Seasonal Waste Heat Storage in Energy-Efficient Finnish Apartment Buildings

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1 Introduction

In Finland, most urban areas are heated with district heating systems. The heat is mostly generated by combustion of local biomass or fossil fuels like peat, coal and natural gas. Thanks to the low carbon electricity generation, electrification of heating by switching to heat pumps has been found to be a very effective solution for decarbonizing heating [1]. In large heat pump systems, ground-source heating is a

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M. Kioumarsi, B. Shafei (eds.), *The 1st International Conference on Net-Zero Built Environment*, Lecture Notes in Civil Engineering 237,
https://doi.org/10.1007/978-3-031-69626-8_41

common option. However, in urban areas, geothermal systems with high energy coverage may not be feasible due to the space requirement of the borehole field. The boreholes need to be spaced far enough apart to prevent the ground in the borehole field from cooling too much. Otherwise, this might cause premature freezing of the water-grouting in the boreholes and malfunctioning of the heat pump system.

A borehole thermal energy storage system (BTES) is a borehole field that is used not only to extract energy but also to store it [2]. BTES has been considered for seasonal energy storage with solar energy systems in Canadian [3] and Finnish conditions [4]. Industrial waste heat is another potential heat source to store in borehole fields [5]. While industrial sources are not widely available, ambient air is another promising alternative. In [6], a dry-cooler was connected to a two-part BTES system for heat and cold storage. Sewage heat also shows some potential for energy storage. Sewage heat recovery was compared to a solar energy solution and was found to be economical when electricity prices are low and the heat source is plentiful [7].

Ventilation heat recovery (HR) is required in new buildings in Finland, but the standard method only preheats incoming supply air with air-to-air heat exchangers. In warm weather, the potential heat is lost as there is no way to store the heat. The building regulations do not require sewage heat recovery, which is why it generally is not implemented. Using these additional heat sources for borehole regeneration and direct load reduction, a tightly spaced borehole field in a space-limited urban area might be feasible.

This study examines the effect of tight borehole spacing on borehole field ground temperature and heat transfer fluid temperature in the case of an up-to-code apartment building in Finland. The potential of ventilation and sewage heat recovery for borehole field regeneration is shown. The research questions are How is the long-term ground temperature of ground-source heat pump systems impacted by borehole field spacing and size? What is the benefit of thermal regeneration of borehole fields by residential waste heat?

2 Methodology

2.1 Simulation Tools

To estimate the impact of various borehole field and heating configurations, a heating demand profile was generated using the building energy simulation tool IDA-ICE [8]. The borehole field seasonal storage, heat recovery and heat pump systems were modeled in TRNSYS [9], which used the generated demand profile as input data. The TRNSYS model was used to estimate the temperature of the borehole field and the heat transfer fluid.

2.2 Building Description

The simulation study is based on a cold climate case study in Finland, where space heating is needed for 8 months of the year. The examined building was an apartment building that meets the requirements of the current Finnish building code. U-values of the envelope were 0.17, 0.09, 0.16 and 1.0 W/(m^2K) for the external walls, roof, floor and windows, respectively. Ventilation was handled by a balanced mechanical ventilation system with a heat recovery efficiency of 65%. The annual space and ventilation heating demand was 110 MWh (22.1 kWh/m^2), while the annual domestic hot water (DHW) heating demand was 128 MWh (25.7 kWh/m^2). The heated floor area of the building was 4994 m^2, with 88 occupants. Heating demand was calculated using the Helsinki TRY2020 weather file [10].

The ventilation system was operated constantly, with a total exhaust air flow of 7200 kg/h. The minimum temperature of the exhaust air was 21 °C, according to the indoor temperature setpoint. The air-to-air heat recovery system was allowed to reduce the waste air temperature down to 2 °C. Total water consumption in the building was assumed to be 120 L/occupant/day, of which 35% was hot water (42 L/occupant/day) [11]. The average sewage temperature was assumed to be 26 °C [12]. This is for the total water flow, as even cold water gets heated up while standing in pipes and toilets.

2.3 Waste Heat Recovery System

In the reference system, waste heat was only recovered from ventilation exhaust air to preheat incoming fresh air. The studied heat recovery scheme is shown in Fig. 1. In this system, two additional heat recovery methods were added. An air-to-liquid HR system was included to recover any heat remaining after the reference HR system. This is used to take advantage of energy contained in the air outside the heating season. The air-to-liquid heat exchanger was assumed to operate at a constant 60% efficiency. Sewage heat was recovered using a HR tank with an indirect heat exchanger of 74% efficiency [12]. The tank was filled with brine, allowing direct flow of the heat pump fluid through it.

The same fluid was circulated from system to system. First, cold heat transfer fluid from the heat pump was fed into the borehole field. After initial heating, it was further heated by the ventilation excess heat and then by the recovered sewage heat. After the three stages, the fluid was sent to the heat pumps, which produced heat to the hot water storage tank for DHW and space heating. For simplicity of control, the heat pump was divided into two parts which heat different sections of the same hot water storage tank. The low-temperature heat pump keeps the lower section of the hot water tank at 45 °C, while the high-temperature heat pump keeps the top part of the tank at above 55 °C to ensure adequate DHW temperature level. If the heat transfer fluid temperature remained high after the heat pumps, any excess heat would

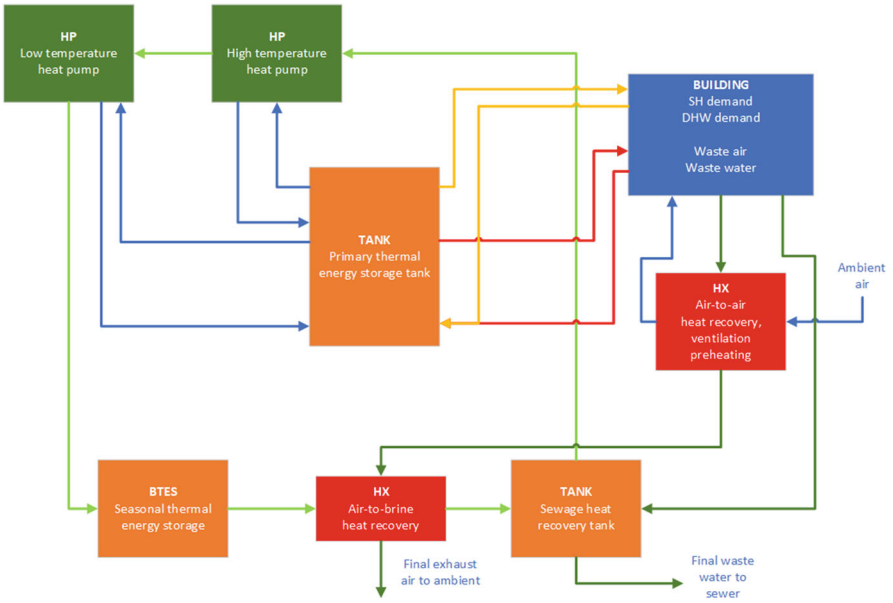

Fig. 1 Heating system schematic

be stored into the borehole field. Thus, the borehole field works in two directions and can be considered to be a borehole thermal energy storage system (BTES). The heat conductivity of the ground was assumed to be 3.5 W/(mK), the heat capacity was 2200 kJ/(m^{3}K), and the starting temperature of the ground was 5.6 °C. The heat collector was a U-pipe of 40 mm diameter, filled with a glycol-water mixture of 3.67 J/(kgK) specific heat capacity. The grout around the borehole was water.

2.4 Studied Scenarios

The reference borehole field was sized according to a simple rule of thumb, where a typical borehole will provide 80–100 kWh/m of annual heating. The various system configurations are shown in Table 1. The 'exhaust air heat recovery' column indicates whether the air-to-liquid HR was utilized in addition to the default air-to-air HR system, which was always included. In cases where seasonal storage charging was active, the heat transfer fluid was kept in constant circulation, even when the heat pumps weren't running. This way, the BTES was injected with additional heat recovered from ventilation and sewage during period of low energy consumption.

Scenario 1 describes the default situation with the heat pumps dimensioned to 80% of peak heating load, using typical borehole spacing. The total borehole length was estimated to cover all of the annual heating needs of the building. Scenario 2 was otherwise the same, but the boreholes were closer together. Scenario 3 included

Table 1 Scenario descriptions

Scenario	# of boreholes	Borehole depth (m)	Borehole spacing (m)	Exhaust air heat recovery	Sewage heat recovery	Seasonal storage charging	BH field horizontal surface area (m^2)
1A	10	300	12	No	No	No	1250
2A	10	300	5	No	No	No	216
3A	10	300	5	Yes	No	No	216
4A	10	300	5	Yes	Yes	No	216
5A	10	300	5	Yes	Yes	Yes	216
1B	100	300	12	No	No	No	12,500
2B	100	300	5	No	No	No	2160
3B	100	300	5	Yes	No	No	2160
4B	100	300	5	Yes	Yes	No	2160
5B	100	300	5	Yes	Yes	Yes	2160

additional heat recovery from ventilation, thus reducing somewhat the energy drain on the borehole field. Scenario 4 added the sewage heat recovery as the third heat source. In Scenario 5, the borehole field was really used as a BTES, with constant charging whenever heat was available.

The A scenarios describe a case with a single apartment building, while the B scenarios show the same cases for a block of ten identical buildings. Instead of ten separate small borehole fields, there was a single large borehole field evenly shared by all the buildings. In both groups, reducing the borehole spacing reduced the surface area requirement of the borehole field by 83% compared to the reference case (Scenario 1).

3 Results

3.1 Ground Temperature

The purpose of the seasonal waste heat storage was to maintain borehole temperatures while reducing the surface area requirement of the borehole field through tighter spacing. To estimate the feasibility of the recovery system, the average ground temperature in the borehole field is presented in Fig. 2. Scenario 1A shows the reference system with heat pumps receiving all heat from the ground in a conventional setup. Over five years of operation, the average ground temperature gradually decreased from 5.6 °C down to 4.2 °C but remained at reasonable levels for continued use. In Scenario 2A, the borehole spacing was switched from 12 m to 5 m, significantly reducing the total energy storage capacity around each borehole. Now, the final ground temperature was reduced to 2.0 °C. In both cases, a decreasing temperature trend was in effect at the end of the simulation, indicating further 0.2–0.3 °C/year temperature reduction with continued operation. In Scenario 3A,

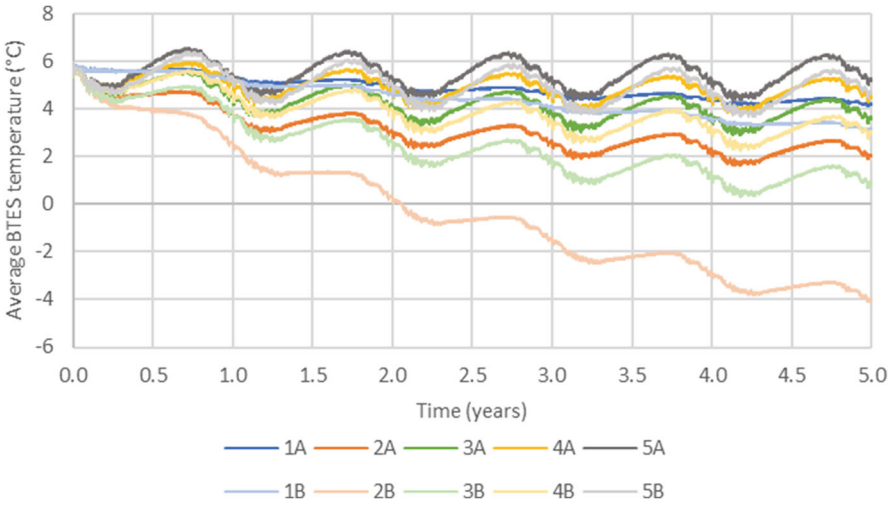

Fig. 2 Development of the average borehole field temperature in different scenarios

however, the additional energy provided by the utilization of ventilation waste heat slowed the cooling of the ground, ending up at 3.6 °C at the end of the fifth year. A clear seasonal variance was now observed compared to the pure GSHP cases, as the ground was allowed to rest during summer and some heat was even charged into the ground. In Scenario 4A, sewage waste heat was also utilized, which shifted the whole temperature curve upwards, ending with 4.5 °C at the end of the fifth year. In both Scenarios 3A and 4A, the BTES temperature was still reducing by 0.1 °C/year at the end of the simulation. However, in Scenario 5A, the heat supply flow into the BTES was increased by constantly injecting recovered heat, even if the heat pumps weren't running. This further raised the temperature levels in the ground and resulted in the final temperature remaining at 5.2 °C in years 3, 4 and 5. This means that the borehole field temperature could be maintained indefinitely without fear of excessive cooling, despite much tighter borehole spacing.

The B scenarios represent cases with larger borehole fields. In these cases, the surface-to-volume ratio of the BTES went down by 76–82% compared to the A scenarios, which means that there was less contact with the surrounding ground. This resulted in lower natural regeneration of the borehole field from the heat contained in the environment. Thus, Scenario 1B resulted in a similar, but faster temperature reduction trend as 1A. The final temperature after the fifth year was only 3.1 °C, with an expected further reduction of 0.5 °C/year. In the tightly spaced system of Scenario 2B, this effect was even more drastic. The final average borehole field temperature was −4.0 °C, which would mean total freezing of the water-filled boreholes. While further reduction would still be expected, in practice the system would stop functioning long before this, preventing the temperatures from actually reaching such levels. In a large GSHP system without additional heat sources, such a tight spacing is clearly infeasible and would drastically reduce the energy coverage. However,

with the addition of the waste heat sources in Scenarios 3C and 3D, despite the tight spacing, there was a notable rise in the average ground temperature. The ventilation heat alone was not enough, as further temperature drop of 0.5 °C/year was still to be expected. With sewage heat, the expected reduction at the end of simulation was 0.2 °C/year. Finally, when active charging of the ground was included, the final temperature after the fifth year of operation was 4.6 °C, with an expected drop of only 0.1 °C/year.

3.2 Heat Transfer Fluid Temperature

It was seen that regenerating the boreholes with residential waste heat can sustain the average temperature in the BTES indefinitely, at least in the case of the smaller field. However, low temperatures within the water-filled boreholes themselves may cause local freezing, which may cause malfunctions in the heating system. Freezing may occur if the heat transfer fluid temperature remains below zero for extended periods (e.g. a whole day). Figure 3 shows the temperature of the heat transfer fluid exiting the BTES during the fifth year of operation in each scenario. The local temperature in the borehole may be assumed high enough if the exiting fluid temperature is above 0 °C.

Scenario 2A is the only one of the single building scenarios where the exit temperature is below zero for extended periods of times. However, the reducing trends in average borehole temperatures show this risk remains during long-term operation of the system. Scenario 3A shows elevated temperature levels during the summer, but in winter there is little energy left from the conventional ventilation heat

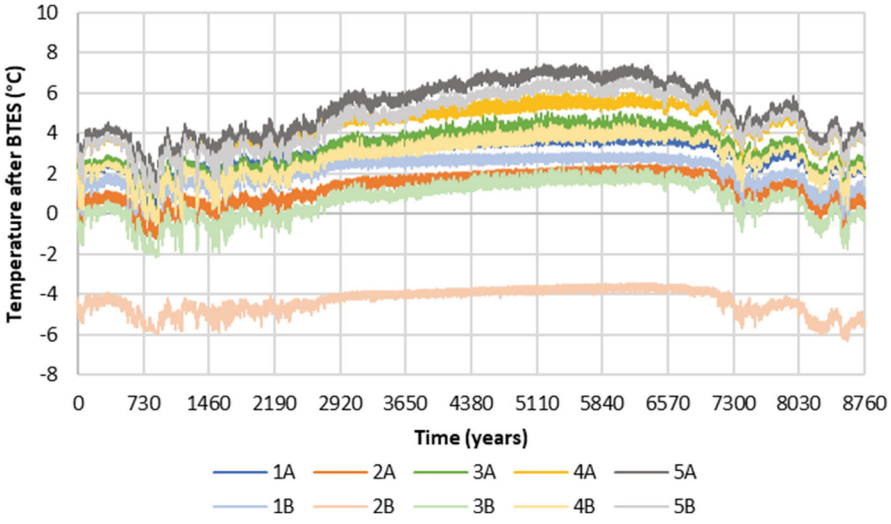

Fig. 3 Temperature of the fluid exiting the BTES during the fifth year of operation

Table 2 Temperature statistics

Scenario	1A	2A	3A	4A	5A	1B	2B	3B	4B	5B
Final BTES temperature (°C)	4.2	2.0	3.6	4.5	5.2	3.1	−4.0	0.8	3.0	4.6
Total time output below 0 °C (h)	0	537	11	0	0	162	8760	2202	63	0
Longest period output below 0 °C (h)	0	197	5	0	0	58	8760	404	9	0

recovery to provide further benefits to the ground heat collection loop. The addition of sewage heat recovery (4A) notably raises the temperature level of the heat collection loop and seasonal storage further increases the temperature (5A).

Seasonal trends are identified in all of the scenarios. During the coldest parts of the year, the risk of low temperatures in the boreholes was increased. The heat transfer fluid temperature correlated with the BTES temperature. Thus, the fluid temperature was lower in the larger borehole fields in the B scenarios. Tight borehole spacing exacerbated the situation as shown in the extreme case of 2B. Higher temperatures compared to the reference case (1B) were realized in the large BTES with sewage recovery (4B) and regeneration (5B), despite the tighter borehole spacing.

The temperature levels may be better illustrated by duration data, shown in Table 2. It shows the total hours the BTES output is below 0 °C and the longest consecutive period of subzero hours. In the reference Scenario 1A, the heat transfer fluid temperature exiting the BTES remained quite stable and always stayed above 0. However, with the tighter spacing in Scenario 2A, there was several week's worth of subzero hours in the borehole output temperature. Scenarios 1B, 2B and 3B are identified as other problematic cases.

4 Discussion

This study examined borehole field regeneration under a limited amount of scenarios. No optimization of the connections was done, and the reference scenario was designed in a simplified way. A more complete study with a wider range of examined parameters could reveal further information about the potential of regeneration.

Electricity consumption in circulation pumps was ignored, but according to [4, 13], it is negligible compared to the electricity consumption of heat pumps. Heat losses in piping were not included in the calculation model, and the practicalities of connecting the various heat sources were not considered. Horizontal piping from the borehole field to the buildings was similarly ignored. According to [13], heat losses in a low temperature heating grid could be 3–5% of delivered heat. These things should be accounted for in more detailed life cycle calculations, but here the idea was to demonstrate the basic idea and potential of the residential waste heat recovery.

The block of several buildings was modeled by simply multiplying the flow rates from a single building. In a more practical case, there could be individual variations between load profiles of buildings within the same location, which might reduce peak heating loads compared to simple multiplication. This would make it easier to keep the system temperatures within acceptable limits.

5 Conclusions

This simulation study examined the seasonal storage of residential waste heat to reduce the ground space requirements of boreholes in a heat pump-based heating system in a cold climate. Reducing the distance between boreholes can reduce the surface are requirement of a borehole field by over 80%. This improves the feasibility of borehole systems designed in urban areas with very little usable space around buildings. Borehole fields of 10 and 100 boreholes were examined.

The simulation results showed that if borehole spacing was reduced without the addition of borehole regeneration, after five years of operation the borehole temperatures were reduced enough to cause significant risk of freezing and system malfunction due to low heat transfer fluid temperatures for long periods of time. This was especially the case in larger borehole fields, with a very low surface-to-volume ratio and resulting low natural regeneration rate. Keeping the final borehole field temperature above 4 °C improved the chance of keeping outlet temperatures high enough.

Utilizing the waste heat from the building's ventilation and sewage flows helped mitigate the long-term cooling of the boreholes when tight borehole spacing was used. However, to fully stabilize the temperature levels in the long term required active borehole regeneration with the excess heat whenever there was no immediate need for heating. With larger borehole fields, the stabilization process may need more time, alternative control strategies, or additional energy input.

The seasonal storage of residential waste heat shows great potential for reducing the space need of urban ground-source heat pump systems. This is especially true of larger energy systems, where a block of buildings could share the same borehole field or thermal energy storage system. Further studies could examine optimal borehole configurations and heat source connection methods and how to reduce the total borehole field length and cost.

Acknowledgements This study received funding from the research program 'Hiilineutraalit energiaratkaisut ja lämpöpumpputeknologia', which is funded by Paavo V. Suomisen rahasto, Sähkötekniikan ja energiatehokkuuden edistämiskeskus STEK ry, Granlund Oy, Ramboll Finland Oy, Senaatti-kiinteistöt, HUS Tilakeskus and HUS Kiinteistöt Oy.

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