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Techno-economic analysis of energy renovation measures for a district heated multi-family house

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Abstract

Renovation of existing buildings is important in the work towards increased energy efficiency and reduced environmental impact. The present paper treats energy renovation measures for a Swedish district heated multi-family house, evaluated through dynamic simulation. Insulation of roof and façade, better insulating windows and flow-reducing water taps, in combination with different HVAC systems for recovery of heat from exhaust air, were assessed in terms of life cycle cost, discounted payback period, primary energy consumption, CO_2 emissions and non-renewable energy consumption. The HVAC systems were based on the existing district heating substation and included mechanical ventilation with heat recovery and different configurations of exhaust air heat pump.

Compared to a renovation without energy saving measures, the combination of new windows, insulation, flow-reducing taps and an exhaust air a heat pump gave up to 24% lower life cycle cost. Adding insulation on roof and façade, the primary energy consumption was reduced by up to 58%, CO_2 emissions up to 65% and non-renewable energy consumption up to 56%. Ventilation with heat recovery also reduced the environmental impact but was not economically profitable in the studied cases. With a margin perspective on electricity consumption, the environmental impact of installing heat pumps or air heat recovery in district heated houses is increased. Low-temperature heating improved the seasonal performance factor of the heat pump by up to 11% and reduced the environmental impact.

Keywords: *District heating, air heat recovery, heat pump, LCC, primary energy, low-temperature heating*

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Nomenclature	
CO_2	carbon dioxide
COP	coefficient of performance
DH	district heating
DHW	domestic hot water
DPB	discounted payback
EAHP	exhaust air heat pump
HVAC	heating, ventilation and air conditioning
LCC	life cycle cost
LCCA	life cycle cost analysis
MVHR	mechanical ventilation with heat recovery
NRE	non-renewable energy
PEC	primary energy consumption
PEF	primary energy factor, kWh/kWh
RE	renewable energy
SFP	specific fan power, W/(l·s)
SPF	seasonal performance factor
U	heat transfer coefficient for building parts, $W/(m^2{\cdot}K)$

1. Introduction

District heating (DH) is well established in Sweden, serving around 85% of the dwellings in multi-family houses [1]. This is a high share in a European context, although in Denmark, Finland and the Baltic countries DH systems serve more than 50% of the citizens [2]. In total, there are 2.4 million dwellings in multi-family houses in Sweden, 75% of which are more than 40 years old [3]. This suggests a need for renovation, and a great potential for energy savings [4, 5]. 68% of the multi-family houses built within the period 1961-1980 have a mechanical exhaust ventilation system, while ventilation with heat recovery increased in popularity during 1981-2000 [6]. The DH in Sweden is, on average, to 87% derived from recovery of excess heat or from renewable fuels [7]. The share of fossil fuels is higher during starts and stops in production, which are required to meet the variations in demand [8, 9]. Moreover, there is typically a regional variation, for DH as well as for electricity, in how energy is produced and what the resulting CO_2 emissions, non-renewable energy (NRE) consumption and primary energy consumption (PEC) are [7, 10]. The total PEC is also dependent on the conversion factor. For example, heat production has a higher conversion factor than electricity production.

Although energy renovation of buildings is deemed a key in the work towards increased energy efficiency in the European Union [11], energy renovation of district heated buildings is a complicated matter for a number of reasons, including the relatively high share of renewable energy in DH production and the cogeneration of heat and electricity in many DH plants. In a system perspective it can often be better to reduce the electricity consumption than the heating demand, since reducing the heating demand of a district heated building could deteriorate the conditions for electricity production [12-14]. However, from the building owner's perspective it can be interesting to take energy saving measures in conjunction with a renovation to reduce the energy costs. Improving the energy performance of a house can also have positive effects on the indoor climate [15] and increase the value of the building [16]. Future district heating systems are likely to have a lower distribution temperature, 50 – 60 °C rather than today's 70 – 90 °C [17-20], to meet the needs of new and renovated buildings with low heating demand. As a result, the district heating temperature will also be better suited for low-temperature heating systems, such as floor heating or low-temperature radiators, with distribution temperatures of 35 – 45 °C [21].

Previous studies by Gustafsson et al. [22, 23] have shown that exhaust air heat pump (EAHP) and mechanical ventilation with heat recovery (MVHR) can both be beneficial solutions, with respect to cost and energy consumption, for energy renovation of single family houses in northern and central Europe, and that the advantage of heat recovery from exhaust air becomes larger in cold climates. Furthermore, these studies showed that low-temperature radiator systems improve the energy performance of heat pumps. Liu et al. [24] studied energy saving measures for multi-family houses in Gävle, Sweden. The study showed promising technical potential, although many of the studied measures were deemed unprofitable, in particular façade insulation, windows with low U-value and MVHR. This, however, was based on a reference case where no renovation was done to the building. They also pointed at the need for more research on EAHP as an alternative to MVHR, especially in leaky buildings where the MVHR would struggle to achieve a good level of efficiency. Truong et al. [25] and Gustavsson et al. [26] discussed, also in a Swedish context, the complexity of evaluating effects of energy saving measures in buildings with district heating, pointing at the importance of the interaction between end-use measures and supply systems. Truong et al. [25] and Dodoo et al. [27] concluded that MVHR could lead to significant savings of primary energy in a Swedish climates, although without comparison with EAHP as an alternative heat recovery system. The potential primary energy savings were shown to be larger in houses with direct electric heating than in district heated houses [27], and the size of the savings in district heated houses depend on the energy mix in the local DH production [25].

The present study complements the existing research on renovation of residential buildings, investigating environmental and economic aspects of HVAC systems with air heat recovery and measures to reduce the energy demand of a district heated multi-family house. The studied HVAC systems included three systems with EAHP together with DH in different configurations: EAHP used for space heating or for both space heating and domestic hot water (DHW) production, including one variant with a low-temperature radiator system. The three heat pump systems, plus one system with MVHR, were compared against a reference system with only DH and exhaust ventilation without heat recovery. All systems were evaluated in combination with two sets of energy renovation measures: better insulating windows and flow reducing water taps, and insulation on roof and façade. The aim of this study was to investigate the possible economic incentives and environmental benefits for owners of district heated houses to perform energy efficiency measures as part of a planned renovation.

The renovation measures were assessed in terms of life cycle cost (LCC), discounted payback (DPB) time and, with respect to the European climate and energy goals [28], CO_2 emissions, PEC and NRE consumption. For NRE, the EU goal is formulated as a target share of 27% renewable energy sources. Here, both the total amount of NRE and the non-renewable share of the total energy consumption were considered.

The building and the HVAC systems were modelled and simulated in TRNSYS 17 [29]. All HVAC systems were designed to provide space heating, DHW and ventilation, while cooling was left out of the scope. Likewise, periodic time variations of energy prices and of environmental factors were disregarded in this study, but the impact of economic factors and different assumptions on electricity production was investigated.

2. Building and system models

The building model used in this study represented a four-story residential building, with a heated area, including stairwells, of 4700 m². Most of the 2340 m² brick façade and the 700 m² windows and doors were oriented towards east and west, as shown in Figure 1. The roof had an area of 1210 m² and 4° inward inclination along the central line. In the model, there were nine zones for the living area – three zones per floor on three floors, each zone comprising three apartments – plus three zones for the stairwells and one for the unheated attic. To get results for a complete floor (15 apartments), adiabatic connection to adjacent zones was assumed and the results of the middle living zone and stairwell were multiplied by three, as illustrated in Figure 1. Similarly, to get results for four floors, results for the entire middle floor were multiplied by two. Heat transfer between the ground floor slab and the ground was modelled in accordance with ISO 13370 [30]. Internal shading was applied on windows facing east, west and south when the total solar radiation on the respective surface exceeded 200 W/m², and removed when the radiation dropped below 150 W/m². Windows and balcony doors on the east and west sides were also partially shaded by the balconies. All zones had a total air change rate of 0.5 h^{-1}, in accordance with Swedish building regulations [31]. For the living zones, 0.1 h^{-1} of this was assumed to be infiltration and 0.4 h^{-1} controlled ventilation through supply air ducts. For the attic and stairwell zones, all ventilation was assumed to be infiltration. Simulations were done with hourly climate data from Meteonorm [32] for Stockholm (Bromma Airport weather station). The yearly average dry bulb temperature for the simulated location was 6 °C.

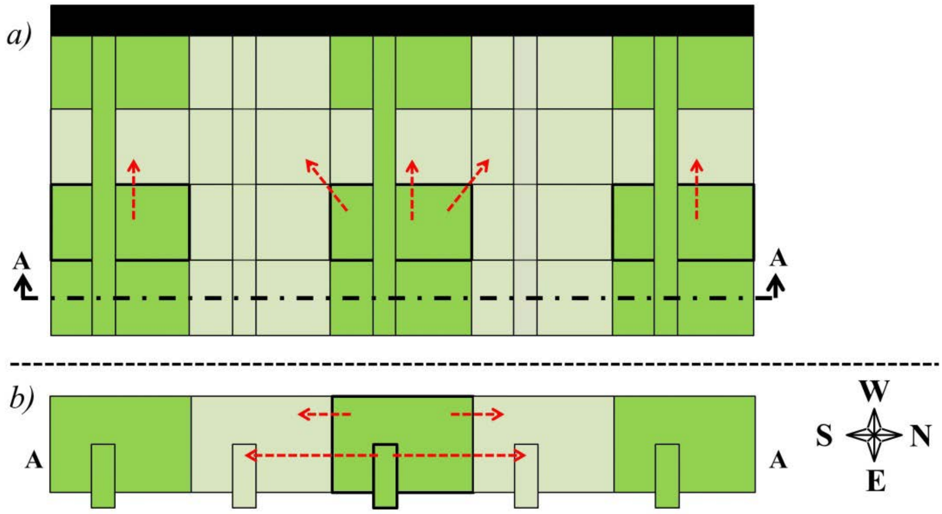

Figure 1: *Layout of the building model. Nine living zones and three stairwells were modelled (dark), and results of the middle zones, middle stairwell and middle floor were multiplied to represent additional zones and render results for the whole building: a) View from front: vertical multiplication of middle floor; b) View from above: horizontal multiplication of middle zones.*

Simulations of the building model and the HVAC systems were done in TRNSYS 17, a software for transient simulation of buildings and energy systems [29]. One year of operation was simulated, plus an initial stabilizing period of one month, with a time step of three minutes. Radiators were simulated with an Excel model [33], connected to the rest of the system via a link embedded in TRNSYS. There was one Excel sheet for each type of radiator: traditional and ventilation radiators in the living zones and traditional radiators in the stairwell zones. The outputs from these models were then multiplied, analogous to the zones, to obtain the total water flow and heat output for the whole heating system. The building model was created in the TRNSYS interface TRNBuild.

Three renovation levels were defined, as listed in Table 1. Level 0 (reference level) included basic renovation and repairs to maintain functionality of the building, such as change of windows, façade repairs, tuning of radiator system and change of water taps. The house then had U-values of 0.60 W/(m²·K) for walls and 2.58 – 2.72 W/(m²·K) for windows and balcony doors, varying depending on the frame-to-glazing ratio. The DHW demand was set to 53 l/day per person at 45 °C [34]. Levels 1 and 2 included changing to triple glazed windows and balcony doors rather than double glazed. For level 2, insulation of façade (80 mm) and roof (195 mm) was added. The flow reducing water taps and shower heads applied for levels 1 and 2 were assumed to reduce the total DHW demand by 27%, reducing the flow of all draw-offs except for baths by 30% [35].

Table 1: *U-values of building elements and DHW demand for renovation levels 0, 1 and 2.*

Level	U-value, W/(m²·K)			DHW demand, l/(p·day) @ 45 °C
	Walls	Roof	Windows and doors	
0	0.60	0.60	2.58 – 2.72	53
1	0.60	0.60	1.22 – 1.38	39
2	0.26	0.15	1.22 – 1.38	39

Heat gains from people, six persons per zone, were set to 120 W/person, corresponding to seated, light activity according to ISO 7730 [36]. Electrical appliances and lighting contributed on average 3.6 W/m². Schedules setting internal gains from people and electrical equipment were generated separately for each zone using stochastic probability models [37]. Once generated, schedules were fixed and equal in all simulations. Schedules for DHW use were generated and applied in a similar way, but with one aggregated profile for the whole house, taking into account different types of DHW use and the non-simultaneity of draw-offs [38]. The maximum flow rate for the whole house was 145 l/min. Examples of DHW use and internal gains for one day are shown in Figure 2. All schedules had a time resolution of three minutes.

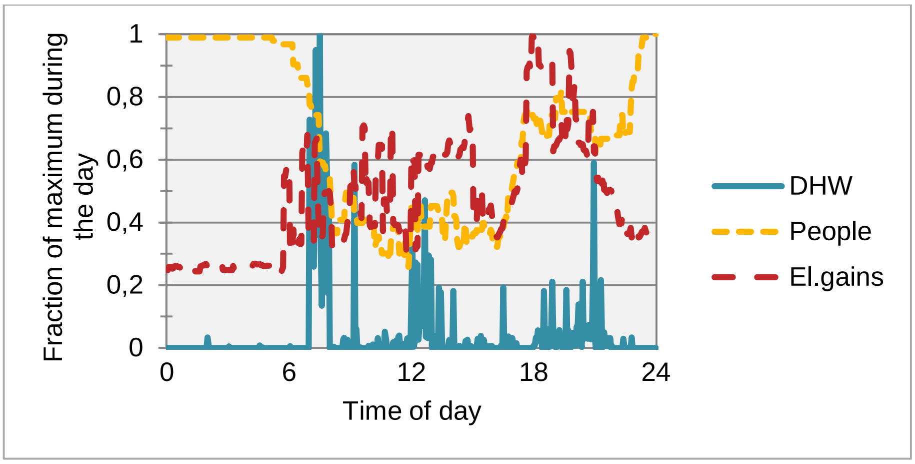

Figure 2: *Example of schedules for DHW use and heat gains from people and electrical appliances for one day.*

The house was assumed to have a simple parallel, single stage DH substation, hydronic radiator system and mechanical exhaust ventilation before renovation. The radiators were sized, for the reference case, for a distribution temperature of 55 °C in winter conditions. In addition to the existing HVAC system, denoted “0”, four other system combinations were studied: A) 0 + MVHR; B) 0 + EAHP for heating; C1) 0 + EAHP for both heating and DHW; C2) C1 + some radiators converted to ventilation radiators. System layouts are shown in Figure 3. The conversion of radiators to ventilation radiators implies installing air ducts through the wall behind them. The radiators will then preheat supply air and enable a lower water temperature in the heating system [22, 39]. In C2, 7 of the 14 radiators in each zone were converted to ventilation radiators, giving an air flow of 8.9 l/s per ventilation radiator. The layout and function of systems B and C1/C2 were based on investigations by the Swedish District Heating Association on combinations of DH and EAHP in multi-family houses [40, 41]. The heat pump used in these systems was a Thermia Mega XL with a variable speed compressor [42], which means it can adjust the compressor speed to match the load. The maximum heat output and compressor speed were limited by the available energy content in the exhaust air. Hence, the heat pump operated according to the ventilation flow rate. It had a nominal coefficient of performance (COP) of 4.71 and compressor output of 11 kW at brine/water temperature 0/35 °C. Performance data, with compressor power for a range of compressor frequencies, brine and water temperatures, was provided by the manufacturer and used as a performance map for the heat pump model. The heat output was calculated as the sum of net compressor power and net heat from exhaust air when cooled from room temperature to 5 °C.

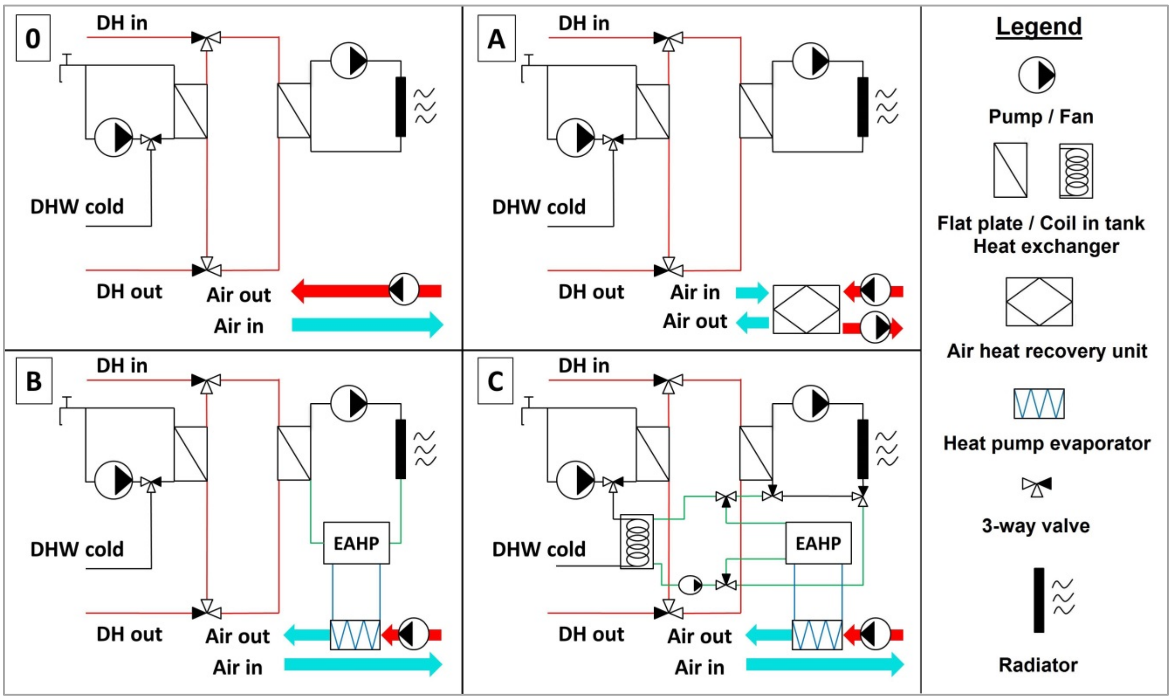

Figure 3: *System combinations for space heating, DHW and ventilation. System C had two variants: C1 with traditional radiators and C2, where some of the radiators were converted to ventilation radiators.*

For all cases, the DH distribution temperature was set to 78 °C, increasing by 1 °C for each degree the outdoor temperatures fell below 0 °C, and the DH flow was regulated by on/off-controllers to meet the DHW and space heating loads. The DH controllers were set to keep the DHW temperature, for draw-offs as well as circulation, at 50 °C (±0.50 °C), and the convective air temperature in the living zones at 22 °C, with a lower dead band of 0.25 °C. In practice, this meant the room temperature was kept at 21.75 °C during the heating season. The stairwell radiators were sized to keep a room temperature of 18-19 °C when the living zone temperature was 22 °C.

All ventilation fans were run all year around. The MVHR in system A was assumed to have a constant thermal efficiency of 85%, but the heat recovery unit of system A was bypassed at outdoor temperatures above 14 °C. Hydronic pumps were included in the system models, while energy use for fans was calculated based on air flow and type of ventilation. Exhaust ventilation (system 0) was assumed to have a specific fan power (SFP) of 0.45 W/(l·s), increasing to 0.75 W/(l·s) when exhaust air was used as source for EAHP. The SFP of the MVHR system was assumed to be 1.50 W/(l·s). These values correspond to 75% of the maximum values recommended in Swedish regulations for new buildings [31]. For systems 0, B, C1 and C2, the existing ventilation ducts were assumed to be sufficient, while for system A additional supply air ducts had to be installed.

The heat pump in systems B, C1 and C2 was placed in series with the DH substation with the heat pump first, as shown in Figure 3, to obtain the lowest possible inlet temperature for the condenser and improve the COP of the heat pump. It was operated with the same type of controllers as the DH but with a higher room temperature set point (22 °C) for heating. That way it could be run at maximum capacity and cover as much as possible of the heating demand before the district heating started acting as backup. Furthermore, this configuration ensures that all systems provide at least the same room temperature as the reference system. In systems C1 and C2, the heat pump of was set to keep the temperature at 1/3 of the height in the DHW preparation tank at 40 °C (±3 °C). Cold water was preheated in the tank through an internal heat exchanger, and then heated to the required temperature in the DH heat exchanger. The heat pump was set to prioritize DHW preparation before space heating, while DHW circulation losses were covered by DH.

3. Economic and environmental impact analysis

The economic analysis included life cycle cost analysis (LCCA) and discounted payback period (DPB). In an LCCA, the options are compared in terms of life cycle cost (LCC), where the one with the lowest LCC is considered the most profitable [43]. DPB period is the time it takes for the savings to repay the investment [44]. Both methods take into account the net present value of future costs; the difference is that the DPB calculations end at the point where the investment reaches break-even.

The time frame of the LCCA in this study was set to 30 years, starting at installation and not including disposal costs. Future costs, including annual energy and maintenance costs, were converted into net present value, taking into account an interest rate of 4%, as recommended in guidelines from the European Commission on methodology for calculation of cost-optimal energy renovation of buildings [45]. The same method was used to account for reinvestment costs for systems and components that reached the end of their technical lifetime before the end of the calculation period, and residual value of those that did not reach the end of their technical lifetime. Net present values for DPB were calculated the same way, with the same interest rate.

Investment costs, maintenance costs and technical lifetimes of the renovation measures are listed in Table 2. For windows, doors, water taps and shower heads, only the extra costs compared to conventional alternatives were considered, as they were assumed to be replaced in the frame of the basic renovation (level 0). For the same reason, the initial investment cost for exhaust fans was excluded for systems 0, B, C1 and C2 and subtracted from the MVHR cost for system A to give the net cost of additional air ducts, heat recovery unit and supply air fan. Costs for HVAC systems and building elements were taken from manufacturers and retailers [46, 47], technical reports [48, 49] and a database for construction calculations [50]. The cost for MVHR can vary greatly between buildings. The value used in this study was therefore taken to fit within a range found in different sources [48, 49]. Taking maintenance costs into account, all systems were assumed to be fully functional until the end of their technical lifetime, i.e. their performance was assumed not to degrade over time. Maintenance costs for HVAC systems were assumed to be 1% of the initial investment costs, whereas water taps and measures to the building envelope were assumed to not increase maintenance costs compared to the reference level. Labor costs were taken from statistics [51] and are included in the total costs in Table 2.

Table 2: *Investment costs, maintenance costs and technical lifetimes for the studied renovation measures. *Cost for system B; x2 for systems C1 and C2.*

Category	Renovation measure	Total investment costs, €	Maintenance costs, €/year	Technical lifetime, years
Heating	EAHP	17 200	172	20
	Pipes, valves and controllers for EAHP*	6 000	60	30
	DHW prep. tank	6 100	61	20
Ventilation	Exhaust fans	26 300	263	15
	MVHR	198 100	1 981	15

	Radiator air ducts	16 800	168	30
Building envelope	Windows (3-pane ins.)	168 100	-	30
	Balcony doors (ins.)	30 700	-	30
	Roof ins. (195 mm)	62 100	-	30
	Façade ins. (80 mm)	71 900	-	30
DHW	Flow red. taps and showers	2 800	-	15

Prices for DH and electricity for domestic consumers, including taxes, were taken from statistics [2, 52]. The energy price growth rate, for both electricity and district heating, was set to 3%/year for the whole period, including a 1% inflation rate. No periodic variation was assumed. The primary energy factors (PEF), CO_2 emission factors and shares of RE were calculated for Swedish average DH and Nordic electricity mix by weighting factors for the different inputs [7]. The Nordic electricity production is to 67% based on hydropower, 20% nuclear and 13% combined heat and power, while the DH production is mainly based on biofuels and waste, with some fossil fuels and electricity to cover peak loads. The PEFs include the energy of the energy carrier for fossil fuels and potential energy for hydropower, but not energy from waste or wind energy for wind power [7]. The environmental impact analysis was limited to the use phase and did not include embodied energy of materials, assuming the contribution of embodied energy would be relatively small in the life cycle perspective [53]. Energy prices, PEFs, CO_2 emission factors and share of RE are listed in Table 3. Time variations of environmental factors were not included in this study, i.e. the values in Table 3 were assumed to be constant over the whole 30 years.

Table 3: *Energy prices, primary energy factors, CO_2 emissions and share of renewable energy for district heating in Sweden, for Swedish and Nordic electricity mix, for 100% renewable electricity production and for 100% non-renewable electricity production.*

Energy carrier	Production	Energy price, €/kWh	PEF, kWh/kWh	CO_2 em. g/kWh	Share of RE, %
DH	Swedish av.	0.074	0.79	89	87
Electricity	Swedish mix	0.138	2.10	36	55
	Nordic mix	0.138	1.74	97	67
	100% NRE	0.138	3.00	1000	0

In the economic sensitivity analysis, investment and maintenance costs were varied by ± 20%, while interest rate and energy price growth were changed by ± 1 percentage point. In the environmental sensitivity analysis, the impact of using factors for Nordic electricity mix was compared to Swedish electricity mix [7] and marginal electricity production. The factors used are listed in Table 3. Marginal electricity production implies that all additional electricity used, compared to the reference case, is derived from 100% NRE.

4. Results

Life cycle costs, primary energy consumption, CO_2 emissions and non-renewable energy consumption for all systems and renovation levels are shown in Figure 4. The reference case (system 0, renovation level 0) is used as index (= 0), marked with a thick border line. Results for all the other cases are set in relation to this, where values < 0 indicate an improvement for that specific factor, and values > 0 indicate that the reference case is better. All systems were found to be able to provide heating and DHW at desired temperatures. The average room temperature was slightly higher with the heat pump systems, due to the higher set temperature used for the heat pumps. However, most of the time the heat pump did not cover the whole heating demand and the room temperature was equal to the set point of the DH.

The heat pump systems B, C1 and C2 were nearly equal with respect to both economic and environmental performance. Compared to the reference system for the same renovation level, the heat pump systems had up to 19% lower LCC (system C1), 26% lower PEC (system B), 37% lower CO_2 emissions (system B) and 23% lower NRE consumption (system B). System A was on the same level in terms of PEC (up to -25%) and NRE (up to -24%) but not as good regarding CO_2 emissions, and the LCC was higher than for the reference system. Renovation level 1 had lower LCC than level 0 in all cases, while level 2 had slightly higher LCC than level 1 for the heat pump systems. PEC, CO_2 emissions and NRE consumption (Figure 4) all decreased for higher renovation levels, while the share of NRE increased for systems A, B, C1 and C2 and for higher renovation levels. The best combination altogether was renovation level 2 and system B, closely followed by C1 and C2. Compared to the reference case, this case had 24% lower LCC, 58% lower PEC, 65% lower CO_2 emissions and 56% lower NRE consumption.

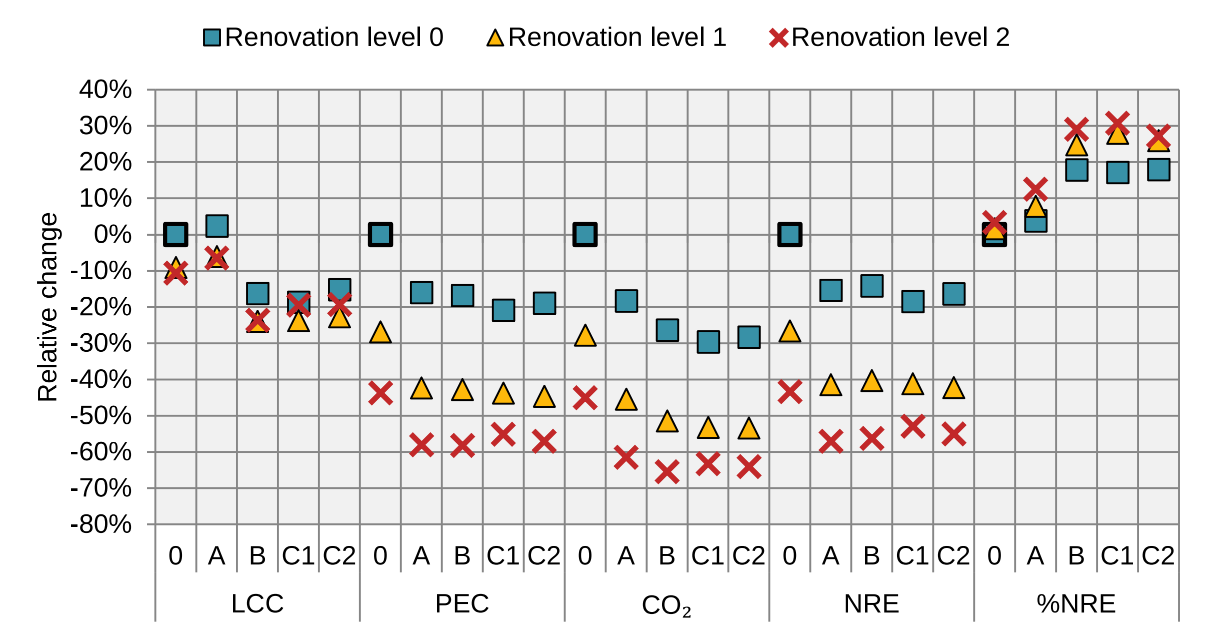

Figure 4: *Life cycle cost, primary energy consumption, CO_2 emissions and absolute and relative non-renewable energy consumption of all studies cases.*

The heat pump systems had the shortest payback periods (Table 4): 2.6 years, 3.3 years and 5.6 years, respectively, for renovation level 0. For the same renovation level, system A did not save enough on the energy cost to pay back the higher investment cost, and for levels 1 and 2 the payback period for system A was over 40 years. With the heat pump systems, levels 1 and 2 had payback periods of 13 – 14 years and 19 – 23 years, respectively.

Table 4: *Discounted payback period for all renovation levels and HVAC systems.*

Renovation level	Discounted payback period, years				
	0 (ref)	A	B	C1	C2
0	N/A	-	2.6	3.3	5.6
1	22.8	41.8	12.8	13.3	14.4
2	28.8	44.4	19.2	22.6	23.2

Table 5 shows the seasonal performance factors (SPF) of the heat pump in systems B, C1 and C2. For the DHW part, the SPF in C1 and C2 was 5.29. The low-temperature radiators in system C2 resulted in up to 11% higher SPF of the heat pump (level 0) and lower environmental impact, but the cost was similar to or slightly higher than C1. Likewise, the radiator temperature decreased and the SPF increased by reducing the heating demand from level 0 to levels 1 and from level 1 to level 2.

Table 5: *Seasonal performance factor (SPF) of the heat pump for all system combinations and renovation levels*

Renovation level	Heat pump SPF		
	B	C1	C2
0	4.55	4.58	5.09
1	5.09	5.06	5.58
2	5.64	5.68	6.13

In Table 6, the share of heating demand (space heating, DHW and total) covered by the heat pump is shown for systems B, C1 and C2. In system B, the heat pump was able to cover a larger share of the space heating demand, as in C1 and C2 the heat pump prioritized DHW. The total coverage, however, was larger for these two systems. The exception was C2 at renovation level 2. The total output of the heat pump was slightly reduced in system C2 compared to C1, as the compressor speed was lower at the lower temperature of the heating system, leading to a lower percentage of heating demand covered by the heat pump.

Table 6: Share of heating demand – space heating, DHW and total – covered by the heat pump in systems B, C1 and C2 for all renovation levels

Renovation level	System	Heating demand covered by heat pump		
		Space heating	DHW	Total
0	B	44.0%	-	35.4%
	C1	41.8%	16.7%	37.2%
	C2	40.9%	16.7%	36.4%
1	B	54.8%	-	43.7%
	C1	52.2%	20.2%	46.5%
	C2	51.1%	20.2%	45.6%
2	B	66.8%	-	49.0%
	C1	57.8%	20.2%	49.4%
	C2	52.4%	20.2%	44.7%

The specific energy consumption (electricity + DH) for all systems and renovation levels is shown in Figure 5. The reference case had 4 kWh/(m²·a) of electricity consumption, for ventilation fans and circulation pumps, and 137 kWh/(m²·a) of DH. The energy consumption decreased, for all systems, from level 0 to level 1 and from 1 to 2. Installing a heat pump without any other energy savings measures (level 0) was approximately equal to renovating to level 1 and keeping the reference heating system, in terms of total energy consumption. Renovation level 1 in combination with a heat pump gave lower energy consumption than the reference system at level 2.

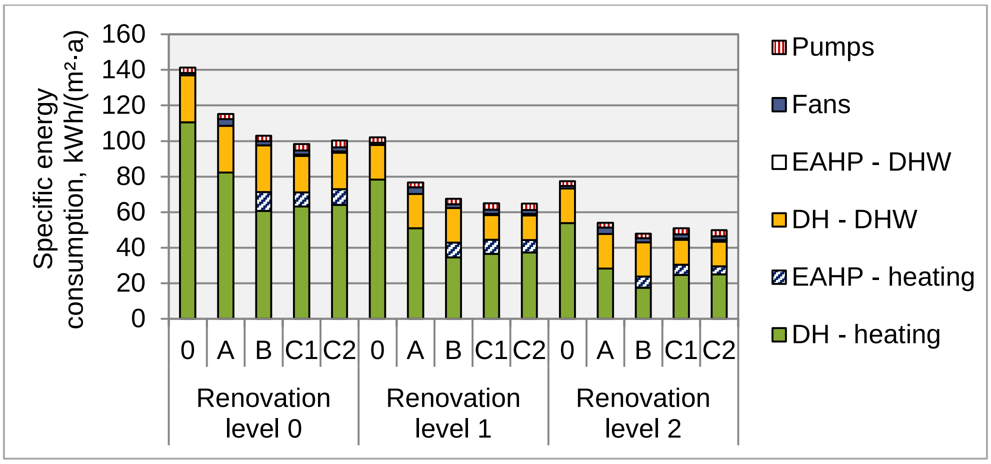

Figure 5: *Specific energy consumption (district heating and electricity) for all renovation levels and HVAC systems*

Figure 6 shows the LCC divided into investment costs for climate shell, heating system and ventilation system, energy costs for district heating and electricity, maintenance costs and reinvestment costs. System A had the highest costs for investment and maintenance, due to the high cost of installing ventilation with heat recovery (see Table 2). For renovation level 2, investment costs constitute between 36% (system 0) and 51% (system A) of the LCC.

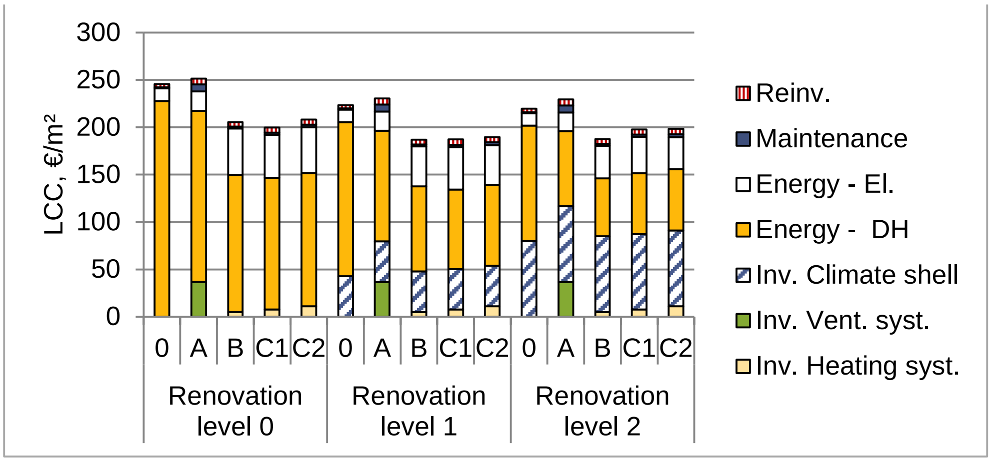

Figure 6: *Detailed LCCA results for all renovation levels and HVAC systems.*

The sensitivity analysis for environmental factors of electricity is shown in Figure 7 for renovation level 1. A marginal perspective on increased electricity consumption increases the PEC, absolute and relative NRE consumption and particularly the CO_2 emissions of the heat pump systems. There are also moderate increases for the MVHR system, although the PEC is still lower for this system and for the heat pump systems than for the reference system. With Swedish electricity mix, the PEC and the NRE consumption are slightly increased, while the CO_2 emissions are reduced.

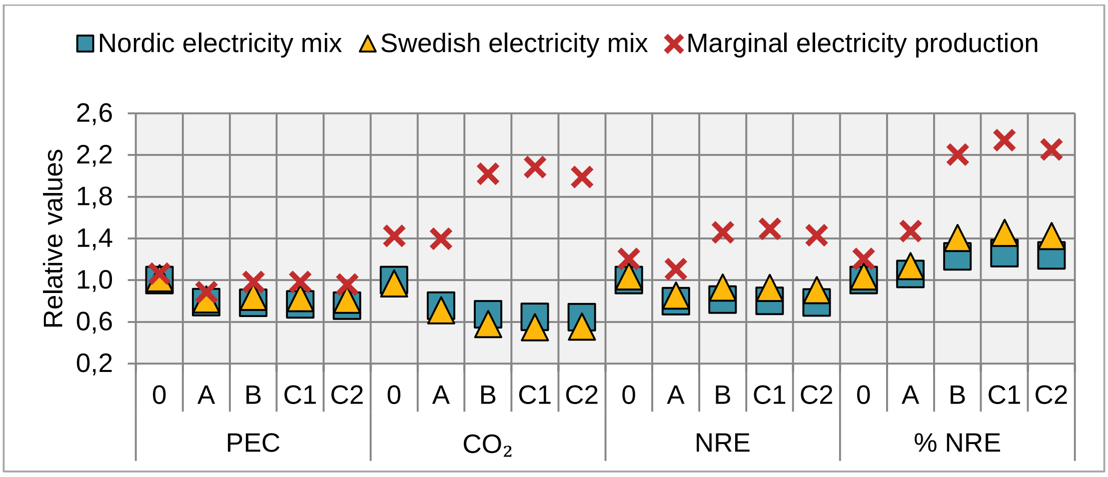

Figure 7: *Relative PEC, CO_2 emissions, NRE consumption and share of NRE with factors for Nordic electricity mix, Swedish electricity mix and marginal electricity production for renovation level 1*

The effects on LCC of varying interest rate, investment and maintenance costs and energy price growth are shown in Figure 8 for renovation level 1. The interest rate is seen to have equally large impact on all systems. Investment and maintenance costs have most influence on system A, and with 20% lower costs the LCC of system A is lower than the reference system. Electricity price growth mainly affects the heat pump systems, but that alone is not enough to increase their LCC to the level of the reference system. The DH price growth mainly influences the reference system.

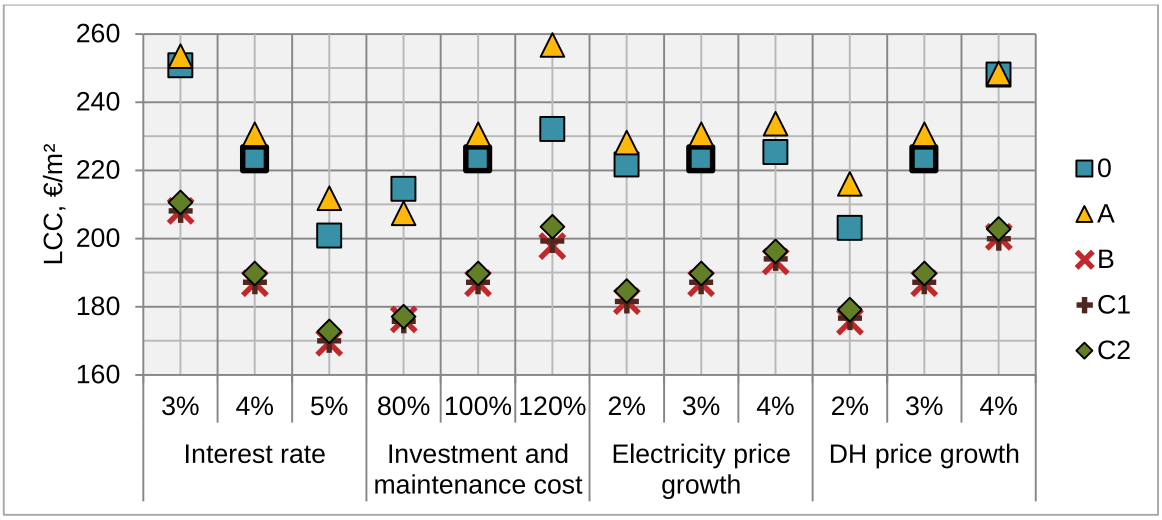

Figure 8: *Influence on LCC of interest rate, investment and maintenance cost, electricity and DH price growth for renovation level 1.*

5. Discussion

In this study, the economic and environmental viability of building envelope and HVAC systems renovation measures in a district heated multi-family house have been assessed. As economic indicators, life cycle cost (LCC) and discounted payback (DPB) period were used, while the environmental aspects were selected based on the European climate and energy goals for 2030: primary energy consumption (PEC), CO_2 emissions and non-renewable energy (NRE) consumption.

Exhaust air heat pump (EAHP) was found to be the most beneficial complement to DH in terms of LCC, PEC, CO_2 emissions and, for most renovation levels, NRE consumption. When the heat pump provides both DHW and space heating, with DH as backup, it can be used even during summer when there is no space heating demand. The difference between this and system B (heat pump for space heating only) was larger for lower heating demands, as DHW constituted a larger share of the total demand. A low-temperature heating system, in this case with ventilation radiators, makes the heat pump more efficient. Although not shown in this study, ventilation radiators should also be a favorable choice for good thermal comfort, since they provide warm supply air and reduce cold draft [39]. If the heat pump prioritizes space heating before DHW, the low-temperature heating system should have even larger impact on the heat pump performance. This configuration will be a subject of future studies. It would also be of interest to do a more extensive environmental analysis, to compare the environmental impact of the renovation measures from cradle to grave, taking into account embedded energy and use of material.

The EAHP in this study used only exhaust air as energy source, which means the heat output is limited by the ventilation rate and the compressor speed. In practice, EAHPs for multi-family houses may use a secondary heat source, e.g. ground heat, to compensate for this limitation and enable the heat pump to cover a larger share of the heating demand. This would of course increase the investment cost and the electricity consumption, but could reduce the energy costs. Another possibility, although even more costly, would be to combine an air source or ground source heat pump with MVHR. Additional DHW storage tanks might also be necessary to cover peak loads.

From an economic perspective (Figure 4), renovation level 1, with better insulating windows and doors and flow reducing water taps and shower heads, was profitable for all systems. Renovation level 2, adding insulation on roof and façade, had lower LCC than the reference level but higher than level 1 in combination with the heat pump systems, as the reduced energy costs were smaller than the added investment costs. However, the discounted payback period for level 2 was only around 19 – 23 years with a heat pump system and 29 years with the reference system, which is still less than the expected lifetime of such renovation measures. The possible added value of the building following energy renovations [16] might increase the viability of level 2, but that was not considered in this study. Moreover, improving the thermal performance of the building reduces the peak heat load, thus lowering the peak power demand of the energy generation system [12, 14]. Reducing the transmission losses through roof and façade will also increase the mean surface temperature in the room, thereby improving the thermal comfort.

When it comes to PEC, CO_2 emissions and NRE consumption (Figure 4), they all decreased with higher renovation levels, i.e. lower heating demand. The share of non-renewable energy (NRE) increased with higher share of electricity use, as the electricity production has, on average, a lower share of RE than the DH production (Table 3). This was most clearly seen for the heat pump systems and the higher renovation levels. However, the absolute amount of consumed NRE decreased for the same cases. Seeing that even a reduction of heating demand in a district heated house increases the share of NRE, it seems more correct to use the absolute numbers as indicator when assessing the energy performance of a building with respect to the climate and energy goals.

With a margin perspective on changes in electricity consumption, assuming that all changes affect the use of NRE in electricity production (Figure 7), all environmental indicators increase for the heat pump systems as well as for the MVHR system (A). On the other hand, excluding the potential energy of hydropower in the calculation of PEF for electricity, which is a perfectly reasonable assumption [7], the MVHR and heat pump systems would have even lower environmental impact. The margin effect on DH production [8] was not included in the comparison, as it is difficult to generalize, but that, as well as a variation of DH production mixes and solar PV panels to cover part of the electricity consumption, would be of interest for future studies.

One of the difficulties in LCCA, DPB and other forecasting methods is to predict the change in governing parameters such as energy prices and environmental factors. The common approach is a constant energy price growth and constant environmental factors, but the Swedish electricity price, for example, has had little or no net increase over the last eight years [52]. Seasonal variation is another aspect which will be addressed in future studies.

The system analysis was in this case limited to a single building, considering only the local impact of energy renovation measures. The placement of the heat pump in systems B, C1 and C2, before the DH heat exchanger, will lead to an increased return temperature for the DH, which is not optimal for the performance of the DH plant. With low-temperature heating, one possibility, beside low-temperature district heating [17], would be to heat the house with the DH return temperature instead of the supply, thus lowering the return temperature rather than increasing it. This will be investigated in future studies.

With the current assumptions regarding energy consumption, heating and ventilation system for the existing case, the studied building model represents a large share of the Swedish residential building stock [1, 3, 6]. The results should also, to some extent, be applicable to other Nordic countries, as well as the Baltic countries. For other countries in Europe, the conditions are a bit different; even though the age structure of residential buildings is similar to that in Sweden in many countries [54], district heating is less common [2]. The local conditions regarding energy production mixes and energy prices should also be considered, especially for other countries but also for specific cases within Sweden.

6. Conclusions

The results of this study show that it is possible for the owner of a district heated multi-family house to reduce both the costs and certain environmental impact through energy saving measures as part of a renovation. EAHP in combination with flow-reducing water taps and improvements of the building envelope reduced the life cycle cost by up to 24%, primary energy consumption up to 58%, CO_2 emissions up to 65% and non-renewable energy consumption up to 56%, compared to the reference case with only district heating and no energy saving measures. The payback period of the EAHP alone was 2½ – 5½ years. The overall environmental impact of the MVHR system was almost as good as that of the heat pump systems, but it was not profitable. The low-temperature heating system improved the SPF of the heat pump by up to 11%, and adding DHW preparation increased the total share of heating demand covered by the heat pump compared to only using it for space heating.

When it comes to non-renewable energy consumption, the absolute amount should be considered rather than the relative share of non-renewable energy, which can in fact increase following a renovation of a district heated house, as it often increases the relative share of electricity consumption. With a margin perspective on electricity consumption, the CO_2 emissions and non-renewable energy consumption increase when installing heat pumps or air heat recovery in district heated houses. However, the primary energy consumption still decreased compared to the reference system and could be even lower, depending on how the primary energy factor for electricity is calculated.

Of the studied building envelope renovation measures, better insulating windows and flow reducing water taps were found to be both economic and environmentally beneficial if done in combination with a planned renovation. Additional insulation on façade and roof did not add to the economic savings, but reduced the environmental impact.

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