Sustainable building ventilation solutions with heat recovery from waste heat

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by

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Stockholm, September 2019
Behrouz Nourozi

Abstract

The energy used by building sector accounts for approximately 40% of the total energy usage. In residential buildings, 30-60% of this energy is used for space heating which is mainly wasted by transmission heat losses. A share of 20-30% is lost by the discarded residential wastewater and the rest is devoted to ventilation heat loss.

The main objective of this work was to evaluate the thermal potential of residential wastewater for improving the performance of mechanical ventilation with heat recovery (MVHR) systems during the coldest periods of year. The recovered heat from wastewater was used to preheat the incoming cold outdoor air to the MVHR in order to avoid frost formation on the heat exchanger surface.

Dynamic simulations using TRNSYS were used to evaluate the performance of the suggested air preheating systems as well as the impact of air preheating on the entire system. Temperature control systems were suggested based on the identified frost thresholds in order to optimally use the limited thermal capacity of wastewater and maintain high temperature efficiency of MVHR. Two configurations of air preheating systems with temperature stratified and unstratified tanks were designed and compared. A life cycle cost analysis further investigated the cost effectiveness of the studied systems.

The results obtained by this research work indicated that residential wastewater had the sufficient thermal potential to reduce the defrosting need of MVHR systems (equipped with a plate heat exchanger) in central Swedish cities to 25%. For colder regions in northern Sweden, the defrosting time was decreased by 50%. The temperature control systems could assure MVHR temperature efficiencies of more than 80% for most of the heating season while frosting period was minimized. LCC analysis revealed that wastewater air preheating systems equipped with temperature stratified and unstratified storage tanks could pay off their costs in 17 and 8 years, respectively.

Keywords: wastewater heat recovery, balanced mechanical ventilation, defrosting reduction, heat recovery efficiency, thermal load shifting, renewables

Nomenclature

Abbreviations

AP	Air preheater
BBR	Swedish building regulations
DH	District heating
DHW	Domestic hot water
HX	Heat Exchanger
IAQ	Indoor air quality
LCC	Life cycle cost
MVHR	Mechanical ventilation with heat recovery
NPV	Net present value
SEE	Standard error of estimate
WW	Wastewater

Latin Symbols

$c_{p,air}$	Air specific heat capacity	$J/(kg°C)$
$c_{p,ww}$	Wastewater specific heat capacity	$J/(kg°C)$
m_{air}	Ventilation air mass	kg
$\dot{m}_{air}$	Ventilation air mass flowrate	kg/s
$\dot{m}_{ww}$	Wastewater mass flowrate	kg/s
P_w	Available thermal power in brine/wastewater	W
Q	Recovered heat (from ventilation air and wastewater)	W
T_{exh}	Exhaust air temperature (from MVHR)	$°C$
T_{Inlet}	Inlet air temperature (to MVHR)	$°C$
T_{pre}	Preheated air temperature	$°C$
T_{return}	Return air temperature (from building)	$°C$
T_{supply}	Supply air temperature (to building)	$°C$
$T_{surface}$	Heat exchanger surface temperature	$°C$

Greek Symbols

$\Delta\theta_{air}$	Reduction in ventilation air temperature (after heat recovery)	$°C$
$\Delta\theta_{ww}$	Reduction in wastewater temperature (after heat recovery)	$°C$
η_{MVHR}	Temperature efficiency of MVHR	%

Table of Contents

List of publications

This licentiate thesis is a summary of the following scientific papers which are appended at the end of the text.

Paper I **Behrouz Nourozi**, Qian Wang, Adnan Ploskić, Energy and defrosting contributions of preheating cold supply air in buildings with balanced ventilation. Journal of Applied Thermal Engineering 146 (2019) 180-189.

Paper II **Behrouz Nourozi**, Qian Wang, Adnan Ploskić, Maximizing thermal performance of building ventilation using geothermal and wastewater heat. Journal of Resources. Journal of Conservation and Recycling 143 (2019) 90-98.

Paper III **Behrouz Nourozi**, Qian Wang, Adnan Ploskić, Identifying frost threshold in a balanced mechanical ventilation system by inlet and exhaust air temperature control. In: proceedings of The 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) 12-15 July 2019, Harbin, China.

Paper IV **Behrouz Nourozi**, Qian Wang, Adnan Ploskić, Preheating cold supply air to mechanical balanced ventilation using wastewater or passive geothermal energy. In: proceedings of The 16th International Building Performance Simulation Association (IBPSA), 2-4 September 2019, Rome, Italy.

Paper V Simon Härer, **Behrouz Nourozi**, Qian Wang, Adnan Ploskić, Frost reduction in mechanical balanced ventilation by efficient means of preheating cold supply air. In: proceedings of The 10th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings (IAQVEC), 5-7 September 2019, Bari, Italy.

Other publication by the author not included in the thesis:

Paper VI **Behrouz Nourozi**, Simon Härer, Qian Wang, Adnan Ploskić, Life cycle cost analysis of air preheating systems using wastewater and geothermal energy. The REHVA European HVAC Journal 56 (1) (2019) 47-51.

1. Introduction

The ever-increasing dependency of human being and our society to energy is inevitable. Scarcity of non-renewable energy resources, devastating impacts of using traditional energy sources and their rocketing prices are among the reasons that mandated significant and continual revision in minimum energy performance requirements of different sectors. The expanding residential and service sector is currently responsible for approximately 40% of the total energy usage from which, 90% is attributed to the households and non-residential buildings [1]. Following the directive 2009/28/EC of the European Parliament, two amended directives, 2018/2001 and 2018/2002 of the European Parliament and of the Council of 11 December 2018 on “the promotion of the use of energy from renewable sources” and “energy use” were released, respectively [2], [3]. The directives established a set of binding measures as the 2030 perspective to cut greenhouse gas emissions by 40% and increase the energy efficiency by 40% relative to the levels in 1990.

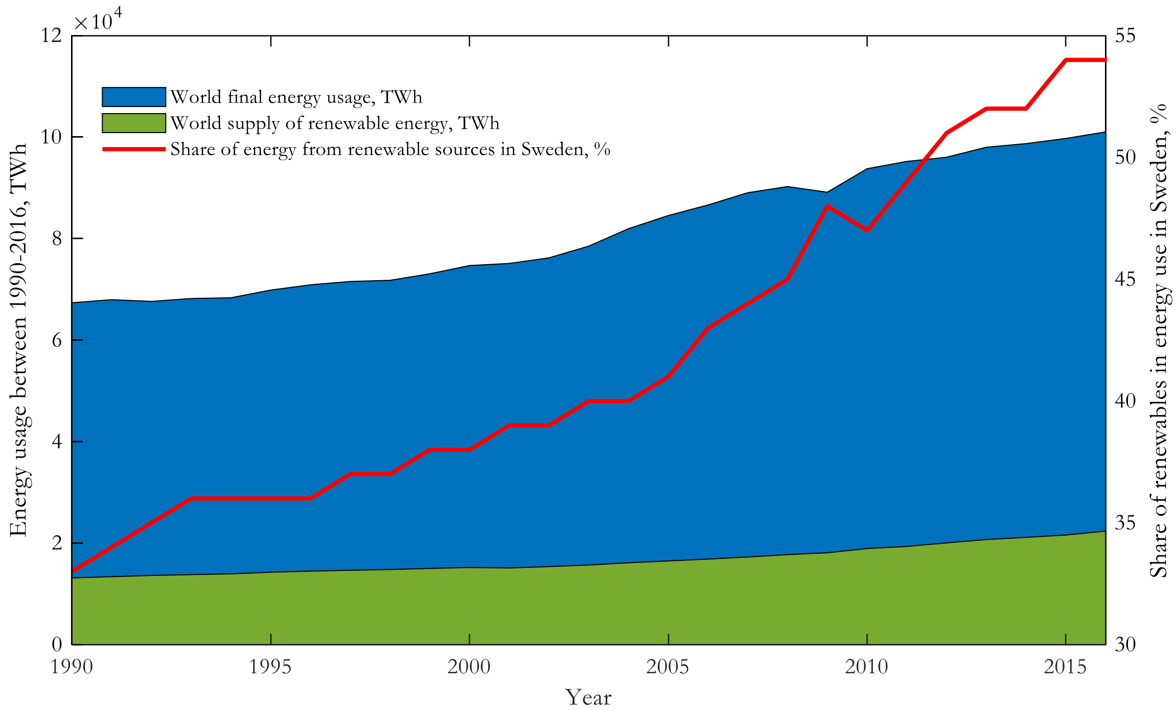
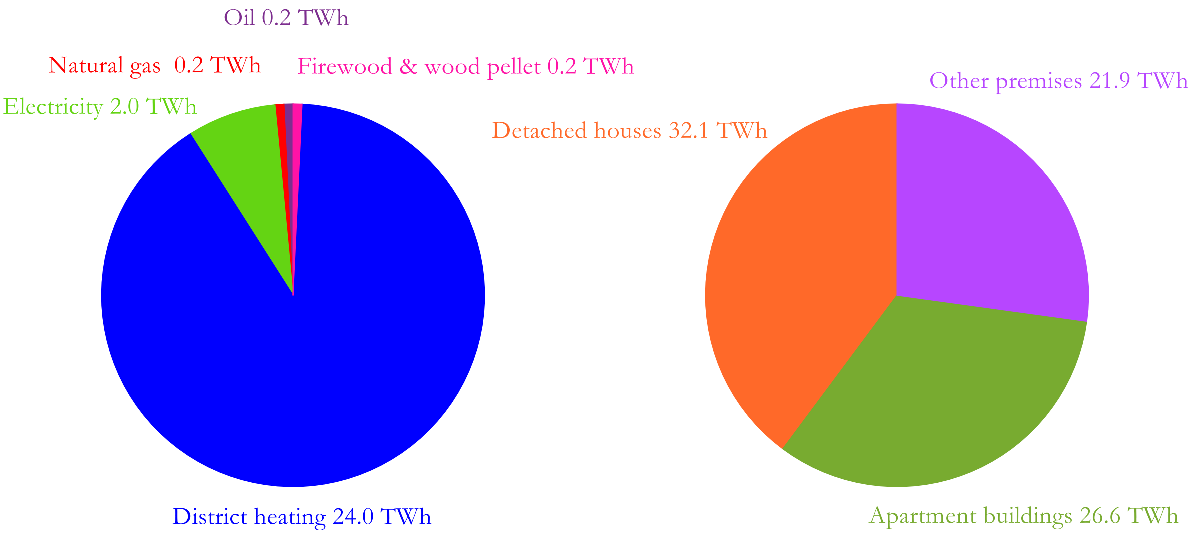


Figure 1: Share of renewables in total energy usage [4]

Figure 1 shows how the share of renewable energy sources have increased from 1.31×10^4 TWh in 1990 to 2.34×10^4 TWh in 2016 (from 19% to 22% of the total energy use). The share of renewables in Sweden however, has been more than the average world records. It was augmented to more than 54% of the total energy usage in Sweden in 2016.



a) Share of heating energy providers to apartment buildings   b) Required heating energy based on building types

Figure 2: Total energy usage for heating and DHW in 2016 [5]

Heat recovery from waste heat in residential buildings can increase the overall energy efficiency of this sector. The comfortable room temperature in Swedish residential buildings is 20°C and the outgoing wastewater has an average temperature of 20°C (varies between 19°C-25°C), as well. Using heat recovery technologies for both sources, the outgoing wastewater and air temperature can be reduced to 5°C. Assuming daily water usage of 160 l/person and 1000 kg/person of ventilation air for the whole population can reveal the potential of the total wasted heat by wastewater and ventilation in the entire country.

$$Q = \left(\dot{m}_{air} C_{p,air} \Delta\theta_{air} + \dot{m}_{ww} C_{p,ww} \Delta\theta_{ww}\right) \times population \approx 70 \ {}^{GWh}/_{day} = 25 \ {}^{TWh}/_{year}$$

The wasted heat energy from both ventilation air and wastewater in residential buildings in Sweden is approximately equal to the required annual energy for heating and DHW for multi-family buildings, as depicted in Figure 2. The intention to further use renewables has triggered the idea of recovering the waste heat from buildings and reuse it in order to improve buildings' energy performance.

1.1. Research motivation

In Sweden, the peak energy load occurs during November to February, see Figure 3. Due to high power demand in this period, fossil fuels are used during the coldest periods to meet the market requirements. In fact, this period is also associated with highest CO_2 emission and production costs

[6]. Therefore, this stipulates an attempt to reduce both the energy usage (kWh) and both electrical and thermal peak loads (kW) in this period [7].

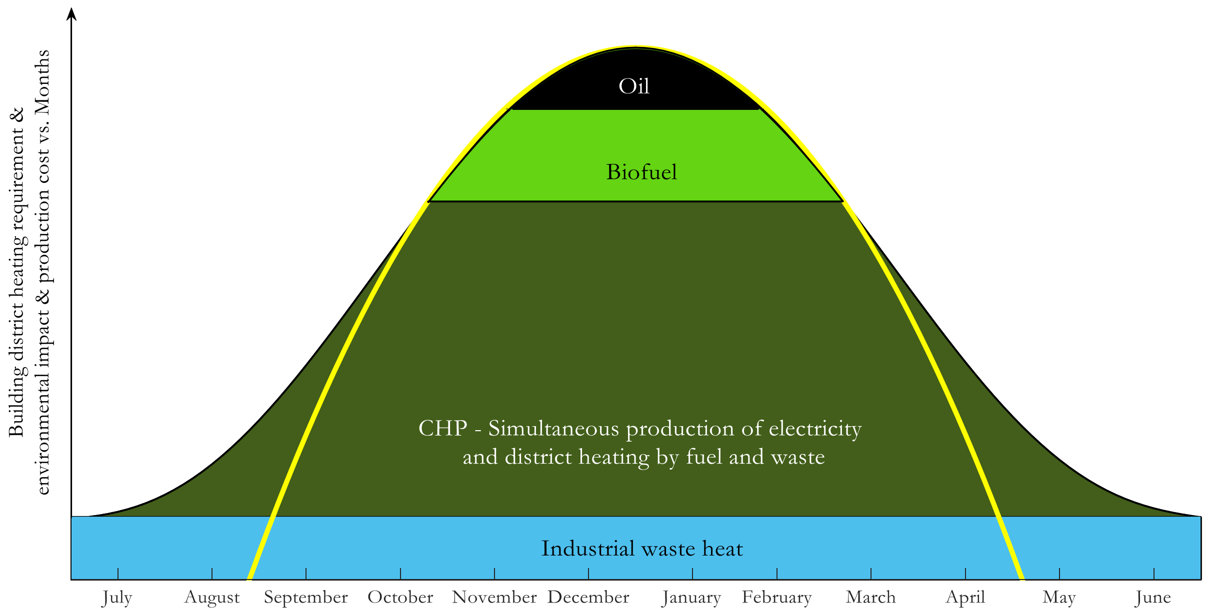


Figure 3: Annual buildings demand for district heating (DH) – The energy generation costs and environmental impacts [7]

Major thermal losses in buildings, especially in cold climate countries, are the transmission heat losses, ventilation heat loss and the thermal energy by discarded wastewater. Thanks to improvements in building materials, major retrofitting of existing buildings and further insulation of buildings' envelope in Sweden have resulted in decreased energy loss by infiltration and transmission. Swedish building regulations (BBR) were revised in 2018 [8]. Chapter 9 of the latest version provides the mandatory provisions and general recommendations on energy conservation. "*Buildings shall be designed in such a way that energy use is limited by low heat losses, low cooling demands, efficient use of heat and cooling and efficient use of electricity*". Buildings shall meet the requirements for primary energy factors provided by BBR, and the suggested thermal transmittance (U-value) for all components of the building envelope shall be pursued.

The heating energy cost in district heated areas in Sweden currently consists of both the total energy usage (kWh) and the thermal load (kW) during a year. Figure 4 illustrates the required heating energy and the energy cost of a multi-family building in the suburbs of Stockholm [9]. The building (2140 $m^2_{\text{floor heated area}}$) heating demand was 66 kWh/($m^2_{\text{floor heated area}}$.year). The required thermal load cost can comprise 19%-90% of the monthly expenditures and, annually it composes 37% of the total heating expenditures. Therefore, interest should also be given to buildings' heating load reduction in parallel to making efforts to reduce the buildings' heating energy demand.

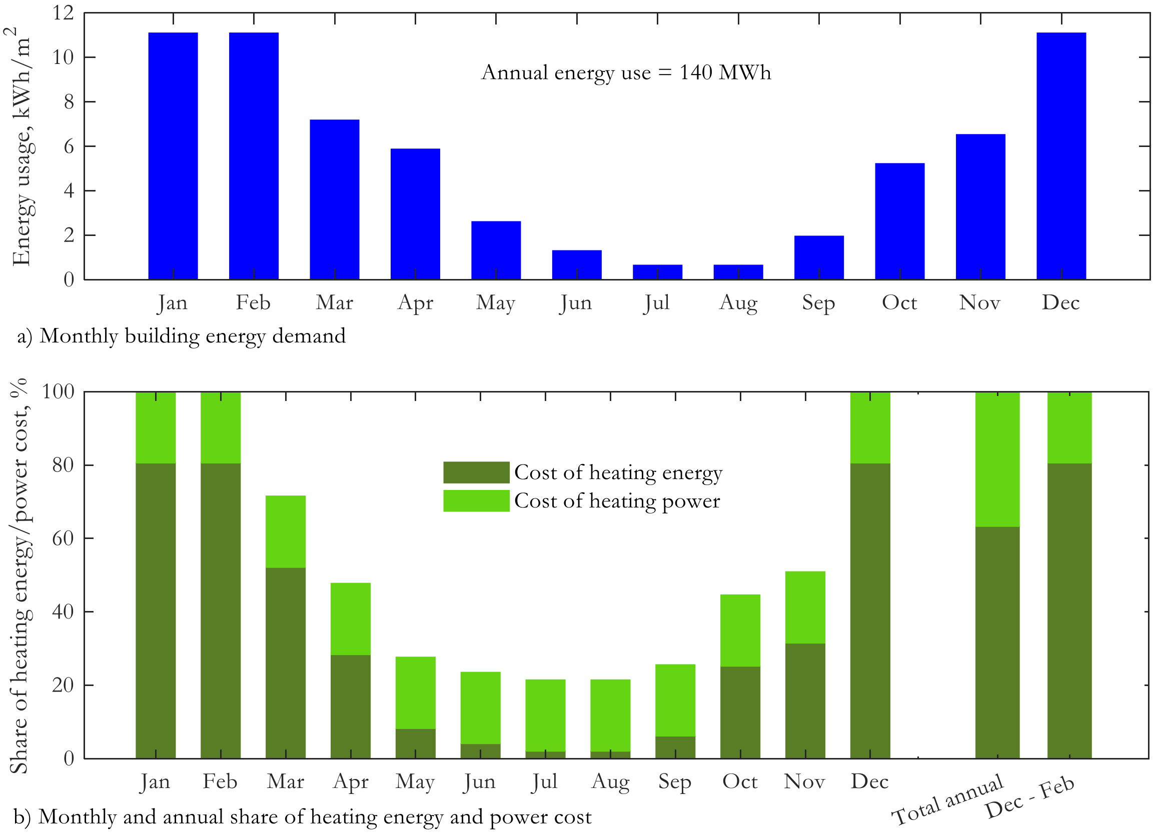


Figure 4: Monthly distribution of heating energy demand and the energy-power costs in a multi-family building

Moving from buildings constructed in mid- and late 20th century to the current high thermal performance constructions, not only the share of domestic hot water (DHW) heat demand has not been equally improved, it is doubled [10]. Reducing the transmission thermal losses from a building by enhancing the airtightness and insulation demands more effective ventilation systems to meet the indoor air quality (IAQ) requirements of the building. Ventilation systems have to operate in order to maintain the IAQ level and ensure the perceived thermal comfort standards. Although ventilation systems without heat recovery could provide the required amount of fresh air, the ventilation heat losses in these systems are significant in the cold regions. Therefore, mechanical ventilation system with heat recovery (MVHR), which nowadays has an annual energy recovery efficiency up to 80% was utilized in this work.

A major drawback of MVHR systems is formation of a layer of ice at the heat transferring surfaces of the heat recovery exchanger at low outdoor temperatures. Accumulation of frost in the heat exchanger reduces the heat transfer rate between the return air from the building and the fresh outdoor air. Other negative effects are blockage of the return airflow, degradation of heat transfer surfaces, increased required fan power and compromised indoor air quality [11]–[13].

Various methods have been developed to remove the ice from the heat exchanger surface. Passive techniques including changing surface morphology, anti-frost coating and hydrophilic coating delay initialization of frosting by reducing the amount of water on the cold surfaces. Active methods such as low-frequency and ultrasonic vibrations, reverse cycle of hot gas, electric heater and employing desiccants are also effective in removing frost or delaying frost formation [12]. However, frost prevention is proved to be a more energy efficient method for tackling frost problem [13]. Return (room) air dehumidification and preheating the outdoor air before these two airflows are sucked in the MVHR are the main frost preventative measures. Electrical air preheaters are the most common method that have been used to increase the outdoor air temperature prior to the heat exchanger. This, of course, requires additional electricity consumption which is a high grade energy source.

Renewable heat sources can also been utilized as the preheating source of energy instead of electricity. Rather constant ground temperature compared to outdoor air temperature provides a fairly relatable thermal potential for heating and cooling purposes in buildings. In Sweden, geothermal energy has been utilized to preheat the incoming outdoor air to MVHR in recent studies between 2015 and 2018 [14]–[16]. In these studies, the geothermal energy was extracted without use of a heat pump.

1.2. Research objective

The main objective of the research in this work was to tackle the frost problem of the heat recovery exchangers in MVHR systems in multi-family buildings. The aim was to target the peak heat loads during coldest days in winter when the defrosting the heat exchangers largely increase the peak heating load even more. The goal was the use the heat from the outgoing wastewater from the building to preheat the incoming outdoor airflow to MVHR and thereby, reduce the defrosting need during the coldest days.

1.3. Hypothesis

"By preheating the incoming cold outdoor air to an MVHR system during winter period, frosting in heat exchanger can be reduced or eliminated. Residential wastewater has sufficient thermal potential to lift the outdoor air temperature

above frost threshold. This will result in improved MVHR performance and also reducing building's peak heating requirements."

2. Methodology and Tools

In this research work, energy simulation tools, analytical methods, literature review and life cycle cost (LCC) analysis have been used to investigate the potential of the studied heat recovery systems. Figure 5 illustrates the investigated wastewater air preheaters.

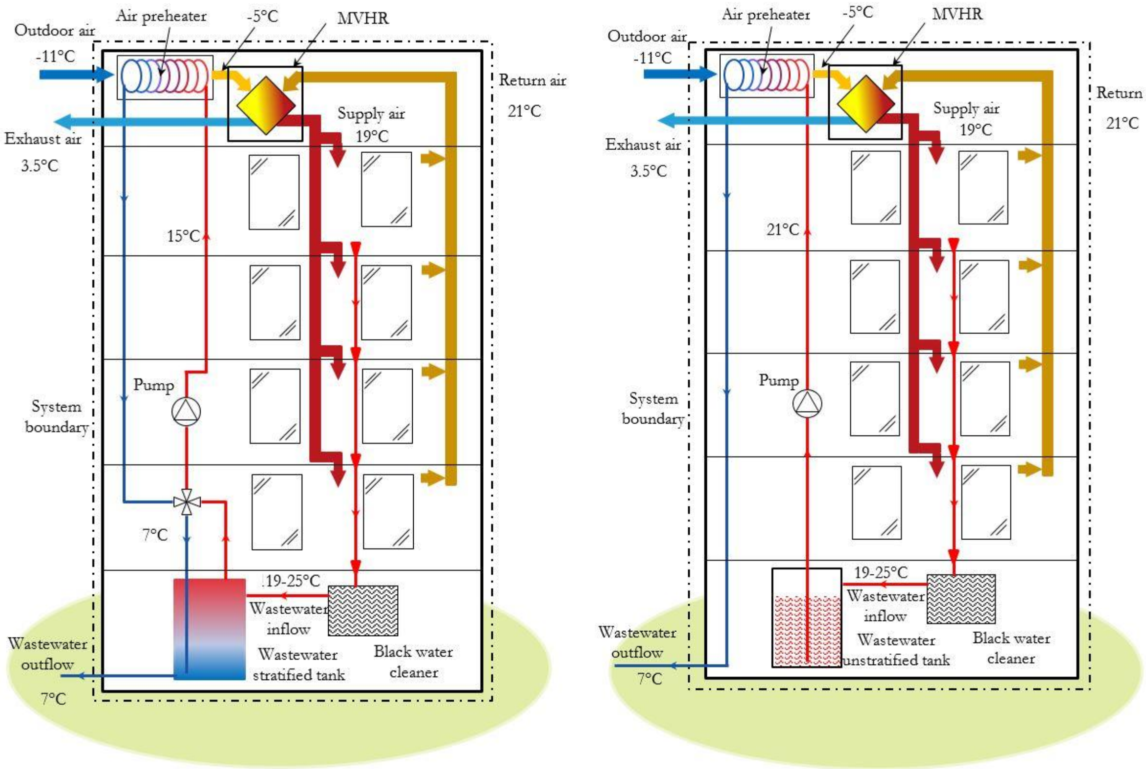


Figure 5: Schematic flow charts of the studied air preheating systems using wastewater from the stratified tank (left) and the unstratified tank (right)

Two outdoor air preheating systems which benefit the thermal potential of residential wastewater were suggested and their performance was evaluated by dynamic simulations. The discarded wastewater was stored in a black waster cleaner before it was accumulated in a thermal storage tank. Despite large scale wastewater separators are more commonly used in wastewater treatment plants, smaller devices are currently developed and are available in the market [17], [18]. The performance of the black water cleaner was not in the scope of this research work; however, it was assumed that the outgoing grey water was sufficiently purified to be pumped to a water-to-air heat exchanger. This grey water (wastewater is often used in this text and the appended papers) was stored in two storage tanks, a temperature stratified and an unstratified tanks, see Figure 5. A pump circulated the wastewater to a water-to-air heat exchanger where the outdoor air could be preheated before entering the MVHR. The following subsections provide information about the methodologies used for evaluation of the studied air preheating systems. More details can also be found in paper II.

2.1. Simulation tool

The major method utilized in this research work was dynamic simulation using the commercial software *TRaNsient SYstem Simulation Program*, TRNSYS 17. TRNSYS is a transient simulation software which is capable of simulating several dynamic systems such as thermal and electrical energy systems as well as traffic flow [19]. The extensive libraries in TRNSYS enable the user to select among the available components while there is the possibility of modifying or creating new ones for specific purposes.

The processing engine in TRNSYS (called kernel) iteratively solves the systems made by a number of components from the libraries. TRNSYS original solver, Solver 0 or successive substitution, starts from a components and obtains the outputs by solving its equations using the initial inputs. This continues to the other components and the output from the last component can be the first component's input. A tolerance between the initial input and the last obtained output will define the convergence for the first time-step. After convergence is reached in every time-step, the same loop will be repeated for the next one and this will continue for the entire simulation period.

Several building models from different climatic zones in Sweden have been utilized to evaluate the performance of the suggested systems. Since the focus of the study was on the ventilation system and the proposed air preheating systems, a single zone model (Type660) represented the considered buildings. However, all models were validated by the measured data provided in reference studies.

The built-in climatic files in TRNSYS for Europe were used in all simulations. These files were generated using Meteonorm under license from Meteotest [20]. Meteonorm is capable of generating a representative typical year of any place on earth by choosing up to more than 30 different climatic parameters [21]. Hourly climatic data as well as the user input data contributed to performing more realistic energy simulations. The hourly information of the outgoing wastewater temperature and flowrate and defining the heat recovery efficiency of MVHR as a function of inlet air temperature were the main user input files to TRNSYS.

2.2. Investigated system

This subsection briefly summarizes the heat recovery systems from the ventilated air and residential wastewater in the building. Two multi-family buildings were modeled in TRNSYS. Both buildings were equipped with mechanical ventilation with heat recovery systems. The building located in Stockholm utilized a rotary heat exchanger in the MVHR and the one located in the city Örebro was equipped with a plate heat exchanger. The difference in the heat exchanger type resulted in various defrosting requirements and frosting thresholds. Various previous measurement studies have shown that the defrosting heat load is approximately 6.2 $W/m^2_{floor\ area}$[14]–[16], [22]. Two recent studies by Ploskić and Wang have revealed that the thermal potential of residential wastewater was sufficient to avoid frosting in MVHR systems [23], see Figure 6.

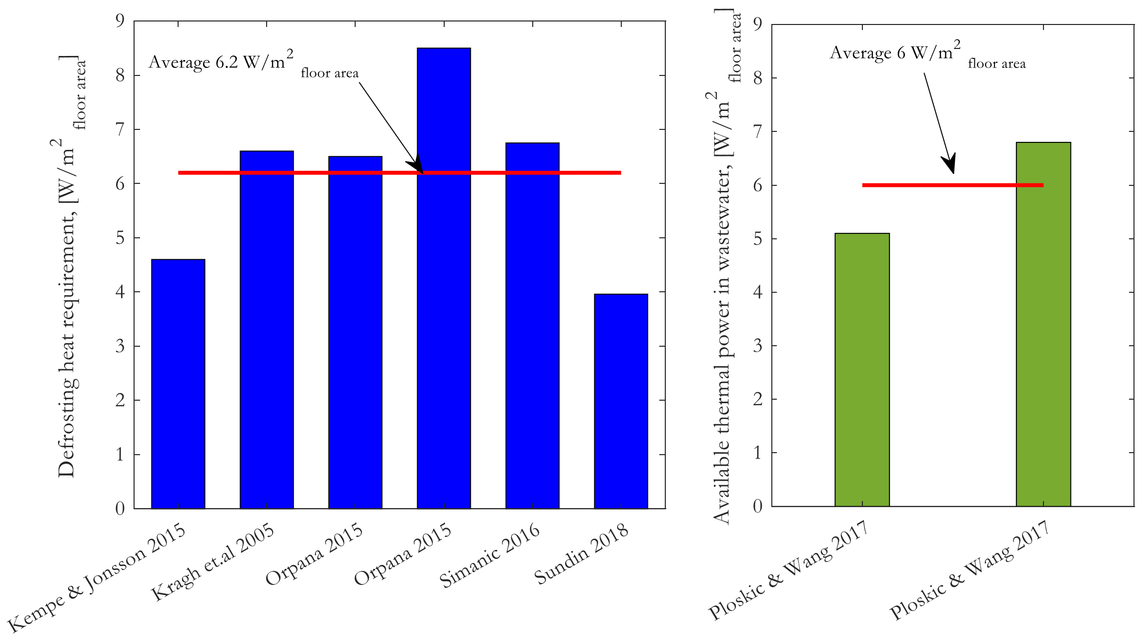


Figure 6: The average required heating power for defrosting and the available wastewater thermal potential

A case of a multi-family building located in southern Swedish city of Växjö is shown in Figure 7 [24]. The building heating power demand with and without a mechanical ventilation heat recovery system during a year is depicted. By installing an MVHR system, the required heating power was decreased 5-20 kW during the year. The green graph shows the reduction in load demand by using MVHR system (thermal power saving). However, this was not achieved since frosting occurred during winter period. The outdoor temperature in Växjö is below -5°C for about 30 days in a year. This temperature is the frosting threshold of a plate heat exchanger. Therefore, 6.2 $W/m^2_{floor\ area}$ heat power would be required to defrost a plate heat exchanger, see Figure 7, (dashed purple line). Despite the significant reduction of building heat load by installing an MVHR system, the temperature (heat recovery) effectivity of the heat exchanger can be reduced from 80-90% to 30-40% during defrosting mode due to defrosting [15].

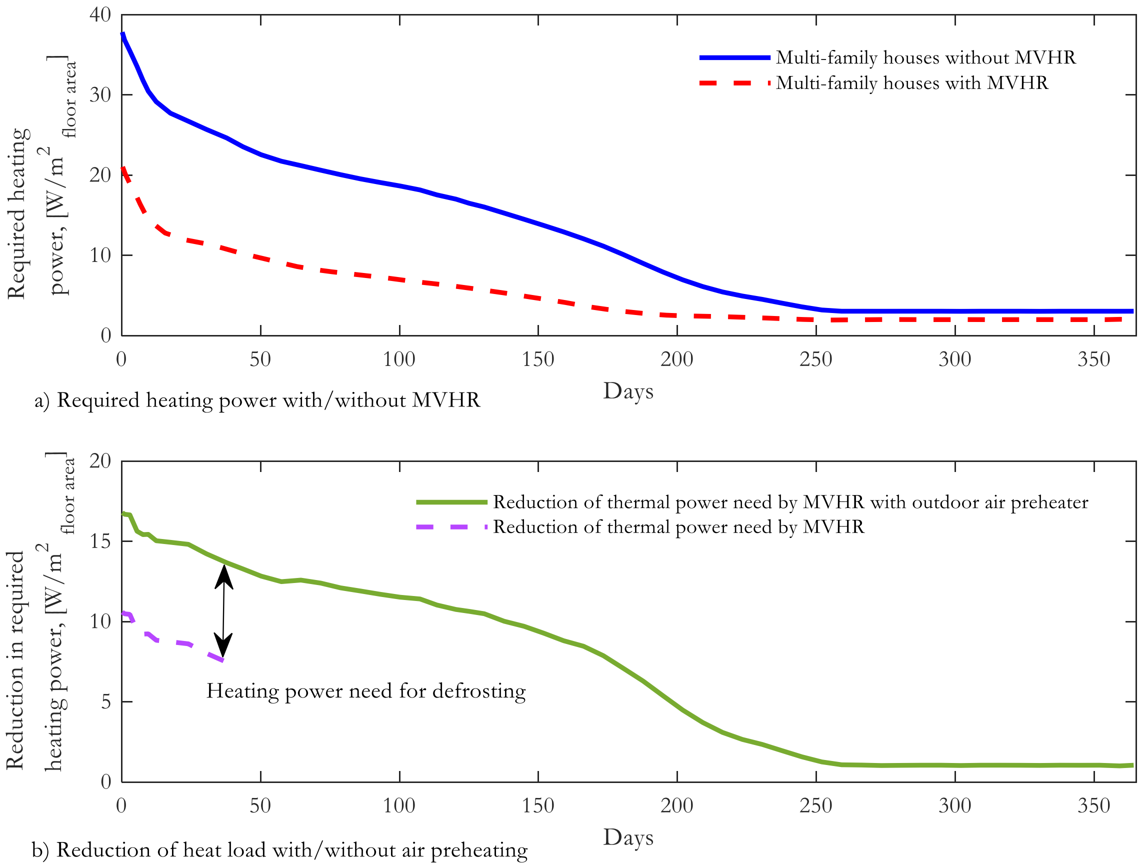


Figure 7: Energy saving potential in multi-family buildings by MVHR [24]

2.3. Model validation

The main components in each simulation model presented in the appended papers were validated by measured data reported by others. The building models which were continuously in response to the MVHR system were the main validation cases. The annual and monthly heating energy demand of the building cases were validated against the measured data by the presented references. The detailed information regarding the building model verification is provided in Paper I.

The performance of the outdoor air preheating system was validated with measurement data from similar preheating systems. In Paper I, the range of the simulated air temperature increase versus the outdoor air temperature was plotted and compared with the corresponding measurements [25]. Since each of measurement studies had specific settings, the increase in air temperature was weighted by the recovered heat power from circulated water and the air mass flow rate for each case. Therefore, the ratio of the preheated air temperature to the unit specific enthalpy is plotted against the outdoor air temperature in Figure 8.

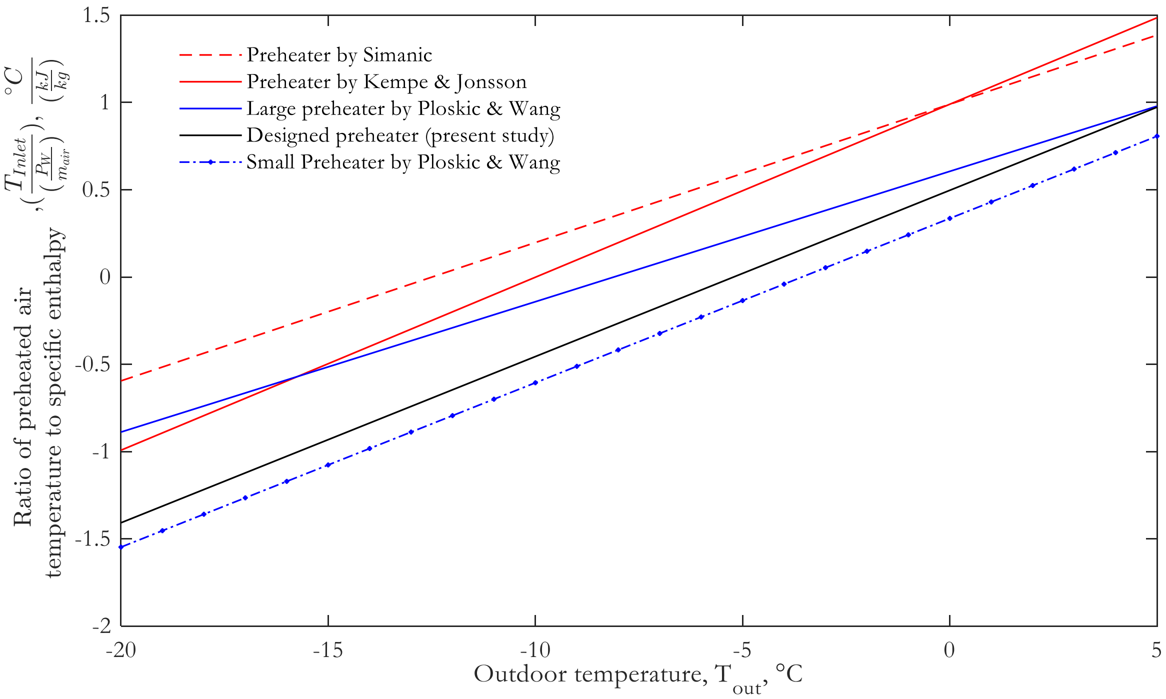


Figure 8: Weighted preheated air temperature to MVHR by specific enthalpy [25]

In the outdoor temperature span between -20°C to +5°C, the deviation between the simulated and the measured values were less than 1°C/(kJ/kg). As can be seen, all considered systems followed the same increase trend.

The simulated air preheater in Paper II was validated against measurements for two short periods with moderate and cold outdoor temperatures in November and January in the city of Örebro, respectively [26]. The average percentage difference between the simulated and measured temperatures were 6.6% and 12.0% in November and January, respectively.

The Standard Error of Estimate (SEE) was used to rate the deviation between the simulated and the measured values for January as it was more palpable of this month. The SEE value for the measured and simulated cases was 1.7°C and the simulated temperature was close to the measured temperature line except for a few hours when the circulation pump was off. As can be seen from Figure 9, the simulated values were within the range of ±1.5×SEE (=± 2.5 °C) for almost the entire studied period. More detailed about validation for this part can be found in Paper II.

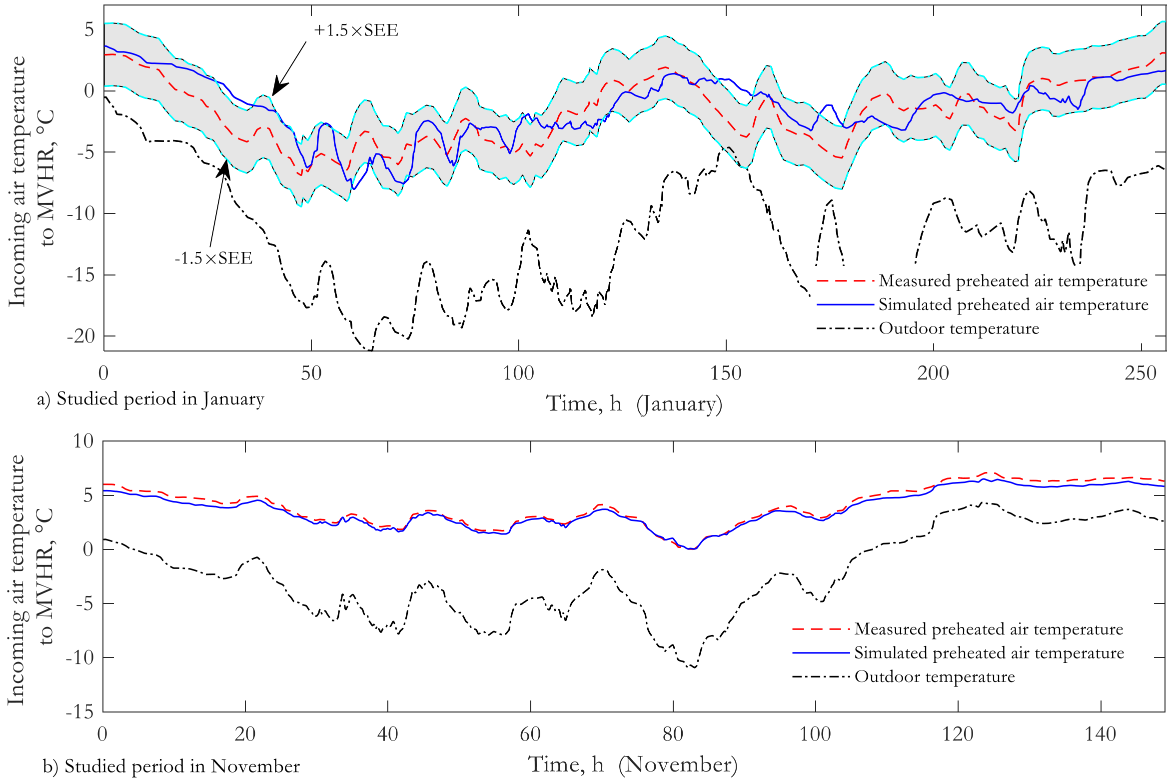


Figure 9: Preheated air temperature, TRNSYS simulation versus field measurements [26]

2.4. Life cycle cost (LCC) analysis

The life cycle cost analysis was used to assess the cost effectiveness of the investigated outdoor air preheating systems. The assessment of the analyzed heat recovery systems undergoes a life cycle cost analysis further to their energy and power saving potential. The Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings has established a framework for calculation of cost-optimal minimum energy performance requirements for buildings [27]. In this directive, the general principles of cost calculation and categories of costs are provided which comprise the basis of the LCC analysis in this work.

The net present value (NPV) method was used to evaluate the cost effectiveness of the suggested air preheating systems. NPV is used for products and processes in which most expenditures are required after the initial investment. The value of the money at the time, inflation, initial investment costs and cash flow are considered in this calculation. More details can be found in [28].

The cash flow in each period can break down into maintenance costs, energy costs, repair and replacement costs and recycling costs. The initial costs also comprise manufacturing price, installation costs, sales tax and the retail markups [28]. Comparing the cumulative costs of the studied systems with a base system (the building equipped with MVHR without air preheating system) can indicate the discounted payback period. The payback time of each system is the duration of time to reach a break-even point where the expended initial investment is regained due to savings by using more energy efficient equipment.

3. Results and Discussions

In this section, a short review of the most important results of the conducted research is presented. The more detailed discussions and results can be found in the appended papers.

Papers I and II mainly presented the results dealing with the performance evaluation of the suggested heat recovery system while Papers III and IV presented the results of the potential of the wastewater storage and the reduction of the defrosting need in the heat recovery exchanger, respectively. Paper V provided an evaluation of the studied systems in terms of the cost effectiveness.

Figure 10 illustrates the MVHR system with an air preheater- with the associated notations.

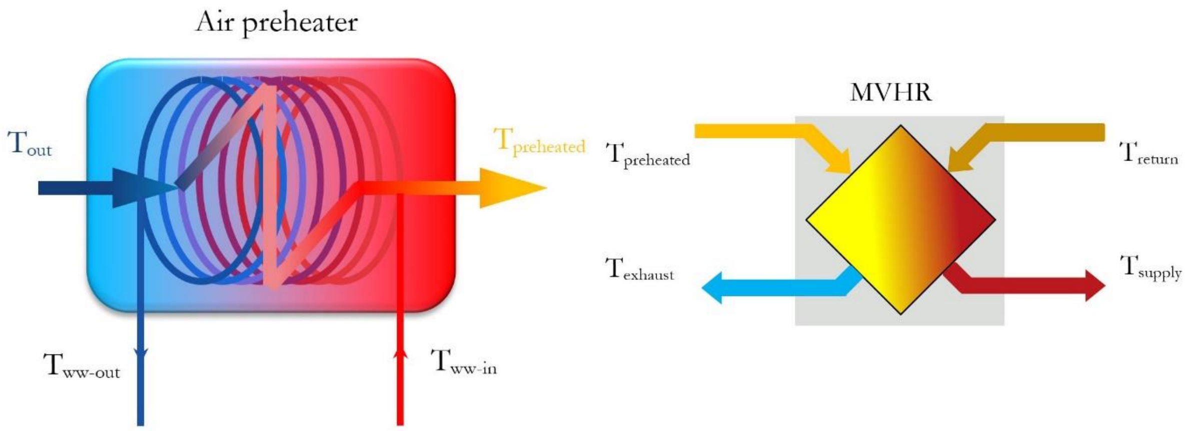


Figure 10: The air preheater and MVHR system

Papers I and II mainly focused on evaluating the potentials of an outdoor air preheating system using wastewater heat and geothermal energy to preheat the incoming air to MVHR. TRNSYS simulation results of a multi-family building located in Stockholm proved that the wastewater air preheater could increase the inlet temperature to above the frost threshold for most of the period, see Figure 10. In Paper I, it was shown that initial defrosting period (without air preheating) for a plate heat exchanger could be reduced by 50%. In case of an MVHR equipped with a rotary heat exchanger, frosting was eliminated for the entire heating season.

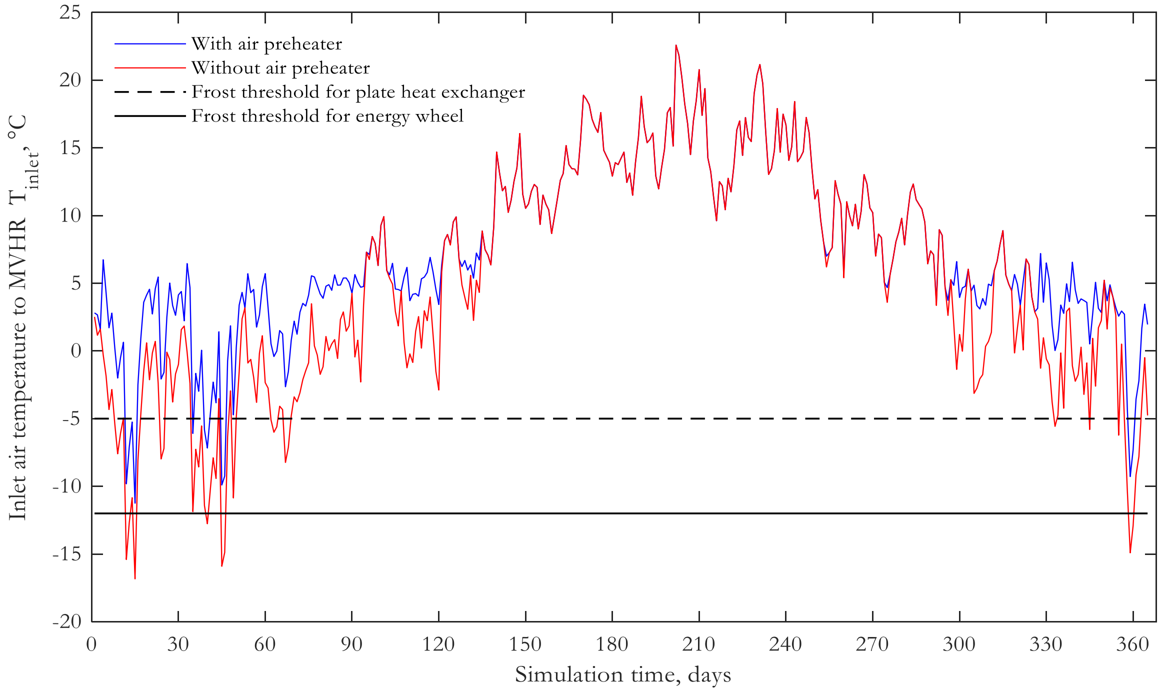


Figure 11: Chance of frost formation in MVHR served with and without air preheating [25]

However, the preheated air temperature shown in Figure 10 was not controlled to just above the frost threshold. Identifying the frost threshold was vital in order to optimally use the thermal potential of the stored wastewater when required as well as maintaining the efficiency of MVHR at the highest allowable value. In Paper III, the frosting threshold for an MVHR system equipped with a plate heat exchanger was investigated. Return room air with an average relative humidity of 30% was studied to find the heat exchanger surface temperature and the frosting threshold.

Figure 12 illustrates the incoming air temperature to MVHR below which frosting starts at the surface of the heat exchanger. The studied period was bounded to part of the heating season when there was a chance of frosting in the heat exchanger which was approximately 5 months in city of Örebro in central Sweden.

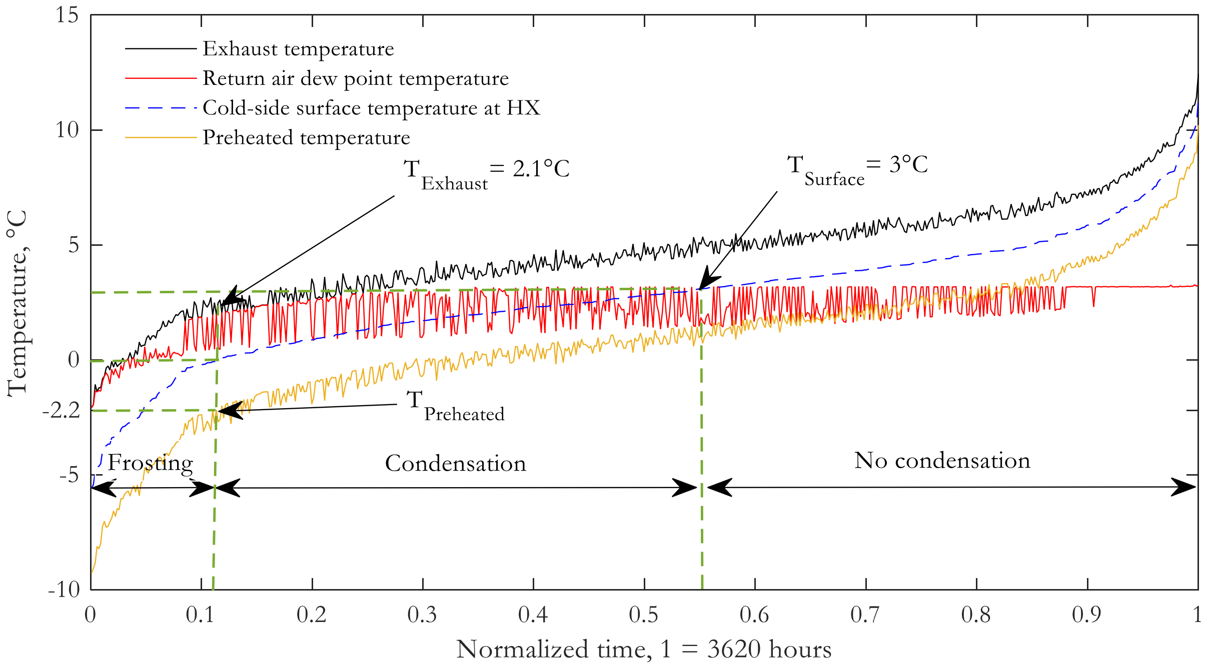


Figure 12: Frosting threshold in a plate heat exchanger by controlling the preheated air temperature [29]

Figure 12 shows that frosting in the heat exchanger in MVHR started when the outdoor temperature was below -2.2°C. The frosting threshold can vary with the return air relative humidity; therefore, the air preheater was on operation for inlet temperatures below -3°C.

In Paper II, the effects of utilizing a preheated air temperature control was investigated in more details. Figure 13 depicts the frosting duration for air preheating systems with and without a temperature control system. The simulated period for this case was also bounded to the part of heating season when frosting was expected, which was four months. It can be seen that the defrosting period for both was reduced to approximately less than 10% of the evaluation time but the preheated air temperatures are different. Therefore, controlling the preheated outdoor air temperature did not affect the defrosting period. However, preheated outdoor air temperatures significantly above the frost threshold influenced the heat recovery efficiency of the MVHR system negatively.

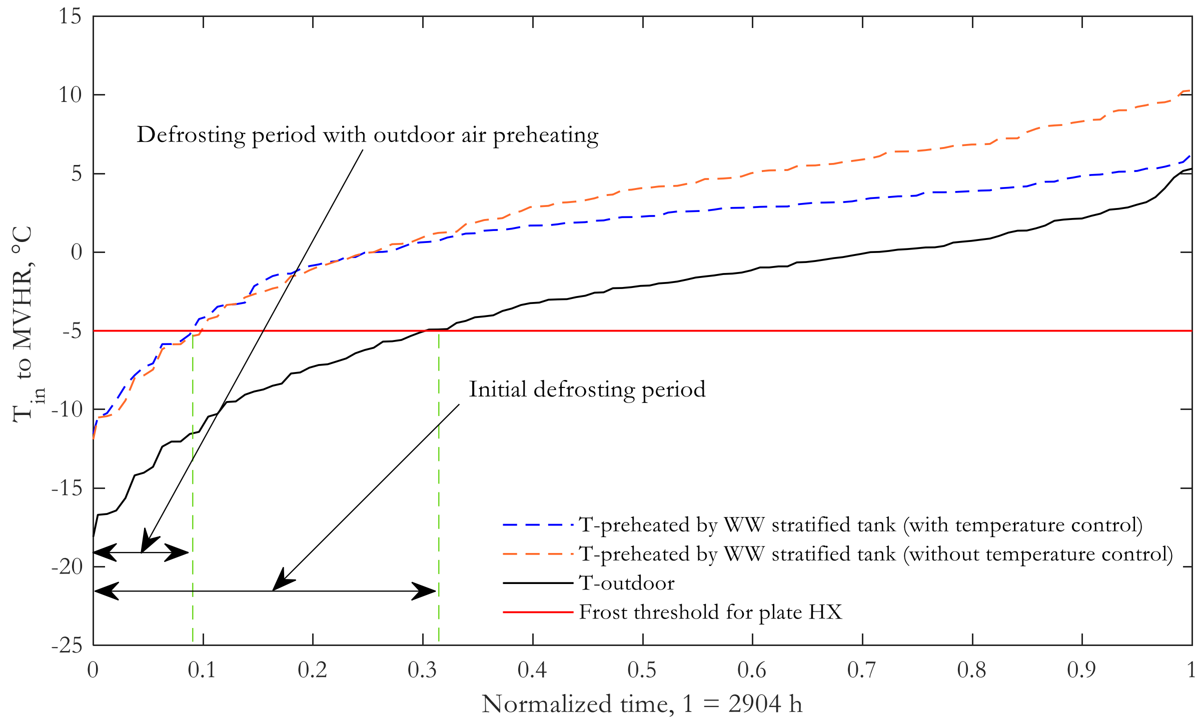


Figure 13: Reduction of defrosting need of MVHR by outdoor air preheating systems without and with temperature control [26].

In Papers I and II, the effect of utilizing a temperature control system on the heat recovery efficiency of the MVHR was studied. Higher inlet air temperature to the MVHR decreases its heat recovery efficiency. Unnecessary high inlet temperature, as discussed in both papers, is only increasing the exhaust air temperature which leaves the building. With other words, a large amount of the recovered heat in that case would be simply just bypassed to the outdoor environment. Equation 1 represents the temperature transfer efficiency of an MVHR system. It shows how an increase in exhaust temperature leads to lower temperature transfer efficiency of MVHR. Therefore, by using an air preheater in front of an existing (in series with) MVHR, the temperature efficiency of the heat exchanger in MVHR will drop. This will result in an unnecessary energy loss.

$$\eta_{MVHR} = \frac{T_{supply} - T_{exhaust}}{T_{return} - T_{exhaust}} \tag{1}$$

Figure 14 depicts how an unnecessary increase in outdoor air temperature above the frost threshold can affect the temperature efficiency of the heat exchanger at MVHR. According to Equation 1, by maintaining supply and return temperatures constant, the decrease in efficiency results in higher exhaust air temperature as shown in Figure 14a. This means that air with higher temperature which transfers more thermal energy is directed to outdoor, see Figure 14c.

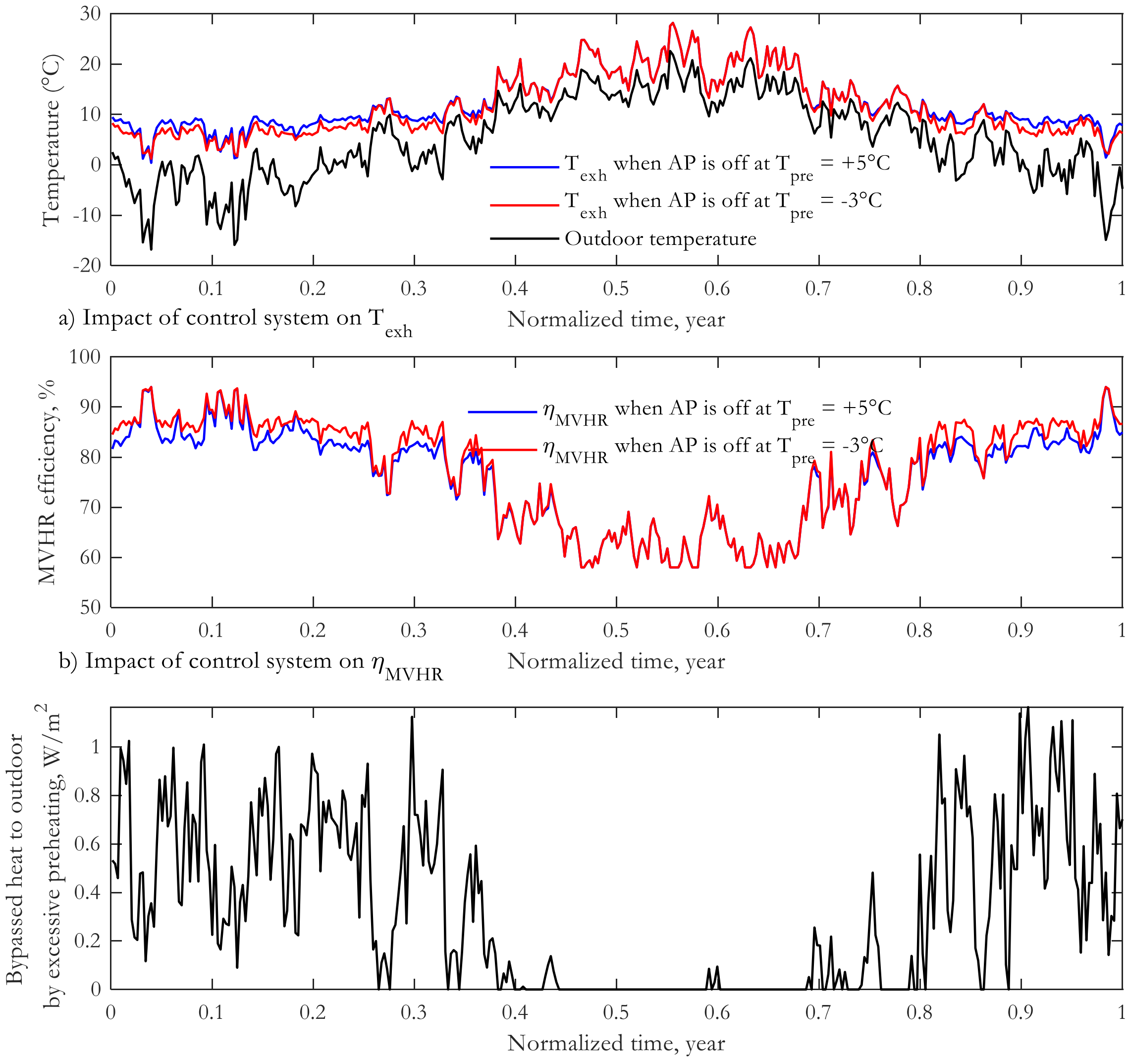


Figure 14: The effect of preheating outdoor air above threshold on exhaust air, MVHR temperature efficiency and bypassed energy

In Paper II, IV and V, three outdoor air preheating systems were compared from two different perspectives; one was the potential of each system in utilizing renewable heat sources to increase the outdoor air temperature above the frost threshold, and the second was the evaluation of the cost effectiveness of each system for a 20-year period. Geothermal energy as an available renewable heat source (System 1) and the residential wastewater stored in two types of storage tanks were compared in details; stratified storage tank which was denoted as System 2 and unstratified storage tank which was identified as System 3.

Figure 15 illustrates the heat recovery potential of the three air preheating systems and the required energy for the circulation pumps. System 1, the air preheater using geothermal energy as the heat source, required noticeably higher pumping power in comparison to the wastewater air preheaters. This was mainly due to circulation of brine in the borehole's u-pipe heat exchanger. Howbeit, the transmitted heat rate to the outdoor air by System 1 was similar to System 3 and lower than System 2, see Figure 15b.

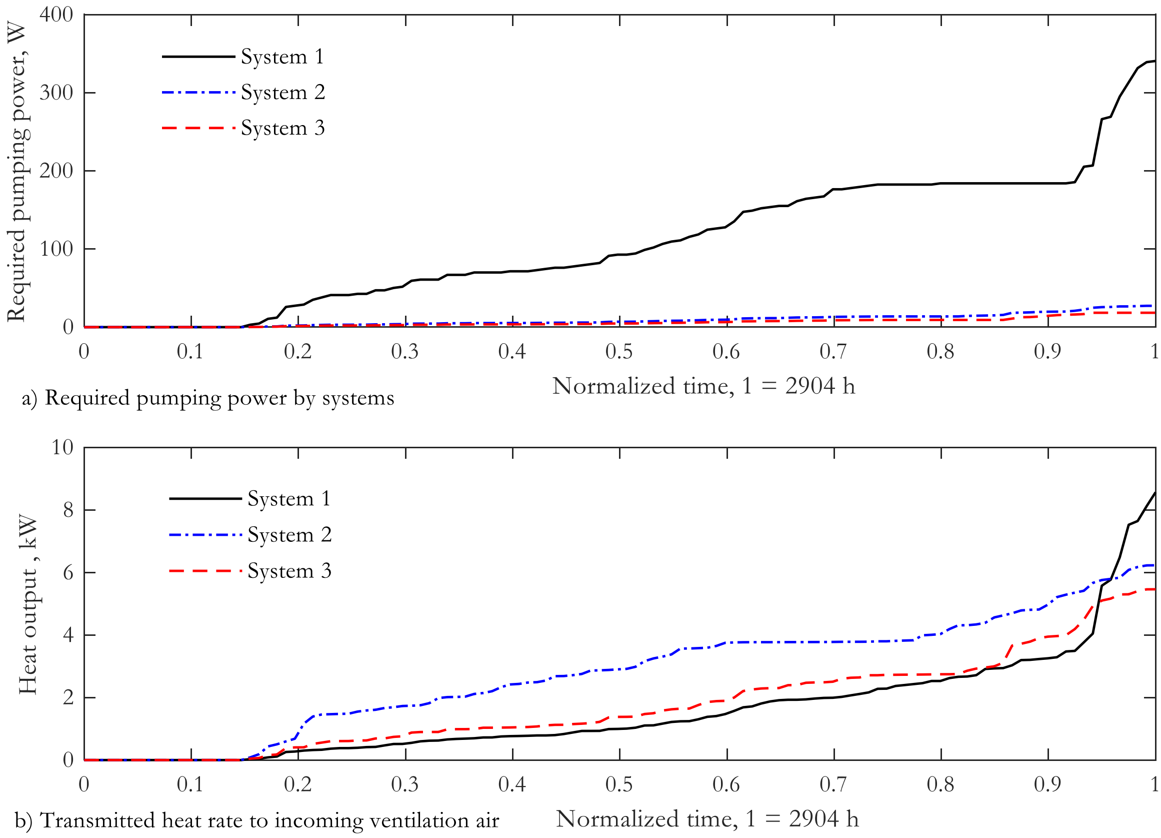


Figure 15: Required pumping power and the output heat rate, 1 = 2904 h [26]

Figure 16 shows the accumulative initial and operational costs of each system compared to the base case in a 20-year period. The payback time for each system can be identified at the intersecting points of the each system curve with the base case. It can be seen that System 3 had the shortest payback time which was approximately 8 years. This was mainly due to minor electricity requirements for the circulation pump and lower initial investments since the unstratified tank was much cheaper than the stratified tank and drilling a borehole. A break-even point for System 2 was reached at about 17 years. Although the average increase in accumulated costs for all air preheating systems was 13 000 SEK/year, the benefits from System 1 could not break even with the costs within the 20-year period. The initial costs for System 1, mainly drilling the borehole, was more than twice as high in comparison to the base system.

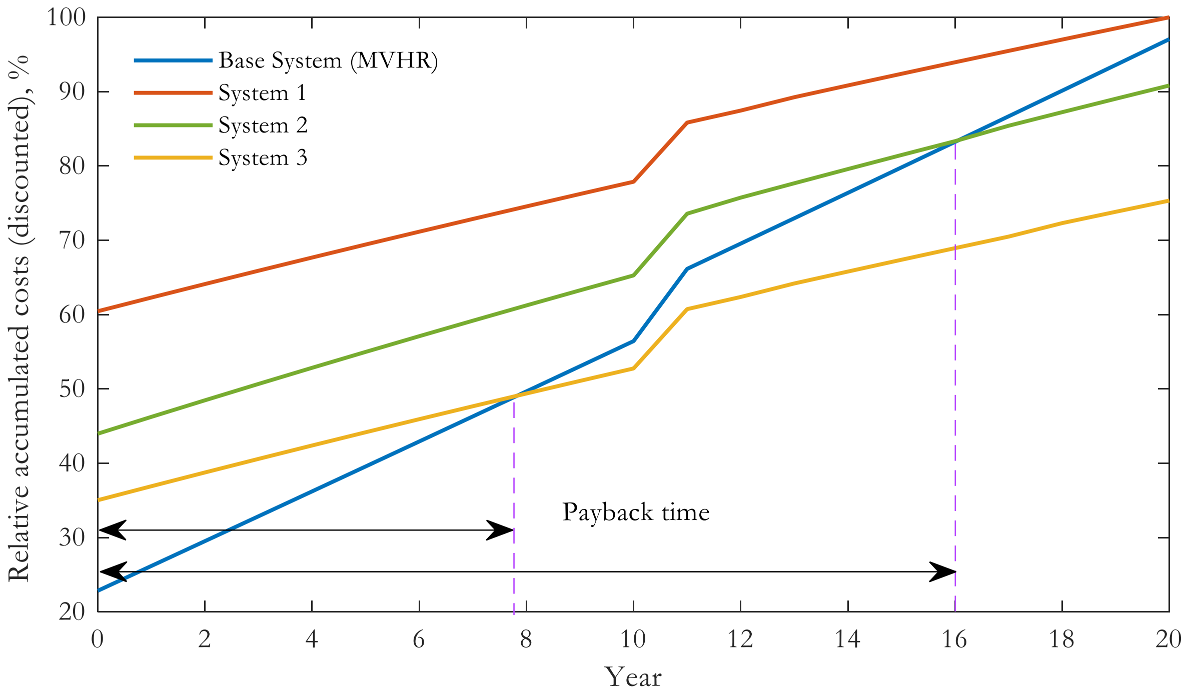


Figure 16: Accumulated cost and discounted payback period of the studied systems [30].

The tips and guidelines regarding outdoor air preheating in order for frost avoidance are presented in a flowchart in Figure 17. By wastewater heat recovery, the outgoing grey water temperature from the building decreases from 19-25°C to 5-7°C. This recovered thermal energy is utilized for increasing the incoming outdoor air temperature to MVHR. If preheated air temperature is above the frost threshold, the temperature efficiency of MVHR drops a lot which results in higher exhaust air temperature. Therefore, the recovered heat from wastewater would be bypassed and not saved in the system.

The highest possible temperature efficiency of MVHR is accomplished by preheating the incoming ventilation air just to above frost threshold. This provides closest supply and return air temperatures, increases the heat recovery efficiency while frosting in the heat exchanger is avoided. The exhaust air temperature in this case increases just to the point to assure a heat exchanger surface temperature on the cold side above 0°C to avoid the internal frost formation. Thus, the lowest possible amount of the recovered heat energy from wastewater is bypassed to the outdoor air. (see Figure 17)

Preheating the cold outdoor air, as shown by this study, can reduce or eliminate the defrosting need of MVHR; however, this approach will further decrease the relative humidity of the supply air to the building. The low relative humidity of the preheated air is not suitable in terms of indoor air quality and health issues. This, which was not in the scope of current research work, can be further investigated.

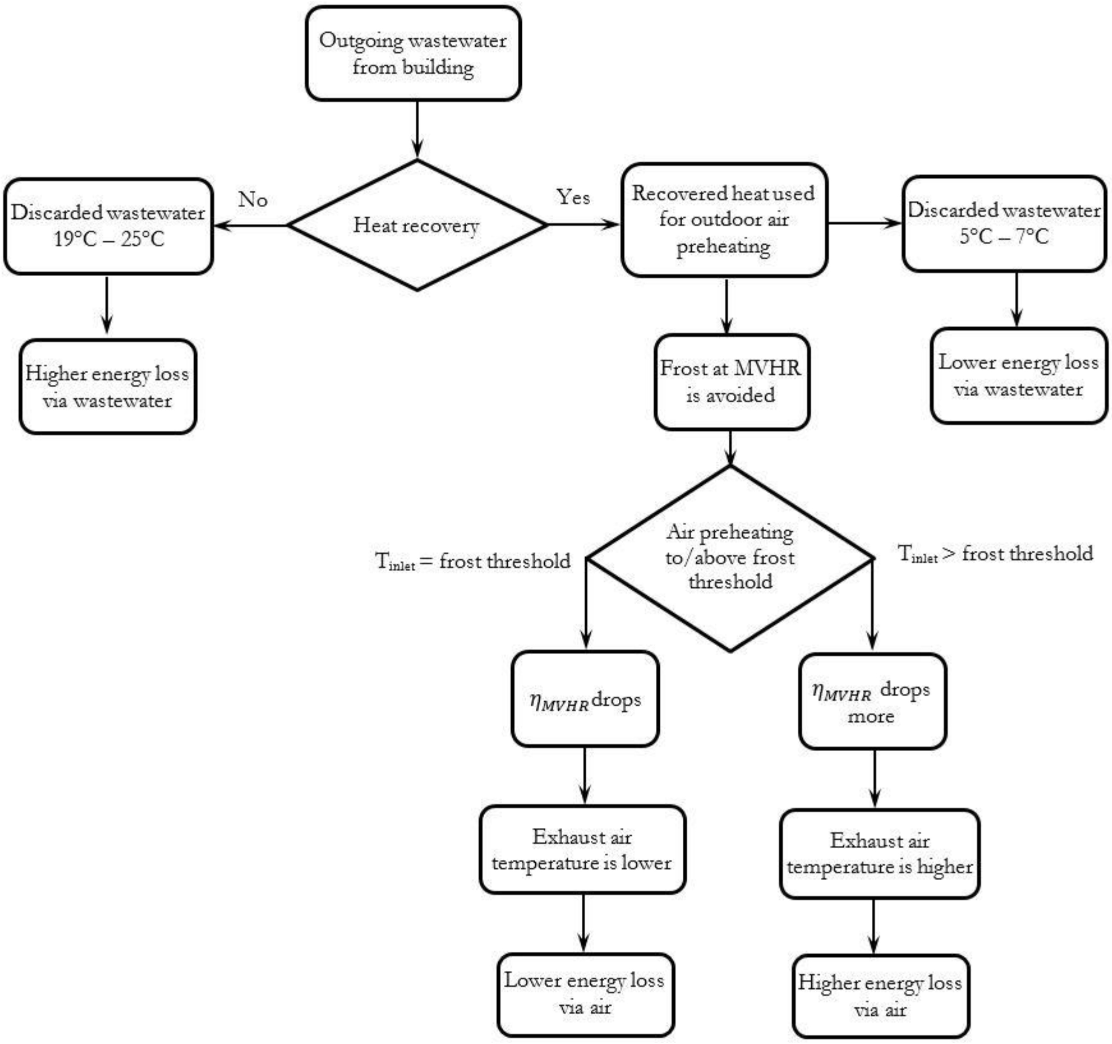


Figure 17: Energy flow and the impact of preheated temperature control on energy saving

4. Conclusions and Future Work

This thesis presented a brief summary of the entire research work on the heat recovery potential of residential wastewater for preheating the inlet air to mechanical ventilation systems in cold climate countries. Based on the presented results in this thesis and the appended papers, the following conclusions are drawn:

The efficiency of the heat exchanger at MVHR is the most decisive factor in frost formation. Higher efficiencies of heat exchanger aim to provide supply temperatures close to return temperature. This would decrease the exhaust air temperature below the dew point for cold outdoor air. Therefore, by preheating the inlet air to MVHR, the efficiency of heat exchanger decreases and this results in higher exhaust air temperature and subsequently, heat exchanger surface temperature.

Utilizing a control system to preheat the outdoor air to just above the frost threshold will ensure the highest possible heat exchanger efficiency at MVHR and decrease the operation time of the wastewater or brine circulation pump. Thus, identifying the frosting limit is crucial. In case of constant 30% relative humidity in the return air, frosting starts at temperatures below -2.2°C. This is valid for plate heat exchangers. For rotary wheels, frosting occurs at lower temperatures around -12°C at the same relative humidity in return air.

Wastewater circulation pump requires a lower electrical power compared to the one installed in for the borehole system.

Outdoor air preheating systems using heat from the stored wastewater have a higher probability of generating savings within the 20-year operation period. Break-even time for the systems utilizing wastewater was reached after 8 to 17 years (for unstratified and stratified tanks, respectively). The geothermal energy exploitation, however, requires higher initial investment and operational costs which make the payback period longer than 20 years.

4.1. Future work

A precise control strategy, as it was mentioned earlier in the thesis, plays an important role in managing the available energy sources. A further step towards a smart building would be utilizing the real time evaluation system in which the return air relative humidity level and the outdoor air temperature are monitored and the corresponding frost threshold is calculated. This would optimize the energy flow within the system boundaries by preheating the outdoor air just to the frost threshold.

Since the suggested heat recovery systems target only the coldest periods of a year, a wastewater heat pump can complement heat recovery duration in the rest of time span. In combination to a smart control system where frosting is anticipated, utilizing a wastewater heat pump would contribute to the hot water production when there is no risk of defrosting. Further investigations regarding the compliance of wastewater heat pumps with the district heating grid are of high importance.

A next step is also to study the interconnectivity of heating and ventilation systems to reduce the defrosting need in an MVHR system. For district-heated buildings, lower the return water temperatures to the heating grid are desirable. Therefore, using the return water from radiators as a heat source for preheating the outdoor air results in lower return temperatures as well as a decrease in defrosting need. This would benefit the district heating supplier while the thermal energy/load requirements of the building abate.

The heat recovery efficiency of MVHR in a large body of research studies as well as provided information by manufacturers of heat recovery devices is expressed by temperature efficiency. According to the dry air condition in laboratories, temperature efficiency gives rather accurate estimation of the overall heat recovery efficiency. This, however, can be quite different in real working conditions where the air contains moisture, and latent heat transfer is not negligible. Figure 18 illustrates the temperature transfer efficiency in comparison with enthalpy transfer efficiency for the building case in Stockholm, studied in Paper I. There is a considerable distinction (20-25%) between the temperature and enthalpy efficiencies. This disagreement does not affect the validity of the obtained results in the current work since the performance of all components is verified and validated by references (see section 2.3.) and the heat recovery device is regulated to the reference component by temperature efficiency. However, the suggestion for future improvements to consider latent heat transfer in real working conditions is vital.

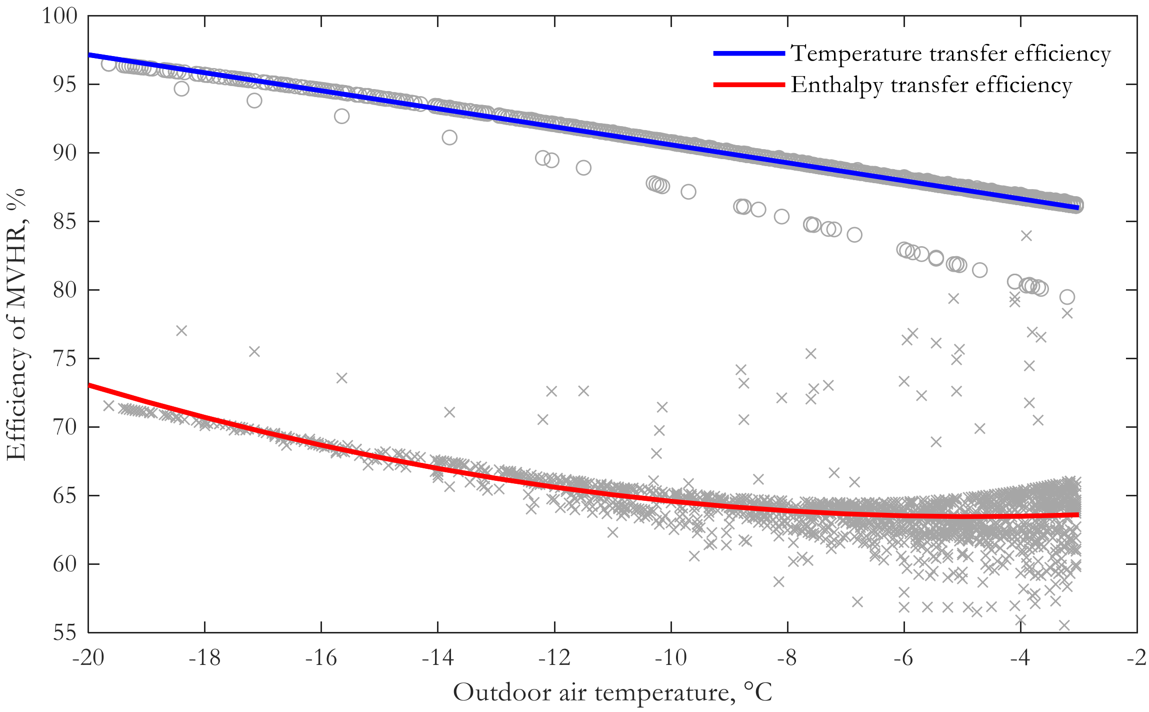


Figure 18: Temperature transfer efficiency vs. Enthalpy transfer efficiency at MVHR

References

[1] "Energy in Sweden 2017," 2017.

[2] *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast).* The European Parliament, 2018.

[3] *Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 - amending Directive 2012/ 27/EU on energy efficiency.* The European Parliament, 2018.

[4] "Energy in Sweden - facts and figures 2019."

[5] L. Nilsson, "Summary of energy statistics for dwellings and non-residential premises for 2016 (Energistatistik för småhus, flerbostadshus och lokaler 2016)," 2017.

[6] E. Karlsson and R. Jonsson, "One house, five possibilities - Demonstration project for energy efficiency in existing multi-dwelling buildings from the million program time (Ett hus, fem möjligheter - Demonstrationsprojekt för energieffektivisering i befintliga flerbostadshus från mil," Malmö, 2014.

[7] R. Jonsson, "A house, five possibilities (Ett hus fem möjligheter)," Malmö, 2014.

[8] *Boverket´s mandatory provisions and general recommendations, BBR. BFS 2011:6 with amendments up to BFS 2018:4.* Swedish National Board of Housing, Building and Planning (Boverket), 2018.

[9] "Vattenfall." [Online]. Available: https://www.vattenfall.se/foretag/fjarrvarme/priser/#%23result_container. [Accessed: 28-May-2019].

[10] F. Meggers and H. Leibundgut, "The potential of wastewater heat and exergy: Decentralized high-temperature recovery with a heat pump," *Energy Build.*, vol. 43, no. 4, pp. 879–886, Apr. 2011.

[11] M. Rafati Nasr, M. Fauchoux, R. W. Besant, and C. J. Simonson, "A review of frosting in air-to-air energy exchangers," *Renew. Sustain. Energy Rev.*, vol. 30, pp. 538–554, Feb. 2014.

[12] M. Song and C. Dang, "Review on the measurement and calculation of frost characteristics," *Int. J. Heat Mass Transf.*, vol. 124, pp. 586–614, Sep. 2018.

[13] M. Rafati Nasr, M. Kassai, G. Ge, and C. J. Simonson, "Evaluation of defrosting methods for air-to-air heat/energy exchangers on energy consumption of ventilation," *Appl. Energy*, vol. 151, pp. 32–40, 2015.

[14] P. Kempe and R. Jonsson, "BeBo-evaluation, Newly built multi-family house with preheated air using heat from boreholes - HSB-FTX geo-energy without heat pump (BeBo-utvärdering, Nybyggt flerbostadshus med förvärmning med borrhålsvatten - HSB-FTX geoenergi utan värmepump), Technical," 2015.

[15] B. Simanić, "Preheating ventilation air using heat from boreholes without use of heat

pumps, case study Vivalla Örebro (Förvärmning av ventilationsluft mha borrhålsvärme utan värmepump, fallstudie Vivalla Örebro); Technical report, SBUF Development Fund of Swedish Con," Malmö, 2016.

[16] M. Sundin, "Geothermal preheating of ventilation air: An evaluation of the ventilation efficiency of the ventilation system (Geotermisk förvärmning av ventilationsluft: En utvärdering av ventilationssystemets energieffektivitet)," Uppsala University, 2016.

[17] "SHARC Energy Systems." [Online]. Available: http://www.sharcenergy.com/. [Accessed: 27-Jul-2019].

[18] "Hydropress Huber AB - Wasre Water Solutions." [Online]. Available: https://www.hubersverige.se/KrattomloppsgallerRakeMax.htm. [Accessed: 27-Jul-2019].

[19] "TRNSYS : Transient System Simulation Tool." [Online]. Available: http://www.trnsys.com/. [Accessed: 27-May-2019].

[20] "We are Meteotest | Meteotest." [Online]. Available: https://meteotest.ch/en/. [Accessed: 27-May-2019].

[21] "Intro | Meteonorm." [Online]. Available: https://meteonorm.com/en/. [Accessed: 27-May-2019].

[22] L. F. Orpana, "Air treatment system in energy calculations A study of product data and calculation methods (Luftbehandlingssystem i energiberäkningar En studie av produktdata och beräkningsmetoder)," Malmö, 2015.

[23] A. Ploskić and Q. Wang, "Evaluating the potential of reducing peak heating load of a multi-family house using novel heat recovery system," *Appl. Therm. Eng.*, vol. 130, pp. 1182–1190, Feb. 2018.

[24] N. Le Truong, A. Dodoo, and L. Gustavsson, "Effects of heat and electricity saving measures in district-heated multistory residential buildings," *Appl. Energy*, vol. 118, pp. 57–67, Apr. 2014.

[25] B. Nourozi, Q. Wang, and A. Ploskić, "Energy and defrosting contributions of preheating cold supply air in buildings with balanced ventilation," *Appl. Therm. Eng.*, vol. 146, 2019.

[26] B. Nourozi, Q. Wang, and A. Ploskić, "Maximizing thermal performance of building ventilation using geothermal and wastewater heat," *Resour. Conserv. Recycl.*, vol. 143, pp. 90–98, 2018.

[27] *Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012*. Brussels: The European Parliament, 2012.

[28] S. Härer, "Life Cycle Cost Analysis of novel Heat Recovery Systems using renewable Heat Sources - A Case Study of a Multi-Family Building in Sweden," Reutlingen University, 2019.

[29] B. Nourozi, Q. Wang, and A. Ploskić, "Identifying frost threshold in a balanced mechanical ventilation system by inlet and exhaust air temperature control," in *The 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC)*, 2019.

[30] S. Härer, B. Nourozi, Q. Wang, and A. Ploskic, "Frost reduction in mechanical balanced ventilation by efficient means of preheating cold supply air," in *The 10th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings (IAQVEC)*, 2019.