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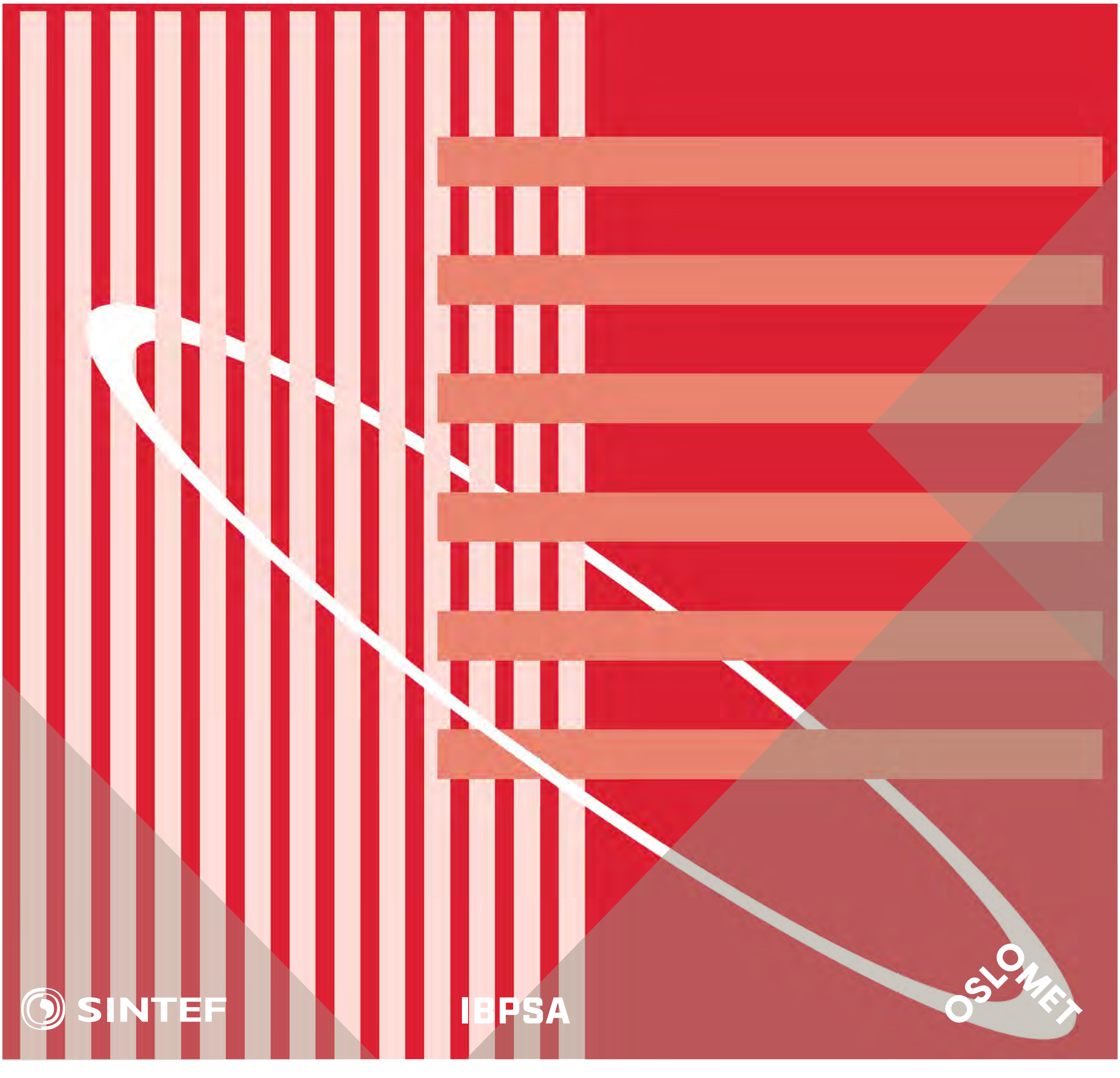

SINTEF Proceedings

Editors:
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Numerical analysis of heat recovery options in old Finnish apartment buildings

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Abstract

Ventilation heat recovery in residential buildings is well established. However, waste heat recovery from sewage is focused on industrial applications and is not commonly done in Finland at the residential building level. This study examines the CO_2 emission reduction potential of heat recovery from sewage and ventilation exhaust air in various configurations in an apartment building built before ventilation heat recovery systems were mandatory. The study was done by dynamic simulation using TRNSYS and the IDA-ICE building simulation software. The lowest costs and emissions were obtained by combining both the exhaust air and sewage heat recovery using heat pumps. Thus, heat recovery can reduce emissions even while lowering life cycle costs. CO_2 emissions were reduced by 12 to 50% using a series connection between district heating and waste heat sources and 21 to 37% using a parallel connection. Utilities enforce the use of parallel connection, which reduces heat recovery potential. With heat exchanger based ventilation heat recovery, the emissions were reduced by 23 to 29%. The key performance indicator for energy efficiency is the primary energy consumption. However, systems with similar primary energy consumption can have very different emissions. The mismatch between emissions and primary energy use suggests a need for a policy update.

Introduction

The Finnish building code introduced the requirement of ventilation heat recovery for residential buildings in 2003 (Ministry of the Environment, 2017). However, most Finnish apartment buildings have been built before this and have no ventilation heat recovery (HR), which wastes a lot of energy. In addition, there is no requirement of recovering heat from sewage even in new buildings. Sewage heat is typically recovered in a centralized manner in waste water treatment plants or even in district heating facilities (Helen Oy, 2020). However, while a far-away treatment plant might recover 10 to 30% of the original energy content in the sewage, on-site recovery at the waste producing site could allow 70 to 90% recovery (Mazhar et al., 2018). This spells out the need for improved heat recovery systems implemented directly at the building.

Exhaust air pumps (EAHP) are quite a well established technology. Various EAHP configurations have been analysed in (Thalfeldt et al., 2018). Special focus was given on integrating the EAHP with district heating (DH), which is also the most common heating type for apartment buildings in Finland. EAHP systems could cover almost all heating needs in summer, but raised the average DH return temperatures. Three EAHP connections were analysed, including series and parallel connection, but no significant performance differences were found between the cases. This was attributed to prioritizing production of domestic hot water (DHW). Study by (Kensby et al., 2017) revealed the non-correlation of district heating and electricity prices. It showed that costs could be reduced by optimizing the heat source timing in a DH/EAHP hybrid, instead of always using the EAHP for base load generation. Advanced control algorithms for a solar electric EAHP hybrid systems were examined in (Psimopoulos et al., 2019). Various priorities between battery and thermal energy storage and between space heating or hot water focus were examined. The value of heat pump control algorithms was greater if no battery electric storage was available.

Ventilation heat recovery was examined in (Ploskić and Wang, 2018). Sewage HR was connected to the inlet air supply of a low-energy house in northern Sweden to reduce ventilation heating demand. Using the waste heat, the ventilation system could more often meet the air supply temperature requirement and reduced the ventilation heating demand by up to 40%. Similarly, sewage HR and geothermal energy were used to reduce frosting in ventilation heat recovery (Nourozi et al., 2019). The sewage HR system did more than halve the total defrosting time in the air-handling unit, but major use of recovered sewage heat reduced the temperature efficiency of the ventilation HR system. The buildings in these studies utilized a mechanical balanced ventilation system, which is not installed in most Finnish apartment buildings. Another study found that sewage HR could cover 80% of DHW heating demand (Hervás-Blasco et al., 2020). This system utilized two connected hot water storage tanks. Comparison was made between infinite available sewage and finite, but constant availability and finite, but variable availability. With proper system design (heat pump or tank sizing), the variability had only a minor impact on system performance.

This study examines the CO_2 emission reduction potential and cost-effectiveness of various hybrid heat recovery solutions in Finnish apartment buildings. It compares the stand-alone ventilation or sewage heat recovery systems to combined systems with both HR methods integrated.

Ideal heat pump connections are compared to systems that are commonly accepted by utilities.

Methods

Building description

The Helsinki municipal housing company (Heka Ltd.), which is the biggest lessor in Finland, owns 531 buildings, with a combined net heated floor area of 2 815 000 m^2. Requirements of ventilation heat recovery were not added to the Finnish building code until the year 2003, but 85% of Heka's buildings have been built before the year 2000 (Heka Ltd., 2020). With an average heating demand of 197 kWh/m^2/a, there is a great potential for efficiency improvements through ventilation or sewage heat recovery. The buildings use district heating, which in Helsinki is supplied mostly through coal power, adding to the emission benefits of heat recovery. A typical apartment building without any heat recovery systems was modelled in IDA-ICE 4.8 to serve as a calculation basis. The properties of the building are shown in Table 1 and Figure 1. Figure 2 shows a comparison of the monthly heating demand in the existing and simulated buildings. The measured data was from the year 2017, while the simulation was done using the TRY2012 weather data (Kalamees et al., 2012) and corrected using degree day weighting for the year 2017. The simulated heating demand for the whole year was 4.3% lower than the measured demand, showing a good correlation between simulation and practice. Hourly comparison was not an option due to non-matching weather profiles.

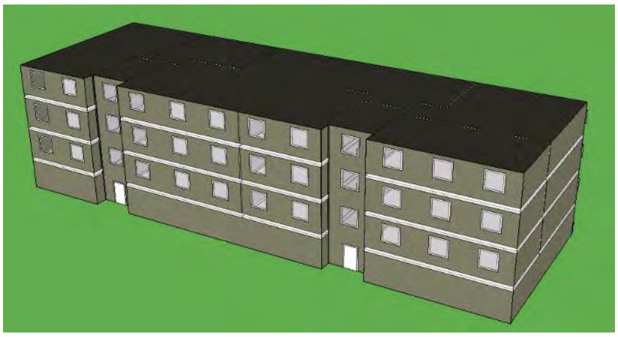

Figure 1. IDA-ICE model of the simulated apartment building.

Water consumption in the reference building was 163 L/resident/day, based on measured data. 40% of this was assumed to be domestic hot water, as is instructed in the building code (Ministry of the Environment, 2018a). Since only monthly consumption was available, hourly use profiles were based on measured results from other apartment buildings (Koivuniemi, 2005). DHW consumed 49% of the heat used in the reference building, with the remainder used for space heating.

Table 1. Building properties.

Feature	Value	Feature	Value
Construction year	2000	Ventilation	
U-values of envelope (W/m^{2}K)		Type	Mechanical exhaust
External wall	0.28	Heat recovery	-
Floor	0.36	Air change rate (1/h)	0.5
Roof	0.22	SFP (kW/m^3/s)	1.5
External doors	1.4	Water radiators (ºC)	70/40
Windows (triple-glazed, clear)	1.7	Heat distribution efficiency	0.8
Window g-value	0.71	Heating set point (ºC)	
Window direct transmittance	0.64	Living spaces	22
Window light transmittance	0.75	Other spaces	19
Infiltration (estimate)		Domestic hot water demand (L/resident/ day)	65
n_{50}, (1/h)	1	Residents	108
q_{50} m^3/(h m^2)	2.60	Heated net area (m^2)	3855
		Envelope area (m^2)	1608
		Window area (m^2)	315

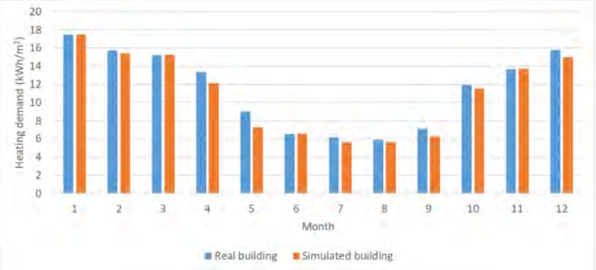

Figure 2. Measured and simulated heating demand of the apartment building.

Energy system options

The reference building had mechanical exhaust ventilation with no heat recovery systems. In this paper we compare the cost-effectiveness of various methods of heat recovery. We analyze combinations of ventilation heat recovery with heat exchangers (HX) or an exhaust air heat pump and sewage heat recovery with heat exchangers or a heat pump. The examined scenarios are shown in Table 2. In cases 2 and 3, a mechanical balanced ventilation system was installed. In cases 4 to 8, EAHP and sewage HR systems were connected to the district heating system in an ideal manner i.e. in series, preheating the circulating fluid. In cases marked with B, regulation-acceptable parallel connections were used instead.

Table 2. Examined scenarios with different heat recovery options.

Scenario	Ventilation type	Ventilation HR	Sewage HR
1	Exhaust	-	-
2	Balanced	HX	-
3	Balanced + VAV	HX	-
4	Exhaust	EAHP	-
5	Exhaust	-	HX
6	Exhaust	-	HP
7	Exhaust	EAHP	HX
8	Exhaust	EAHP	HP
4 B	Exhaust	EAHP	-
6 B	Exhaust	-	HP
8 B	Exhaust	EAHP	HP

Energy system model

The building was modelled using the dynamic building energy simulation tool IDA-ICE 4.8. The IDA-ICE model was used to calculate the heating demand under all different ventilation systems (Scenarios 1 to 3). The heating demand profile from Scenario 1 (which includes space heating (SH), ventilation heating and domestic hot water) was used as an input for the remaining scenarios. The energy systems for these scenarios were simulated using TRNSYS 17, to allow more flexibility in the system design. The TRNSYS model consisted of heat exchangers (Type 91), flow mixers/splitters (Type 11h, 11f), stratified thermal storage tanks (Type 534) and a custom heat pump model.

Heat pump performance was based on the NIBE F1345-60 heat pump (NIBE AB, 2017). Flow rates of source and load side were determined from the HP data sheet. Part-load operation was allowed, in which case the power and flow rates were adjusted in the same proportion. Figure 3 shows the thermal power of the F1345 60 kW heat pump under different heat source temperatures (x-axis) and load-side temperatures (separate lines for 35, 50 and 65 °C). The power values were linearly scaled down for the smaller heat pumps utilized in this study.

Scenario 1 used mechanical exhaust ventilation, where the exhaust air from rooms was blown outdoors without any heat recovery. In Scenario 2, a constant flow mechanical balanced ventilation system was used instead. Now, heat from exhaust air was recovered using a heat exchanger with 70% temperature efficiency. This exceeds the minimum requirement (Saari and Airaksinen, 2012), but is still lower than some commercial products. The supply air temperature was 17 °C. Scenario 3 was otherwise the same, but variable air flow ventilation (VAV) was utilized. The air flow was 0.14 L/s/m^2 when a room was unoccupied and increased linearly to 0.36 L/s/m^2 at full occupancy.

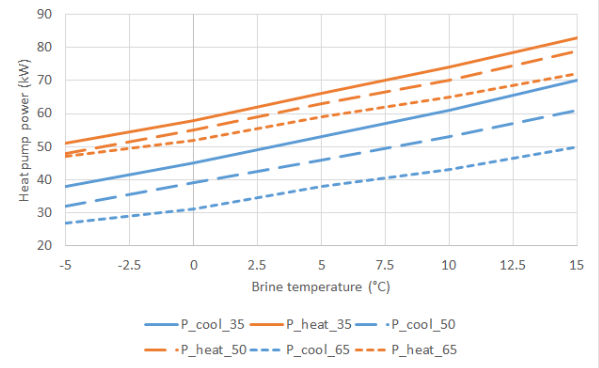

Figure 3. Heating and cooling power of the heat pump NIBE F1345-60. Blue lines represent the cooling power of the heat source and orange lines the heating power of the load. The numbers in the legend signify the output temperature (°C).

Heat recovery series connection

Scenarios 4 to 8 utilized a series connection between the heat recovery and district heating. Any waste heat was first used to preheat the return flow from the space heating circuit and the cold water in the DHW circuit. A stratified primary storage tank (TRNSYS Type 534) with 2 m^3 volume was used with the EAHP. A separate 2 m^3 secondary tank was used for sewage heat recovery in the DHW circuit. When in use, the EAHP capacity was 30 kW$_{th}$ and the sewage HP capacity was 15 kW$_{th}$. The heat recovery system configuration is shown in Figure 4. The figure shows the most complex configuration, Scenario 8, with two heat pumps and two storage tanks. Other scenarios can be obtained by removing either heat pump or the sewage tank from the system. The connection between waste heat and district heating is shown in Figure 5 (series) and (parallel).

When operating the EAHP, waste heat from the exhaust air was transferred to a brine circuit via a HX. The brine was used as a heat source for the EAHP. The EAHP was activated on full power whenever the primary storage tank temperature was 5 °C below the set point. The idea was to keep the share of EAHP use high, while reducing the amount of on-off-switching. In addition, the heating demand on the load-side was monitored and the EAHP was operated on partial power relative to the demand to slow down the temperature decay in the tank. The set point was determined by the SH control curve, but it was at least 45 °C and a maximum of 60 °C. SH flow was preheated in the primary tank before utilizing district heating to get to the required temperature level.

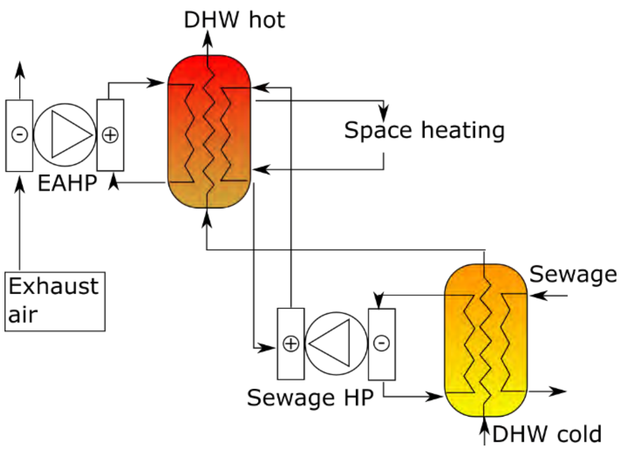

Figure 4. Schematic of the heat recovery system with both exhaust air and sewage HR using heat pumps.

Sewage HR was arranged through a secondary thermal storage tank. Sewage flow at 20 °C was pumped through the secondary tank's heat exchanger to recover the waste heat. Average sewage temperatures of 23 °C have been measured in Finland (Koikkalainen, 2016). However, a conservative temperature value was used to compensate for the ideal heat recovery tank. The sewage flow rate equalled the total water consumption, not only the DHW consumption, as even cold water gets warmed up in the piping between times of use. DHW was preheated by letting the cold inlet water at 5 °C flow through the secondary tank. When a heat pump was used for sewage HR, the secondary sewage tank was used as a heat source and the primary SH tank as a heat sink. The sewage HP was prioritized over the EAHP by the use of a higher set point, to take advantage of the higher heat source temperature provided by the sewage. In the series connection case, both the DHW and SH supply flows were preheated in the primary tank before using DH to prime the flow to the final temperature.

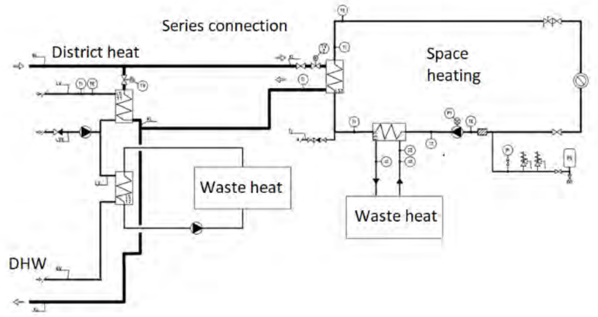

Figure 5. Series connection of waste heat and DH.

Heat recovery parallel connection

Scenarios 4 B, 6 B and 8 B were similar to the base scenarios. However, district heating companies wish to minimize the return temperature of the DH flow and generally don't allow a series connection for secondary heating systems. In the B scenarios a parallel connection for waste heat was used instead (). In the SH circuit (right side), the return flow was split into two parts, one going to the primary HR tank (Waste heat) and one to the DH HX, both at the same temperature. The heated flows were then mixed. The DH flow was adjusted to obtain the desired final temperature. Waste heat was not used for preheating, but had equal priority to district heating. This raised the required output temperature for heat pumps and reduced the share of energy produced with waste heat.

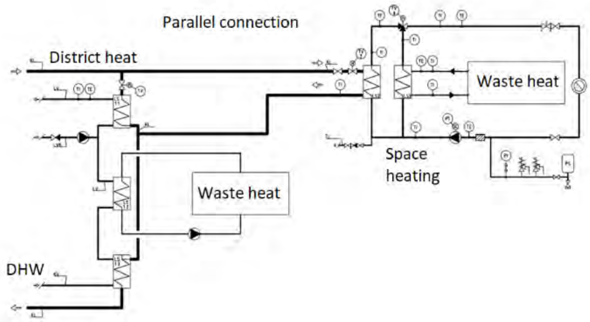

Figure 6. Parallel connection of waste heat and DH.

The DHW loop in the parallel configuration (left side of) contains three heat exchangers. The return flow from the DH circuit was used to preheat the cold DHW flow (lowest HX). The preheated DHW was further heated by waste heat from the primary HR tank (middle HX) and raised to the final temperature by another DH HX (top HX). Because in the parallel connection DHW preheating was done with district heating, the water temperature was so high that sewage HR using only the low temperature tank without heat pump was not feasible.

Primary energy, emissions and costs

Finland utilizes primary energy factors (PEF) to convert the combined electricity and district heating consumption into a single energy efficiency parameter, the primary energy consumption (PE). District heating has a PEF of 0.5 and electricity a PEF of 1.2 (Finlex, 2017). The PE consumption of the reference case was 107 kWh/m^2/a. For reference, the Finnish limit for a new nearly zero energy apartment building is 90 kWh/m^2/a (Ministry of the Environment, 2018b). The results of this study were not generated using all the background assumptions required for official PE accounting (the "E-luku") and are not directly comparable to the nearly zero energy building (nZEB) limit, which is only used for new buildings.

CO_2 emissions of the building were calculated using an emission factor of 164 kg-CO_2/MWh for district heating (Motiva Oy, 2017) and an average emissions factor of 132 kg-CO_2/MWh for electricity (Finnish Energy, 2017). The emission factors of electricity were determined separately for each month, such that during summer the minimum emission factor was 81 kg-CO_2/MWh and in winter the maximum emission factor was 174 kg-CO_2/MWh.

The cost of district heating had a fixed monthly component based on annual peak power demand and a consumption based component dependent on the season. The consumption price was 37 €/MWh from May to September, 64 €/MWh from October to December and 72 €/MWh from January to April. The price of electricity was a constant 122 €/MWh through the whole year.

The life cycle costs (LCC) were calculated over the time period *n* of 30 years. Interest rate *i* was 3% and the energy price escalation rate *e* was 2%. The LCC was calculated as follows:

$$r_e = \frac{i - e}{1 - e}$$

$$a = \frac{1 - (1 + i)^n}{i}$$

$$a_e = \frac{1 - (1 + r_e)^n}{i}$$

$$LCC = C_{investment} + aC_{maintenance} + a_e C_{energy}$$

where $C_{investment}$ is the initial investment cost of the building retrofit, $C_{maintenance}$ is the annual maintenance cost and C_{energy} is the combined annual cost of district heating and electricity consumption.

Results

The main results of the study are presented in Figure 7. It shows the district heating and electricity demand in the building in each scenario, as well as the annual CO_2 emissions. Shown above the bars are the primary energy consumption and the heat recovery rate as a percentage of demand, as well as the annual peak DH power consumption. Cases 4, 6 and 8 and their B counterparts are shown in different shades of colour to identify the scenario pairs.

The annual emissions in the reference case were 105 t-CO_2. As expected, the lowest emissions resulted from the use of both the EAHP and the sewage HR with HP (Scenario 8). Using the ideal series connection, the emissions dropped by over 50% to 52 t-CO_2. With the more acceptable parallel connection (Scenario 8 B), the emission s were 66 t-CO_2. Using the series connection, the PE value fell to 79 kWh/m^2/a. With the parallel connection, the PE consumption was 93 kWh/m^2/a. The parallel connection guarantees the cooling of district heating flow, which suffers from high return temperatures in the series connection. The series connection allows the heat pumps to operate on lower temperatures, which increases the amount of heat generated while restricting the rise of electricity consumption. This is also evident between Scenarios 4 and 4 B, which have almost the same amount of heat recovered. Due to the lower COP in the B case, less DH was replaced by the heat recovery system. In Scenario 4, the seasonal COP over the whole year was 5.33, while in Scenario 4 B it was 4.45. The worse heat pump performance had a direct effect on the emissions in the all the B scenarios. Emissions in Scenarios 4 B, 6 B and 8 B were 11%, 8% and 26% higher than in the series connected versions.

Figure 8 shows the cost distribution in each scenario. District heating costs are divided between consumption based energy cost and fixed cost based on annual maximum power demand. The lowest cost case was Scenario 8, which also had the lowest emissions. Investment costs were highest in Scenarios 2 and 3, which included a replacement of the ventilation system. Scenario 8 was the only one where the electricity costs exceeded the cost of district heating, due to the effective reduction of DH demand and increased electricity use by heat pumps.

Sewage HR with just a HX (Scenario 5) had the lowest investment cost, but it was the least effective way of reducing emissions. This was because of the limited temperature range in the heat recovery of DHW. The 5 °C inlet water was preheated to 20 °C by the sewage HR system (set point of DHW was 55 °C), but the energy was

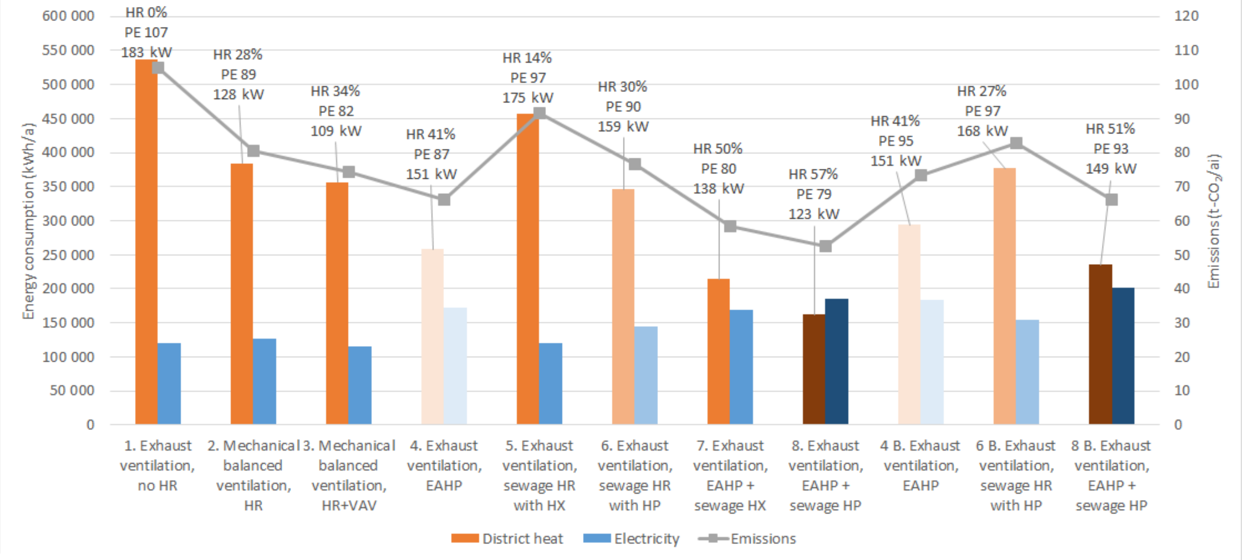

Figure 7. Annual district heating and electricity use and CO_2 emissions in the apartment building under different scenarios. Also shown are the heat recovery, primary energy use and annual peak DH power demand.

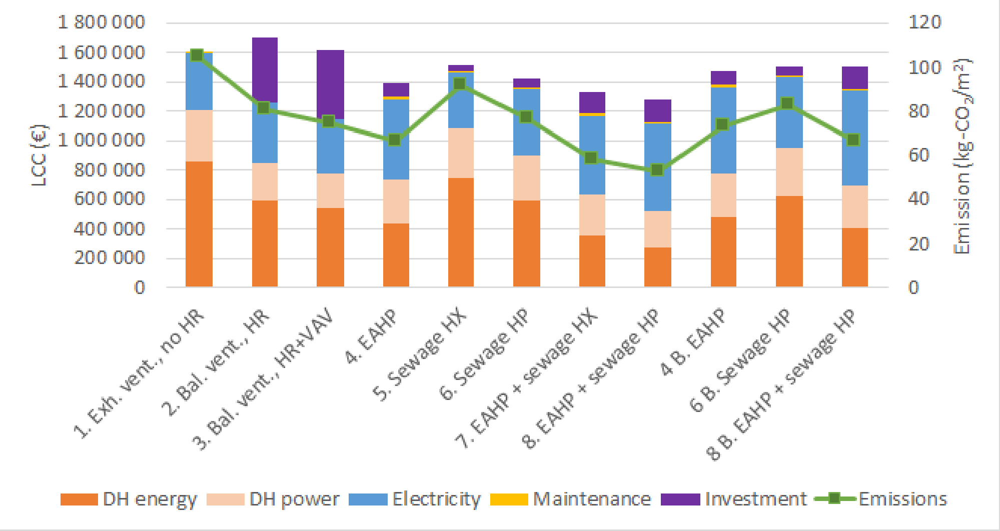

Figure 8. LCC distribution of each retrofit option.

only used in the DHW circuit, not for SH. Using the utility-acceptable connection, this setup was not considered feasible.

The combined benefit of both the sewage and ventilation heat recovery systems was less than the sum of the individual benefits. DH consumption was reduced by 70% in Scenario 8, while the sum of the reduction in Scenarios 4 and 6 was 87%. With the parallel connection, Scenario 8 B had a 56% reduction in DH demand, while the combined reduction in Scenarios 4 B and 6 B was 75%.

Replacing the old exhaust ventilation system with mechanical balanced ventilation (Scenario 2) was about as effective in reducing DH use and emissions as the parallel-connected sewage HR with HP (Scenario 6 B). The electricity use remained at a lower level, which would imply the ventilation retrofit to be a superior choice. However, as shown in Figure 8, the investment costs and LCC of Scenario 2 were much higher. Adding the VAV (Scenario 3) lowered both life cycle cost and emissions, but the LCC was still higher than in any of the retrofit scenarios with the original ventilation system. On the other hand, the primary energy use in Scenarios 2 and 3 was below many of the heat pump scenarios. Specifically, the PE consumption of Scenarios 2 and 3 was lower than in Scenario 8 B. Conversely, the CO_2 emission were lower in Scenario 8 B. This highlights an issue in the Finnish building code: Primary energy consumption can go up, even while emissions are decreased.

Figure 9 shows the monthly district heating and electricity use in the lowest emission utility-acceptable scenario, 8 B. It shows the district heating energy saved compared to the reference building as well as the increased electricity use resulting from the heat pumps. From June to August, 92% of heating demand was covered by the

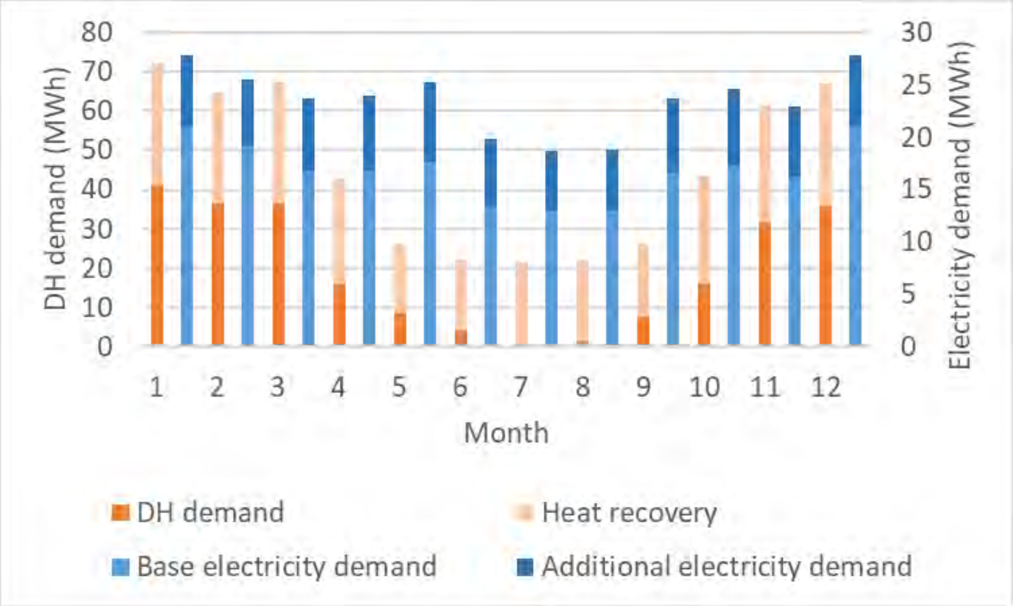

Figure 9. Recovered heat and additional electricity demand in Scenario 8 B vs. the reference.

heat recovery systems. From November to March, the recovered heat covered 45% of heating demand.

Discussion

While the energy demand of the simulated reference building was quite close to the measured data, there were some limitations in the accuracy of the study. The heat pump model was based on linearly fitted power curves and nominal flow rates, but did not take into account pressure changes in the heat transfer fluids. The seasonal COPs of the heat pumps were quite high (4 to 5), which may be a result of omitting some details. In the parallel connection scenarios, the DH flow was perfectly adjusted every timestep to match energy demand alongside the heat pump generation. This helped to minimize wasted energy.

The heat recovery from ventilation and sewage was handled using two separate heat pumps. This way each HR component could be added or removed without adjustment to the other. It would also be possible to run both waste heat streams through the same singular heat pump. This would have some effect on the average temperature of the heat source. Which configuration would perform better is a good topic for further study.

There are some issues which can limit sewage heat recovery potential. Here it was assumed that all sewage flows go through a single pipe where they can be easily routed to the HR system. If a building has many independent sewage outlets, it might not be cost-effective to recover heat. Here a plug flow tank model was used to collect the sewage heat allowing perfect recovery. In practice, the limited capacity of internal heat exchangers could prevent taking advantage of the peak waste flows. In a building with more residents, the ratio of peak to average sewage flow goes down, making it easier to recover heat. Conversely, sewage HR can be challenging in very small residential units. An ideal heat exchanger was used for sewage heat recovery in this study, but the sewage temperature was assumed to be lower than what has been measured in practice. This should reduce the chance of having too optimistic results.

The control algorithm of the heat pumps was not optimized. For example, district heating is very cheap in summer and it might make sense to turn off the heat pumps completely for this part of the year. This is a potential topic for future study. Unlike in (Thalfeldt et al., 2018), significant performance differences were discovered between the series and parallel EAHP connections. This was likely because of prioritizing space heating instead of DHW.

Conclusions

The installation of heat pumps was a more cost-effective way to reduce emissions than a ventilation retrofit. Heat recovery from ventilation had more potential than HR from sewage. The lowest LCC and the lowest emissions were provided by Scenario 8, which utilized both the ventilation and sewage heat recovery system with a HP, using a series connection with respect to district heating. Combining both the HR methods in a hybrid system provided diminishing returns, as there was some overlap in their operation and the combined benefit was less than the sum of their parts.

Using a series connection between heat pumps and district heating helped achieve lower primary energy consumption and emissions than the parallel connection. This contrasts previous findings where no differences were found. The likely reason is that the EAHP control prioritized space heating instead of DHW. Using the series connection for HP, emissions were reduced by 12 to 50% depending on the HR methods, compared to 21 to 37% with parallel connection. However, it could be possible to improve the performance of the parallel connected heat pumps using better control algorithms or connection configurations, especially when two waste heat sources are in use. One avenue of research would be to store excess heat in the ground during summer, to improve heat pump performance in the winter.

In some cases, a major drop in emissions could be accompanied by no change in primary energy consumption. This suggests that there is a need for a policy update so that the building code takes actual emission performance into account better. The series connection of waste heat recovery was found to be more effective, but it is not typically allowed because of undesirably high DH return temperature. Finding a use for higher temperature DH return flows would be a worthy topic of research.

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