Waste heat recovery potential in residential apartment buildings in Finland's Kymenlaakso region by using mechanical exhaust air ventilation and heat pumps

Tuija Korpela, Maunu Kuosa*, Hannu Sarvelainen, Erja Tuliniemi, Paulus Kiviranta, Kirsi Tallinen and Hanna-Kaisa Koponen

South-Eastern Finland University of Applied Sciences, Pääskysentie 1, 48220 Kotka, Finland.

Abstract

With the growing share of ventilation heat loads, the heat recovery over the mechanical ventilation systems appears as one of the key solutions to reduce heat loss and generate energy savings. Finland's long-term renovation strategy aims for a highly energy-efficient and almost carbon-free building stock by 2050. One of the greatest potentials for energy savings relates to those built between the 1960s and 1980s where no heat recovery exists.

This study addresses the wasted heat potential of apartment buildings in the Kymenlaakso region in Finland and how EAHPs can utilize it.

The wasted heat potential was mapped by selecting buildings of different ages in Kotka from the 1950s to 2010 and for which the thermal energy balance was determined. The apartment buildings with mechanical exhaust ventilation in Kymenlaakso were surveyed. If all the mapped exhaust air waste energy could be utilized by EAHPs, it could produce the thermal energy combined from different decades up to 18.7 GWh/a in Kotka and 36.8 GWh/a in Kouvola. The calculated annual reduction in CO_2 emissions might be about 590 and 944 tCO_2 in Kotka and Kouvola, respectively. The calculated payback periods varied from 7 to 13 years for the selected buildings.

*Corresponding author

Keywords: exhaust air heat pump, heat recovery, apartment building

Nomenclature

c_p	specific heat capacity of air	kJ/kg°C
P	electrical power of compressor	kW
Q_C	energy of condensation	kWh
Q_E	energy of evaporation	kWh

Q_v	heat loss of ventilation	kWh
ΔT	exhaust air and outdoor temperature difference	°C
ρ	density of air	kg/m^3
ι	ventilation unit running time	h
$\Delta\iota$	length of period	h

Abbreviations

COP	coefficient of performance
DHW	domestic hot water
EAHP	exhaust air heat pump
DH	district heating
HR	heat recovery
HRV	ventilation with heat recovery
SCOP	seasonal coefficient of performance

1 Introduction

With the growing share of ventilation heating loads, heat recovery over the mechanical ventilation systems appears as one of the key solutions to reducing heat losses and generating consequent energy savings.

Several different ventilation systems exist. A gravity-based system was most common until the 1960s. Gravity ventilation is based on the upward flow of warm air, which is lighter than cold air, and the pressure difference between the indoor and outdoor air due to the temperature difference. The air is removed from the exhaust air chimneys, and the replacement air is introduced into the living areas along the replacement paths.

Mechanical exhaust ventilation was general between 1960 and 1990. In this technology, the air is removed by a roof fan from the premises through exhaust air ducts, and replacement air is introduced into the living areas via replacement air paths. Adjustment usually takes place with a cooker hood.

In mechanical supply and exhaust ventilation, the air is supplied and removed by fans. This more precisely controlled ventilation is not affected by the weather. Thermal energy is recovered from the exhaust air, and the supply air is filtered and preheated if necessary. The building is designed to be low-pressure with respect to the outside air to avoid moisture damage to the structures.

Ventilation units are currently equipped with heat recovery equipment almost without exception. The heat contained in the exhaust air removed from the building is transferred to the supply air by different methods. Thus, part of the waste air energy is recovered in the building's supply air, and the building's heating need is reduced.

Today's modern way of carrying out heat recovery is to use a heat pump as a heat exchanger. This way, the energy contained in the exhaust air can be transferred very efficiently to the radiator heating, domestic hot water, or supply air heating.

The most common heat recovery methods are as follows: a rotary heat exchanger, plate heat exchanger, water glycol heat exchanger, and the exhaust air heat pump.

The annual efficiency of the exhaust air recovery shows how well the property's heat recovery works. In Finland, in the building's construction and alteration work, heat must be recovered from the ventilation exhaust air of the building in an amount corresponding to at least 45% of the heat required for ventilation heating; i.e., the annual heat recovery efficiency must be at least 45% [1]. In a new building, 55% must be used as the annual efficiency of heat recovery in the exhaust air of the building when calculating the reference heat loss. The value of the annual efficiency of heat recovery has been raised from 45% to 55%. Increasing the annual efficiency not only improves energy efficiency but also moves air flows in a controlled way and reduces the use of separate removal ducts and the lower pressures caused by these ducts, which increases the risk of indoor air problems [2].

The heat recovery of the exhaust air means that the thermal energy of the air leaving the house has to be recycled back into the determined amount of heat for the property at an annual minimum. The exhaust air effectiveness is calculated by the following formula: (indoor temperature T_i - blowout temperature T_{ex}) / (indoor temperature T_i - outdoor temperature T_{out}) [3].

With an efficient heat recovery (HR) cell and a heat pump optimized for HR operation, the blowout temperatures of +2 °C … +4 °C might be continuously reached during the heating season. The blowout temperature must be greater than zero degrees to prevent freezing. For the study, a blowout temperature of 2 ºC was selected. These exhaust air temperatures are received only with a sufficient large HR cell; otherwise, the annual efficiency of the exhaust air heat recovery would be lower. The efficiency of the exhaust air heat recovery ventilation with the heat pump system may be over 100% at higher outdoor temperatures. In the Kymenlaakso, Finland, the outdoor temperatures in winter are below 0 °C, in spring from 0 ºC to 10 ºC, in summer above 10 ºC and in autumn below 10 ºC [4].

Mechanical supply and exhaust ventilation with heat recovery (HRV) and exhaust ventilation with an exhaust air heat pump (EAHP) are the two main possibilities to assure good indoor air quality and energy efficiency in renovated apartment buildings in a cold climate [5]. Performance of a renovated apartment building with HRV and three different EAHP connection schemes were compared by Thalfeldt et al. [5] (2018). The purpose was to quantify the effect HRV and three different EAHP connection schemes on district heating (DH) return temperatures and the seasonal coefficient of performance (SCOP) by simulation, combining whole-building and DH substation

models. Based on simulations, the simplest EAHP connection scheme with lowest DH return temperature was suggested [5].

There are various possibilities for connecting an exhaust ventilation with an EAHP to the DH. It has a significant impact on the return temperature of DH and on the seasonal coefficient of the EAHP performance. Thalfeldt et al. [5] proposed a DH substation scheme for testing connection schemes in a real building. The main difference between the EAHP connection schemes was the location of heat pump connections to the substation (its connections to the radiator and DHW heating). The delivered energy calculated with DH models showed that the EAHP decreases the DH use approximately two times compared to HRV. The EAHP covered the majority of the domestic hot water (DHW) heating need in all cases because it was a priority in the control of the EAHP. The SCOP was close, at 3.6 for all EAHP schemes.

Mikola and Kõiv [6] studied long-term parameter measurements of the EAHP system in a newly built apartment building. The building was equipped with the exhaust air ventilation system and exhaust air heat pumps for ventilation heat recovery. The results showed that the coefficient of performance (COP) of the EAHP was mainly related to the temperature graph of the heating system and the supply temperature of domestic hot water. According to the analysis, the COP was 2.9–3.4 in winter conditions and 3.0 in the summer.

In addition to the exhaust air as an energy source, there are also other potentially available energy flows and methods related to the heating of the residential buildings.

Brückner et al. [7] studied possibilities of using industrial and commercial waste heat as a residential heat supply. The real-world neighborhood of Lockstedt in the North German city of Hamburg was used as a case study. Residential heat demand was estimated based on building age, floor space, and volume. The estimated heat demand was 12.8 GWh/a for the area and a waste heat potential of 0.47–0.93 GWh/a (3.7–7.3%). They concluded that, when using only local, small industry and commerce industries (e.g. bakeries, textile cleaners etc.) as waste heat sources, it is not possible to cover the residential heat demand of an average city quarter within its borders. Still, even in such residential neighborhoods, industrial waste heat could cover at least a smaller portion of the residential heating demand.

Žandeskis et al. [8] reviewed solutions for energy-efficient and sustainable heating of ventilation air. The work reviewed the technologies and methods for the heating of ventilation air as a key aspect for high energy and environmental performance of buildings located in a cold climate.

Bertrand et al. [9] studied the impact of waste heat recovery at a city scale from domestic hot water (DHW) by aggregating building data that have not yet been addressed. Furthermore, waste heat recovery potential and relevance was not yet quantified as a function of the specific inhabitant and household numbers, end-use occurrence, and building type and age. They concluded that the grey water heat recovery could be of particular relevance in low-energy and passive residential buildings.

Wallin and Claesson [10] analysed the efficiency of a heat pump–assisted drain water heat recovery system that uses a vertical inline heat exchanger. The investigation showed that a heat

recovery system of this type has the possibility to recover a large portion of the available heat if it has been sized to match the drain water profile.

Energy consumption in the housing sector was studied by Rashad et al. [11]. Several passive cooling and heating strategies (use of ambient energy) were reviewed. The aim was to evaluate how to implement them better in a cost-effective way in existing and new houses. The literature review confirmed the need for further investigation of energy-efficient HVAC systems.

According to Jouhara et al. [12], recovery of waste heat can be conducted through various waste heat recovery technologies to provide valuable energy sources and reduce overall energy use.

Ventilation and air conditioning systems are also object of interest when it comes to the transmission of pathogens and should be appropriately designed and operated. This was studied by Lipinski et al. [13] in light of facing an unforeseen pandemic in the world.

Sarvelainen et al. [14] made a sustainable development study about the energy efficiency of underused buildings and how to improve the ventilation of actively used buildings. The interior study included carbon dioxide concentration, temperature, and moisture content. As a result, several actively used and underused buildings in Finland have the potential to optimize their energy use.

This study addresses the waste heat potential of the exhaust ventilation of apartment buildings in the Kymenlaakso region in Finland and its utilization by EAHPs.

2 Waste heat from residential apartment buildings

Finland's long-term renovation strategy was published in March 2020, aiming for a highly energy-efficient and almost carbon-free building stock by 2050 [15].

In Finland, the building stock is about 62,000 apartment buildings, most of which are quite old. About 60% of the apartment buildings were built before the 1980s. The bar graph (Figure 1) shows the total floor area of apartment buildings in different decades. The largest total floor area, about 24 million (10^6) m², came from 1970 to 1979. Since the 1980s, the total floor area in each decade has lagged behind less than 15 million (10^6) m². The total floor area of the apartment buildings completed in different decades was 104 x 10^6 m^2 at the end of 2019 [15]. The greatest potential for energy savings relates to structures built between the 1960s and 1980s, typically energy-intensive apartment buildings.

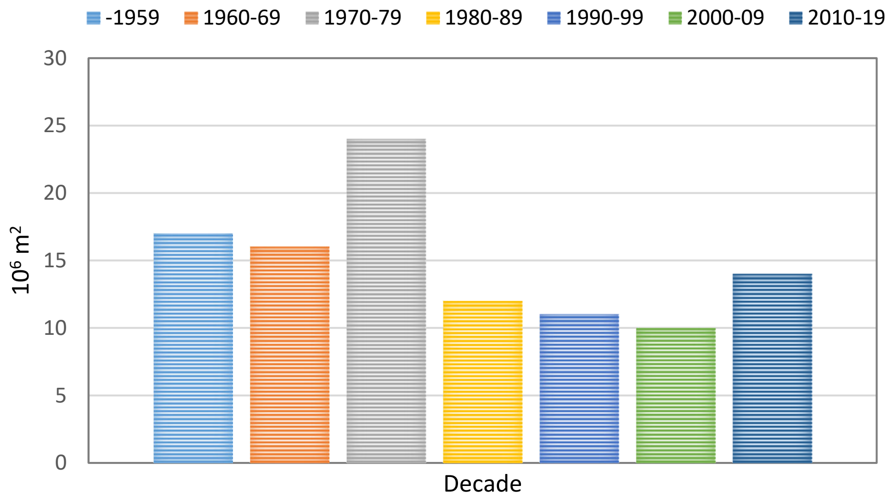


Figure 1. The total floor area of the apartment buildings completed in different decades [15].

Heat sources in buildings can include exhaust air, grey water (household washing water) and condensing heat for property-specific cooling (heat from the condensers of refrigeration machines), all of which are best utilized in the building itself where possible. Electricity, space heating, domestic hot water and cooling consumption profiles and house-specific energy use profiles differ significantly by building type and the year of construction [16].

The waste heat potential of residential apartment buildings in Kymenlaakso was mapped by selecting apartment buildings of different ages from Kotkan Asunnot properties from the 1950s to 2010. First, the amount of energy purchased by buildings (district heating use) and the share of domestic hot water were studied. The exhaust air temperatures, air flow rates and operating times of the ventilation units were determined. From this data, the waste heat released through the ventilation was calculated. Heat loss from the ventilation of a building was calculated according to equation (1)

$$Q_v = \rho \cdot c_p \cdot q_v \cdot \Delta T \cdot \tau \,, \qquad (1)$$

where Q_v is the heat loss of ventilation during the heating season [kWh], ρ the density of air (kg/m³), c_p the specific heat capacity of air (kJ/(kg°C)), q_v the exhaust air flow rate [m³/s], ΔT the temperature difference between the exhaust air temperature and the outdoor temperature [°C] and τ the ventilation unit running time. [17]

Figure 2 shows a seven-storey apartment building built in the 1980s as an example in Kotka town and its thermal energy balance based on energy use, calculated heat losses and outdoor temperature stability values from 2019.

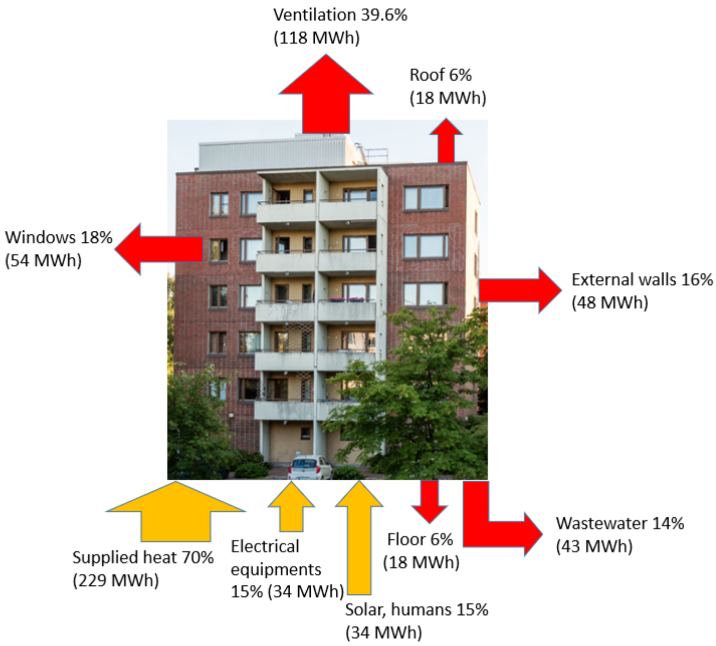


Figure 2. Thermal energy balance of a seven-storey apartment building built in the 1980s in Kotka.

In the example building, 229 MWh of purchased energy has been needed for heating, which is about 70% of the total energy demand. An energy share of 15% is obtained through electrical equipment (34 MWh) and about 15% from the radiation of the solar and the humans [18]. Ventilation heat losses are 39.6% (118 MWh), the wastewater losses 14% (43 MWh), losses through windows 18% (54 MWh), and external wall losses 16% (48 MWh). The roof and floor losses are 6% each (18 MWh). Conduction losses of a building through walls, windows, roof and floor are based on estimates of heat losses found in the literature [18].

The greatest waste heat potential lies in the mechanical exhaust air of apartment buildings if the ventilation machine does not have heat recovery (cf. 39.6%, Figure 2). Mechanical exhaust ventilation was general between 1960 and 1990, including mainly ventilation machines without HR. Potential buildings can also be found outside this delimitation, especially during 1990–2002. After 2002, heat recovery from the exhaust air became obligatory in building regulations [19].

3 Exhaust air heat recovery by means of a heat pump

Exhaust air heat recovery can be achieved by supplementing the existing heating system with a heat pump. In this case, the exhaust air heat can be transferred to the water circulating heat system, e.g. space heating, and the domestic hot water (DHW) preparation.

In residential apartment buildings, the heat pump system that uses exhaust air as a heat source consists of the heat pump, water accumulator, exhaust air fan with a heat exchanger and a heat recovery piping (Figure 3). The heat recovery from the extract air is carried out with heat exchangers and exhaust air fans. That energy is delivered via heat recovery piping to the heat pump and is used as a heat source for the heat pump cycle. The water/glycol solution is transferring heat to the evaporator of the heat pump from the exhaust air heat exchanger. The observed temperature of the solution in the collector circuit towards the HP is over 0 ºC [20]. In cold winter weather, EAHP frost protection can limit heat recovery effectiveness to prevent harmful freezing [17]. The HP condensing heat is delivered to the water heat storage tank (accumulator). The produced warm water is pumped for use in the DWH and the space heating.

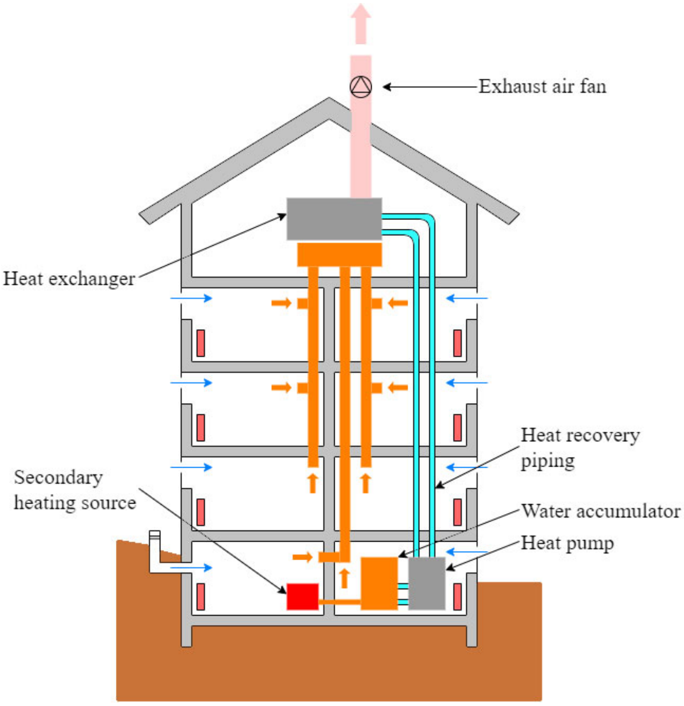


Figure 3. Schematic diagram of a building with the mechanical exhaust air ventilation and heat recovery by means of a heat pump. [18]

The system also always needs an additional heat source because the heat of the exhaust air is never enough to cover the heat demand of the entire apartment building. The heat energy produced by the exhaust air heat pump system is usually able to cover 30–50% of the heat demand of a residential apartment building. The existing heating system, e.g. district heating, is used as an additional heat source [18].

The acquisition of the EAHP system must always be assessed on a case-by-case basis. Certain basic technical framework conditions should be met in order to allow the system to be implemented in a technical and economical manner. These include the already mentioned mechanical exhaust

ventilation and the water circulating heating system. In addition, there should most often be at least a three-storey apartment building and 15–25 apartments, and the temperature levels of the heating/radiator network should be suitable for the heat pump system [21]. This is to increase systems capacity and to make the investment, not least the expensive piping, more profitable.

Technically, the EAHP system can be implemented even if the housing association consists of several apartment buildings and the heat distribution room is located in only one of them [20]. The exhaust air fan or fans may be located on the water roof, in the fan room or in the attic. Typically, the air flow rate of one fan should be at least 250–500 l/s. Regarding the temperature levels of the heating network, one important thing is, for example, the temperature of the water returning from the radiators, which should preferably be below 55 °C in the coldest weather. An example of a particularly well-suited structure for the EAHP system is a single-stairs, three–six-storey apartment building, where mechanical exhaust ventilation is implemented with a single fan [21].

4 Method for calculating the heat recovery potential

The following calculations are examples of the heat lost through mechanical exhaust ventilation and heat recovered by an EAHP in residential buildings in Kotka and Kouvola, in the most significant municipalities of Kymenlaakso, Finland.

The Kymenlaakso apartment building stock was studied by mapping the apartment buildings from different decades as accurately as possible. The apartment buildings that can utilize the heat lost through ventilation were studied from the residential building stock. As stated above, the greatest potential is in high-rise apartment buildings from the 1960s to 1980s with mechanical exhaust air ventilation. Figure 4 shows a map of the 1960s–1980s apartment buildings from the Kouvola centre area. Apartment buildings with mechanical exhaust ventilation are marked separately.

As seen in Figure 4, there are many apartment buildings with mechanical exhaust ventilation in Kouvola. In addition, these are generally located very close to each other, in a group.

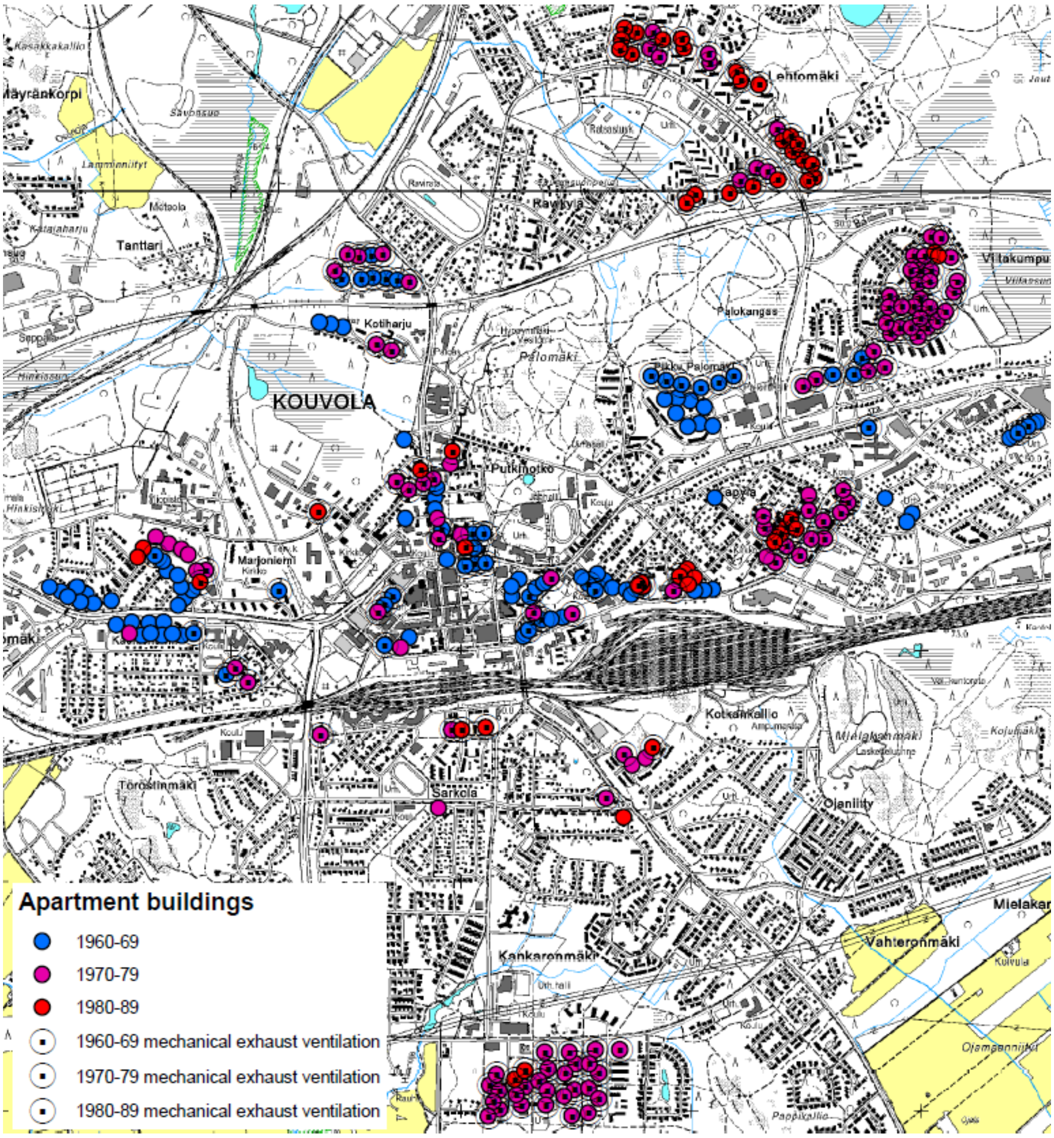


Figure 4. Apartment buildings from the 1960s–1980s and buildings with mechanical exhaust ventilation in the Kouvola centre area.

As already verified, the EAHP captures heat energy from the ventilation exhaust air and transfers it to domestic hot water or a water circulating heating system, e.g. space heating. Most of Finland’s apartment buildings have water-circulating radiator heating connected to the district heating network. Water circulates most commonly in a so-called two-pipe system, where the supply and return water have their own piping and each radiator receives the same temperature of the supply water. The water circulation in the piping is affected by a circulating water pump [22].

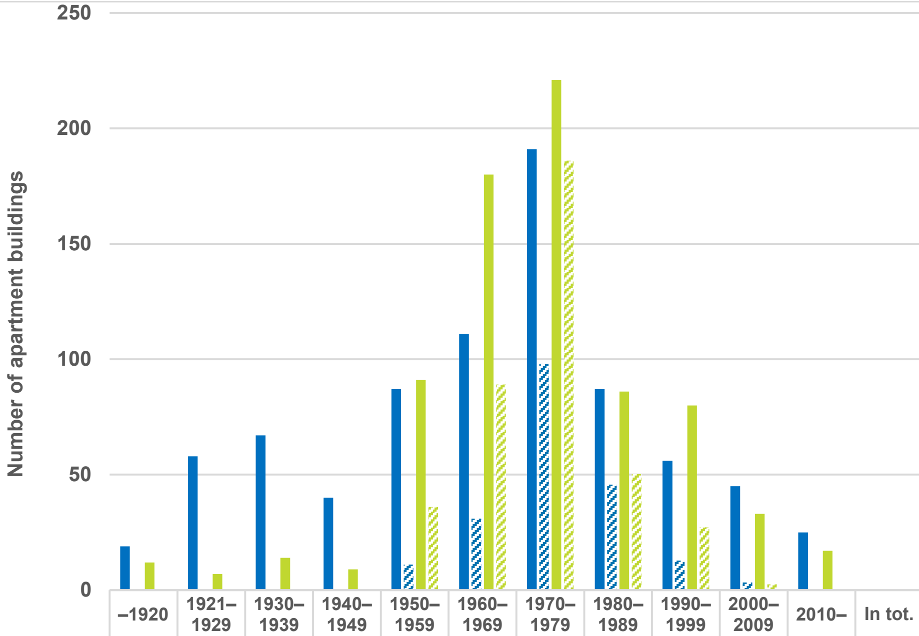
The specific heat consumption of the apartment buildings varies according to the age of the building stock (see Table 1). The specific heat consumption of the 1960s apartment building can

be nearly 70% higher on average than that of those from the 1980s and 1990s. Older apartment buildings have a more massive frame, and newer ones have improved their thermal insulation.

Table 1. Average specific heat consumption of an apartment building in different decades [23]

Building decade:	Specific heat consumption: kWh/m^{2}a
1960–1969	200
1970–1979	170
1980–1989	120

The stock of residential apartment buildings and the number of residential apartment buildings with mechanical exhaust ventilation in Kotka and Kouvola are shown in Figure 5. Figure 5 shows apartment buildings built in different decades (1920–2010) in Kotka (blue) and Kouvola (green) (may contain some already decommissioned buildings). Earlier (1920–1950), more buildings were constructed in Kotka, and later, more were built in Kouvola (1960–2000). In the 1950s, the mechanical exhaust ventilation became more common, when earlier buildings mainly had gravity-based ventilation.



	–1920	1921–1929	1930–1939	1940–1949	1950–1959	1960–1969	1970–1979	1980–1989	1990–1999	2000–2009	2010–	In tot.
Kotka	19	58	67	40	87	111	191	87	56	45	25	786
Kotka, with mechanical exhaust vent.	0	0	0	0	11	31	98	46	13	3	0	202
Kouvola	12	7	14	9	91	180	221	86	80	33	17	750
Kouvola, with mechanical exhaust vent.	0	0	0	0	36	89	186	50	27	3	0	391

Figure 5. Stock of residential apartment buildings and the number of residential apartment buildings with mechanical exhaust ventilation in Kotka and Kouvola.

The construction of apartment buildings was at its peak between the 1960s and 1980s, when mechanical exhaust ventilation was in use (blue and green line pattern) (Figure 5) [22]. The fact that a lot of heat was wasted in apartment buildings in the 1960s and 1970s is due to the large number of buildings and their high specific heat consumption, which is lost mainly through exhaust ventilation.

Starting in the 1990s and through the two last decades, mechanical supply and exhaust ventilation became more common and, with it, the heat recovery (HR) equipment also. HR through a heat exchanger works by transferring the heat of the exhaust air to the supply air either directly or via a heat transfer fluid inside the heat recovery device. The addition of such an HR device requires a mechanical supply and exhaust ventilation system. The HR is not as suitable as an EAHP for use in conjunction with mechanical exhaust ventilation. If there is no mechanical supply air, the heat of the exhaust air can be utilized mainly through a heat pump. Based on information about the building's ventilation development, it was estimated that about 200 apartment buildings with mechanical exhaust ventilation systems were built in Kotka and almost 400 in Kouvola during different decades (Figure 5).

The waste heat potential with mechanical exhaust ventilation of apartment buildings in Kotka and Kouvola is presented in Figures 6 and 7 (may contain some already decommissioned buildings). These figures show the heat use of residential buildings made in different decades, the annual heating energy wasted, recoverable and producible thermal energy by the exhaust air heat pump, as well as the electricity consumption of the heat pumps (MWh/a).

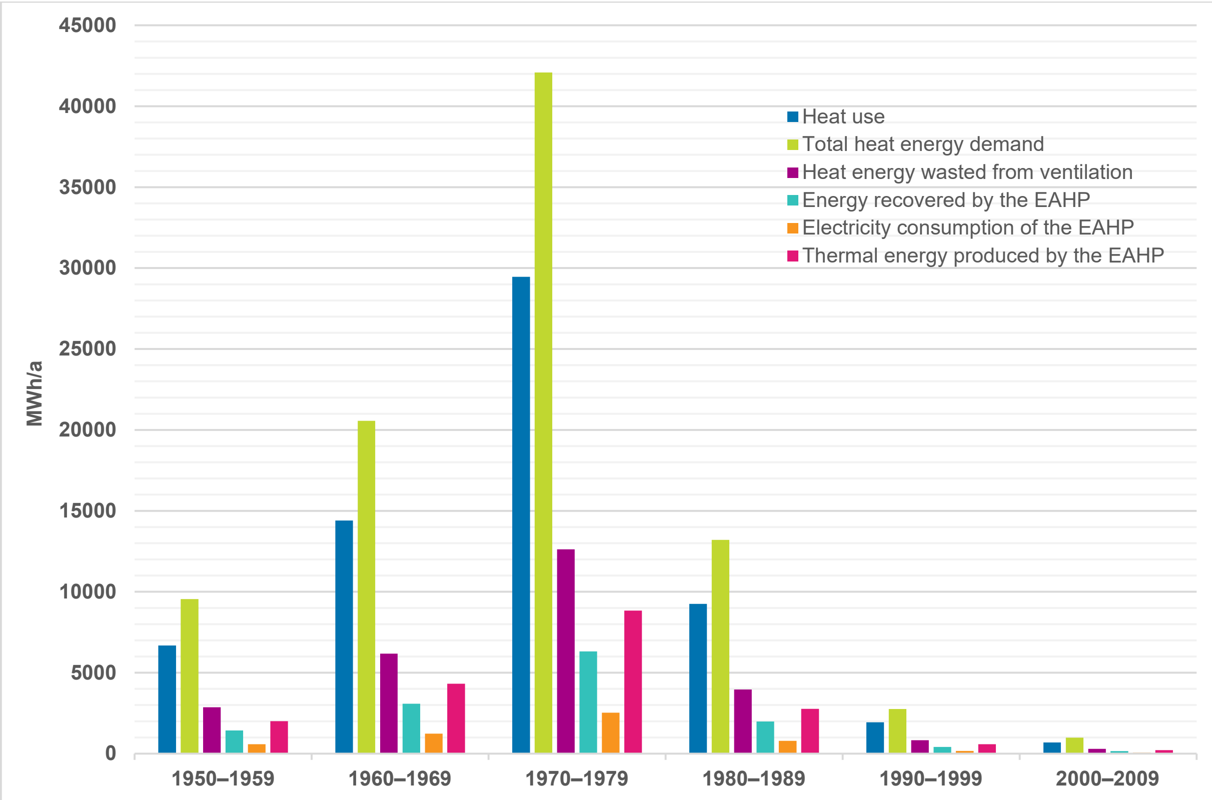


Figure 6. The waste heat potential of mechanical exhaust ventilation of apartment buildings in different decades and the recovery potential with an EAHP in Kotka.

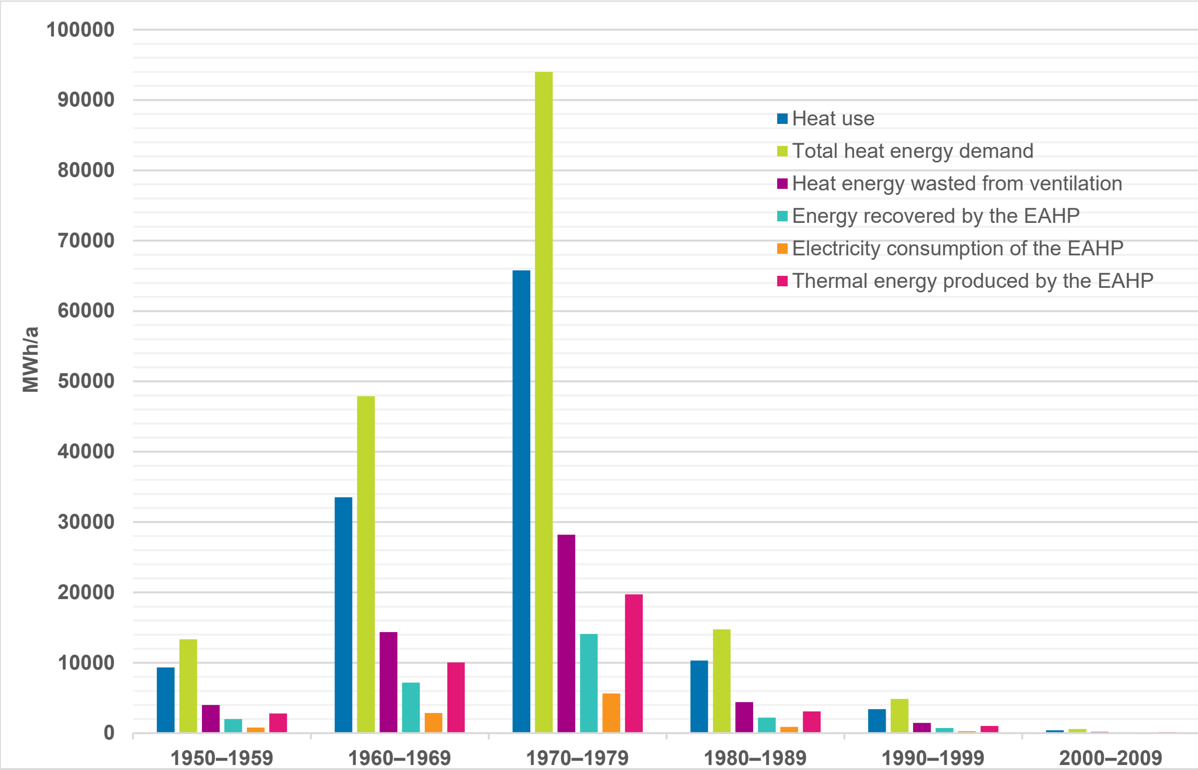


Figure 7. The waste heat potential of mechanical exhaust ventilation of apartment buildings in different decades and the recovery potential with an EAHP in Kouvola.

In Figures 6 and 7, the blue color indicates the heat use of the buildings (floor area x specific heat consumption). The numbers and size categories (floor areas) of apartment buildings were obtained from statistics maintained by Kotka and Kouvola. To determine the specific heat use of buildings, a literature source [23] was consulted, along with the study [24] regarding the development and energy use of Finnish building stock, which estimated the heat use (kWh/m^2) for houses of a certain age.

The green represents the total energy demand, which includes the energy from electricity (15%), solar and human (15%) (Figure 2). The purple is the energy wasted from ventilation (30% of the total energy). This 30% is based on the calculated energy balance of the apartment building (Figure 2), which determines the heat energy wasted through ventilation. The light blue is the energy recovered by the heat pump. An estimate of 50% for the energy recovered by the EAHP was used in the calculations. Although in some conditions the efficiency of the heat pump may be more than 100%, a conservative value was used to cover as wide a range of buildings as possible [25]. The electrical energy use of the EAHP compressor is presented in orange. It was calculated using the energy of evaporation equation (2) as follows:

$$Q_E = (\mathrm{COP} - 1) \cdot \mathrm{P} \cdot \Delta\tau, \quad (2)$$

where Q_E is the energy of evaporation [kWh], COP the coefficient of performance, P the electrical power of the compressor [kW] and Δτ the length of the period [h] [17]. In the calculations, a value of 3 was used as the COP. This rather conservative assumption is based on analysis of long-term parameter measurements of the EAHP system in a newly built apartment building. Based on the measurements, the COP was about 3.0 in winter conditions and about 3.3 in the transition period [6].

The thermal energy produced by the heat pump (presented in Figures 6 and 7 in red) was calculated according to equation (3):

$$Q_C = \mathrm{COP} \cdot \mathrm{P} \cdot \Delta\tau, \quad (3)$$

where Q_C is the energy of condensation [kWh], COP the coefficient of performance, P the electrical power of the compressor [kW] and Δτ the length of the period [h] [17].

The total heat demand (green) and heat use (blue) are highest in buildings built between the 1960s and 1980s. These apartment buildings have the highest energy wasted in ventilation (purple), which means that the heat recovery potential produced by the heat pump (red) is also the highest (Figures 6 and 7). The heat use of buildings (Figures 6 and 7) in Kotka and Kouvola has decreased over the last decades. The reason for the lower heat use in the 1980s, 1990s and 2000s is due to the spread of the mechanical supply and exhaust air ventilation systems, improved waste heat recovery from ventilation systems and better insulation. There is HR mostly included in the mechanical supply and exhaust air ventilation systems what is missing in the solely exhaust air ventilation systems.

As stated earlier, the houses built in the 1960s and 1970s waste the highest amount of thermal energy through ventilation. According to calculations, buildings from the 1960s and 1970s, to which the EAHP might be added, could produce thermal energy annually in the amounts of 4320 MWh/a and 8837 MWh/a in Kotka by EAHPs, and 10057 MWh/a, and 19738 MWh/a in Kouvola, in that order. If the annual waste heat potential of the entire building stock (Figures 6 and 7, light blue columns) could be harnessed by the EAHPs, it might mean 18.7 GWh/a in Kotka and 36.8 GWh/a in Kouvola.

The reduction of carbon dioxide (CO_2) emissions was calculated for apartment buildings where the main heat source is district heating. Of the buildings from the 1950s to the early 2000s, that were estimated to have mechanical exhaust ventilation, the main heat source is DH in 69% of the buildings in Kotka and 82% of those in Kouvola. Other heat sources in addition to district heating are mainly oil and some gas, electricity, and geothermal. Emission factors for DH by a local energy company were used to calculate the CO_2 emission reduction. The national average is about 150 $kgCO_2$/MWh [26]. In Kotka, the factor is 84 $kgCO_2$/MWh [27], and in Kouvola, it is 68.2 $kgCO_2$/MWh [28]. These lower-than-average coefficients are the result of a large share of renewable energy in DH production.

The heat pump reduces the amount of heat purchased, but at the same time, it consumes electricity, and the resulting emissions increase. The share of electricity was taken into account by using the emission factor for electricity and subtracting it from the emission reductions achieved through thermal energy savings. The average CO_2 emission factor for electricity production in Finland, calculated as a five-year moving average, is 135 $kgCO_2/MWh$ [26]. This emission factor, calculated based on annual averages, can be used to describe the long-term impact of changes (more than 10–20 years).

If the annual waste heat potential of the entire building stock (Figure 6 and 7, light blue columns) could be recovered by the EAHPs, the annual CO_2 emission reduction would be about 590 tCO_2 in Kotka and 944 tCO_2 in Kouvola.

The total economic savings potential (savings in heating minus the costs of additional electricity by EAHPs, k€) in buildings built in different decades might be average, as presented in Table 2. As expected, the economic potential to install the heat pump might be greatest in apartment buildings built in the 1960s and 1970s (savings 179 and 366 k€ per year in Kotka and 417 and 818 k€ in Kouvola). The total savings potential, summed from different decades, is 775 k€ in Kotka and 1526 k€ in Kouvola.

Table 2. Total economic savings potential, per decade, by EAHPs installed in apartment buildings built in different decades in Kotka and Kouvola

Decade	Total savings per decade in Kotka, k€	Total savings per decade in Kouvola, k€
1950–1959	83	116
1960–1969	179	417
1970–1979	366	818
1980–1989	115	128
1990–1999	24	42
2000–2009	8	5

5 Profitability simulation

Some apartment buildings in Kotka, Finland were selected and studied in more detail to find potential locations for installation of an exhaust air heat pump.

The EAHP for the apartment building was dimensioned using information about the exhaust air volume flow and the exhaust air temperature. Based on these values, the share of heat from the exhaust air heat pump condenser was calculated and can be utilized for the space and DHW heating. The buildings in review were under EG EnerKey SaaS, which is a sustainability and energy management system that is cloud native [29]. The total heat, electricity and water consumption of the apartment buildings were retrieved from the system on an hourly basis. The amount of used hot water was not measured separately. It was assumed to be 40% of the total water consumption. If the amount of domestic hot water has not been measured separately, it is assumed to be 40% of the total water consumption in residential buildings and 30% of the total water consumption in other buildings [30]. The energy use of hot water Q_{DHW} (kWh/a) was calculated

based on the hot water consumed by the formula $Q_{DHW} = 58 \times V_{DHW}$, where V_{DHW} is the amount of hot water used (m^3/a), and 58 kWh/m^3 is the amount of energy required to heat the water (temperature change 50 °C) per cubic meter [30]. In addition to the amount of energy required to heat the actual hot water, the heat losses in the hot water circuit are included in the energy required to heat the hot water. The DHW circuit has a hot water circulation line, with which the hot water is continuously circulated to keep its temperature constant for instant use. Water from the municipal water supply network is most often heated by district heating in a separate DHW heat exchanger. The recommended temperature of the DHW is +55–65 °C. Too low a temperature favors the growth of the bacteria legionella [22].

Heat losses in the DHW circulation system were estimated from the energy use during the night hours in July when there is no space heating or DHW use. Based on the estimation, the actual hourly heat use was shared between the space and the DHW heating. Further, the shares of the produced heat by the EAHP were calculated and might be utilized for the space and the DHW heating during the year. Usability of the heat from the heat pump was first considered separately for the space heating and the heating of DHW and then for both the space and the DHW heating. The COP was estimated to be a value of 3 in space heating and 2.5 in hot water production. In the simulations, the COP was estimated to be constant. The combined effect of the heat for both the space and the DHW heating was the most profitable and has been presented in the study. Table 3 presents the indicators of energy efficiency received from the use of the EAHP with the district heating in apartment buildings. These indicators are the district heating energy (share of DH), the EAHP's produced energy, EAHP electricity consumption, saved energy costs with the EAHP concept, savings in the DH base charge, total savings and the payback period (Table 3).

Table 3. The indicators of energy efficiency received from the use of the EAHP with district heating in apartment buildings

Apartment building (households)	Share of DH MWh/a	EAHP energy produced MWh/a	EAHP electricity consumption MWh/a	EAHP savings €/a	DH base charge savings €/a	Total savings €/a	Payback period a
A (30)	206.4	153.6	51.2	5025.4	1208.0	6230	11
B (34)	229.2	157.3	52.4	5146.3	1208.0	6350	11
C (31)	226.5	146.2	48.7	4783.4	1098.1	5880	12
D (30)	245.5	150.3	50.1	4919.0	1098.1	6020	12
E (27)	240.9	139.2	46.4	4555.4	988.3	5540	13
F (45)	251.2	193.8	64.6	6339.7	1647.2	7990	9
G (54) 2 buildings	499.5	271.8	90.6	8894.1	756.0	9650	7

The following assumptions were used in calculations (Table 3): the exhaust air temperature cooling (ΔT) 17 °C, the coefficient of performance of the heat pump (COP) 3, the price of electricity 91.60

€/MWh, DH energy price 63.25 €/MWh and the investment in the EAHP varied between 1940-3900 €/kW depending on the case.

The buildings under consideration were apartment buildings A–G. Houses A–F were quite similar in size, with DH use between 206.4 and 251.2 MWh/a. House G consisted of two buildings with a combined DH use of 499.5 MWh/a. The produced thermal energy with the EAHP varied between 146.2 and 193.8 MWh/a in a one-building apartment building and were 271.8 MWh/a in a two-building apartment complex. The EAHP increased electricity consumption by about 50 MWh/a (90 MWh/a for the two buildings). The saved energy costs with the EAHP concept were approximately 5000 €/a (8900 €/a for the two buildings). In this case, the savings were also achieved by the reduced base charge for the DH. This increased the savings by about 1000 €/a (800 €/a for the two buildings). The use of EAHPs also increased the electricity consumption and the base charges for electricity to some extent, but these have not been accounted for in the study. At annual prices of 63.25 €/MWh for heat and 91.60 €/MWh for electricity, the payback periods (investment estimate 70 000 €) varied between 7 and 13 years.

In addition to the savings mentioned above, after installing the EAHP system, the building's carbon footprint will decrease, and the building's energy efficiency will increase. The hybrid heating system (DH+EAHP) is under constant control, which ensures the low life cycle costs. The building will receive a better calculated purchasing energy use of the building per square meter per year, along with the E-factor [31]. In Finland, the energy certificate has been in use since 2008. The aim is to increase the possibilities for setting and comparing the energy efficiency of buildings. It is also intended to promote the energy efficiency of buildings and the use of renewables. The classification of buildings into energy efficiency classes and the preparation of an energy certificate are based on a calculated energy efficiency factor, i.e. the E-factor. The E-factor is a coefficient weighted annual consumption of purchased energy per heated net area [32]. Energy produced in the building, e.g. by an EAHP, reduces the need for purchased energy, affecting the E-factor positively [33].

However, it was not decided to invest in EAHPs in the buildings described above, as the payback period was considered to be slightly too long for these buildings. An acceptable payback period would be normally 5–7 years. Among other things, profitability was affected by the fact that the size of buildings selected for the study were relatively small (the heat use about 200 MWh/a) and the price of the district heating in the area low compared to other areas.

6 Conclusions

With the growing share of ventilation heating loads, heat recovery (HR) over the mechanical ventilation systems appears as one of the key solutions for reducing heat losses and generating consequent energy savings. The ventilation units of the mechanical supply and exhaust air systems are equipped nowadays with HR, almost without exception. The addition of such HR requires a mechanical supply and exhaust ventilation. The mechanical exhaust ventilation was general between 1960 and 1990. If there is no mechanical supply air, the heat of the exhaust air can be utilized mainly by a heat pump (HP).

The mechanical supply and exhaust ventilation with heat recovery (HRV) and exhaust ventilation with an exhaust air heat pump (EAHP) are the two main possibilities to assure good indoor air quality and energy efficiency in renovated apartment buildings in a cold climate. In Finland, in construction and alteration work of the building, the annual heat recovery efficiency must be at least 45%. Finland's long-term renovation strategy aims for a highly energy-efficient and almost carbon-free building stock by 2050.

The impact of waste heat recovery on a city scale by utilizing the building data has not been addressed much. This study addresses the waste heat potential of apartment buildings in Finland's Kymenlaakso region and how EAHPs can utilize it.

In residential apartment buildings, the heat pump system that uses exhaust air as a heat source consists of the heat pump, water accumulator, exhaust air fan with a heat exchanger and heat recovery piping. The heat sources in buildings are best utilized in the buildings themselves, which reduces the need for external heating and costs. The energy produced by the EAHP system usually covers 30–50% of the heat demand of residential apartment buildings [14]. In Figures 6 and 7, the energy produced by the heat pump is slightly lower due to selected conservative input values, such as the heat pump COP (= 3). However, the acquisition of the system must always be assessed on a case-by-case basis. Certain basic technical conditions should be met for the system to be technically and economically feasible (e.g. at least a three-storey building and 15–25 apartments). Technically, the EAHP system can be implemented even if the housing association consists of several buildings and the heat distribution room is located in only one of them.

This study examined the heat lost through mechanical exhaust ventilation and the heat recovered by an EAHP in the residential apartment buildings in Kouvola and Kotka, the most significant municipalities of Kymenlaakso Finland region.

The different thermal energy balances of apartment buildings were determined by selecting buildings of different ages from Kotkan Asunnot properties from the 1950s to 2010. A thermal energy balance of a seven-storey apartment building built in the 1980s was presented as an example. Heat loss through the exhaust ventilation comprised 39.6% of all losses.

The apartment building stock of the largest municipalities in the Kymenlaakso area was surveyed from different decades. The construction of the buildings peaked in the 1960s and 1970s, when mechanical exhaust ventilation was in use. It was estimated that about 200 apartment buildings with mechanical exhaust ventilation systems have been built in Kotka and almost 400 in Kouvola during different decades. A lot of heat is lost due to the large number of apartment buildings in the area but also due to their high specific heat consumption, which is wasted mainly through exhaust ventilation. Therefore, the greatest potential was in high-rise apartment buildings from the 1960s–1980s. The thermal energy use of the apartment buildings has decreased over the last decades.

If all the mapped exhaust air waste energy could be utilized by an EAHP, it could produce thermal energy combined from different decades up to 18.7 GWh/a in Kotka and 36.8 GWh/a in Kouvola. The total economic savings potential with the EAHP, summed from different decades, was 775 k€ in Kotka and 1526 k€ in Kouvola. The mapped building stock may contain some already decommissioned buildings.

The annual reduction in carbon dioxide (CO_2) emissions was calculated for apartment buildings with DH as a main heat source. Of the buildings from the 1950s to the early 2000s, the main heat source is DH in 69% of the buildings in Kotka and 82% in Kouvola. If the annual waste heat potential of the entire building stock studied in Kotka and Kouvola could be utilized by the EAHPs, the annual CO_2 emission reduction would be about 590 tCO_2 in Kotka and 944 tCO2 in Kouvola.

Some apartment buildings were selected and studied in more detail to find potential locations for the installation of the EAHP. The combined effect of the heat for both the space and DHW heating were considered. However, EAHPs were not chosen to be implemented in these buildings because payback periods were too long. The indicators for the energy efficiency were received from the use of the EAHP with the district heating.

Acknowledgements

This study is supported by the ERDF-funded project, 'Networks and opportunities for utilization of waste heat in Kymenlaakso region – Hukkaveks'. The authors would like to thank the cooperating companies and the financiers of the project.

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