Solar Energy Advances 4 (2024) 100050

Contents lists available at ScienceDirect

Solar Energy Advances

journal homepage: www.elsevier.com/locate/seja

Solar photovoltaic/thermal (PVT) technology collectors and free cooling in ground source heat pump systems

Christopher Pourier, Francisco Beltrán [*], Nelson Sommerfeldt

KTH Royal Institute of Technology, Brinellvägen 68, Stockholm 100 44, Sweden

ARTICLE INFO

This paper was submitted to and presented at SWC 2023 - the ISES Solar World Congress 2023

Keywords:
Passive cooling
Solar hybrid
Solar PVT
Heat pumps
Low energy buildings

ABSTRACT

Ground source heat pump (GSHP) systems offer a low carbon heating and cooling solution for the decarbonization of buildings. As global temperatures rise, the cooling requirements of buildings will grow, even in regions where cooling systems have been historically uncommon due to their colder climate, such as Sweden. The combination of free cooling (FC) with GSHPs seems like a natural way to meet the increasing cooling needs, since the heat extracted from the building during the summer months can be injected into the ground to potentially regenerate the borehole field and enhance heat pump performance. However, a technology that is generally integrated with GSHP systems for borehole regeneration are photovoltaic/thermal collectors. This study investigates the performance of a ground source heat pump system with free cooling for a multi-family building in Stockholm, Sweden, and the interference on the free cooling capabilities of the system when photovoltaic/thermal collectors are present. The results demonstrate that the integration of PVT and FC not only maintains the cooling supply but also enhances heat pump performance, all the while reducing borehole length and land area requirements.

1. Introduction

The decarbonization of buildings is a crucial step towards achieving a net-zero carbon future. Buildings account for 27 % of the total energy sector emissions and 30 % of the global final energy consumption, with heating and cooling alone accounting for a large portion of it (IEA, 2022). As a result, it is essential to transition to low-carbon heating and cooling systems if climate goals are to be met. Ground source heat pumps (GSHP) offer such solution, especially in cold climates, by utilizing the more stable temperature in the ground as a heat source. However, some problems can arise when the amount of heat that is being extracted from the ground is significantly higher than the amount of heat that is injected to regenerate the ground temperatures. Known as an unbalanced system, the ground temperature gradually decreases over time, reducing the overall system efficiency and causing the heat pump to shut down. Solar photovoltaic/thermal (PVT) collectors can be combined with GSHP systems to act as a secondary source to the heat pump therefore reducing the load on the ground, and to regenerate undersized or degraded borehole fields with excess heat during the summer months [16]. In addition, PVT has the potential to reduce land area requirements and borehole length and spacing substantially [5,17].

Another solution for borehole regeneration that has gained traction for residential buildings in recent years, mainly due to the increase in global cooling demand and more efficient system design, is free cooling [2]. However, the extent of research investigating free cooling for borehole regeneration and its combination with solar technology remains limited. Therefore, this paper explores the integration of FC and PVT technologies into GSHP systems and assesses their influence on the technical and economic performance throughout the system's operational lifespan.

2. Background

The European Union has set ambitious climate goals. It is committed to achieving climate neutrality by 2050 and aims to reduce emissions by a minimum of 55 % by 2030 compared to 1990 levels, aligning with the objectives of the Paris Agreement [8]. To reach these targets, the European Green Deal serves as the overarching framework, encompassing a range of policies, legislations, and initiatives. One key aspect of the European Green Deal focuses on enhancing the sustainability of residential buildings. This includes improving heating and cooling systems within homes, as well as the preparation and supply of domestic hot water (DHW). Currently, buildings are responsible for approximately 40 % of the European Union's total energy consumption, with over 35 % of

---

[*] Corresponding author.
E-mail address: fbeltran@kth.se (F. Beltrán).

https://doi.org/10.1016/j.seja.2023.100050
Received 2 October 2023; Received in revised form 7 December 2023; Accepted 30 December 2023

Nomenclature

Abbreviations

ASHP	air source heat pump
BH	borehole heat exchanger
DHW	domestic hot water
FC	free cooling
GSHP	ground source heat pump
HP	heat pump
PV	photovoltaic
PVT	photovoltaic-thermal
SC	space cooling
SH	space heating
SPF	seasonal performance factor

Symbols

Q_{sh} [kWh$_{\mathrm{th}}$]	thermal energy for space heating
Q_{dhw} [kWh$_{\mathrm{th}}$]	thermal energy for domestic hot water
E_{hp} [kWh$_{\mathrm{th}}$]	electric energy for heat pump compressor
$E_{p,src}$ [kWh$_{\mathrm{th}}$]	electric energy for borehole circuit pump
$E_{p,snk}$ [kWh$_{\mathrm{th}}$]	electric energy for heat delivery pump
E_{bb} [kWh$_{\mathrm{th}}$]	electric energy for backup heat pump heater
$E_{b,dhw}$ [kWh$_{\mathrm{th}}$]	electric energy for backup tank heater
$E_{p,pvt}$ [kWh$_{\mathrm{th}}$]	electric energy for PVT circulation pump
$E_{p,pv}$ [kWh$_{\mathrm{th}}$]	electric energy from PV
Q_{ext} [kWh$_{\mathrm{th}}$]	total heat extracted from boreholes
Q_{inj} [kWh$_{\mathrm{th}}$]	total heat injected into the boreholes

greenhouse gas emissions stemming from outdated and inefficient fossil fuel-powered systems. Enhancing the energy efficiency of buildings through the adoption of efficient appliances and better insulation is a vital step in reducing energy consumption and, consequently, emissions. Transitioning to electric heating and harnessing locally sourced renewable energy can significantly contribute to the decarbonization efforts.

Recent advancements have paved the way for the combined implementation of series connected photovoltaic/thermal collectors and heat pump systems, where the PVT can either be used as the sole source for the heat pump or as a secondary source to support a borehole field or air heat exchanger. There are several studies that have looked at PVT collectors acting as the sole source of a heat pump. Schmidt et al. [15] found that rear insulated and unglazed PVT collectors acting as the sole source of a heat pump could efficiently provide space heating and domestic hot water, even for ambient temperatures as low as −10 °C. Chhugani et al. [4] explored the performance of a fin-tube PVT also acting as the sole source of a heat pump, reporting a seasonal performance factor (SPF) of 3.3 during the winter season in Germany. Furthermore, Fraunhofer ISE developed a novel PVT collector featuring an optimized double-finned micro-channel heat exchanger, that when used as the primary heat source for a heat pump system can achieve a SPF of 3.6 [9].

When looking at PVT collectors as an alternative source, a particularly promising application is the integration with ground-source heat pump systems (GSHP). The use of GSHPs with unbalanced heating and cooling demands can potentially lead to thermal degradation of the soil in the long term. To mitigate this issue, PVTs offer a solution by regenerating the ground with excess heat in boreholes, thereby extending the system's operational lifespan. Additionally, PVTs can also act as a secondary thermal source to the heat pump which reduces the load on the ground. Bertram et al. [3] investigated a PVT + GSHP pilot system in a large single-family dwelling near Frankfurt, Germany. The results showed that PVT can improve the SPF of a GSHP system with an undersized borehole field by 0.36 on the 1st year of operation and interpolated to 0.51 on the 20th year due to the higher ground temperatures. Sommerfeldt & Madani [17] conducted research on the integration of PVT with GSHP in multi-family houses in Sweden with TRNSYS. They found that in a PVT+GSHP system, the baseline SPF could be maintained if the borehole length was reduced by 18 % or the spacing by 50 %. While PVT+GSHP systems typically have higher life cycle costs compared to PV+GSHP systems, the potential for saving up to 89 % of land area due to the PVT component could contribute to overall system cost reduction. Chhugani et al. [5] compared different heat supply systems for a single family house through TRNSYS simulations, and found that the addition of PVT to GSHP systems would allow to design 35 % smaller borehole field without affecting system efficiency. Qiu et al. [12] investigated the performance of a dynamic PVT+GSHP model on TRNSYS, and found that the addition of PVT can reduce borehole length by 48 %, land area requirements by 69 %, while increasing 10 % the heating COP. The study was carried out for a 200 m^2 office building with heating and cooling demands in Jilin, northeast China.

With the exception of Qiu et al. [12], space cooling is generally disregarded in PVT heat pumps applications for cold climates. However, based on data collected by the Swedish Meteorological and Hydrological Institute (SMHI), projections indicate that by the end of this century, temperatures in Sweden could rise by 2–6 °C compared to the range observed from the 1960s to the 1990s. While these temperature increases are expected to lead to reduced heating requirements, they will also necessitate a shift towards greater cooling needs. One promising solution for addressing these hotter summers is the implementation of free cooling (FC) systems. In the context of ground source heat pump systems, free cooling, also known as direct-ground cooling or passive cooling, utilizes the soil as a heat sink using only a heat exchanger and a circulation pump. This approach allows the heat to be taken from indoor spaces to provide cooling while simultaneously regenerating the borehole heat exchanger. Recent research on free cooling has predominantly centered on its implementation in data centers. These systems typically employ chillers as their primary cooling units, utilizing ambient air or nearby bodies of water as the main cooling medium [18,19]. In another case study, an air-source heat pump (ASHP) was used for waste heat recovery in conjunction with air-side and water-side economizers for free cooling, resulting in energy savings of up to 250 MWh/year [7]. Desideri et al. [6] conducted a study involving a two-apartment building in Italy, comparing summer operation scenarios with a reversible GSHP and a standard GSHP equipped with a free cooling bypass. Simulation results indicated that, over 25 years, soil temperatures in the free cooling scenario decreased by 1.09 °C, whereas the reversible GSHP case exhibited a 1.63 °C drop. This difference was attributed to the continuous operation of the free cooling system compared to the intermittent operation of the reversible GSHP. Furthermore, operating costs for free cooling were found to be lower than those for the compressor-based reversible GSHP. Arghand et al. [2] delved into free cooling systems (referred to as direct ground-coupled cooling) and examined the influence of continuous cooling on ground loads and borehole fluid outlet temperatures. The study demonstrated that continuous cooling could achieve a 0.8 °C reduction in the outlet borehole temperature compared to intermittent cooling. Additionally, it was possible to reduce the length of new borehole heat exchangers by 18 % with this cooling strategy.

An operational low-temperature district heating and cooling network (LTDHC) system was implemented in Rotkreuz, Switzerland, featuring several components: borehole fields for seasonal storage, a warm duct serving as a heat source for decentralized heat pumps, a cold duct for free cooling, as well as PV and PVT systems generating electricity for system operation. Additionally, PVT and free cooling units were utilized to provide waste heat for regenerating the borehole field. Monitoring the system's initial 5-year operation revealed an issue where PVT units had to be shut down due to their interference with free cooling. To address this problem, reversible heat pumps were proposed as a solution [14]. Similarly, an LTDHC system in Switzerland was modeled for three distinct types of residential buildings, each with unique heating and cooling demands. The analysis indicated that the contribution of regeneration from free cooling was relatively minor compared to that of PVTs, especially in areas with extensive PVT coverage (800 m^2), where the fraction of free cooling was only 6 % [10].

3. Knowledge gap and objective

GSHP projects commonly encounter two primary challenges in their initial phases: substantial capital costs and limited available land area. Over the long term, a persistent issue arises from the gradual degradation of soil temperatures, resulting in decreased system performance and an increase in electricity expenses. PVT technology has demonstrated its ability to mitigate soil temperature degradation either through direct injection or by supporting the heat pump during DHW and SH production. Consequently, the cumulative lifetime electricity consumption of GSHP systems can be reduced, despite the overall life cycle cost increase attributed to the PVT investment.

Research regarding the implementation of free cooling in residential applications, especially in conjunction with GSHPs, is notably limited. While PVTs and free cooling have been studied together in LTDHCs the application of free cooling has primarily been confined to intermediary sinks situated between boreholes, such as ice storage or cold ducts. Additionally, the impact of the potential mutual interference between these two components when directly integrated into a GSHP system remains inadequately understood.

Hence, the primary objective of this paper is to evaluate both the technical and economic viability of integrating free cooling (FC) and photovoltaic/thermal collectors (PVT) into a GSHP system designed for Multi-Family Housing (MFH) applications.

In pursuit of this objective, this paper will delve into the following research questions:

- What is the impact of integrating free cooling on both the technical and economic performance of GSHP systems?
- How can the potential interference between a PVT array and a FC system be effectively mitigated when integrated with a GSHP?
- What are the comparative advantages and disadvantages of employing a Multi-Source (MS) system in contrast to FC+GSHP, PVT+GSHP, and standalone GSHP systems?

4. Methodology and scope

This study builds upon the PVT+GSHP TRNSYS model developed by Sommerfeldt and Madani [17], and later adjusted by Olausson and Wernius [11] to increase flexibility and decrease simulation time. Fig. 1 illustrates a conceptual diagram of the base PVT+GSHP system without free cooling, and the new system with the integration of a free cooling loop. Various configurations of the free cooling (FC) heat exchanger within the PVT + GSHP system will be explored to optimize the overall system efficiency. A comparative analysis will be conducted against a GSHP-only system to ascertain the potential for downsizing the borehole field. A parametric study will then be conducted to assess the feasibility of reducing system costs and minimizing land area requirements by either eliminating boreholes or adjusting their spacing.

Additionally, PVT collectors will be added to the FC+GSHP system to investigate potential interference between FC and PVT. It is expected that the interference may lead to a reduction in cooling supply due to the presence of PVT, along with a potential reduction in thermal yield for the PVT system. The final step will involve an extensive parametric study aimed at mitigating interference, optimizing technical performance, and minimizing financial implications.

This study evaluates the performance of the heating and cooling supply system using a simplified building and heating/cooling distribution system, and therefore radiators, fan coils, or other distribution equipment within the building is beyond the scope of this work. Furthermore, the lack of a white-box building model means that the evaluation of thermal comfort for building occupants will not be considered in this analysis.

4.1. Base model description

The climate data utilized for this study is derived from Meteonorm 7.2 [13] and is based on a typical meteorological year for Stockholm, Sweden. The system consists of space heating, domestic hot water and space cooling loads connected to a variable-speed ground source heat pump system with a nominal heating capacity of 52 kW (B0/W35) at 3600 rpm. A 100 kW backup heater is also included in the model to support the heat pump when it is unable to meet the peak loads or when it needs to be shut down due to low evaporator inlet temperatures. The heating and cooling loads are representative of a 2000 m^2 low energy building in Stockholm, Sweden, with a specific heating demand of 26.6 kWh/m^2/yr, a specific cooling demand of 5.1 kWh/m^2/yr, and a domestic hot water demand of 37 kWh/m^2/yr. The building is modelled using Type 963, a lump-capacitance building model that allows for lower simulation time. The heating and cooling set point temperatures are 21 °C and 22 °C respectively. The borehole field is modelled with Type 557a and consists of 12 parallel single U-tube boreholes in a triangular pattern, which are 300 m deep and 15 m apart. A maximum collector array size of 144 PVTs is connected in a series/regenerative configuration to the GSHP system. The PVT collectors are modelled using Type 560, and are based on a 280 W$_p$ commercially available unglazed and uninsulated sheet and tube PVT collector. Two Type 60d

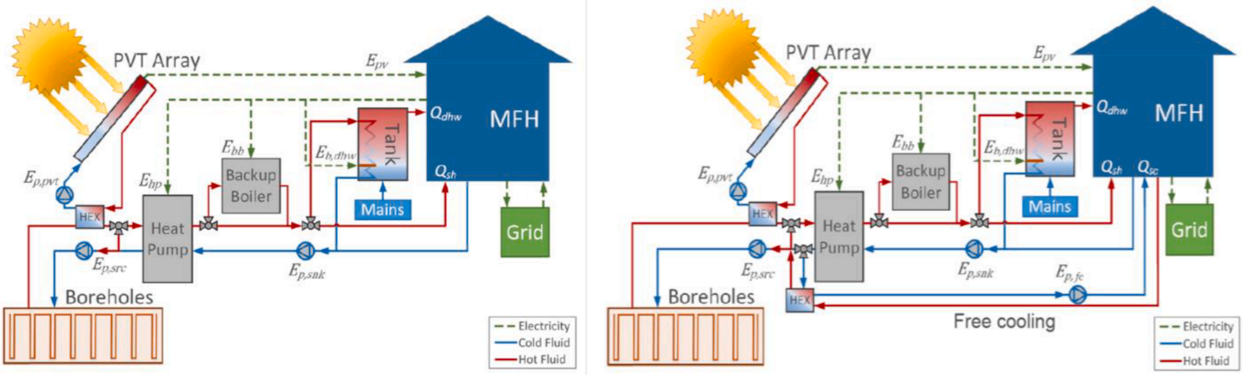

Fig. 1. Conceptual diagram of a PVT + GSHP without FC (left) and with FC (right).

water tanks of 1000 l each are used for storing DHW. The temperature setpoint for DHW is 55 °C. A simplified version of the MS TRNSYS model with PVT, FC and GSHP can be seen in Fig. 2.

4.2. Borehole field and gshp re-sizing

The borehole field in the model consists of 12 boreholes, 300 m deep and 15 m apart. However, since the building considered in this study has a much lower heating demand than the original model, it is necessary to re-size the borehole field. In Sweden, there are multiple approaches to designing borehole fields. Designers often rely on numerical software tools like Earth Energy Designer, but they also frequently incorporate general best practices, as outlined by Andersson & Gehlin [1] for designing boreholes of this scale. For the purpose of this study, the borehole field will be sized based on the following criteria:

- Ensuring a minimum brine outlet temperature of the borehole field of 0 °C by the 20th year of operation.
- Limiting the operation of the electric backup heater, with the GSHP ideally supplying over 99 % of the heating demand.
- Minimizing the projected TLCC for the entire system.

The borehole field sizing is conducted using the base GSHP-only model. The borehole arrangement, which is rectangular, and individual borehole depths, will remain constant.

As can be seen in Fig. 3, a borehole field containing four boreholes or fewer, consistently maintains an outlet temperature below 0 °C for the given loads and ground conditions during the 20-year timespan. Given that the 5-borehole field (not presented in the graph) falls below 0 °C and reaches −0.56 °C by the 20th year, a 6-borehole field is the minimum length that fulfills the first condition. While none of the simulated borehole fields fully meet the second condition (as shown in Fig. 4), the 6-borehole configuration is the worst performing with around 2.5 % of backup heater use (when excluding the 4-borehole field). However, there is less than a 1 % absolute difference with the 12 borehole system by the 20th year of operation. The cost of these borehole fields ranges from 1.85 to 2.19 million Swedish Kronor (MSEK) (see Table 1), with an inflection point occurring at the six-borehole arrangement, where the project cost increases more rapidly with the number of boreholes. Consequently, the 6-borehole field will be utilized further in this report as it best aligns with the specified criteria.

A reduction in the borehole field size also results in a downsized heat pump. Adjusting the heat pump’s size is not a simple task, as the fundamental model is configured based on experimental data and tailored controls for that specific heat pump. To determine the appropriate size a resizing process was conducted, by proportionally scaling the heat pump’s output to match the heating requirements as closely as feasible. This resulted in a significant reduction of the heat pump’s size, ultimately reaching 63.75 % less than the original size, with a capacity of 33 kW (B0/W35) at 3600 rpm.

4.3. Free cooling configuration

A series configuration of FC can be connected in three different ways to a PVT + GSHP system, as shown in Fig. 5. The first configuration (C1), connects the free cooling heat exchanger between the HP and the BH field. The second configuration (C2), connects the free cooling heat exchanger between the BH and the PVT. The third configuration (C3) connects the free cooling heat exchanger between the PVT and the HP. The effect of the different configurations on system performance will be studied in the following sections.

4.4. Key performance indicators

To facilitate the comparison of different systems, it is essential to establish key performance indicators (KPIs). Given that the technologies present in the system predominantly serve to provide energy to the building in the form of electricity and heating, the chosen performance indicator is the seasonal performance factor SPF_{4+} [17], shown in Eq. (1):

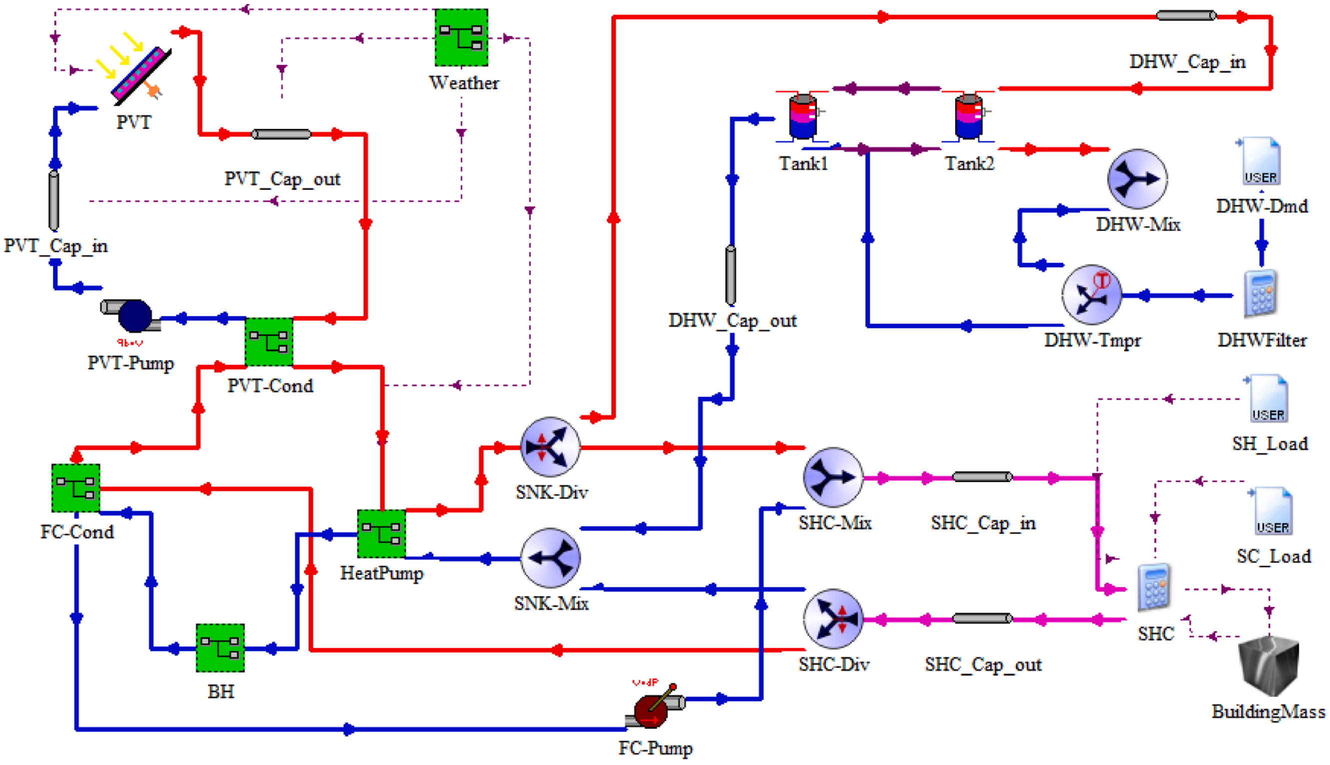

Fig. 2. Simplified version of the MS model in TRNSYS.

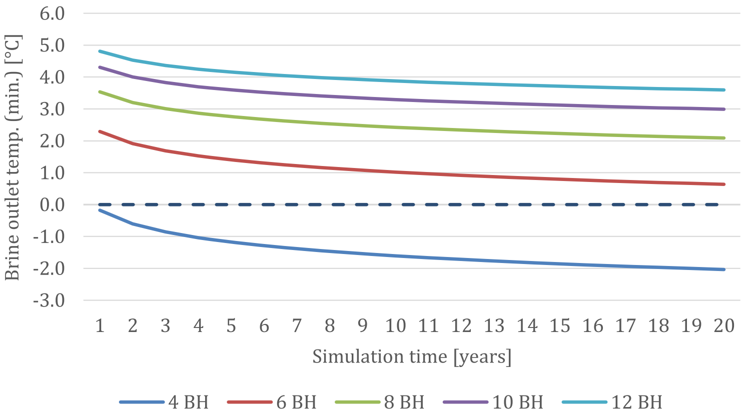

Fig. 3. Yearly minimum borehole brine outlet temperature.

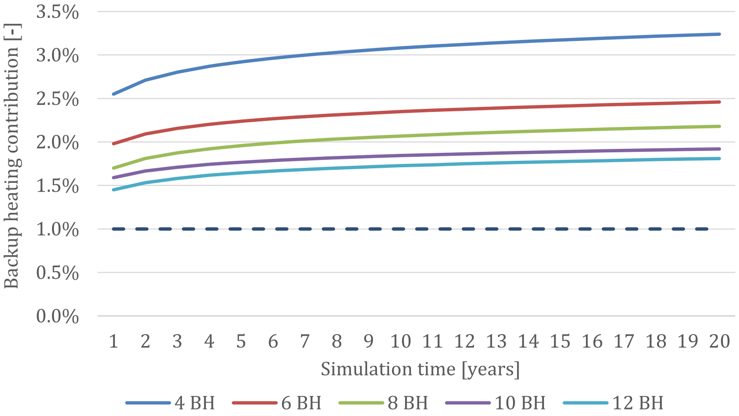

Fig. 4. Percentage of total annual heat supplied by electric backup heater.

Table 1
Economic parameters.

Parameter	Unit	Value
Purchase electricity price	SEK/KWH	2.00
Wholesale electricity price	SEK/KWH	0.60
Heat pump cost	SEK	239,000
PVT cost	SEK/MODULE	5000
PVT fixed cost	SEK	100,000
PVT variable cost	SEK/MODULE	3000
FC cost	SEK	21,000

$$SPF_{4+} = \frac{Q_{sh} + Q_{dwh}}{E_{hp} + E_{p,src} + E_{p,snk} + E_{bb} + E_{b,dwh} + E_{p,pvt}} \tag{1}$$

Two additional technical KPIs include the thermal imbalance ratio (TIR) and interference ratio (IR). The TIR, defined by Eq. (2) quantifies the annual disparity between the total heat extracted from the boreholes and the total heat injected into the boreholes. This difference is then divided by the maximum value between Q_{ext} and Q_{inj}. In a heating-dominated scenario, TIR is typically positive, and achieving a balanced system is indicated by TIR reaching 0 %.

$$TIR = \frac{Q_{ext} - Q_{inj}}{\max\left(Q_{ext}, Q_{inj}\right)} \cdot 100\ \% \tag{2}$$

IR is defined by Eq. (3) serves as an indicator of the operational interference faced by the free cooling system, which prevents it from fully satisfying the total cooling demand Q_{cool} during a specific time frame. The variable C_{cool} acts as a control signal, dictating the activation

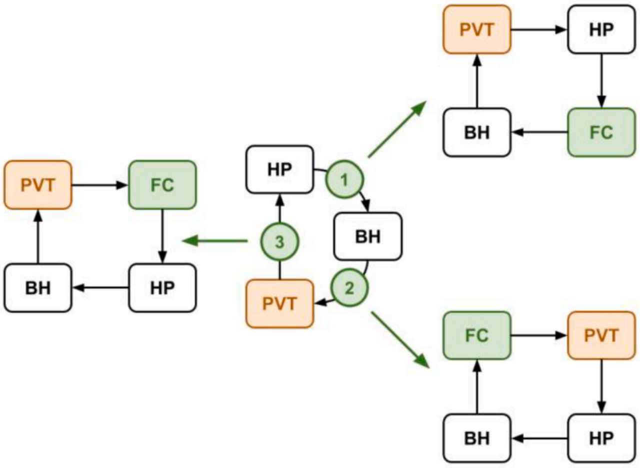

Fig. 5. The three possible multi-source system configurations 1,2 and 3.

($C_{cool} = 1$) or deactivation ($C_{cool} = 0$) of the FC system based on factors like the brine fluid temperature.

$$IR = \frac{Q_{interfered}}{Q_{cool}} \cdot 100\ \% \tag{3}$$

Where $Q_{interfered}$ is defined as follows,

$$Q_{interfered} = \begin{cases} Q_{cool}, \ if \ Q_{cool} < 0 \cap C_{cool} = 0 \\ 0, \ otherwise \end{cases}$$

To assess the economic performance, total life cycle cost (TLCC) is utilized. TLCC comprises three primary components: I_x, (CAPEX - Capital Expenditure), $O\&M_{syst}$ (OPEX - Operating Expenditure), and RV_x (residual value). Total life cycle cost is then calculated as seen in Eq. (4):

$$TLCC = I_{hp} + I_{bh} + I_{fc} + I_{pvt} + O\&M_{syst} - RV_{pvt} - RV_{bh} \tag{4}$$

The main components are summarized below, along with the key figures presented in Table 1. The details of the TLCC calculation are carried out the same way as outlined in Sommerfeldt and Madani [17], using the parameters presented in Table 1. Economic parameters with a real discount rate of 3 %.

- $I_{hp}, I_{bh}, I_{pvt}, I_{fc}$ are the initial investment for the heat pump, borehole field, PVT array and free cooling, respectively.
- $O\&M_{syst}$ constitutes the electricity consumption costs of the HP, PVT and FC systems over the 20-year lifetime of the system, subtracting when applicable the sale of PVT electricity generated.
- RV_{pvt} is the discounted residual value of the PVT, considering a 30-year lifetime and no salvage value. It is calculated with a net value of electricity saving and sales due to the PVT, while subtracting a 1 % yearly maintenance cost. This is discounted for the 21st and 30th year of the PVT system.
- RV_{bh} is used to distribute the initial investment of the BH field over its 60-year lifetime using the lifetime equivalent annual cost method.

5. Results

This section presents the outcomes derived from the model simulations in TRNSYS. The simulations have been run for 1 year and 20 years in order to be able to answer the research questions formulated in Section 3.

5.1. FC + GSHP system

When considering a free cooling and ground source heat pump system, there are two possible configurations: placing the free cooling loop after the heat pump or placing the free cooling loop after the boreholes. If we exclude the PVT system from Fig. 5, then the first configuration corresponds to C1, and the second corresponds to C2. The heat extracted from the building can be utilized for either borehole regeneration or DHW production, as indicated in Table 2. In this table, it can be seen that C1 regenerates the borehole with 7.6 % more heat compared to C2, but C2 provides more energy to the HP. However, the choice between these two FC+GSHP configurations is essentially arbitrary because the ultimate goal is to reduce the long-term load on the borehole field, regardless of where the heat is directed.

To evaluate the borehole regeneration potential of the FC system, a parametric study is conducted, involving variations in the number of boreholes and their spacing. The borehole count is varied between 4 BH and 6 BH in steps of 1 BH, whereas the spacing is varied between 5 m and 15 m in steps of 5 m.

Fig. 6 presents the SPF_{4+} evolution over 20 years, comparing systems with and without FC for different number of boreholes. On the 20th year, there is an average SPF_{4+} reduction of 3.88 % for the GSHP-only system and 3.48 % for a FC+GSHP system when compared to the initial year. In the case of four boreholes, the SPF_{4+} for the GSHP system is 2.98, while for the FC+GSHP system, it is 3.01, representing a 1 % system performance enhancement.

Table 2
Heat utilization from free-cooling for both configurations.

Configuration	TO BH	TO HP
C1	**61.3 %**	**38.7 %**
C2	**53.7 %**	**46.3 %**

In the case where SPF_{4+} experiences the most significant drop (4 BH), the brine outlet temperature highlights the role of free cooling in maintaining the borehole field's temperature during the coldest months, showing it to be 0.28 °C warmer than with a GSHP-only setup (see Fig. 7). Notably, the plot reveals a substantial peak during the summer months of July and August, corresponding to the operational period of FC, which contributes to DHW production and borehole regeneration. While its impact is minimal, FC does help mitigate soil degradation over time.

Similarly, when considering borehole spacing for a FC+GSHP system, there is no significant difference in SPF_{4+} compared to the GSHP-only system. The initial SPF_{4+} values for all systems are either equivalent or higher than those achieved with reduced borehole counts (as observed in Fig. 8). As expected, SPF_{4+} diminishes more rapidly in the early years, falling to levels below those of configurations with wider spacing, illustrating the interaction between boreholes. The average thermal imbalance ratio for all FC+GSHP systems is 93.73 %, which represents an improvement over the zero heat injection for the original system but it is still far from having a balanced load. In milder climates with balanced heating and cooling loads, the influence of FC on system performance is expected to be more noticeable.

Table 3 displays the TLCC and TIR values for both systems with varying borehole count and spacing. Systems with FC prove to be more costly than those without it, as could be expected. Although FC reduces compressor operation and subsequent electricity consumption, both the borehole and free-cooling circulation pumps operate in the FC+GSHP system, resulting in minimal electricity savings compared to the investment required for the FC system.

5.2. Interference reduction in multi-source (MS) system

Since both the PVT and FC loops are competing against each other during the summer months to use the borehole field as a heat sink, it becomes necessary to do an interference analysis of the MS system for the three different system configurations presented in Fig. 5. The results of this analysis are summarized in Table 4.

It can be seen that C1 and C3 exhibit notable FC interference compared to C2. In C3, where the FC heat exchanger is positioned after the PVT heat exchanger, the impact on cooling supply is most pronounced. Higher cooling demand coincides with elevated ambient air temperatures and irradiation, resulting in higher fluid temperatures as they enter the FC heat exchanger. C1 has a lower interference ratio than C3, with a value of 12.20 %. This is primarily due to the PVT contribution to DHW production during the summer, helping to reduce the brine fluid temperature before it reaches the FC heat exchanger.

Among the MS system configurations, C2 stands out as the best performer, with an IR of only 0.89 %. However, it should be noted that this configuration has the lowest PVT thermal yield of the three with a decrease of 7.24 % compared to the 76.22 MWh_{th} obtained for the baseline PVT+GSHP case, whereas the other two configurations exhibit an average decrease of 3.52 %. Considering these results and the objectives of the MS system, C2 is selected due to its relatively low FC interference when compared to the other two alternatives.

By conducting a parametric study on PVT control, we can devise an optimal controller aimed at enhancing the thermal yield of C2. The study involves a range of parameters, as outlined in Table 5. The operation of the circulation pump in the PVT system is regulated by monitoring the temperature differential between the glycol-water mixture exiting the PVT module and the brine fluid exiting the borehole. Based on this difference, compared against cut-out and cut-in temperatures of 1 °C and 6 °C respectively, the controller determines whether to activate or deactivate the pump. To mitigate pump oscillations between the on and off states, a 2 °C deadband is considered in the parametric study.

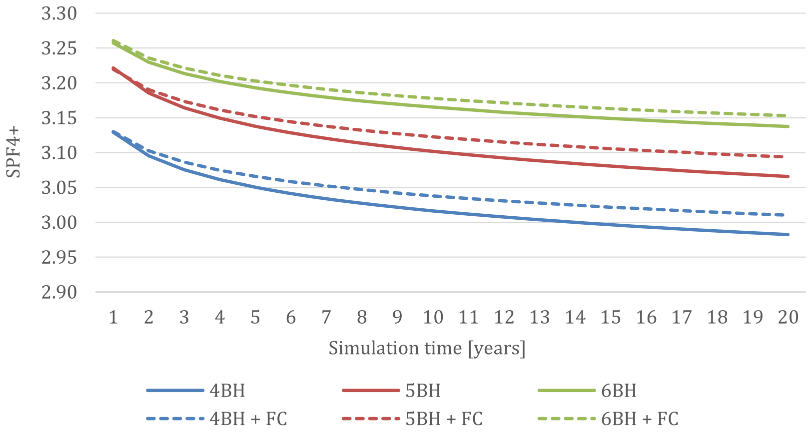

Fig. 6. Effect of borehole count on GSHP system with and without free cooling.

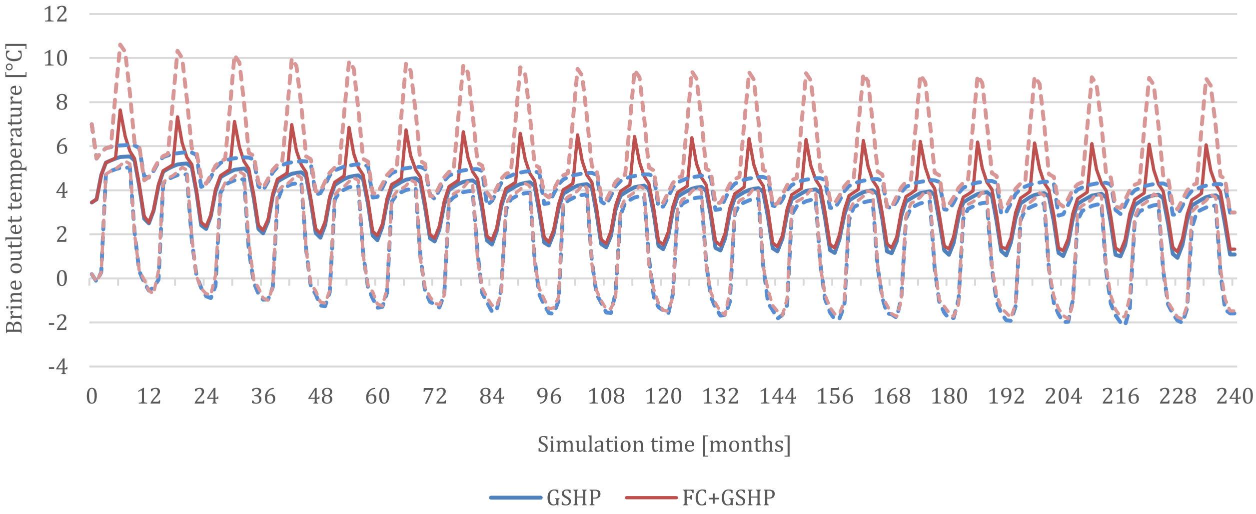

Fig. 7. Brine outlet temperature from borehole for the two systems. Solid lines represent monthly averages and the dashed lines are monthly minimum and maximum.

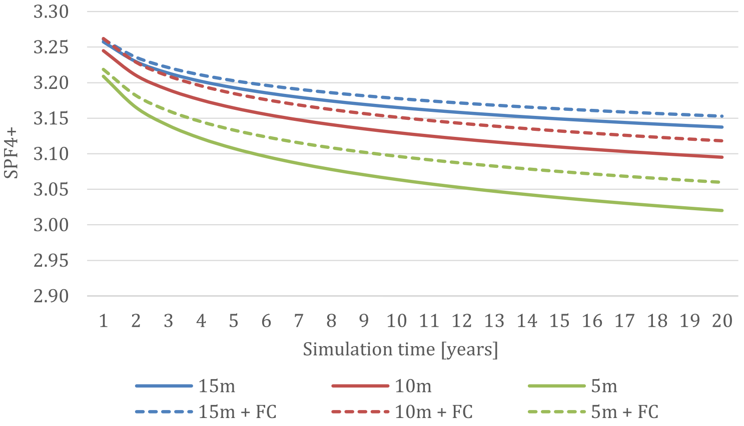

Fig. 8. Effect of borehole spacing on GSHP system with and without free cooling.

The results are illustrated in Fig. 9 through a heat map depicting the ratio of PVT thermal energy to PVT circulation pump electricity consumption, with the objective of maximizing this ratio. The baseline PVT parameters encompass a flow rate of 20 l/hr/m^2 and cut-out and cut-in temperatures of 1–6 °C. If a new controller’s thermal yield falls short of the baseline controller’s yield, the ratio is set to zero. In general, lower yields are observed for flow rates at 10 l/hr/m^2, with an average reduction of 20 % compared to the baseline scenario.

Intuitively, as the flow rate increases, electricity consumption also rises, while the amount of heat that can be extracted from the PVT remains relatively low compared to the added pumping demand. However, increasing the deadband reduces electricity usage because the

Table 3
TLCC and TIR for GSHP and FC+GSHP systems for varying borehole count and spacing.

System	BH count	Spacing [M]	TLCC [MSEK]	TIR [%]
GSHP	**6**	**15**	**1.85**	**100.00**
	5	**15**	**1.87**	**100.00**
	4	**15**	**1.90**	**100.00**
	6	**10**	**1.92**	**100.00**
	6	**5**	**1.94**	**100.00**
FC+GSHP	**6**	**15**	**1.87**	**93.73**
	5	**15**	**1.89**	**93.70**
	4	**15**	**1.92**	**93.69**
	6	**10**	**1.93**	**93.74**
	6	**5**	**1.95**	**93.79**

Table 4
Interference ratio and PVT thermal yield for the FC+GSHP, PVT+GSHP and MS systems for all three FC configurations.

System	Configuration	Interference ratio [%]	PVT yield [MWHTH]
MULTI-SOURCE SYSTEM	**1**	**12.20**	**73.55**
	2	**0.89**	**70.70**
	3	**19.25**	**73.50**

Table 5
PVT controller parameters varied for parametric analysis.

Parameter	Range	Step	Unit
Specific PVT-flowrate	**10–50**	**10**	**L/(H.M2)**
Cut-in temperature	**3–6**	**1**	**°C**
Cut-out temperature	**1–4**	**1**	**°C**

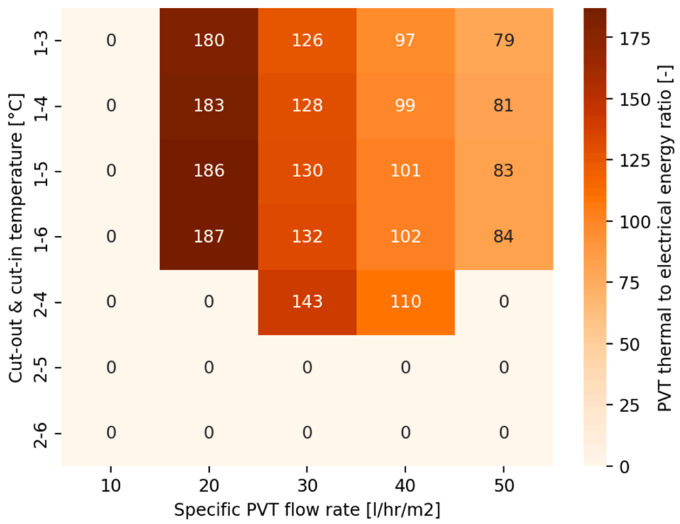

Fig. 9. Heat map of the PVT parametric study on flow rate and cut-in/out temperatures.

controller becomes less sensitive to temperature fluctuations. The study indicates that the baseline controller remains the most optimal design. Nevertheless, if thermal yield is a primary design criterion, lowering the cut-in temperature enhances the yield by 2.22 %, albeit at the expense of a 6.35 % increase in electricity consumption for circulation. It's worth noting that pump electricity consumption stands at 378 and 402 kWh for the baseline and the '1–3 °C and 20 $l/h/m^2$' controller, respectively, which is nearly negligible when compared to the total system electricity consumption of 56,184 kWh_{el}.

5.3. System performance comparison

For the analysis presented in this section, configuration 2 for the position of the free cooling heat exchanger within the system will be employed, and the PVT controller settings will be retained in line with the baseline controller. To evaluate the technical and economic performance of the various systems, the Key Performance Indicators introduced in Section 4.4 will be utilized. The initial two studies involve variations in borehole count and borehole spacing, utilizing the parameters outlined in Table 6. Additionally, the size of the PVT array will be adjusted for each parameter configuration in four incremental steps. This adjustment will involve increasing the number of PVT modules as follows: 0, representing the GSHP and FC+GSHP systems, 48, 96, and 144. Throughout this section, the borehole depth will remain constant at 300 m. The SPF_{4+} values presented are averaged over the 20-year operational lifespan.

The borehole count is represented in terms of specific borehole length in Fig. 10, which is a normalized value obtained from dividing the total length of the borehole field by the total heating demand of 127 MWh/yr (SH + DHW). As observed in the initial section of this chapter, free cooling has a minimal impact on the $SPF_{4+}$of the GSHP system, enhancing it at most by 0.7 % for the smallest borehole field. On the other hand, the SPF_{4+} of the GSHP+PVT systems gradually converges with that of a multi-source system as the number of PVT modules increases. This phenomenon arises because the proportion of heat injected by the PVT system becomes more significant relative to that of FC. For instance, a PVT array consisting of 96 modules, combined with 4 boreholes, achieves a similar SPF_{4+} to a GSHP system with 6 boreholes, effectively reducing land area requirements by 50 %. Furthermore, the largest PVT array offers a 5 % SPF_{4+} increase while simultaneously reducing the thermal imbalance ratio by 65 %.

The impact of borehole spacing can already be seen for the case with 5 m spacing, where the spf4+ is lower compared to the 10 m and 15 m spacing configurations. This difference arises because the compressor must operate for an extended period to extract an equivalent amount of heat from a lower-quality heat source, which is a consequence of the interaction between boreholes. Across all spacing configurations tested, the introduction of pvt modules consistently enhances the system's spf4+ while simultaneously reducing the required land area, with the maximum reduction reaching 88.9 %. As more pvt modules are added, the injection of heat into the ground increases, thereby limiting thermal degradation of the ground. It is worth noting that even with increased spacing, the spf4+ of the system with 144 pvt modules remains relatively constant.

In Fig. 11, the graph illustrates the brine outlet temperature of the three studied systems: GSHP, FC+GSHP and GSHP+PVT. These systems are configured with 6 boreholes spaced 15 m apart. For the case of 144 PVTs, the ground temperature remains constant throughout the 20 years considered in the study. Adding 48 PVTs increases the minimum temperature in the ground by 0.42 °C and 0.58 °C if compared to the FC+GSHP and GSHP-only systems on the 20th year of operation.

6. Discussion

As global temperatures continue to rise, the demand for cooling residential spaces is poised to surge to maintain comfort levels. Even in regions where cooling systems have been historically uncommon due to their colder climate, such as sweden, the need for cooling solutions is

Table 6
Borehole parameters that are varied in parametric analysis.

Parameter	Range	Step	Unit
Borehole count	**4–6**	**1**	**–**
Borehole spacing	**5–15**	**5**	**M**
PVT module count	**0–144**	**48**	**–**

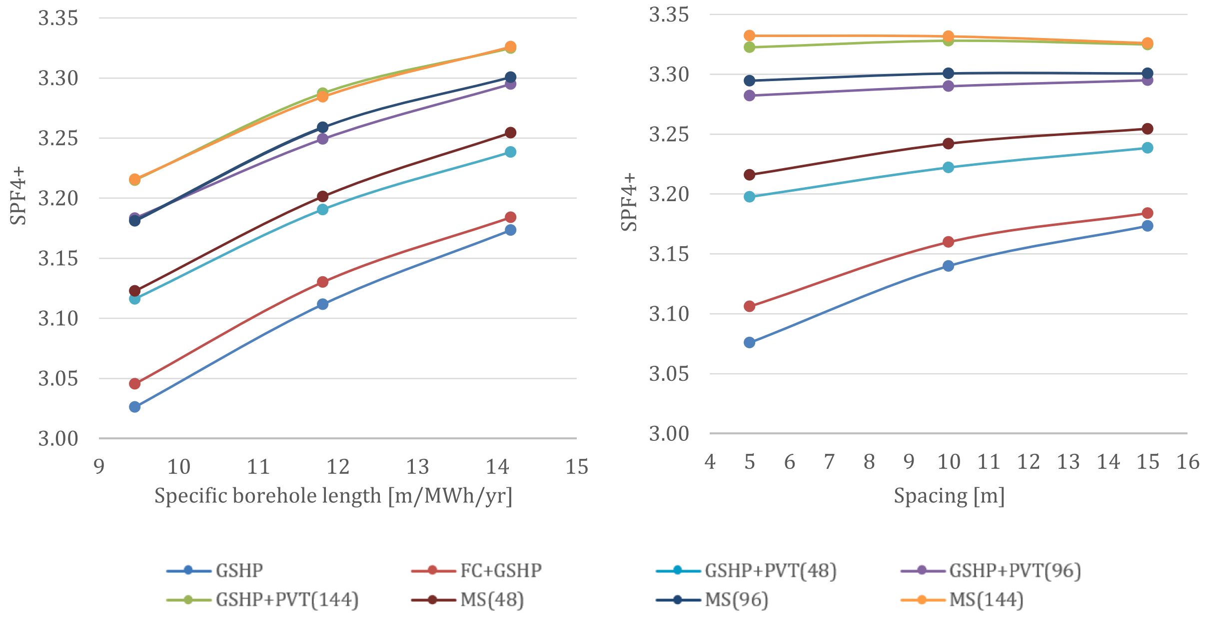

Fig. 10. Parametric study of MS system varying borehole count and spacing.

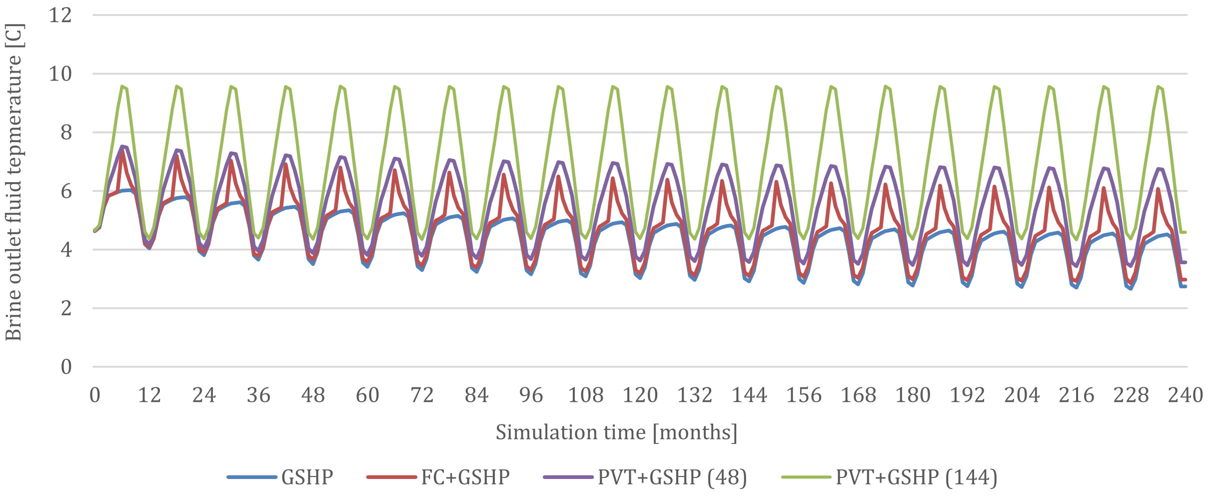

Fig. 11. Brine outlet temperature from boreholes for four systems.

becoming increasingly evident. The combination of free cooling with gshp seems like a natural way to do that, since the heat extracted from the building during the summer months can be injected into the ground to potentially regenerate the borehole field. However, there might be interferences with other systems in place, such as photovoltaic/thermal collectors.

The results presented in Section 5 show that the level of interference between free cooling and pvt systems largely depends on the placement of the respective heat exchangers relative to each other. Where they are situated affects how well they complement each other, or potentially create operational conflicts. The pvt's impact on the operation of the fc system is more substantial than the reverse situation. This can be explained because of the higher operational period of the pvt compared to the fc. The cooling demand is focused during the day and chiefly in july and august, compared to the pvt which is operational throughout most of the year and reaches its peak in the same months as fc. By electing to prioritize a reduction on fc interference, the pvt yield only decreases by 3.73 % compared to where the system is designed for pvt interference reduction. The results show that the most important factor that causes interference between the two systems is their relative placement in the system. If it is desirable to maximize pvt yield, then an alternative is splitting the bh field so that fc regenerates one half and pvt the other half, assuming that the regeneration capability of both are similar. Otherwise, a distribution and control system can be designed to evenly divide regeneration across the whole field. Splitting the bh field does impact the complexity and initial capital cost of the system though and shall be the main drawback.

Although adding fc to a gshp system in a heating dominated climate does improve the tir of the bh field, the amount of heat injected to the ground is low compared to the heat extracted. If a milder climate and different building type is used where the heating to cooling ratio is closer to unity as opposed to more than 12 for the scenario considered, fc can contribute more to bh regeneration. Furthermore, the capital cost of fc is not compensated enough by the electricity consumption costs of the system which leads to fc+gshp systems to be more expensive overall than gshp-only systems. Overall, although fc can provide cooling to maintain comfort levels in a residential building, its capability to regenerate the bh field is negligible and does not provide any substantial improvement in the system's technical performance.

The main limitation of this study lies in the use of lump-capacity building model type 963. This model is overly simplistic since it does not allow dynamic indoor temperature variation. Thermal loads have to be generated elsewhere and be applied to type 963 as opposed to supply systems provisioning space conditioning. This leads to a different dynamic compared to using single or multi-zone building models. Exploring a model with dynamic indoor temperature variation, would offer insights into the interference dynamics between fc and pvt systems. This approach also would allow for the experimentation with fc heat exchanger sizing for optimized temperature control and economic efficiency. However, type 963 was intended to replace the more complex multi-zone building model type 56, which increases computational time exponentially. An alternative would be to find a compromise between these two models, by using type 88, a single zone building model.

7. Conclusions and future work

This study investigated the performance of a ground source heat pump system with free cooling for a multi-family building in Stockholm, Sweden, and the interference on the free cooling capabilities of the system when photovoltaic/thermal collectors are present. The results show that for the studied system, there is no notable technical or economic advantage from adding free cooling into a GSHP system besides providing better comfort. By the 20th year of operation, free cooling can improve the SPF of a GSHP-only system by 0.51 % for a borehole field with 6 boreholes and 15 m spacing. The effect of free cooling could be slightly enhanced for undersized borehole fields, reaching a 1.3 % improvement in SPF for the case with 4 boreholes and 5 m spacing. The thermal imbalance ratio of the FC+GSHP, that is the percentage difference between the heat extracted and injected to the ground, is still very high at a value of almost 94 %.

It was also found that the location of the free cooling heat exchanger relative to the other components in the system defines the amount of interference between free cooling and PVT. The optimal configuration that limits interference to less than 1 % is found to be configuration 2, which places the free cooling heat exchanger after the borehole but before the PVT heat exchanger. However, this configuration reduces the thermal yield of the PVT collector by 7.24 % compared to the PVT+GSHP case, which does not seem to have a noticeable negative effect on overall system performance.

FC's contribution to improving the SPF_{4+} of the MS system is minimal compared to the PVT array. The only scenario studied where FC can reduce the land requirement is if the BH spacing is decreased to 10 m, which leads to a reduction of 66.6 % with a slightly lower SPF_{4+} of 3.16 compared to 3.17 for GSHP-only.

This study highlights that free cooling alone falls short in significantly reducing land area requirements in a ground source heat pump systems. However, the relatively low interference between FC and PVT systems indicates that it is possible to combine them when there is a cooling need in the building. Moreover, it was observed that the reduction of land area is indeed achievable and considerable when PVT is incorporated into the system, but it comes at a high upfront cost.

Future work could delve into replacing the current TRNSYS lump-capacitance building type with a more sophisticated model, such as Type 88 (single-zone building model). It will come at a higher computational cost, but a trade-off between model accuracy and simulation time should be found. Another relevant line of work would be to investigate the performance of such a system for single family houses, or MFH with different heating to cooling demand ratios. Future research could also look into the techno-economic performance evaluation of FC retrofit scenarios, providing insights into the feasibility and advantages of integrating FC technology into existing systems. Rising temperature levels will affect existing buildings as well, so investigating the implementation of efficient cooling systems in these types of buildings is highly relevant.

Declaration of competing interest

None.

Acknowledgements

This research is funded by Mistra Innovation's MI23 program, project name SmartSol^2 (Smart solar hybrid solutions for sustainable European buildings), for which the authors are grateful.

References

[1] Andersson, O., & Gehlin, S. (2018). State-of-the-Art: Sweden quality management in design, construction and operation of borehole systems *2018*. 1–37. http://media.geoenergicentrum.se/2018/06/Andersson_Gehlin_2018_State-of-the-Art-report-Sweden-for-IEA-ECES-Annex-27.pdf.

[2] T. Arghand, S. Javed, A. Trüschel, J.O. Dalenbäck, Influence of system operation on the design and performance of a direct ground-coupled cooling system, Energy Build. 234 (2021) 110709, https://doi.org/10.1016/j.enbuild.2020.110709.

[3] E. Bertram, J. Glembin, G. Rockendorf, Unglazed PVT collectors as additional heat source in heat pump systems with borehole heat exchanger, Energy Procedia 30 (2012) 414–423, https://doi.org/10.1016/j.egypro.2012.11.049.

[4] B. Chhugani, M. Kirchner, M. Littwin, F. Giovannetti, Investigation of photovoltaic-thermal (PVT) collector for direct coupling with heat pumps: hardware in the Loop (HiL) and TRNSYS simulations, in: Proceedings of the BauSIM 2020, 2020. *December*.

[5] B. Chhugani, P. Pärisch, S. Helmling, F. Giovannetti, Comparison of PVT - heat pump systems with reference systems for the energy supply of a single-family house, Sol. Energy Adv. 3 (December 2022) (2023) 100031, https://doi.org/10.1016/j.seja.2022.100031.

[6] U. Desideri, N. Sorbi, L. Arcioni, D. Leonardi, Feasibility study and numerical simulation of a ground source heat pump plant, applied to a residential building, Appl. Therm. Eng. 31 (16) (2011) 3500–3511, https://doi.org/10.1016/j.applthermaleng.2011.07.003.

[7] M. Deymi-Dashtebayaz, S. Valipour Namanlo, A. Arabkoohsar, Simultaneous use of air-side and water-side economizers with the air source heat pump in a data center for cooling and heating production, Appl. Therm. Eng. 161 (July) (2019) 114133, https://doi.org/10.1016/j.applthermaleng.2019.114133.

[8] Fulbright, N.R. (2021). The EU green deal explained. https://www.nortonrosefulbright.com/en/knowledge/publications/c50c4cd9/the-eu-green-deal-explained.

[9] M. Lämmle, G. Munz, Performance of heat pump systems with PVT collectors with optimized finned heat exchangers integrated as single heat source, in: Proceedings of the EuroSun 2022, 2022, pp. 0–4, https://doi.org/10.18086/eurosun.2022.07.06.

[10] M. Noro, S. Mancin, C. Zilio, Energy performance of annual operation of heat pump coupled with ground ice storage and photovoltaic/thermal modules, J. Phys. Conf. Ser. (1) (2022) 2385, https://doi.org/10.1088/1742-6596/2385/1/012007.

[11] H. Olausson, E. Wernius, Development of a Simulation Model for Combined PVT and Ground Source Heat Pump Systems A TRNSYS Model Created for Commercial Use, [KTH Royal Institute of Technology], 2021. https://www.diva-portal.org/smash/get/diva2:1583383/FULLTEXT01.pdf.

[12] G. Qiu, K. Li, W. Cai, S. Yu, Optimization of an integrated system including a photovoltaic/thermal system and a ground source heat pump system for building energy supply in cold areas, Appl. Energy 349 (July) (2023) 121698, https://doi.org/10.1016/j.apenergy.2023.121698.

[13] Remund, J., & Kunz, S. (2018). Meteonorm 7.2 (7.2.4.31876).

[14] F. Ruesch, M. Haller, Potential and limitations of using low-Temperature district heating and cooling networks for direct cooling of buildings, Energy Procedia 122 (2017) 1099–1104, https://doi.org/10.1016/j.egypro.2017.07.443.

[15] C. Schmidt, A. Schäfer, K. Kramer, Single source "solar thermal" heat pump for residential heat supply: performance with an array of unglazed PVT collectors, in: Proceedings of the 12th ISES EuroSun Conference, 2018.

[16] Sommerfeldt, N., Beltran, F., & Madani, H. (2020). High market potential applications for PVT with heat pumps. 10.18086/eurosun.2020.05.11.

[17] N. Sommerfeldt, H. Madani, In-depth techno-economic analysis of PV/Thermal plus ground source heat pump systems for multi-family houses in a heating dominated climate, Sol. Energy 190 (2019) 44–62, https://doi.org/10.1016/j.solener.2019.07.080.

[18] H. Zhang, S. Shao, H. Xu, H. Zou, C. Tian, Free cooling of data centers: a review, Renew. Sustain. Energy Rev. 35 (2014) 171–182, https://doi.org/10.1016/j.rser.2014.04.017.

[19] Y. Zhang, Z. Wei, M. Zhang, Free cooling technologies for data centers: energy saving mechanism and applications, Energy Procedia 143 (2017) 410–415, https://doi.org/10.1016/j.egypro.2017.12.703.