payback period prices for Växjö Municipality as Växjö Energi has a flow rate during the winter months. The figure compares the calculated average energy content in kWh/m³, derived from district heating cost data for Case Building 3_{EAHP}, with the values reported in [21]. For detailed payback period, the calculated values from Case Building 3_{EAHP} have been used, while the values from [21] have been used as a reference.

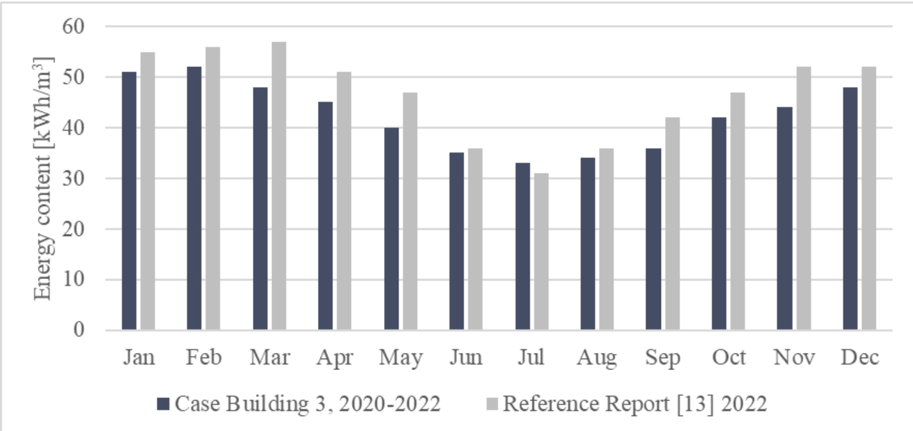

Figure 4. Energy content per m³ of district heating

The profitability of investments is affected by electricity prices. Växjö and Ljungby belong to electricity price area SE4, which is Sweden's southernmost area. The prices exclude VAT and include Vattenfall's electricity certificate fee and surcharge [20].

Investment costs and other costs for the renovation measures are reported in **Table 2**. The most expensive investment was Case Building $1_{C\text{-}HRV}$ which cost SEK 2,667,750 incl. VAT, distributed across 12 apartments, the cost was approximately SEK 220,000 per apartment. The investment for Case Building $2_{DE\text{-}HRV}$ with 16 apartments was SEK 2,042,667 incl. VAT and approximately SEK 128,000 per apartment. The least expensive renovation measure in terms of total cost per apartment was the exhaust air heat pump in Case Building 3_{EAHP} which cost SEK 1,418,750. The property has 76 apartments, corresponding to approximately SEK 19,000 per apartment.

Table 2. Economic summary for the Case Buildings

Category	Case Building 1 C-HRV	Case Building 2 DE-HRV	Case Building 3 EAHP
Investment costs excl. VAT	920 000 SEK	1 634 134 SEK	1 100 000 SEK
Other investment costs excl. VAT	200 000 SEK	N/A	35 000 SEK
Cost for fan room excl. VAT	1 014 200 SEK	N/A	N/A
Total investment excl. VAT	2 134 200 SEK	1 634 134 SEK	1 135 000 SEK
Total investment incl. VAT	2 667 750 SEK	2 042 667 SEK	1 418 750 SEK
Total investment incl. VAT per apartment	222 313 SEK	127 667 SEK	18 668 SEK
Service costs excl. VAT	2 600 SEK	14 000 SEK	3 500 SEK
System lifespan	20 years	15 years	20 years
Discount rate	5%	5%	5%
Annuity factor	0.0802	0.0963	0.0802
Conversion factor to present value	12.46	10.38	12.46
Service costs over the entire usage period incl. VAT	40 502 SEK	181 644 SEK	54 522 SEK

The external financial support that Vidingehem AB applied for and was granted for all measures at Case Building $1_{\text{C-HRV}}$ was SEK 784,670. All investment costs including VAT are calculated using a VAT rate of 25%.

Table 3 shows monthly savings as a result of reduced district heating demand. Växjö Energi AB has different tariffs for winter months (November - March) and summer months (April – October). The flow savings of district heating are based on specific energy content (kWh/m^3) per month and are derived from district heating costs for Case Building 3_{EAHP} that were used for the calculations. Ljungby Energi AB has no flow tariff in 2023. Based on **Figure 3**, the total annual district heating savings have been distributed per month. These values are used for the calculation of the detailed payback period.

Table 3. Monthly distribution of district heating savings due to renovation measures

	Case Building 1 C-HRV				Case Building 2 DE-HRV				Case Building 3 EAHP			
			Savings [SEK]				Savings [SEK]				Savings [SEK]	
	Δ E [MWh]	Δ V [m³]	Växjö	Ljungby	Δ E [MWh]	Δ V [m³]	Växjö	Ljungby	Δ E [MWh]	Δ V [m³]	Växjö	Ljungby
Jan	5.7	112	4 948	3 700	3.5	69	3 431	2 278	29.0	573	22 129	18 199
Feb	5.2	99	4 575	3 413	3.2	61	3 202	2 102	26.4	505	20 230	16 735
Mar	4.8	99	4 348	3 196	3.0	61	3 062	1 968	24.4	506	19 072	15 632
Apr	3.6	79	2 648	2 503	2.2	49	2 015	1 541	18.1	402	10 402	12 095
May	2.4	59	2 090	1 830	1.4	36	1 671	1 127	12.0	300	7 558	8 661
Jun	0.9	24	1 399	995	0.5	15	1 245	612	4.4	124	4 032	4 404
Jul	1.0	30	1 473	1 085	0.6	19	1 291	668	5.2	155	4 413	4 864
Aug	1.0	31	1 482	1 095	0.6	19	1 297	674	5.3	156	4 456	4 916
Sep	1.7	47	1 779	1 454	1.0	29	1 480	896	8.6	238	5 974	6 749
Oct	2.7	66	2 267	2 043	1.7	40	1 780	1 258	13.9	335	8 461	9 752
Nov	3.8	87	3 714	2 653	2.4	54	2 671	1 634	19.5	446	15 837	12 863
Dec	5.6	117	4 923	3 654	3.5	72	3 416	2 250	28.6	596	22 002	17 964
Sum	**38.3**	**851**	**35,645**	**27,621**	**23.6**	**524**	**26,560**	**17,009**	**195.4**	**4,338**	**144,567**	**132,833**

Note: ΔE = district heating energy reduction; ΔV = flow reduction. All monetary values in SEK.

The last row in Table 3 shows the annual cost reduction of district heating after the measure. Case Building $1_{C\text{-}HRV}$ saves SEK 35 645 with prices from Växjö Energi AB and SEK 27 621 with prices from Ljungby Energi AB. Case Building $2_{DE\text{-}HRV}$ saves SEK 26 560 (Växjö) and SEK 17 009 (Ljungby). The largest savings are achieved by Case Building 3_{EAHP}, with SEK 144 567 (Växjö) and SEK 132 833 (Ljungby). Only Case Building 3_{EAHP} shows higher district-heating cost savings under Ljungby tariffs. This is due to the assumption that Case Building $1_{C\text{-}HRV}$ and Case Building $2_{DE\text{-}HRV}$ reduce the district-heating power by 10 kW in Växjö. Växjö Energi AB has changes its energy price for district heating from 1 September 2023. The price increase was +29% for the winter energy price (November–March), rising from 458 SEK/MWh to 590 SEK/MWh including VAT. For April–October, the energy price increased from 266 SEK/MWh to 464 SEK/MWh including VAT, corresponding to a 74% increase.

Simple Payback Period

Simple payback period was calculated using electricity and district heating prices from the report [21]. In Table 4, prices for Växjö for Case Building $1_{C\text{-}HRV}$ and Case Building 3_{EAHP} were used from [21] which were 3.09 SEK/kWh_{el} and 0.80 SEK/kWh_{dh}. For Case Building $2_{DE\text{-}HRV}$, prices for Ljungby were used which were 2.88 SEK/kWh_{el} and 0.70 SEK/kWh_{dh}. All costs include VAT.

Table 4. Simple payback period with electricity and district heating prices based on the report [21] from 2022

Category	Case Building 1 C-HRV	Case Building 2 DE-HRV	Case Building 3 EAHP
Service costs	-3 250 SEK/year	-17 500 SEK/year	-4 375 SEK/year
Electricity costs	-5 773 SEK/year	-18 436 SEK/year	-123 406 SEK/year
District heating savings	30 537 SEK/year	16 555 SEK/year	155 708 SEK/year
Rent/fee increase	20 160 SEK/year	N/A	N/A
Annual savings	41 674 SEK	-19 380 SEK	27 927 SEK
Investment cost	2 667 750 SEK	2 042 667 SEK	1 418 750 SEK
Payback period	64 years	N/A	51 years

The rent increase for the 12 apartments at Case Building $1_{C\text{-}HRV}$ was estimated by Vidingehem AB to be SEK 140 per apartment per month based on previous experience, which sums up to 20,160 SEK/year. No negotiation about a possible rent increase at Ljungbybostäder had taken place regarding Case Building $2_{C\text{-}HRV}$. For Case Building 3_{EAHP} , the apartment fees have been increased but cannot be attributed to the renovation measure.

Payback times are affected by electricity and district heating prices, which in turn vary between price areas and years. In Table 5, electricity and district heating prices from the 2021 report [22] have been used. The price was 1.85 SEK/kWh_{el} and 0.78 SEK/kWh_{dh} for Växjö and is used for Case Building $1_{C\text{-}HRV}$ and Case Building 3_{EAHP}. Ljungby had lower energy prices, which were 1.66 SEK/kWh_{el} and 0.68 SEK/kWh_{dh} and are used for Case Building $2_{DE\text{-}HRV}$. [21]

Table 4 and Table 5 show how electricity and district heating prices affect the payback period. The greatest impact is on the payback period for Case Building 3_{EAHP} , which had 19 years with prices for 2021 compared to 51 years calculated with 2022 energy prices. This is because the exhaust air heat pump at Case Building 3_{EAHP} is the measure that consumes the most electricity, as the average electricity price increased by approximately 67% in 2022 compared to 2021 according to the energy prices above. The change in the price of district heating between 2021 and 2022 is similar and does not affect the difference in the payback period above.

Table 5. Simple payback period with electricity and district heating prices based on the report [22] from 2021

Category	Case Building 1 C-HRV	Case Building 2 DE-HRV	Case Building 3 EAHP
Service costs	-3 250 SEK/year	-17 500 SEK/year	-4 375 SEK/year
Electricity costs	-3 450 SEK/year	-10 644 SEK/year	-73 763 SEK/year
District heating savings	29 941 SEK/year	16 142 SEK/year	152 671 SEK/year
Rent/fee increase	20 160 SEK/year	N/A	N/A
Annual savings	43 401 SEK	-12 002 SEK	74 533 SEK
Investment cost	2 667 750 SEK	2 042 667 SEK	1 418 750 SEK
Payback period	61 years	N/A	19 years

Detailed Payback Period

The detailed payback period below is based on spot prices from 2021 and district heating prices for 2023. The tables also show, for comparison, the electricity cost calculated using 2022 spot prices. The monthly consumption of electricity and district heating is distributed according to **Figure 3**. Fixed costs are generally not affected by renovation measures.

Table 6 and **Table 7** indicate the share of district heating savings attributable to the power tariff. The reduced power for Case Building 3_{EAHP} was 20 kW according to costs for 2021 - 2023. No change in the charged district heating power was observed between 2021 and 2022, as the power level for 2022 is determined using measurement values from 2021. The installation of the exhaust air heat pump was between June 2021 and was completed in January 2022.

For prices applicable to Växjö Municipality, the reduced district heating power for Case Building $1_{\mathrm{C\text{-}HRV}}$ and Case Building $2_{\mathrm{DE\text{-}HRV}}$ was estimated to be 10 kW. The power cost for the calculations was 1200 SEK/kW district heating for all properties. The electricity cost for Case Building 3_{EAHP} also includes the cost of increased power output.

For prices applicable to Ljungby Municipality, the reduced billing-based district heating power is calculated by annual reduction of district heating divided by 2,100 hours. This resulted in Case Building $1_{\mathrm{C\text{-}HRV}}$ reducing its district heating power by 18 kW. Case Building $2_{\mathrm{DE\text{-}HRV}}$ reduced the district heating power by 11 kW and 93 kW for Case Building 3_{EAHP}.

The power tariff for the smaller properties Case Building $1_{\mathrm{C\text{-}HRV}}$ and Case Building $2_{\mathrm{DE\text{-}HRV}}$ was 337.5 SEK/kW/year incl. VAT, belonging to the tariff for 16-99 kW. Case Building 3_{EAHP} was calculated to belong to the tariff 250-999 kW before the measure, which is charged 235 SEK/kW/year incl. VAT and a fixed fee of 14 625 SEK/year incl. VAT. Before the measure, the charged power was 275 kW, which decreased by 93 kW after the measure to 182 kW. Case Building 3_{EAHP} ended up in the 100-249 kW tariff after the measure, which is charged 259 SEK/kW/year incl. VAT and a fixed fee of 8 750 SEK/year incl. VAT.

Table 6. Detailed Payback Period for Växjö Municipality

	Case Building 1 C-HRV	Case Building 2 DE-HRV	Case Building 3 EAHP
Service Costs	-3 250 SEK/year	-17 500 SEK/year	-4 375 SEK/year
Electricity Costs	-3 457 SEK/year	-11 831 SEK/year	-77 522 SEK/year
(Electricity using 2022 spot prices)	(-5 435 SEK/year)	(-18 601 SEK/year)	(-107 167 SEK/year)
District-heating savings	35 645 SEK/year	26 560 SEK/year	144 567 SEK/year
(– of which district-heating power charge)	(12 000 SEK/year)	(12 000 SEK/year)	(24 000 SEK/year)
Rent/fee increase	20 160 SEK/year	N/A	N/A
Annual savings	49 098 SEK	-2 771 SEK	62 670 SEK
Investment cost	2 667 750 SEK	2 042 667 SEK	1 418 750 SEK
Payback period	54 years	N/A	23 years

The power tariff for district heating decreases by approximately the same amount for Case Building 3_{EAHP} in Växjö as in Ljungby municipality. The payback period will be shorter in Ljungby due to the higher energy price in Ljungby.

Table 7. Detailed Payback Period for Ljungby Municipality

	Case Building 1 C-HRV	**Case Building 2 DE-HRV**	**Case Building 3 EAHP**
Service Costs	-3 250 SEK/year	-17 500 SEK/year	-4 375 SEK/year
Electricity Costs	-3 533 SEK/year	-12 093 SEK/year	-73 777 SEK/year
(- using 2022 spot prices)	(-5 511 SEK/year)	(-18 863 SEK/year)	(-108 745 SEK/year)
District-heating savings	27 621 SEK/year	17 009 SEK/year	132 833 SEK/year
(– of which district-heating power charge)	(6 159 SEK/year)	(3 793 SEK/year)	(23 398 SEK/year)
Rent/fee increase	20 160 SEK/year	N/A	N/A
Annual savings	40 998 SEK	-12 584 SEK	54 670 SEK
Investment cost	2 667 750 SEK	2 042 667 SEK	1 418 750 SEK
Payback period	65 years	N/A	26 years

DISCUSSION AND CONCLUSION

Case Building $1_{C\text{-}HRV}$ experienced the most significant improvement. Its primary energy consumption decreased by 23%, corresponding to 22 kWh/m²/year, while the specific energy use dropped by 25.5% (32 kWh/m²/year). The pre-renovation electricity and district-heating consumption numbers were based on aggregated design values from several properties included in Vidingehem's renovation project. The allocation of these aggregated values to Case Building $1_{C\text{-}HRV}$ was done proportionally based on floor area, introducing a certain margin of error. This type of discrepancy between design assumptions and operational data is well documented in the performance-gap literature, highlighting the need for calibration of real-life performance against calculated values, as recommended under EPBD provisions [5] and supported by empirical studies showing that calculations tend to overestimate savings [11]. The strong performance of the C-HRV system can be explained by both its technical configuration and the local tariff structure in Växjö. The system is fully centralised, ensuring uniform airflow, high heat-recovery efficiency and low electricity demand. Since the original system was exhaust-only, introducing balanced ventilation provided a large net reduction in heating needs. In addition, Växjö's district-heating tariff includes a relatively high power-based fee, making reductions in peak heat demand economically valuable. This combination of centralised heat recovery and tariff-driven benefits explains why Case Building $1_{C\text{-}HRV}$ achieves the most favourable improvement despite the high investment cost. Economically, the project involved the highest total cost (SEK 2.7 million), partly due to the construction of a fan room. The shortest simple payback period was 61 years based on 2021 price levels [22]. These calculations do not consider future price developments, and investment decisions for deep renovations that occur within policy frameworks such as the EPBD recast and EU Taxonomy [3], [2].

Case Building $2_{DE\text{-}HRV}$ was the only building where the primary energy number increased. The building originally had natural ventilation, resulting in lower airflow compared to mechanical systems. Installing decentralised HRV units increases ventilation rates to meet indoor-air quality standards, which raised heat losses even if comfort improves [6], [8]. Its specific energy use increased by 7.4% (10 kWh/m²/year). The apartments also lack thermostat limitations, unlike in Case Building $1_{C\text{-}HRV}$ and Case Building 3_{EAHP}, further contributing to higher energy use. In buildings without thermostat limitations, occupants often raise indoor temperatures, which increases space-heating demand. Combined with the higher airflow introduced by the DE-HRV units, this leads to more heated air being exhausted and replaced, helping explain the increased energy use.

It should be noted that no measured ventilation-flow or IAQ data were available for Case Building $2_{DE\text{-}HRV}$, which limits the precision of the energy-balance interpretation. The results should therefore be viewed as indicative rather than exact. The increase in energy use aligns with the behaviour of decentralised systems in older buildings. When passive ventilation is replaced, ventilation volumes typically rise, increasing thermal losses. Each apartment unit also uses its own fans, raising electricity consumption. Since Ljungby has no district-heating power charges, the measure gains little from reduced peak loads. From an economic perspective, the DE-HRV renovation produced a negative annual net outcome, since the additional fan electricity consumption exceeded the corresponding district-heating savings. Combined, these factors make the DE-HRV measure the least cost-effective of the three.

Case Building 3_{EAHP} achieved a 15% reduction in primary energy use (12 kWh/m²/year), and its specific energy use decreased by 24.3% (25.9 kWh/m²/year). Only one of the three on-site buildings provided exhaust air to the heat pump, but the recovered heat served all three buildings, achieving two-thirds of the theoretical potential savings at one-third of the cost. The system also benefits from low supply-temperature requirements, resulting in a high COP of 4.89. These results align with studies showing that EAHPs can be effective deep-renovation measures when distribution temperatures are low [7], [10], and that pairing EAHPs with PV can further improve economic viability [12]. The performance of Case Building 3_{EAHP} reflects the characteristics of exhaust-air heat pumps: stable exhaust-air temperatures support a high COP, but the system simultaneously increases electricity use and raises the building's subscribed electricity power level. This makes the economic outcome highly dependent on electricity prices and local tariff structures. Under 2021 prices, the payback period was 19 years [22], but under 2022 prices profitability decreases sharply. Field evidence from Swedish multi-family buildings indicates that hybrid control and smart energy management can improve cost performance [12]. This sensitivity to electricity price levels explains why EAHP systems show strong energy performance but mixed economic results.

Limitations

This study is based on real-world data from three renovated apartment buildings, which strengthens the practical relevance but also introduces some limitations. The buildings differ in age, construction characteristics and initial ventilation conditions, which influence their baseline energy performance. Although efforts were made to isolate the effects of each renovation measure, the presence of other parallel renovations and the use of normalized hot water values introduce some uncertainty. Economic results are directly dependent on local energy tariffs and may vary under different price scenarios. Furthermore, the detailed payback analysis assumes stable monthly consumption patterns, which may not fully reflect long-term behavioural or climatic variations. These limitations should be considered when interpreting the results and when generalizing the findings to other building stocks or regions.

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NOMENCLATURE

Abbreviations

HRV	Heat Recovery Ventilation
EAHP	Exhaust Air Heat Pump
C-HRV	Central Heat Recovery Ventilation

EU	European Union
EPBD	Energy Performance of Buildings Directive
HVAC	Heating, Ventilation and Air Conditioning
DE-HRV	Decentralised Heat Recovery Ventilation
MEV	Mechanical Exhaust Ventilation
IMD	Individual Metering And Billing
IAQ	Indoor Air-Quality
SFP	Specific Fan Power
BBR29	29th edition of Boverket's Building Regulations
RISE	Research Institutes of Sweden
VAT	Value Added Tax
COP	Coefficient of Performance.
SPB	Simple Payback Period
DPB	Detailed Payback Period
PV	Photo voltaic

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