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Novel heat pump-based energy recycling system im swimming halls and sport arenas

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Abstract

Swimming halls and sports arenas are major energy consumers due to the indoor climate requirements and long opening hours. The specific heating energy consumption (kWh/m^2 or kWh/m^3) of swimming halls is one of the highest among all building types and the heating demand is substantial also during summertime. Due to the significant energy consumption required to maintain the targeted indoor climate conditions (temperature and relative humidity), domestic hot water temperatures and pool water quality, there are major waste heat flows that can be utilized. Various heat recovery applications have been used in swimming halls for decades, but they have mainly been sub-optimized system-specific solutions due to lack of engineering expertise and technological solutions available. The paper presents a novel energy recycling system application based on heat pump technology that is used for both heating and cooling of the swimming hall and sport arena complex located in Rauma, Finland. The system was originally designed in 2020–2021 and it has been operational since 2024. The system is a centralized large-scale heat recovery system utilizing heat pumps instead of several smaller application or system-specific solutions. The produced heat is utilized in all applicable heating networks. The implemented system collects waste heat from sewage water systems, pool rinse systems, exhaust air systems of the air handling units and cooling systems of the studied properties. For comparison, the collected waste heat amount is significant and equals to the heat content of a 64x310 meter optimally designed borehole field applicable to a densely populated city centre. Based on monitoring and measurements of the first six months of regular operation, the performance of the system is promising, although additional fine-tuning is still required. The developed energy recycling concept can also be implemented in renovations and used internationally.

Keywords: Heat pump; Energy recycling; Energy monitoring

1 Introduction

Advancements in energy efficiency within the European building sector are motivated by the European Union's ambitious CO_2 emission reduction targets. By 2030, the EU aims to achieve a 40% reduction in CO2 emissions compared to 1990 levels, have renewable energy comprise 27% of final energy consumption, and improve energy efficiency by 27% [1].

Swimming halls are among the most energy-intensive sports facilities, primarily due to the significant energy demands for water heating, ventilation, space heating, and circulation pump operations [2]. While climate conditions have minimal effect on the energy consumption of swimming pools, there is a strong correlation between pool water usage and overall energy demand [3].

As the second most popular type of sports facility in Europe [4], swimming halls provide substantial opportunities for energy efficiency advancements [5]. The high indoor temperature and humidity requirements, nevertheless, contribute to considerable operating and maintenance costs [2, 3]. Swimming pools hold great potential for energy recycling by utilizing waste heat from exhaust air and sewage water [6, 7]. Implementing

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multi-objective optimization strategies that address factors such as energy efficiency, cost-effectiveness, environmental impact, and thermal comfort is suggested to be highly advantageous during the design phase of swimming halls to achieve a balanced approach to various goals [8]. Then again for long-term operations, one key challenge lies in ensuring the sustained efficiency of the energy system, particularly when using geothermal energy. According to [8], systems powered by geothermal energy involve significant initial investment costs and maintenance expenses, especially when designed to maintain optimal performance over extended periods.

This paper presents a case study of an innovative heat pump-based energy recycling system implemented in a newly constructed multifunctional building that includes a swimming hall. The primary objective of the study was to evaluate the performance of the energy system during its initial six months of operation, identify areas for improvement, and gather valuable lessons from both the construction and operational phases. The second objective was to compare the costs of the energy recycling system with those of a conventional ground source heat pump system offering the same level of heat pump heating energy coverage.

2 Methods

2.1 Investigated multi-purpose sports building with swimming and sports hall

Karin Campus, located in Rauma, Finland, is a multifunctional building designed to offer an innovative learning environment alongside facilities for sports, leisure, and community activities. The campus includes a primary school, a music institute, a civic institute with art and theatre schools, a youth centre, a swimming hall, and a sports hall. The facilities, integrated through a central high atrium, span a gross area of approximately 31400 m². Key facilities include a 4600 m² sports hall with multiple courts, a main court of 1056 m² with telescopic seating for over 800 spectators, and a 1020 m² swimming pool area. The project was first initiated in 2018, with construction initiation in 2021. The campus gradually opened its facilities in phases, starting in August 2024. The swimming hall, one of the key features of the campus, was officially opened in March 2025.

The Karin Campus construction project focused on achieving energy and cost efficiency in its structural and HVAC system designs. Through multi-objective optimization in IDA ICE (Indoor Climate and Energy), the project aimed to minimize purchased energy consumption and 25-year life cycle costs simultaneously. The campus's energy system, the outcome of the multi-objective optimizations, is highly innovative, utilizing advanced waste heat recovery through a heat pump (HP) system to supply heating across the campus. Particularly, the campus swimming hall demonstrates exceptional energy efficiency by maximizing internal waste heat utilization. Under certain outdoor conditions (temperature and humidity), the swimming hall can achieve energy-positive performance, a remarkable achievement for energy-intensive buildings of its kind. The project sets a benchmark for sustainable building solutions worldwide. The project planning phase and design were carried out by two different companies, but collaboration was made throughout the project to reach the initial goals. Fig. 1 shows the complete building alongside a 3D simulation model illustrating its various building blocks.

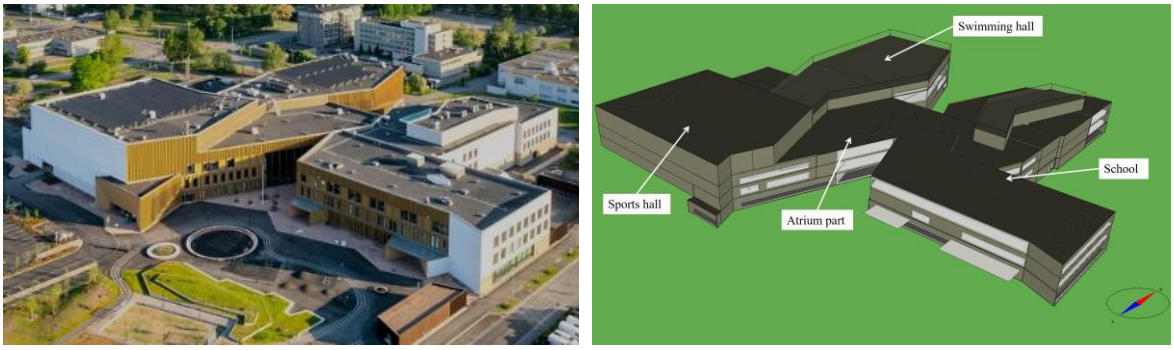

Fig. 1. A picture of the multifunctional building Karin Campus (left) and the IDA ICE simulation model (right) for energy analysis.

The school and sports hall parts of the building received Class A energy certification, with an E-number below 90 $kWh_E/m^2,a$ (scale from Class A to G), according to the standardized calculation method for a specific building type in Finland [9]. Swimming halls in Finland currently lack an energy efficiency classification. A description of the air handling units (AHU), heating and cooling system as well as the main building properties are given in Table 1.

Table 1. Description of the building and its HVAC systems.

Building properties	Description
AHUs in the school building part	13 main AHUs, volume air flow rate 34.6 m³/s, η_{avg} = 70% *1
AHUs in the sports hall building part	2 main AHUs, volume air flow rate 12.6 m³/s, η_{avg} = 71% *1
AHUs in the school building part	7 main AHUs (2 integrated exhaust air HPs), volume air flow rate 27.9 m³/s, η_{avg} = 79% *1
AHU control strategies	- School part: AHU schedules and demand-control on AHU level (worst room conditions) - Sports hall part: AHU schedules and circulation air control - Swimming hall: Partly AHU schedules and circulation air control in the pool areas
Heating networks in the building and dimensioning heating capacities	Three district heating substations with a total of 11 separate heating networks. - 1600 kW for AHU heating networks, 400 kW for space heating networks, 3590 kW for DHW heating networks and 370 kW for water treatment-related heating networks
Cooling networks in the building and dimensioning cooling capacities	- AHU cooling network 550 kW - Cooling network for fan coils 150 kW
Heat transfer coefficients of the building envelope	Walls (7415 m²) 0.17 W/m²K, roof (11614 m²) 0.09 W/m²K, floor towards ground (8660 m²) 0.16 W/m²K, floor towards ambient (2954 m²) 0.09 W/m²K, windows (2330 m²) 0.85 W/m²K and doors (52 m²) 1.00 W/m²K

*1) η_{avg} is the yearly averaged exhaust air heat recovery efficiency of the air handling units

2.2 Description of the investigated heat pump-based energy recycling system

The heat pump-based energy recycling system (energy recycling system) serving the heating and cooling systems of the multifunctional building has been operational since late 2024. However, regular operation including domestic hot water (DHW) production began on April 28, 2025. The energy recycling system recovers residual waste heat from heat recovery coils installed in the exhaust air ducts of three AHUs serving the swimming hall. Additional heat is recovered via a sewage water heat exchanger, which draws sewage water from a 25 m³ basin. The cooling system, serving as the third heat recovery source, is given priority under all conditions, and if less condenser heat is required, exhaust air heat recovery is in the first place reduced. Condenser heat is primarily generated for space heating, water treatment-related heating, and AHU heating networks, while a portion is consistently utilized for DHW heating through super-heating. Condenser heating for DHW is primarily supplied by one of the two HPs for energy recycling, provided the primary condenser-side buffer tank has reached its set-point temperature. Additional cooling during the summer months is produced by a HP dedicated for cooling only. The fundamental operation principles of the energy recycling system, with different heat sources and heating networks, are thoroughly explained in [10]. Fig. 2 illustrates a schematic diagram of the analysed HP system and its connections to the building's HVAC system.

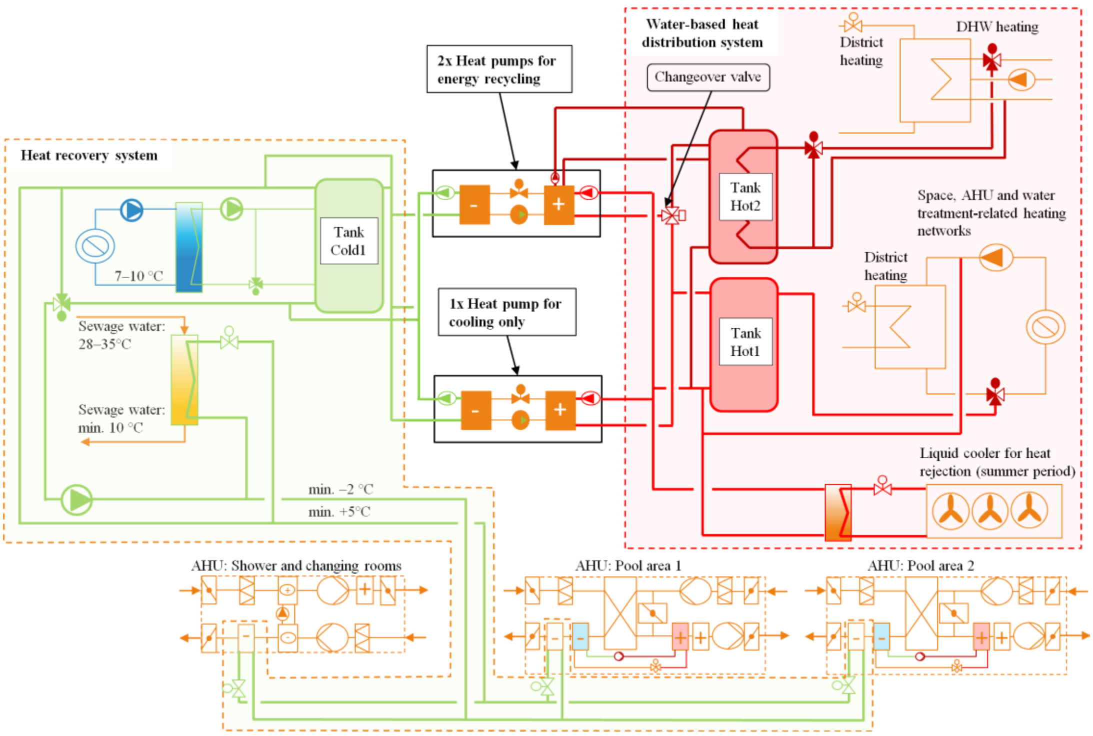

Fig. 2. The schematics of the investigated heat pump system.

The HP system connects to multiple heating networks: 2 for AHU heating, 4 for space heating, 4 for DHW heating, and 1 for water treatment heating. Only one DHW heating network and a portion of the water treatment-related heating rely exclusively on DH, which serves as auxiliary heating. The most relevant dimensioning data of the heat pump system is presented in Table 2.

Table 2. Dimensioning data of the heat pump system.

Design parameter	Description
Dimensioning data of the heat pumps with R513A refrigerant and integrated sub-coolers	- HP1, piston compressors, heating capacity 185 kW, COP=3.3 at rating conditions 5/50 °C (dT=5 °C/dT=20 °C) - HP2, screw compressor, heating capacity 260 kW, COP=3.4 at rating conditions 5/50 °C (dT=5 °C/dT=20 °C) - HP3 (cooling only), screw compressor, heating capacity 680 kW, COP=3.4 at rating conditions 10/45 °C (dT=5 °C/dT=10 °C)
Specifications for the sewage water heat recovery	Heat recovery capacity 140 kW, leaving water +10 °C, brine inlet –2 °C
Specifications for the exhaust air heat recovery coils	Heat recovery capacity 179 kW, leaving air +2.5 °C, brine inlet –2 °C
Specifications of the cooling networks for heat recovery	Heat exchanger capacity 700 kW, water 7/12 °C
Buffer tank on evaporator side	4 m³/Ethanol-water solution (Tank/Cold1)
Buffer tank on condenser side	4 m³/Water (Tank/Hot1) / 2x 3 m³/Water (Tank/Hot2)

2.3 *Energy system simulation*

The energy simulations were carried out using the ESBO plant interface (Early-Stage Building Optimization) in IDA ICE 5.0 (Indoor Climate and Energy) for simulating energy systems. IDA ICE is especially used in the Nordic countries for dynamic building energy simulation purposes, and it is validated against EN 15255-2007 and EN 15265-2007 standards [11] and compared to other simulation programs in previous studies [12] and [13].

To demonstrate the cost-effectiveness and energy performance of the studied energy recycling system, it is simulated and compared to a conventional ground source heat pump system (GSHP) equipped with reference heat recovery solutions (reference GSHP system). The reference GSHP system is sized to match the energy coverage ratio of the energy recycling system for fair comparison. Hence, the reference GSHP system utilizes same HP types specified in Table 2, but the heating capacity is smaller, approximately 285 kW (water out 50 °C / brine in 5 °C) and DH serves as a backup. It is assumed that the AHUs with integrated exhaust air HPs, shown in Fig. 2, are utilized in the pool areas consistent with the investigated HVAC system. Unlike the energy recycling system, the sewage water heat recovery in the reference GSHP system is not connected to the evaporator side of the HP system. Instead, it is conventionally utilized directly for DHW preheating reducing the net DHW heating demand by 30% in the swimming and sports hall parts of the building [14]. The energy system model in IDA ICE, including the adaptations for the reference GSHP system, is illustrated in Fig. 3.

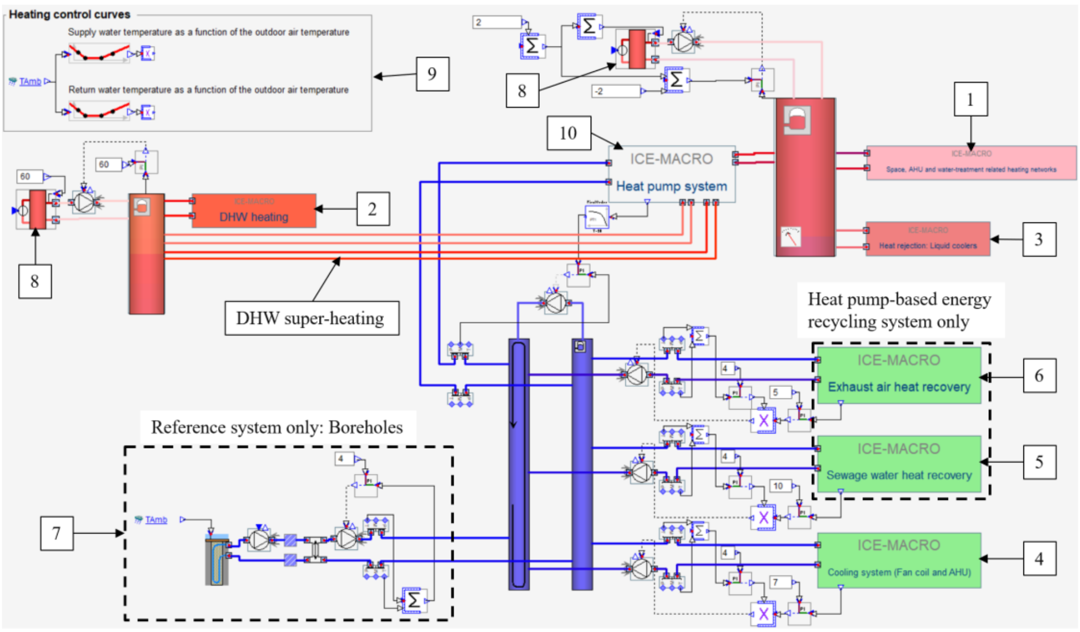

Fig. 3. The energy system interface in the IDA ICE plant for the energy recycling system.

Numbering referring to Fig. 3:

1. Space, AHU and water-treatment heating in the building. Input data includes time series of total heating consumption and supply/return water temperature curves.
2. DHW heating. Input data includes time series of DHW consumption and temperature set-points.
3. Heat rejection through liquid coolers for AHU cooling via the heat pump system.
4. Cooling system consisting of fan coil and AHU cooling.
   - The cooling water production is prioritized in the energy recycling system.
5. Heat recovery from sewage water. Input data includes time series of sewage water flow and temperature, along with heat exchanger dimensioning. Minimum sewage water temperature is 10 °C.
   - Heat recovery allowed if heating is requested and the temperature level in the cooling system is met.
6. Heat recovery from the exhaust air coils (3 pcs). Input data includes air mass flow, absolute humidity, temperature, and cooling coil dimensioning. The lowest exhaust air temperature is 2.5 °C.
   - Heat recovery is permitted if heating is required and both other heat recovery options are in use.
7. Borehole field (reference system only). Input data includes borehole amount, depth and default heat transfer characteristics achieved for boreholes in Finland.
8. Auxiliary heating (district heating) supplied to the heating networks.
9. Heat pump-related supply and return water setpoints based on outdoor temperature.
   - Maximum supply water temperature is 65 °C at -30 °C outdoor temperature and minimum 45 °C.
10. Parametric heat pump model. The condenser side includes pipe connections for space, AHU and water-treatment heating and DHW tank superheating.
    - Superheating is always active, with up to 13 kW heating capacity at full HP capacity.

A parametric heat pump model based on the approach outlined in [10], is utilized in IDA ICE to accurately replicate the HP performance characteristics at various operating conditions and to account for the superheating contribution to thermal capacity during DHW heating. The parametric representation of the condenser capacity and COP based on a performance map approach is described in [15].

3 Case study

3.1 Energy performance based on the testing period

Due to the limited data from the heating season, end of April to November 2025, a representative week from the mid-season was chosen for performance predictions. The average outdoor temperature during the examined week from May 5 to May 11 was 4.9 °C with four colder days in the beginning of the week and three warmer days. The water-based heating system consumed 76 MWh during the week, divided into DHW (21.4%), AHU and space heating (64.2%), and water treatment heating (14.4%). Additional heating is produced by the exhaust air heat pumps integrated into two AHUs serving the swimming pool area according to the schematics shown in Fig. 2. Especially the AHU heating demand is high during the first year of operation due extensive flushing of the spaces from material-related emissions. The total heating demand during the investigated week is estimated to decrease by approximately 18% if AHUs follow weekly schedules and demand-controlled ventilation is utilized in the school and sports hall. Fig. 4 illustrates the heating energy production of the HP system, the heating energy purchased from the DH network, and the total heating demand.

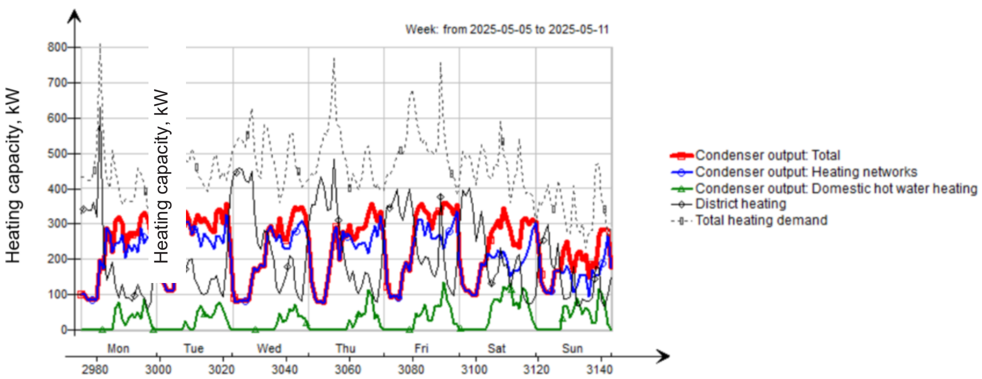

Fig. 4. Heat pump system heat production, district heating and total heating demand.

A major part of the total condenser output, 87%, is dedicated to space and AHU heating as well as to water treatment-related heating. DHW heating amounts 9% of the total condenser output during the first four days (4.2 °C average outdoor temperature) compared to 17% during the later period (5.8 °C). DH consumption is significantly higher at night when AHUs operate at full capacity during the first year. With the initial energy system control setup, the HP system covers 51.5% of the total heating demand, achieving an average COP of 3.2. The COP characteristics and outdoor temperature during the investigated week is shown in Fig. 5.

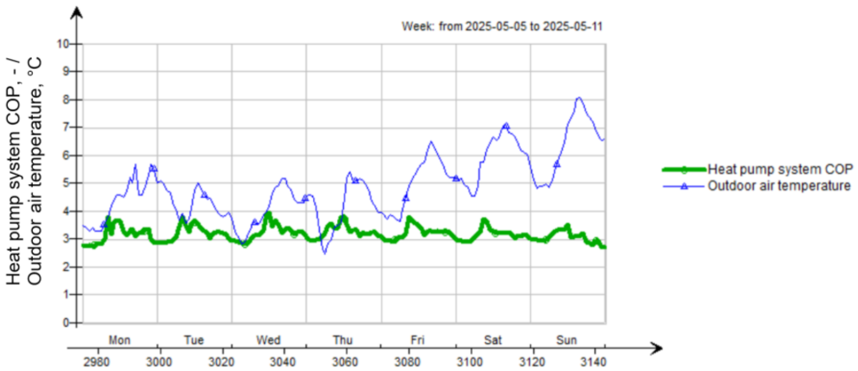

Fig. 5. Heat pump system COP and outdoor air temperature during the investigated week.

It is observed that the nighttime COP decreases to 2.9–3.0 with evaporator outlet temperatures of -1 to -2°C, due to the increased temperature lift in vapor compression. The average COP is influenced by the DHW fraction of the condenser output, resulting in an average COP reduction of 0.1 during the warmer three days at the end of the week, due to an 8 percentage point increase in the DHW fraction of the condenser output. The heat pump's integrated sub-cooler maintains a relatively high COP of nearly 3 during DHW heating, compared to an estimated COP of approximately 2.6 without the sub-cooler, according to the heat pump manufacturer. Fig. 6 displays the heat recovery distribution of the HP system, including exhaust air, sewage water, and cooling system heat recovery.

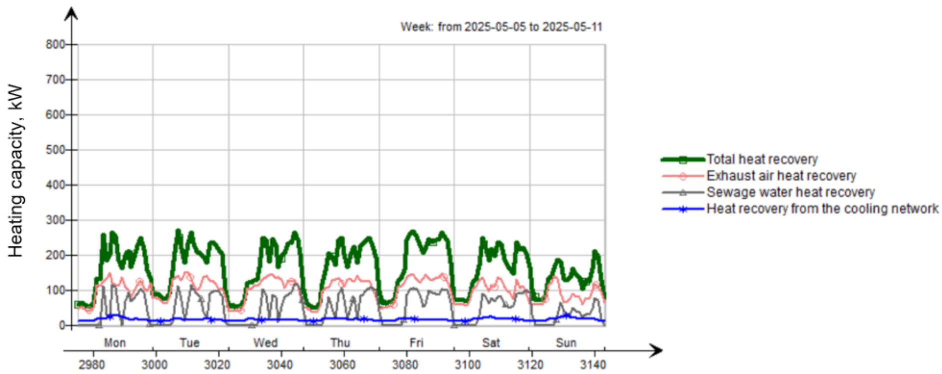

Fig. 6. Heat pump system heat recovery distribution on the evaporator side.

Exhaust air heat recovery from three AHUs forms the basic heat recovery, providing up to 200 kW at full capacity. During night-time, the heat recovery potential is reduced to 50 kW due to high recirculation air ratio. The peak heat recovery capacity from sewage water is 140 kW with an evaporator side outlet temperature of -2 °C. The lower-than-expected heat recovery performance under mid-season conditions is caused by frequent switching to cooling mode, reducing the heat recovery potential from exhaust air and sewage water.

3.2 Energy performance and identified improvement potential

The energy performance of the HP system during the examined mid-season week is summarized in Table 3. Two potential scenarios, V1 and V2, are presented to illustrate the improvement potential based on energy monitoring conducted over a six-month period from May to November 2025.

- Improved performance V1:
  1. Supply water temperature in the AHU and space cooling network increased from 7 to 10 °C during the heating season to reduce frequent switching between heat recovery and cooling modes. Evaporator-side heat recovery temperatures (5–8 °C) are sufficient for cooling needs during mid-season. Previously, cooling mode often lowered the evaporator outlet temperature to -1 °C, reducing COP and limiting HP capacity to around 40%, with only one of two HPs operational.
  2. Implementation of demand-controlled pumping for sewage water through the heat recovery exchanger: Initially, the pump operates at 66% of maximum speed, reducing heat recovery efficiency due to frequent tank drainage. Analysis of water level fluctuations indicates increasing pump speed to 80% prevents tank drainage, improving heat recovery by an estimated 20%.

- Improved performance V2:
  1. The average COP of the HP system is based on the initial setup on a low level. A faulty pump selection and too small heat exchangers in the water treatment heating network resulted in inadequate heat transfer from the HP system at the designed supply water temperature of 45 °C. As a temporary fix, the temperature set-point in the space and AHU heating buffer tank (Tank/Hot1 in Fig. 2) is raised to 60°C, lowering the overall COP.
  2. Listings 1 and 2 from scenario V1 are also considered.

Table 3. Heat recovery performance of the heat pump system based on measurements with possible improvement potential.

Scenario	Heating energy coverage ratio with the heat pump system	Exhaust air heat recovery fraction of collected heat / usage fraction of available heat	Sewage water heat recovery fraction of collected heat / usage fraction of available heat	Cooling system heat recovery fraction	Heat pump system average COP
Measured	51.5%	61.3% / ~66%	28.6% / ~77%	10.1%	3.2
Improved: V1	67.4%	Estimated usage fraction of available heat: 85%			3.1
Improved: V2	66.4%	Estimated usage fraction of available heat: 90%			3.5

Performance predictions from the mid-season week suggest that the heating energy coverage of the HP system can be improved by approximately 15 percentage points with increased utilization of available heat from 69% to 85%. Reducing the AHU and space heating tank set-point slightly boosts HP capacity but decreases the heating energy coverage by 1.3 percentage points due to improved COP and limited evaporator-side heat. The heating energy coverage ratio in scenario V2 is expected to be 75% during the mid-season week when the AHUs are operated on regular schedules in combination with demand-controlled ventilation.

3.3 Estimated annual heating demand, energy recycling potential and heat pump performance

The predicted annual energy consumption of the water-based heating system and its distribution between the heating networks is illustrated in Fig. 7 on monthly basis. The energy consumption is predicted for the normal condition as the swimming hall has been in operation from March 2025 and all AHUs have been working at full capacity since autumn 2024. The normal condition involves utilizing AHU schedules and implementing demand-controlled ventilation as specified in Table 1.

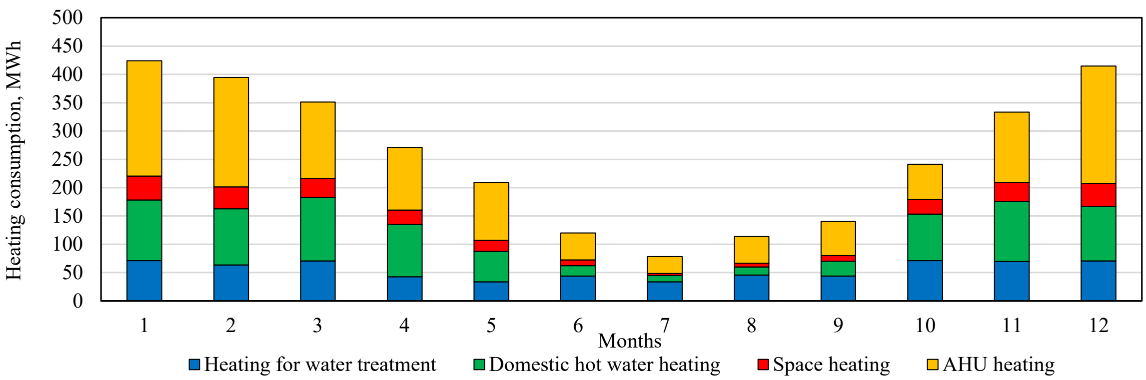

Fig. 7. Predicted energy consumption in the water-based heating networks.

The predicted water-based total heating demand for the multi-purpose building amounts to 3090 MWh, distributed across four primary heating networks: heating for water treatment (21.4%), DHW heating (26.5%), space heating (9.4%), and AHU heating (42.9%). The heating demand is further allocated among the three distinct building sections: the school, swimming hall, and sports hall. The HP system is connected to most of the heating networks. A small portion of 310 MWh for water treatment and DHW, based on July data, is excluded from the HP system and supplied via district heating. The estimated peak heating demand is 1200 kW, with the half-capacity level of 600 kW being exceeded for only 13% of the year.

Additional heating for the pool area, not included in the water-based heating demand, is provided by two AHUs equipped with integrated exhaust air HPs. This heat supply was not available through the central building automation system, but according to simulations performed in the design phase of the building the consumption amounts to 380 MWh. Hence, the estimated total heating demand of the building is 3470 MWh.

The predicted evaporator-side energy recycling potential from cooling networks is based on one year of actual measurements, while the exhaust air heat recovery potential is assessed from recurring peak potential between March and November 2025 and preliminary winter season measurements. The heat recovery potential from sewage water is not measured directly, as only the utilized portion of the total potential is measured. As shown in Fig. 7, DHW consumption is lower between May and September, which directly impacts the sewage water heat potential. The sewage water heat recovery potential was assessed over a two-week period during the heating season (weeks 12 and 15), when the average outdoor temperature was +2 °C. To reflect the enhanced sewage water heat recovery potential outlined in Section 3.2, while avoiding excessive sewage water drainage, the time series data for utilized heat was scaled by a factor of 1.2. The predicted evaporator-side heat recovery potential is presented in Fig. 8 on monthly level. The heat rejection through the liquid coolers schematically shown in Fig. 2 amounts to 190 MWh, with a peak condenser side capacity of 430 kW.

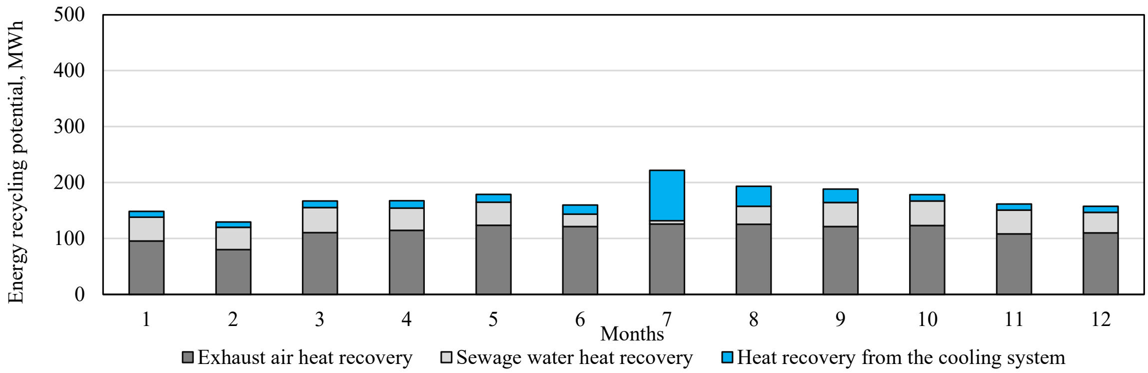

Fig. 8. Predicted evaporator-side heat recovery potential on monthly level.

The utilizable heat recovery from the cooling networks consists of fan coil units operated throughout the year with an average cooling capacity of 19 kW. The increased cooling demand during the summer months is due to HP produced AHU cooling, which is only partially recycled back to the heating networks.

The predicted heat production from heat pumps, along with electricity consumption and district heating usage in the improved performance scenarios V1 and V2, is illustrated on a monthly basis in Fig. 9.

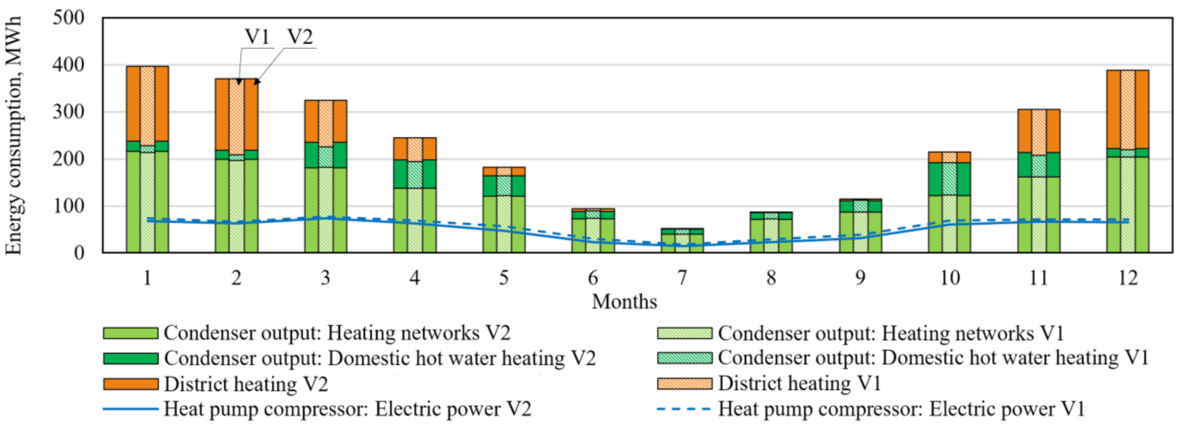

Fig. 9. Predicted heat pump heat production, electricity consumption and district heating consumption in scenarios V1 and V2.

The performance predictions in Fig. 9 indicate that district heating consumption in scenario V2 can be reduced by 5% compared to V1, accompanied by up to an 11% decrease in electricity consumption. Furthermore, the estimated SCOP is 3.4 for scenario V2 and 3.0 for scenario V1. The variation in electricity consumption is approximately 7% during the winter months, increasing to as much as 20% during the summer.

3.4 Energy simulation and comparison to a reference ground source heat pump system

The annual performance of the energy recycling system was simulated based on the Improved Performance V2 scenario, representing normal operation after resolving the faults and control issues outlined in Section 3.2. The energy system comparison to the reference GSHP system was conducted according to the energy consumptions presented in Section 3.3. In the reference GSHP system, the sewage water heat recovery is directly utilized for DHW reducing the heating consumption to 2580 MWh within the HP-heated networks. Fig. 10 shows the simulated time data for the energy recycling system and reference GSHP system, exemplifying one week from May 5 to May 11. The simulated annual heating energy coverage of the energy recycling system is 61.5%, which also represents the design heating energy coverage for the reference GSHP system.

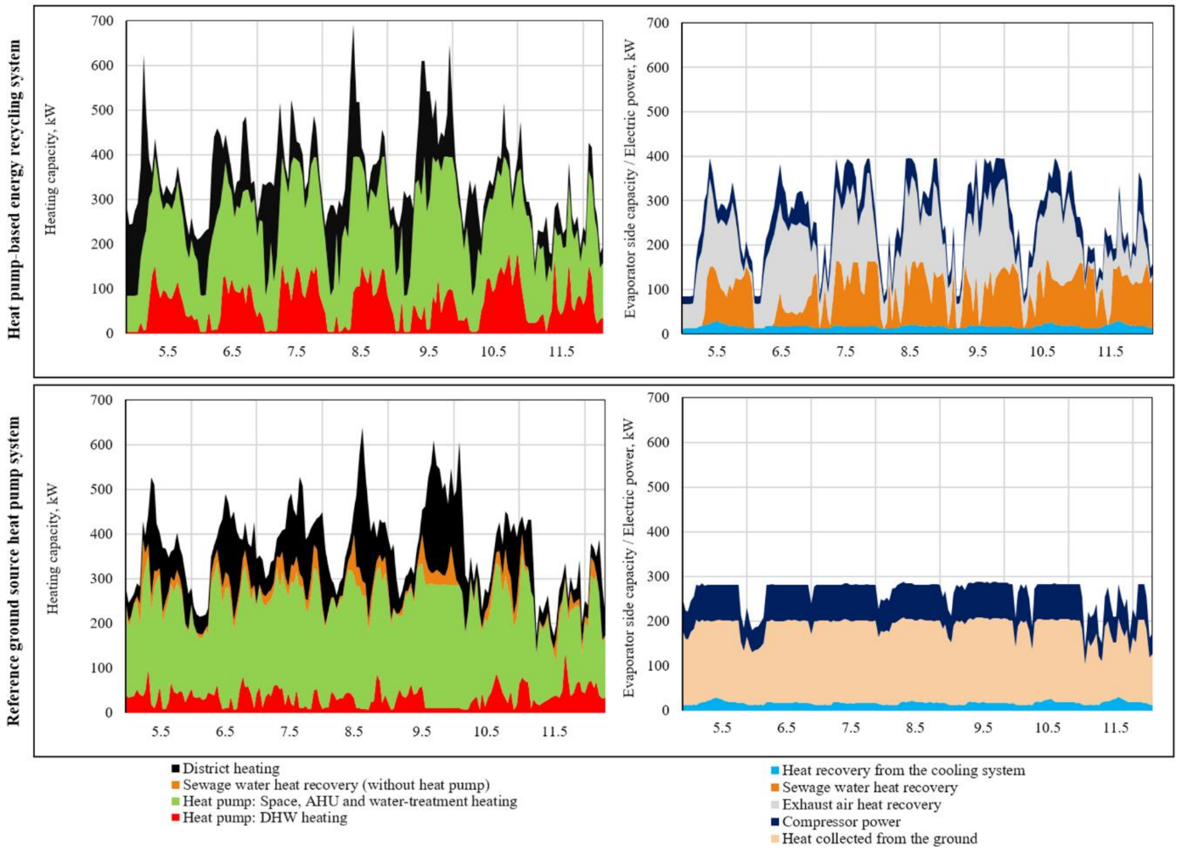

Fig.10. Performance characteristics of the heat pump-based energy recycling system and reference ground source heat pump system.

While maintaining the same heating energy coverage, variations in evaporator-side potential and HP capacity result in differing performance characteristics over time. The key difference lies in DHW production with the HP system, accounting for 36% of the net heating demand in the reference GSHP system, compared to 46% in the energy recycling system. However, the difference in seasonal COP (SCOP) is small, as both systems are designed to operate at comparable evaporator outlet temperatures down to approximately –2 °C.

The borehole field in the reference GSHP system was designed for a 40-year lifespan (480 months), maintaining a minimum monthly average brine temperature of –1 °C. The temperature behaviour of the borehole field was analysed using the GLHEPRO simulation software, which employed heat extraction and loading profiles generated from a single-year IDA ICE simulation. Developed by Oklahoma State University, GLHEPRO has been validated with real-world data from operational ground heat exchangers [16] and benchmarked against the ASHRAE Handbook methodology [17]. Table 4 presents the annual energy balances for both the energy recycling system and the reference GSHP system.

Table 4. Annual energy balances for the compared heat pump systems.

	Heat pump-based energy recycling system	Reference ground source heat pump system
Condenser heat for AHU, space and water treatment-related heating	1520 MWh	1550 MWh
Condenser heat for DHW heating	380 MWh	225 MWh
Compressor energy / SCOP	560 MWh / 3.4	525 MWh / 3.4
Heat collected from the ground	-	1080 MWh
Heat recovered from the cooling network / free cooling	170 MWh	170 MWh
Heat recovered from sewage water	390 MWh	200 MWh
Heat recovered from exhaust air	790 MWh	-
Auxiliary heating: District heating	1190 MWh	1110 MWh

The simulated ground heat collection of 1080 MWh and total free cooling of 250 MWh require a total of 64 boreholes, arranged as two separate 4 x 8 rectangular arrays. The borehole field, consisting of 310-meter-deep boreholes with a total depth of 19840 meters and spaced 15 meters apart, is designed to fit within the compact building plot in the city centre. The available area for drilling within the L-shaped building plot is approximately 22000 m², while the two rectangular arrays with safety distances, occupy close to 15000 m². The design parameters for the borehole field are: ground thermal conductivity of 3.1 W/mK, undisturbed ground temperature of 7 °C, DN45 collector pipe and borehole thermal resistance of 0.12 K/(W/m).

The borehole field in the reference system could be reduced if the building were situated in a rural area with abundant drilling space. Increasing the borehole spacing to 20 meters and utilizing two separate rectangular arrays, each consisting of 2 x 12 boreholes with a depth of 285 meters, would achieve similar temperature characteristics over a 40-year lifespan. Therefore, with the proposed borehole dimensioning, the total depth can be reduced by approximately 30%, significantly enhancing the cost-efficiency of the reference system.

3.5 Investment cost analysis of the compared heat pump systems

The financial feasibility of the energy recycling system, as well as the reference GSHP system, is evaluated through a straightforward comparison of their estimated investment costs. Energy costs are excluded from the analysis since the purchased energy consumption of the energy recycling system is only 7% higher than that of the reference system. The difference is expected to shrink over the lifespan of the borehole field, as decreasing brine temperatures will gradually lower the SCOP of the reference system over time. Moreover, a slight difference in operating costs, favouring the energy recycling system, arises due to a marginally lower DH capacity fee, as the HP capacity in the reference system is smaller.

The investment costs considered account only for the differences between the energy systems, including the costs of heat pumps, the borehole field, and the heat recovery configurations. A summary of the differing investment costs is presented in Table 5. The investment costs for the reference system are determined for the GSHP system designed to fit the actual building plot in the city centre (GSHP system I), as well as for a hypothetical GSHP system located in a rural area (GSHP system II).

Table 5. Summary of the heat pump system dimensioning and estimated investment costs for the compared energy systems.

Heat pump system details / Specific investment costs	Heat pump-based energy recycling system	Reference GSHP system I	Reference GSHP system II
Number of boreholes and total depth	-	64pcs á 310 m	48pcs á 285 m
Heat pump capacity (peak cooling units excluded)	415 kW	285 kW	285 kW
Heating energy fraction with the heat pump system	61.5%	61.5%	61.5%
Investment cost for the heat pumps excluding pumps	149 k€	115 k€	115 k€
Investment cost for borehole field with free cooling configuration *1	-	650 k€	465 k€
Investment cost for sewage water heat recovery without heat pump	-	77 k€	77 k€
Investment cost for the evaporator side energy recycling system	275 k€	-	-
Total investment cost of the energy system-specific components	424 k€	842 k€	657 k€

*1) Investment cost for drilling is estimated to 30 €/m

4 Discussion

Operational experiences from the energy recycling system's first six months reveal improvement potential for both hardware and control-related enhancements. During the first year of operation, auxiliary heating, provided by district heating, remains high due to extensive flushing of spaces to remove material-related emissions. From the perspective of the heat pump system, several issues need to be addressed in collaboration with the companies responsible for its design, construction, and operation.

Experiences indicate that certain design-related faults must be addressed on-site, including replacing some pumps on the condenser side of the heat pump system due to insufficient capacity. A pump replacement is expected to reduce the supply water temperature from the heat pump condenser to the buffer tank (Tank/Hot1 in Fig. 2) from 60 °C to at least 55 °C, thereby enhancing the system's SCOP by approximately 0.1. Greater SCOP improvements up to 0.3 would require replacing the installed heat exchangers for water treatment-related heating with more efficient ones. Therefore, based on initial simulations, replacing the condenser side pump alone is expected to result in electricity consumption approximately 10% higher than the optimal performance level. The performance penalty would still have been higher if regular heat pumps without integrated sub-coolers would have been installed. Measurements indicate that the actual performance penalty will be smaller than suggested by condenser-side design temperatures, as the delivered water temperature decreases close to 45 °C when heat pump capacity is insufficient to meet the heating demand.

Control-related challenges were observed during the mid-season, particularly when outdoor air temperatures exceeded +5 °C – +10 °C, as frequent shifts to the cooling mode occurred with only one heat pump in operation. The issues related to frequent cooling mode changes and unnecessary drainage of the sewage water tank are expected to be resolved, resulting in improved heating energy coverage by the heat pump system. A proposed improvement to the heat recovery performance during the heating season involves lowering the minimum brine outlet temperature from the evaporator from −2 °C to −3 °C, still avoiding ice formation in the exhaust air heat recovery coils.

During the summer months, it was observed that while the cooling system was operational, the heat pump dedicated to cooling experienced malfunctions due to improper fluid flow dimensioning. Hence, implementing both hardware and software changes to the energy system is needed to solve the identified problems. The design and construction project highlights the challenges faced in the field when multiple companies with varying responsibilities collaborate on the same project.

5 Conclusions

The investigated heat pump-based energy recycling system demonstrated promising performance during the initial six months of operation, though enhancements are needed to achieve the estimated performance level. Once the identified hardware and software challenges are solved, the energy system is expected to deliver reliable heat recovery performance, covering approximately 62% of the water-based heating energy consumption. The key findings of the study are listed as follows:

- The heat pump-based energy recycling system demonstrates superior cost efficiency compared to a reference ground source heat pump system with free cooling and conventional sewage water heat recovery. When installed in a densely populated city centre, the system can reduce energy-related investment costs by 420 k€ (–50%). However, in rural areas, where sufficient space allows for optimal borehole field dimensioning, the cost difference decreases to approximately 230 k€ (–35%).
- The energy recycling system delivers a SCOP comparable to that of the reference system, with the advantage expected to grow over the system's lifetime as the borehole field temperature gradually decreases. A properly designed and implemented system is expected to achieve a SCOP of 3.4.
- The case study indicates that the successful design and implementation of the investigated energy recycling system require greater expertise and a deeper understanding of automation-related design compared to the reference ground source heat pump system. Operating with various heat sources and different heat recovery modes, in particular, requires a sufficient monitoring period under diverse conditions to effectively identify potential faults.
- Insights from the project's implementation phase suggest that a higher success rate is achieved when energy system responsibilities and coordination are entrusted to a single experienced overall supplier, rather than being distributed among multiple entities. Project experiences suggest that, from a life cycle perspective, successfully implementing the early-phase design is crucial, even if it requires additional costs from project management, quality assurance and energy system monitoring.

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