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Frost reduction in mechanical balanced ventilation by efficient means of preheating cold supply air

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Abstract. This study has focused on evaluating the financial potential of wastewater and geothermal heat recovery systems in a multi-family building. The recovered heat was used to improve the performance of mechanical ventilation with heat recovery (MVHR) system during the coldest days in central Sweden. The main issue, which was targeted with these solutions, was to reduce frost formation in the system and hence increase its thermal efficiency. By looking at the life cycle cost over a lifespan of 20 years, the observed systems were being evaluated economically. Furthermore, statistical analyses were carried-out to counter the uncertainty that comes with the calculation. It was found that the studied wastewater systems have a high possibility of generating savings in this period, while the one fed by geothermal energy is less likely to compensate for its high initial cost. All designed systems however, managed to reduce operational cost by 35-45% due to lower energy usage.

1. Introduction

Mechanical ventilation heat recovery (MVHR) systems are a common technology in the Swedish market. These systems utilize the recovered heat from the exhaust air for preheating the incoming outdoor air [1]. One major drawback of these systems in cold climates, is the frequent formation of frost on the heat-transferring plates during colder days. The warm, moist the return air can no longer retain its humidity after being cooled down and the condensation starts to freeze. This leads to a decreased thermal efficiency of the system and a higher electricity demand. To cope with the issue, the system switches into a defrosting mode[2] Nasr et al. [3] reviewed defrosting methods and evaluated their thermal efficiency. Preheating the outdoor air before it enters the MVHR-unit was found to be the most effective method to prevent frosting.

The present research work explored the financial performance of an improved MVHR system with an air-preheating solution that employs wastewater or geothermal energy as its heat source to reduce the frost formation in MVHR system during cold periods in Sweden. The aim was to find out if current state-of-the-art technology can compete with conventional ventilation heating systems.

The systems designed for this study were technically assessed and optimized in details in several previous studies [4–6]. The previous study [6] showed that the air preheating systems could reduce the defrosting need by 25%. This would maintain the heat recovery efficiency of the MVHR system above 80% for almost 90% of the studied period. The electricity need of wastewater/brine circulation pumps was 2%-8% of the recovered heat energy from wastewater or borehole. The operational time of the circulation pump was reduced to 37% of the studied time period, when turning off the preheater once outdoor temperatures reached a sufficient level. The outdoor air preheating above the frost start threshold - does not significantly contribute to better efficiency of the entire system.



For this paper, the life cycle cost of each heat recovery system was calculated and compared. Since there is a lack of reliable data in this field to base the calculations on, some assumptions were required. This approach however attributes the result with a degree of uncertainty. To counter the issue of uncertainty risk, two -statistical methods, namely Monte Carlo simulation and sensitivity analysis, were -implemented.

2. Methodology

The studied improved MVHR systems, as shown in Figure 1, are compared to the base - system. The base system was traditional MVHR without additional outdoor air preheating system. System 1 used the geothermal energy as the heating source. The stored geothermal heat was used to preheat the incoming outdoor air in an air preheater (heat exchanger) placed in front of the MVHR. The other two systems used wastewater as a heat source. System 2 was equipped with a stratified storage tank to utilize a benefit of temperature stratification and reach a higher thermal efficiency. System 3 is similar to System 2 but operates with an unstratified tank. Further technical details and boundary conditions of the used system can be found in study by Nourozi et al. [6].

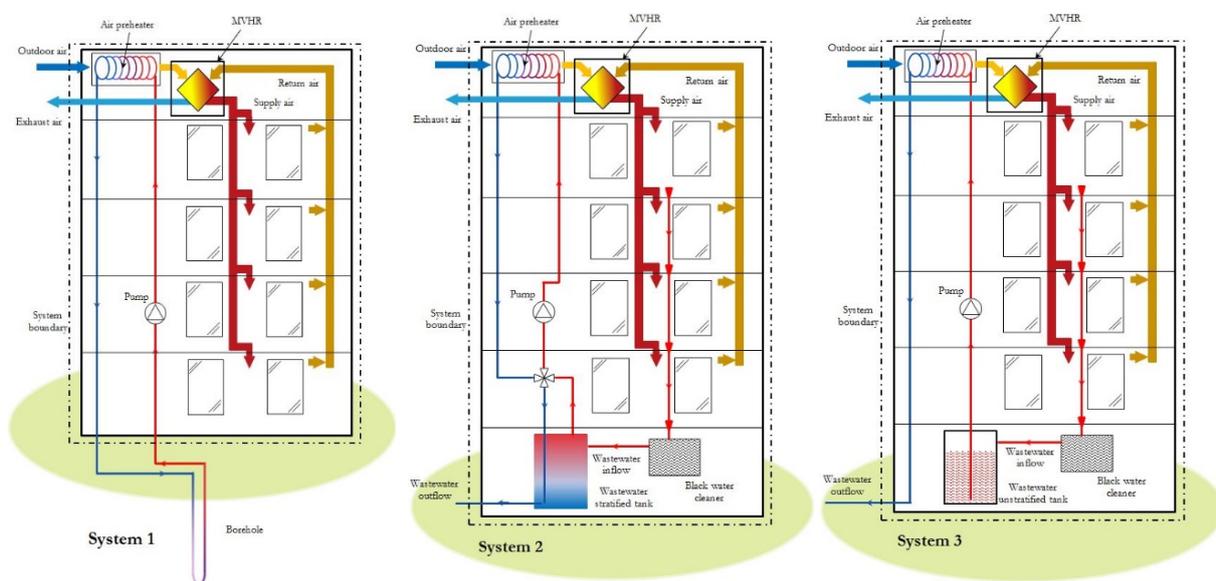


Figure 1: Schematics of the three studied outdoor air preheating systems in combination with the existing MVHR system [6]

The cost factors considered for the LCC included installation and purchasing costs as initial investment cost. Costs for maintenance, repair, energy and replacements were considered as operating cost. Initial investment cost includes the expenses to acquire the components as well as the services for setting up the system. Costs for the ventilation ductwork were excluded in this work, since they are the same for all studied systems, and therefore have no impact on the total cost difference between the systems. The costs are based on the local market prices given by the retailers. For identifying the annual energy demand, a simulation with TRNSYS has been carried out. The cost per unit of energy (kWh) for the first year as well as the annual increase of the electricity price are based on the Swedish energy market development [7].

Maintenance cost was derived from the initial cost. This was a legit approach as confirmed in a study by Wu and Clements-Croome [8], who investigated the ratio of these two cost factors for 20 different types of HVAC solutions. They found the ratio of initial and maintenance cost to be stable between 1.8% to 4.0%. The ratio for both wastewater systems, System 2 and 3, was assumed to be 4% of the initial cost. One can expect the expenses for these two systems to be higher, since maintenance includes more frequent tasks (unclogging, replacing filters, cleaning the tanks) [9]. For System 1, the ratio was set at 2% of the initial cost. The expenditures for replacing a component were approached by

adding their initial cost in the respective year. Recycling costs or end-of-life management costs were not considered, as their impact is assumed to not influence the result significantly. The net present value (NPV) method will be used to discount future cost to a present value. The formula used is as following.

$$NPV = -C_0 + \sum_{n=1}^N \frac{C_n}{(1+r)^n} \quad 0-1$$

Where

NPV: net present value [SEK] C_0 : initial investment costs [SEK] r: discount rate [%]
 N: total amount of periods [year] C_n : cash flow in period [SEK] n: time period [year]

The second metric that will be considered for the LCCA is the discounted payback period to see when the investment will pay off. The discount rate was found by analyzing the interest rate for five-year Swedish government bonds [13], and by using the data of Sweden's consumer price index over the past 30 years [55]. Based on the inputs, a real discount rate of 2.4% was used for the LCC. A lifespan of 20 years for each system was considered in the simulation.

The sensitivity analysis and the Monte Carlo simulation were applied to monitor possible deviations of the input values. The sensitivity analysis is a useful tool to analyze an individual assumption made in the LCC and to identify their contribution to the total costs. This was achieved by monitoring the changes in NPV for varying values of the electricity price trend and the discount rate. The Monte Carlo simulation has the ability to vary all factors at the same time and hence simulate a large number of scenarios with different outcomes. The ranges, in which the inputs were varied, were the same for the performance of the Monte Carlo simulation. However, the inputs are randomized in the defined range using a normal distribution. Table 1 gives an overview over the relevant parameters that were generated for the calculation.

Table 1. Input parameters for the LCC

Cost factor	Value	Range
Electricity price in year 1	1.34 SEK/kWh	
Electricity price trend	3.0%/year	-4% - +10%
Discount rate	2.4%/year	-2% - +7%
Life span	20 years	

3. Results

Figure 2 displays how the cost for each system accumulated over the observed lifespan. The base system had the lowest initial cost. However, it had the highest increase in cost over the following years compared to the other three systems. The average increase in accumulated costs for the base system was 90 000 SEK for every three years, which was 50 000 SEK more than for Systems 1-3. A break-even point was reached after 7.4 years for System 3 and after 16.6 years for System 2. The initial costs for System 1 were more than twice as high compared to the base case. Within the 20 years, it did not break even with the base system, even though the cost gap is closed down to about 25000 SEK.

Figure 3a) highlights the total NPV for the studied systems by splitting up the costs into the initial costs and the operational costs. The operational costs of the base system exceeded its initial costs by around 300%. For System 1, the initial cost dominated over the operating costs with a ratio of about 1.4:1. For the wastewater systems (Systems 2 and 3), both costs were about equally balanced. Compared to the base system, the operational costs for Systems 1-3 were 35 – 45% lower.

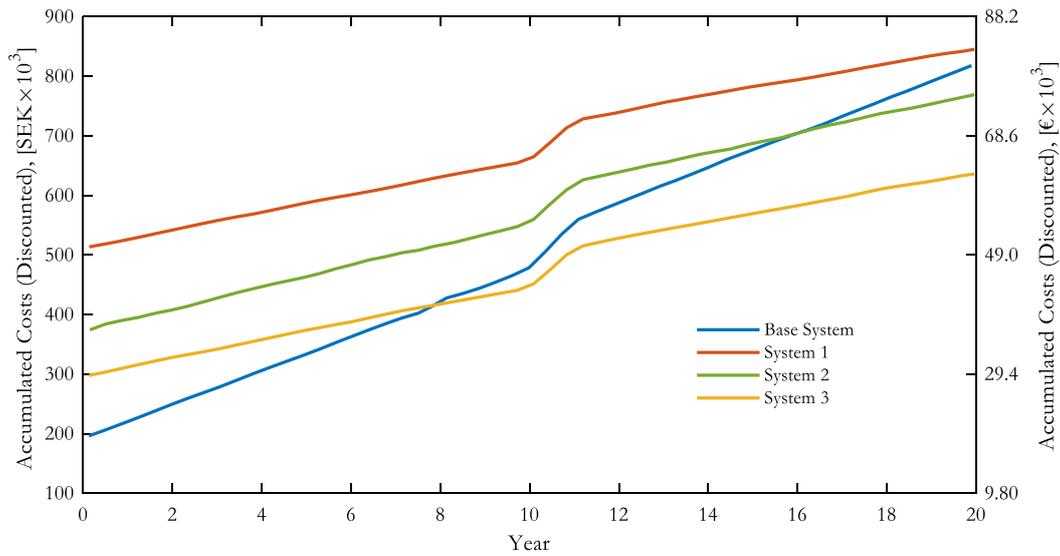


Figure 2. Accumulated cost and discounted payback period of the studied systems

Figure 3b) depicts the total energy cost of the four systems. While the energy cost for the three systems using outdoor air-preheating were on a similar level, the base system (without air-preheating) required more than three times higher energy costs.

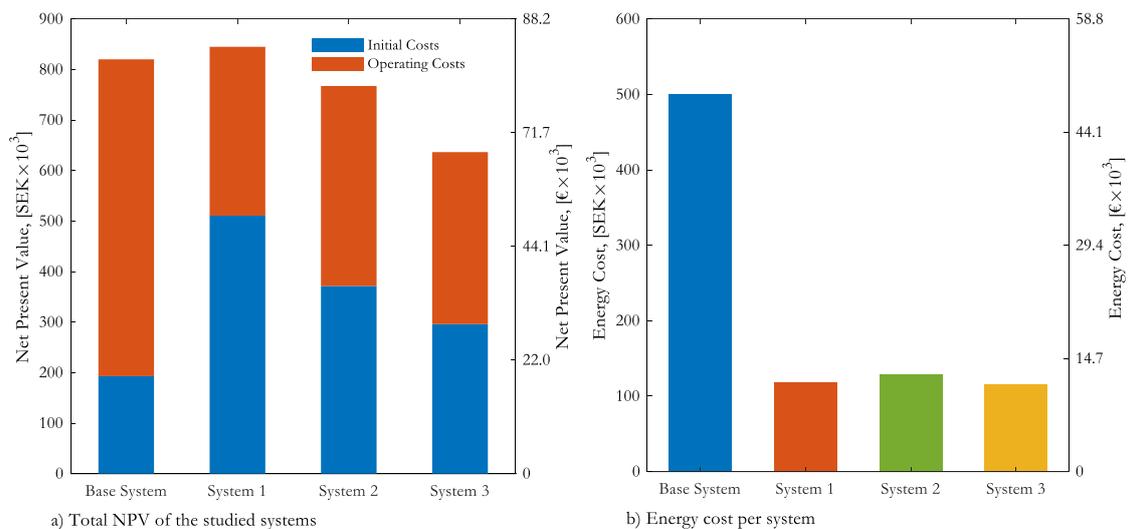


Figure 3. a) Total NPV and b) the energy cost of the studied systems

The results on the sensitivity analysis give insight on the development of the total NPV at the end of year 20 when one single input-factor is varied. The findings in the sensitivity analysis for the electricity price trend (Figure 4a)) show the highest responsiveness for the base system. An annual increase of 6% lifted the total NPV up by 20% compared to the initial trend of 3%. At the same time however, the base system benefited the most from stagnating electricity prices, as well. Costs of Systems 1-3 increased all by just around 180000 SEK over the whole spectrum.

A similar observation can be made for the discount rate (see Figure 5 b). The base system showed the highest responsiveness to changes in this value. Varying the discount rate from -2% to +8% caused the total NPV to change by about 600 000 SEK. Meanwhile, Systems 1-3 decrease in the same range by a value of around 300 000 SEK. For the base system, total cost bursts up to 1 200 000 SEK in case of deflation.

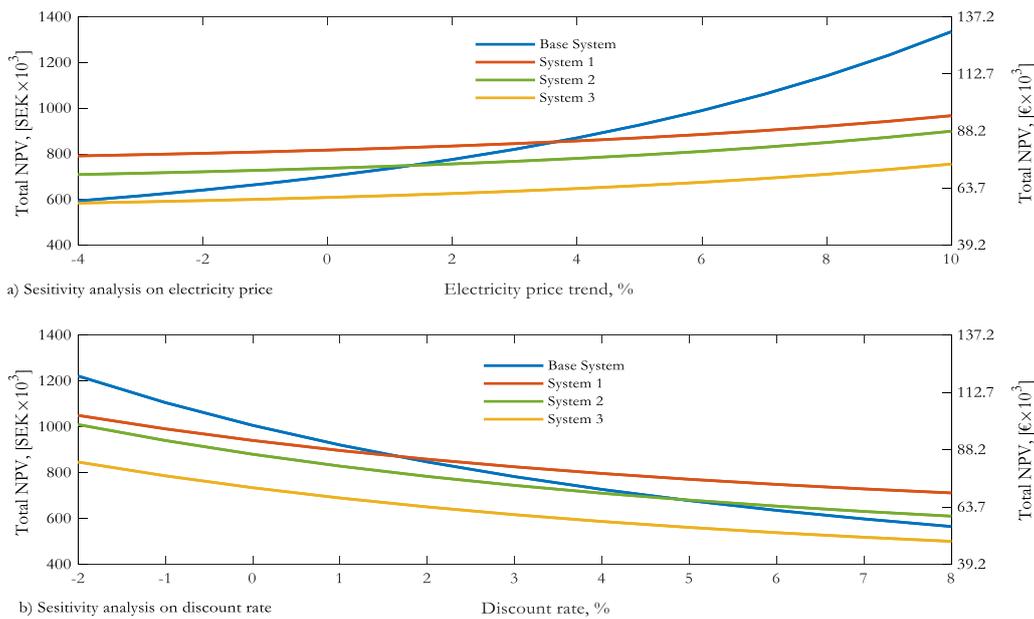


Figure 4. Sensitivity analysis a) electricity price trend b) discount rate

For the Monte Carlo Simulation, the total NPV is displayed in terms of savings compared to the base system. 1000 iterations, in which the inputs were varied, had been carried out for this simulation. The charts in Figure 5 a)-c) display the frequency charts along with the accumulated probability (orange line). The x-axis shows the upper limits of each interval for savings comprised in the representative bar. The y-axis displays the amount of cases computed in each bar - absolute figures on the left and relative figures on the right. The bars in red comprise the scenarios, in which the individual system turned out to not save cost over the base system, while the ones in blue display the cases where profits were generated within 20 years. System 1 has a 36% probability of still turning profitable within the observed period. The probability for System 2 to break-even in 20 years is about 52%. System 3 has a probability of about 85% of turning profitable within 20 years.

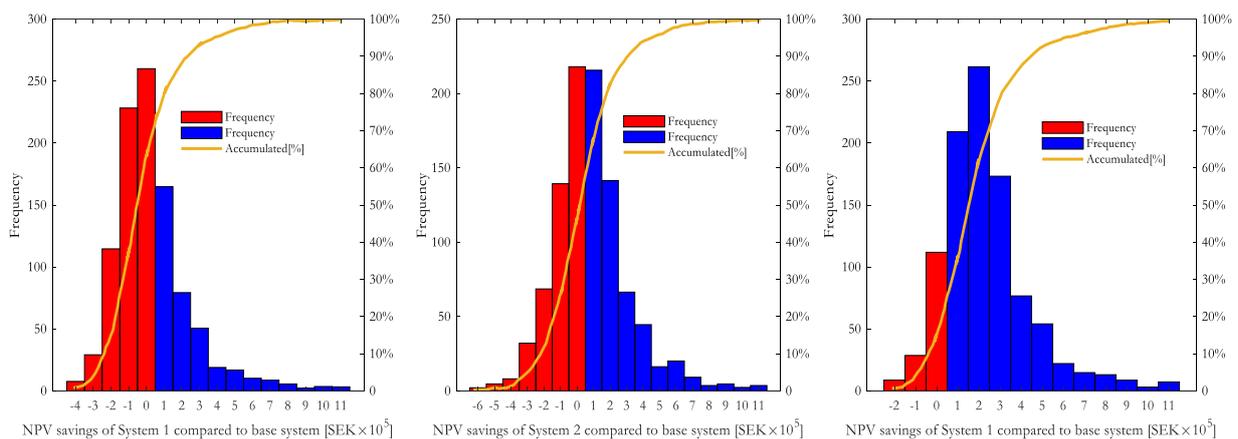


Figure 5. Monte Carlo simulation: a) System 1, b) System 2, c) System 3

4. Discussion

The traditional MVHR without an outdoor air-preheating system (base system) had the highest operational cost, which was its major disadvantage. It should be noted that the base system was the only system not utilizing a circulation pump, however, the energy usage for the fans were same for all four studied systems. Consequently, the major energy cost cuts were created through the reduction of defrosting time and the operational time for the circulation pump. System 1 required the highest investment (initial costs) which made it impossible to break-even within 20 years. The main reason was the high cost for the borehole drilling according to the current market prices. Both wastewater systems

(System 2 and 3) generated savings within the 20 year-period. The more advanced technology of stratified tank that was used in System 2 did not provide the anticipated savings during the operational period. This system was more expensive than the solution with the non-stratified tank (System 3).

In the sensitivity analysis, the base system was very responsive to higher/lower figures for the discount rate or the electricity price trend. All outdoor air-preheating systems showed a higher robustness for unexpected changes in prices and discount rate. The Monte Carlo simulation confirmed the findings from the initial calculation and gave a holistic insight into the risks attributed to the calculations.

5. Conclusion

In this case study, a multi-family house located in central - Sweden equipped with a mechanical ventilation system with heat recovery (MVRH) and an additional outdoor air-preheating system was studied. The outdoor air-preheating systems were fed by stored wastewater and geothermal brine. The cost-effectiveness of the systems was evaluated using the Life Cycle Cost methodology. The systems with outdoor air-preheating system were compared with base MVRH system without air-preheating system. Based on results the following can be concluded:

- While wastewater systems already showed a high probability for generating savings with state-of-the-art technology, there was still a need for improvement in the exploitation of geothermal energy. Break-even points for the wastewater systems were reached after about 8 and 17 years.
- The application of the sensitivity analysis and the Monte Carlo Simulation reveal that certain economic developments could potentially put other systems in favor with the base system being the most responsive one to deviant inputs.
- Frost-avoidance solutions had a great potential for optimizing space heating with MVHR-units; not only from a technical- but also from a financial perspective. Energy cost can be cut significantly with these setups and eventually compensate for higher initial investment cost.

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