Techno-Economical Assessment of a Solar Regenerated Borehole Heat Exchanger Field with PVT Collectors for District Heating

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Abstract

Cold district heating networks distribute heat with few losses or even gains from the heat source to decentralized heat pumps in residential districts. These so called fifth-generation district heating systems have the possibility of being operated entirely by renewable energies and often use a borehole heat exchanger field as the primary heat source. The paper presents a case study and discusses the sustainable dimensioning of borehole heat exchanger fields for district heating by means of system simulations with TRNSYS, focusing on the solar regeneration of the ground with photovoltaic thermal collectors. The simulation results show that the combination with solar regeneration allows the reduction of the ground source by 53 %, increases the efficiency by approx. 5 %, minimizes the levelized cost of heat and improves sustainability in terms of long-term operation.

Keywords: solar regeneration; ground source heat pump; borehole heat exchanger; PVT; 5th gen. district heating

1. Introduction

Several field studies in Germany have shown that the average seasonal performance factor (SPF) of ground source heat pump systems is significantly higher than that of air source heat pump systems (Auer and Schote, 2009; Miara et al., 2011; Günther et al., 2020). The difference between the efficiency levels is most significant in winter, when the ambient temperatures are lowest and the heat demand is at its peak. Therefore, ground source heat pumps with borehole heat exchangers (BHE) should substantially contribute to the future heat supply based on renewable resources. With rising market penetration, the interaction of individual BHEs in large borehole heat exchanger fields or in a cluster of individual BHE systems is at the focus of scientific discussions (Witte, 2018; Fascì et al., 2021). The sustainable operation of BHE fields and clusters requires regeneration with solar, environmental or waste heat. Persdorf et al. (2015) and Sauter et al. (2021) show that the regeneration with solar energy prevents undercooling of the ground in densely populated areas with BHE clusters. However, BHEs for single buildings are expensive and especially cold district heating networks with connected heat prosumers can reduce the specific costs of the shared BHE field. A number of research projects, like +Eins, SmartQuart, EASyQuart, EnVisaGePlus and KNW-Opt, use field tests and simulations to analyze the behavior of cold district heating networks.

This paper discusses the effect of solar regeneration of a BHE field in a residential district heating system using a simulation study with the transient system simulation program TRNSYS. A schematic of the district heating concept is shown in figure 1.

The district comprises 37 multi-family houses (MFH), designed almost according to the Passive House standard, with 450 apartments for 800 inhabitants. The heat for space heating (411 MWh), domestic hot water (DHW, 315 MWh) as well as distribution losses inside the buildings (266 MWh) is provided by heat pumps, which use the cold district heating network as the heat source. A BHE field and a photovoltaic thermal (PVT) collector field that also allows regeneration of the ground provide the required heat to the network. The BHEs are 150 m deep and the cold district heating network has a total length of about 1 km. This type of cold district heating is a so called fifth-generation heating network, which means that the transmission temperatures are commonly in the range of approx. 5 °C to 25 °C and therefore have relatively low heat losses or even gains. The PVT collectors correspond in their design to uncovered thermal collectors, also known as wind and/or infrared sensitive collectors (WISC), and thus efficiently supply heat at or below the ambient temperature (0 °C to 30 °C) as well as electrical energy (not considered in this paper).

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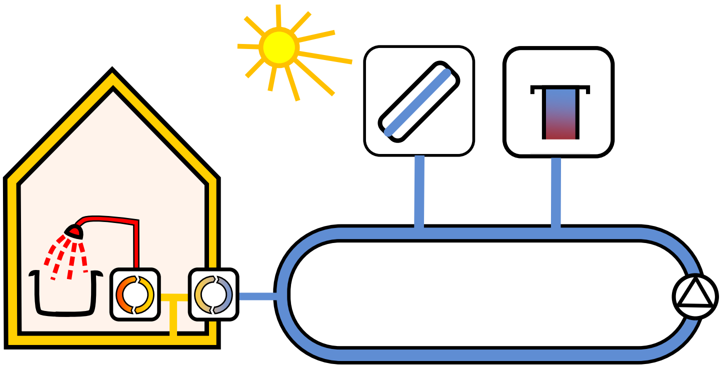

Figure 1: The cold district heating network supplies the heat pumps in the MFHs using the ground (BHE field) as a primary heat source. The PVT collectors assist and regenerate the BHE field.

2. Simulation model and boundary conditions

The heat demand of the district for space heating is simulated with a time step of 15 min in TRNSYS TRNBuild, using the properties of the building materials, the shading, the geometry and the ventilation of the buildings. This results in an average specific space heating demand of 19.2 kWh/(m²·a) and a total of 411 MWh for all MFH. The demand of the domestic hot water is calculated using the district heating load profiles of the software DHWcalc, Version 2.02b (Braas et al., 2020). A demand of 20 l/d per person, based on a hot water temperature of 60 °C and a cold water temperature of 10 °C, results in a specific demand of 14.7 kWh/(m²·a) and a total of 315 MWh for the district. Within the building, the heat is distributed by a 2-pipe-system to heat interface units, which can provide space heating as well as domestic hot water and simultaneously reduce the required flow temperature to approximately 50 °C according to German temperature standards (DVGW, 2004; DIN, 2012). Losses for storage and building internal pipe network increase the demand by 266 MWh. Thus, the heat pumps have to deliver 955 MWh of heat to the buffer storages. To account for simultaneity effects the load profile is aggregated to 1 h-data. Figure 2 (left) shows the yearly heat load profile for the district before storage.

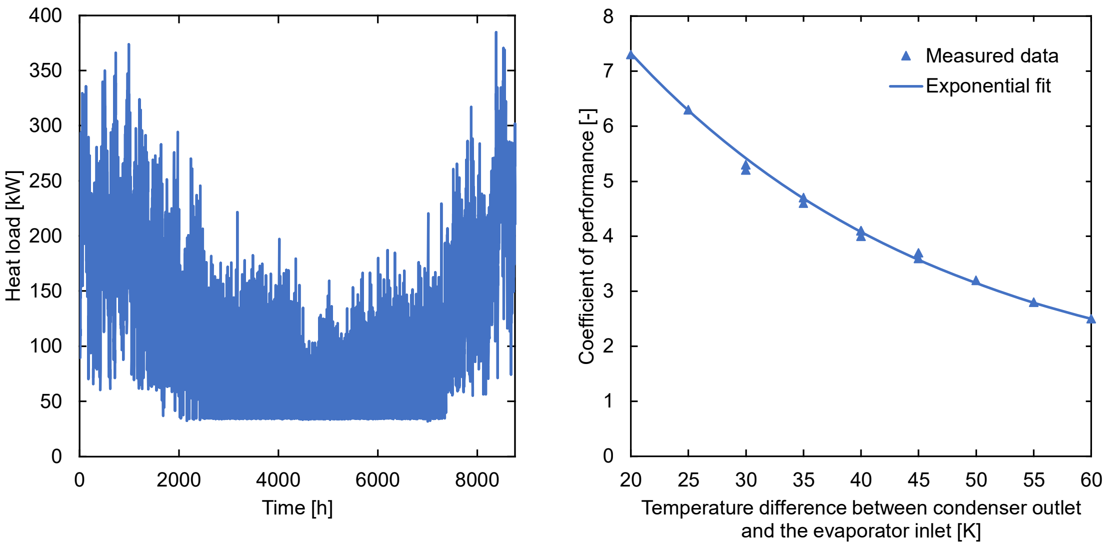

Figure 2: Heat load profile for the district before storage (left) and simplified exponential fit of the coefficient of performance of the heat pump model based on measured data (right)

The load profile for the total heat demand on the load side of the heat pumps (condenser) is read as an input in the following simulation model. The heat pump is modeled with an approximation of the coefficient of performance (COP), assuming no dependency of compressor speed. The simplified fit is based on heat pump test results of the Heat Pump Test Center in Buchs of the Eastern Switzerland University of Applied Sciences (Wärmepumpen-Testzentrum WPZ, 2021). The COP is dependent on the condenser outlet temperature $T_{out,cond}$ and the evaporator inlet temperature $T_{in,evap}$ (see figure 2, right) according to the following equation:

$$COP_{HP} = 13e^{-0.036\cdot(T_{out,cond}-T_{in,evap})} + 1 \quad \text{(eq. 1)}$$

The condenser outlet temperature is constant and set to 51.8 °C, which is a simulated average value needed to ensure a flow temperature of 50 °C at the heat interface unit. Using the COP and the current heating load of the heat pump condenser, the heat flow rate of the evaporator is calculated as follows:

$$\dot{Q}_{HP,evap} = \dot{Q}_{HP,cond} \cdot \left(1 - \frac{1}{COP_{HP}}\right) \quad \text{(eq. 2)}$$

The mass flow through the evaporator is controlled by a constant temperature difference of the heat pump evaporator of 3 K. To simplify the simulations of the cold district heating network and the heat pumps, all heat pumps in the district are combined into a single heat pump. This combined heat pump is located at a common connection point with a shared evaporator inlet temperature. To illustrate the method used to model the network and the setup of the system simulations, figure 3 shows a map of the district on the left side and a system diagram on the right side.

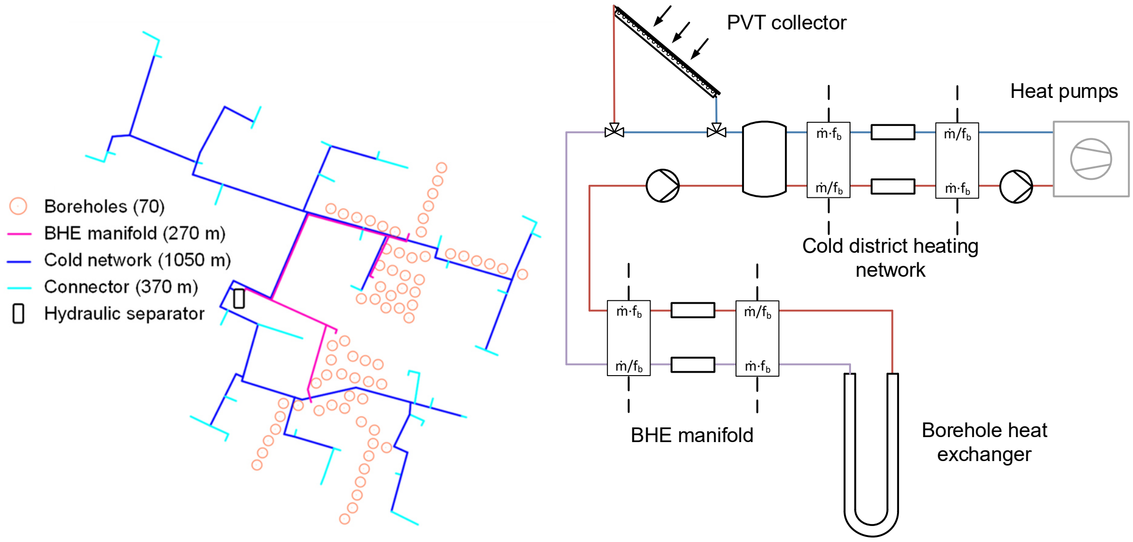

Figure 3: Map of the district with the route of the network and BHE manifold as well as projected positions of BHEs (left) and schematic of the source side model of the heat supply system (right). The PVT collector field is integrated in the return flow and will regenerate the borehole heat exchanger field. The cold district network and the BHE are hydraulically decoupled.

The complex structure of the network, consisting of connecting pipes to each building, the cold thermal network from the hydraulic separator, the BHE manifolds and the BHE distribution pipes (not shown in figure 3), is simplified with the help of a branching factor. To reduce simulation time, the branches of the network are aggregated and combined into a single flow pipe and a single return pipe. Similarly, the connectors to the buildings and the manifolds and the distributors of the BHE field are aggregated into single pipes for flow and return. To account for the branches of the network and to calculate a mass flow through the simulated pipes, we calculate a branching factor f_b of each subsection of the network. This branching factor is defined by the ratio of the total length of the corresponding network l_{tot} and the average length to the connection points l_{avg}:

$$f_b = \frac{l_{tot}}{l_{avg}} \quad \text{(eq. 3)}$$

For example, the length of the simulated pipe of the cold network is the average length between the central hydraulic separator and all connectors of the MFH. Table 1 contains the average lengths of the simulated pipes and the total lengths of the subsections of the network as well as the branching factors. The values for the BHE distributors vary depending on the number of boreholes. The values in the table are given for the case of 70 boreholes.

Table 1: Branching factors of the subsections of the cold district heating network.

Subsection	Pipe diameter	Average pipe length	Total pipe length	Branching factor
Cold network	170 mm	185 m	1054 m	5.7
Connectors	26 mm	10.4 m	364 m	36.0
BHE Manifolds	170 mm	116 m	267 m	2.3
BHE Distributors (70 boreholes)	40.8 mm	35.5 m	617 m	17.4

For calculating the heat transfer of each subsection of the network, the total mass flow is divided by the branching factor of the simulated pipe and the resulting heat transfer of the single simulated pipe is subsequently multiplied by the branching factor. To calculate the heat transfer between the cold district heating network and the surrounding ground the Buried Noded Twin Pipe model (Type 951) developed by TESS is used.

Inside the cold network are two circulation pumps. Their power consumptions $P_{el,i}$ are modeled depending on the mass flow and their respective maximum power consumption:

$$P_{el} = P_{el,max} \cdot \left(0.2 + 0.8 \cdot \frac{\dot{m}}{\dot{m}_{max}}\right) \qquad \text{(eq. 4)}$$

The maximum power consumption $P_{el,max}$ is calculated from the maximum volume flow, the corresponding pressure drop of that part of the network Δp and an efficiency of 0.75:

$$P_{el,max} = \frac{\dot{V}_{max} \cdot \Delta p}{0.75} \qquad \text{(eq. 5)}$$

To estimate the pressure drop, the pipe diameters and average pipe lengths were used. For the cold grid and the connectors this results in a cumulated pressure drop of 39 kPa. The sum of the pressure drops over the BHE manifolds and distributors depends on the number of boreholes. It varies between 59.3 kPa and 66.2 kPa in the case of 30 and 70 boreholes respectively.

The BHE loop is hydraulically decoupled from the evaporator loop by a hydraulic separator. A circulation pump ensures a turbulent flow through the BHE field all year long. The turbulent flow, a borehole diameter of 152 mm and a shank spacing of the double U-tube heat exchanger of 60 mm result in an internal borehole resistance (R_a) of 0.29 (m·K)/W, an external borehole resistance (R_b) of 0.09 (m·K)/W, and an effective borehole resistance (R_b^*) of 0.0978 (m·K)/W. These values are calculated with the software Earth Energy Designer (EED). The ground properties are provided by a thermal response test. The test results for the depth of 150 m show an average undisturbed ground temperature of 12 °C. The thermal conductivity of the ground is specified as 2.1 W/(m·K), the volumetric heat capacity amounts to 2200 kJ/(m³·K), and the density is estimated at 1650 kg/m³. The measured effective borehole resistance is at 0.08 (m·K)/W and thus corresponds very well with the calculated values.

The initial design of the BHE field includes 70 boreholes of 150 m depth each. This is the maximum number of boreholes, that can be built on this site. The location of the individual boreholes is determined by the positioning of buildings, property lines, and other open space planning of the district. The initial configuration design with 70 boreholes is shown on the left side of figure 4. In a parameter study, the number of boreholes is varied between 30 (4500 m total length) and 70 (10500 m total length) in steps of five boreholes each, resulting in nine variants. For the variants, the outer most boreholes are successively removed from the field. The resulting configuration of 30 boreholes is exemplified on the right side of figure 4.

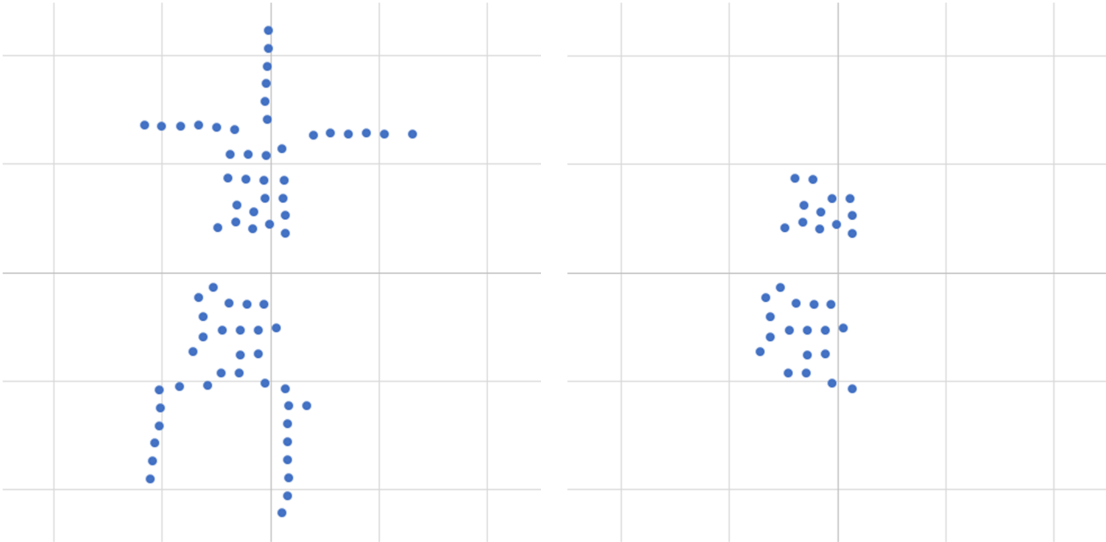

Figure 4: Exemplary BHE field configurations for the parameter study: 70 boreholes on the left side and 30 boreholes on the right side. Each quadrant has a length of 50 m.

The regeneration of the ground is implemented by using PVT collectors, which are incorporated on the return line to the borehole heat exchanger field. The thermal efficiency parameters of the PVT modules are specified by Chhugani et al. (2020) and are shown in table 2:

Table 2: Thermal efficiency parameters of the PVT collector for the open circuit state.

Parameter	Value	Unit	Definition
η_0	0.632	-	zero-loss efficiency of PVT, 0.53 (@MPP)
b_1	19.08	W/(m²·K)	Heat loss coefficient of PVT / c_1
b_2	3.69	J/(m³·K)	Wind dependency of heat loss coefficient / c_3
b_u	0.126	m/s	wind correlation of optical efficiency of PVT collector

The collector field has a slope of 30° and is facing directly south. For the parameter study, the collector area is increased in steps of 100 m² from 0 m² (without regeneration) to 900 m². These ten variants combined with the variations of the BHE field result in a parametric array of 9x10, a total of 90 simulations.

The energetic evaluation criteria of the simulations are the sustainable use of the ground and the efficiency of the heat pumps. In order to ensure a sustainable operation of the geothermal source, the requirements for the use of the ground and the operational restrictions of borehole heat exchangers have to be fulfilled. In Lower Saxony, Germany, the minimum BHE inlet temperature is limited to -3 °C at its peak and to 0 °C for a monthly average (base) to avoid frost conditions in the filling material of the boreholes (Jensen et al., 2022). In contrast, we chose the lowest temperature in the system (evaporator outlet) to incorporate a safety margin. In addition, any long-term increase in groundwater temperature should be avoided. When regenerating the BHE field, this can be achieved if less heat is injected into the ground than extracted. The PVT collectors deliver heat if the temperature hysteresis is 5 K (on) and 2 K (off).

The simulation period as well as the evaluation period is set to 50 years to ensure a long-term operation of the ground source.

The efficiency is evaluated based on the average SPF of the simulation period. The selected evaluation boundaries are decisive for this criterion. In the frame of the IEA SHC TASK 44, Malenkovic et al. (2013) give an overview of the different evaluation boundaries and their suitability for the comparison of different heat supply systems with heat pumps. Gehlin et al. (2022) specify the system boundaries explicitly for ground coupled heat pump systems as part of the IEA HPT Annex 52. Two system boundaries were chosen to assess the efficiency of the system configurations. The first boundary *H1* includes only the heat pump without auxiliary energy (SPF_{H1}). In addition to the heat pump, the second selected system boundary *H2+* includes electrical energy for the circulation pumps and fans on the source-side as well as solar regeneration (SPF_{H2+}).

3. Simulation results

To evaluate whether the individual parameter variation complies with the minimum temperature requirements, the lowest monthly average fluid temperature at the outlet of the evaporator (figure 5, left side) and the lowest hourly evaporator outlet temperature (figure 5, right side) are considered. The heat pump systems are designed to operate in monovalent mode. Therefore, configurations that do not meet the minimum temperature requirements are prohibited and marked grey.

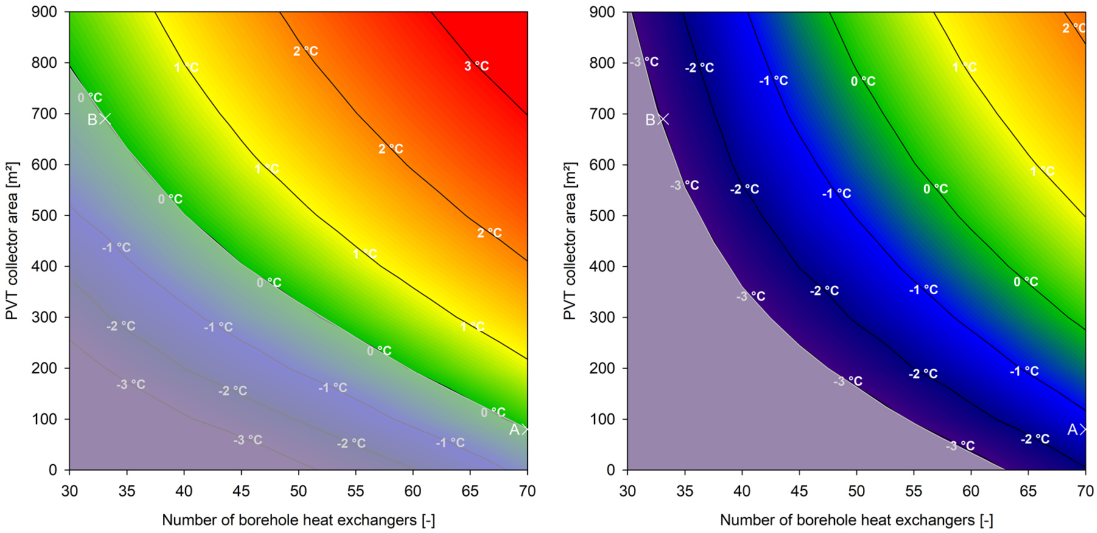

Figure 5: Minimal monthly average evaporator outlet temperature (left) and minimal hourly evaporator outlet temperature (right), A: 70 borehole heat exchangers and 80 m² PVT collectors, B: 33 borehole heat exchangers and 690 m² PVT collectors.

When combining the two minimum temperature requirements the base load is almost exclusively the significant criterion. Only for the smallest BHE field configuration with 30 boreholes, the peak load is the decisive criterion (see figure 6). This can be explained by the fact that a smaller number of boreholes results in a lower usable heat capacity of the surrounding ground to support the heat extraction peaks. Thus, the entire parametric array can be divided into an approvable and a non-approvable (grey) section. Notably, a BHE field with 70 boreholes is not sufficient to be operated without regeneration. The interpolated minimal PVT collector area needed to operate this BHE field is 80 m^2. This is the base scenario for our further evaluation.

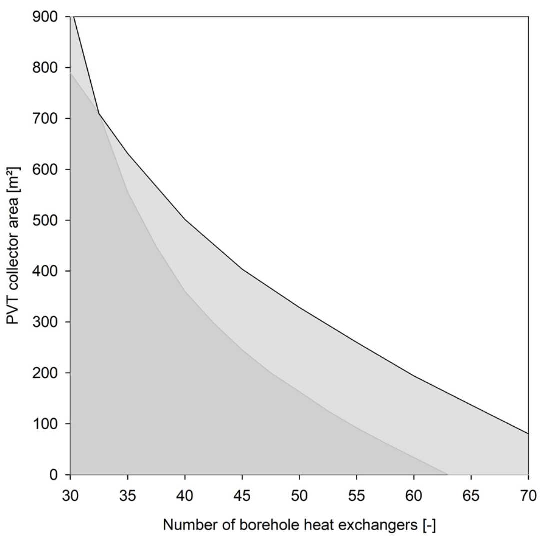

Figure 6: Combined minimum temperature requirement for both base and peak load

The resulting efficiencies of the parameter array are shown in figure 7. The left side features the SPF for the heat pump SPF_{H1}, and the right side features the efficiency of the heat pump including the source-side SPF_{H2+}.

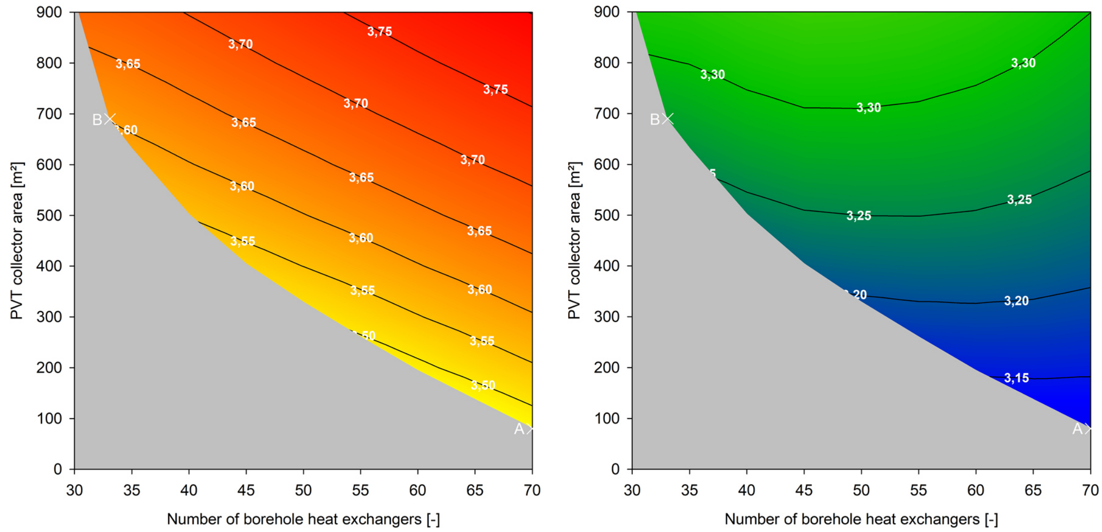

Figure 7: SPF of the heat pumps SPF_{H1} (left) and including the source-side SPF_{H2+} (right) for different no. of BHEs and PVT collector areas. The configurations in the grey area do not meet the sustainability criteria for minimum temperatures, A: 70 borehole heat exchangers and 80 m² PVT collectors, B: 33 borehole heat exchangers and 690 m² PVT collectors.

The results in figure 7 left show that the performance of the heat pump SPF_{H1} improves both with increasing number of boreholes and with increasing PVT collector area. Increasing the number of boreholes by 5 (≙750 m) results in an increase of the efficiency by roughly 0.02. Solar regeneration improves the efficiency of the system approximately by 0.05 per 100 m². In the base scenario of 70 boreholes and 80 m² of PVT collectors an SPF_{H1} of 3.47 is achieved. By using additional 610 m² of PVT panels, the length of the BHE can be reduced by 53 % from 70 to 33 boreholes, or 10500 m to 4950 m, and simultaneously raise the heat pump efficiency to 3.61.

When considering the electrical energy consumption of the circulation pumps on the source side SPF_{H2+} (figure 7 right), the lines with constant efficiency show an optimum. For a given PVT area the efficiency shows a flat minimum, which lies in the range between 45 to 60 boreholes. Due to the higher consumption of the BHE loop circulation pump at higher borehole count, a further increase of the geothermal plant while maintaining the same PVT area, does not improve the SPF_{H2+}.

To further evaluate the results towards a sustainable operation, the net heat extraction from the ground is investigated. The net heat extraction Q_{net} corresponds to the total heat extraction from the ground $Q_{BHE,out}$ minus the amount of heat that is injected into the ground via the borehole heat exchangers $Q_{BHE,in}$ during the same period:

$$Q_{net} = Q_{BHE,out} - Q_{BHE,in} \qquad \text{(eq. 6)}$$

In relation to the total source-side heat at the evaporator of the heat pump $Q_{HP,evap}$, the net heat extraction results in the degree of regeneration f_{reg}:

$$f_{reg} = \frac{Q_{HP,evap} - Q_{net}}{Q_{HP,evap}} \qquad \text{(eq. 7)}$$

On the left side of figure 8, the achieved degrees of regeneration for the last year of the simulation period are plotted. Additionally, the temperature drops over the last five years of the simulation period is shown in figure 8, on the right side. These temperature differences refer to the end-of-year temperatures of the 45th and the 50th year at the evaporator outlet of the heat pump. A small temperature difference corresponds to a more sustainable operation.

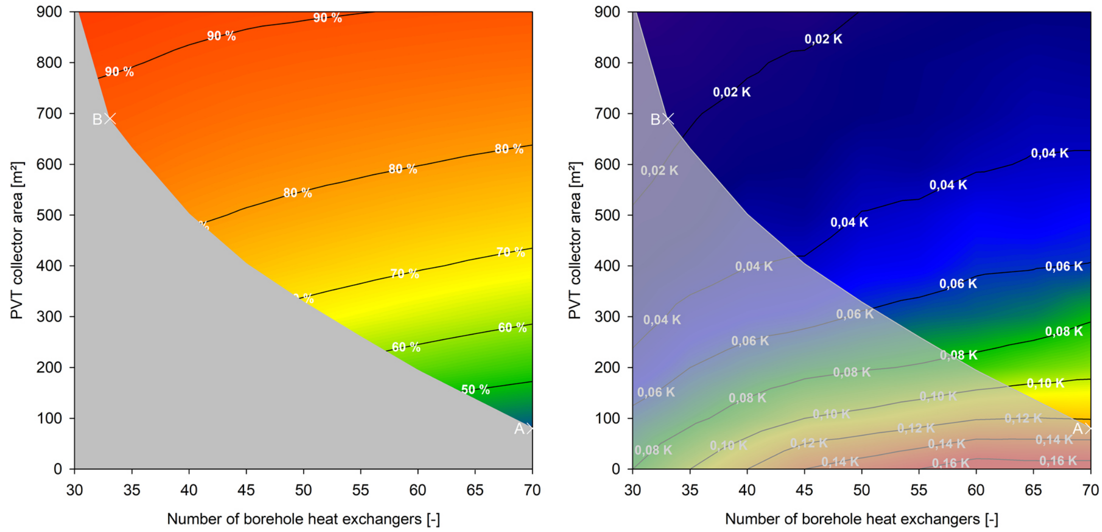

Figure 8: Degree of regeneration (left) and drop of the heat pump evaporator temperature over the last 5 years (right), A: 70 borehole heat exchangers and 80 m² PVT collectors, B: 33 borehole heat exchangers and 690 m² PVT collectors.

The highest degree of regeneration is achieved with the smallest number of BHE and the largest PVT collector area, but stays below 100 %. Smaller fields have higher regeneration degrees than larger fields, since the system is more sensitive to heat loads and the temperatures drops are stronger and thus higher regeneration performances are achieved. However, a complete regeneration or even a net heat injection into the ground is not desirable, since urbanization has already increased groundwater temperatures. A net extraction from the ground can counteract this development to a certain degree.

A higher degree of regeneration leads to a lower long-term reduction of the system temperatures. Thus, a lower temperature difference represents a more sustainable operation. From this point of view, an option with as few boreholes as possible and as much PVT collector area as possible is the most sustainable. The impact of (un)regenerated systems on the ground can also be seen in the horizontal temperature cuts of the two following exemplary variants of 70 BHEs with 100 m² of PVT regeneration and 35 BHEs with 700 m² of PVT regeneration after 50 years of operation (see figure 9).

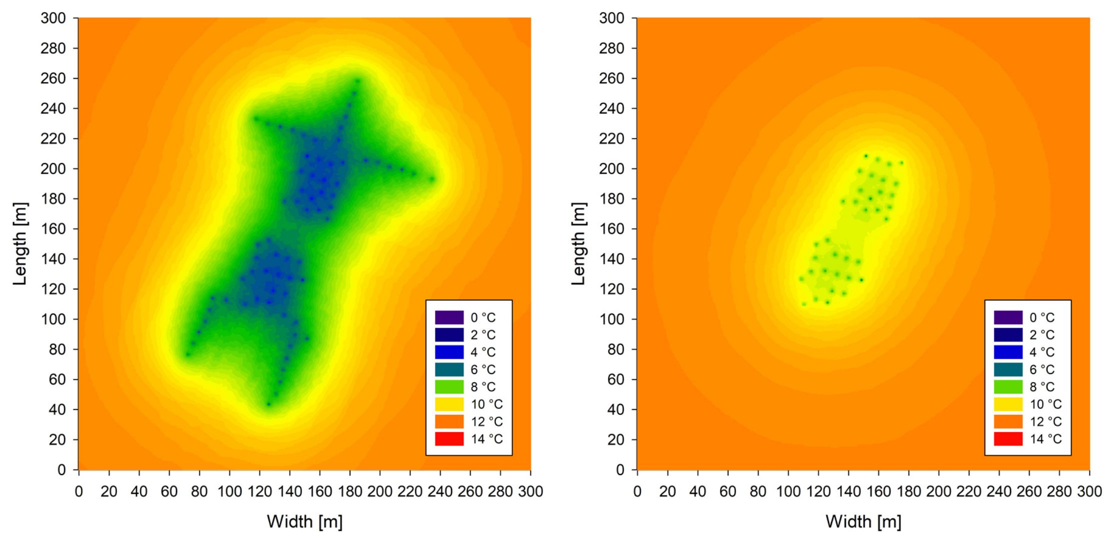

Figure 9: Horizontal temperature cuts at a depth of 75 m after 50 years of operation for a system with low regeneration (left, 70 BHEs and 100 m²PVT) and a system with high regeneration (right, 35 BHEs and 700 m²PVT)

4. Cost analysis

The economic evaluation of the system is based on the static approach of the levelized cost of heat (LCOH) methodology, as defined by Zenhäusern et al. (2020):

$$LCOH = \frac{K_{INV} - S + \sum_{t=1}^{T} OM_t \cdot (1+r)^{-t}}{\sum_{t=1}^{T} Q_{HP,const,t} \cdot (1+r)^{-t}} \qquad \text{(eq. 8)}$$

It includes initial investment costs for the drilling of the borehole heat exchangers, the regeneration with PVT collectors and the cold thermal network K_{INV} as well as a subsidy share S of 49 % of the investment costs and a further construction cost subsidy.

The price assumptions are based on information of an associated planning bureau from 2021. Current developments of inflation and high price increase are not reflected. The specific investment costs for the boreholes k_{BHE} were assumed to be 86 € per meter drilled. For the PVT collectors, only the additional costs compared to simple PV modules are considered, since the areas that are not used for PVT collectors will be used for PV modules any way. These additional specific costs k_{PVT} are assumed to be 370 €/m². The 1912 k€ is the investment costs for the overall cold thermal network including the pipes, sensors, control units and planning. The investment costs are calculated as follows:

$$K_{INV} = 1912\ k€ + k_{BHE} \cdot 150\ m \cdot n_{BHE} + k_{PVT} \cdot A_{PVT} \qquad \text{(eq. 9)}$$

The remaining investment costs after deduction of the subsidy and the construction cost subsidy are financed by a loan with a term of T=50 years and at an interest rate r of 5 %. The annual operating and maintenance costs OM_t are dependent on the investment costs:

$$OM = 19\ k€ + (1070\ k€ + k_{BHE} \cdot l_{BHE} + k_{PVT} \cdot A_{PVT}) \cdot 0.0209 \qquad \text{(eq. 10)}$$

Earnings due to selling the PV-electricity are not considered and the operating and maintenance costs are kept constant. The electricity price k_{el} used in the calculations is assumed to be 30 ct/kWh. From these generalized assumptions, the Levelized Cost of Heat using the net present value method with the present value $pv = 18{,}3$ is calculated accordingly.

$$LCOH = \frac{(K_{INV} \cdot 0.51 - 1027\ k€ + OM \cdot pv + W_{el} \cdot k_{el} \cdot pv)}{(Q_{HP,cond} \cdot pv)} \qquad \text{(eq. 11)}$$

The resulting heat production costs are shown in figure 10.

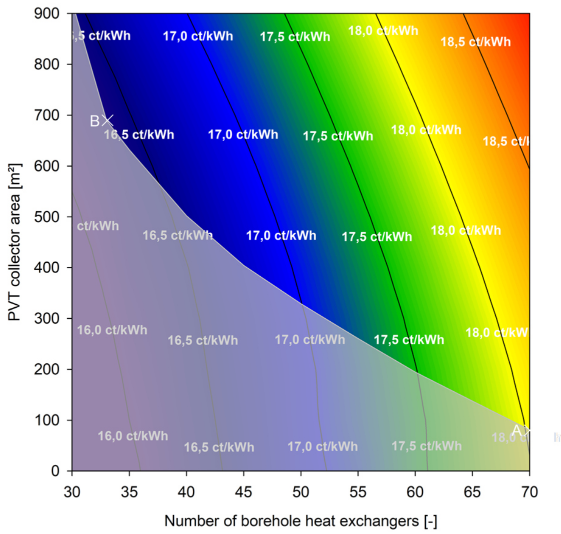

Figure 10: Levelized cost of heat, A: 70 borehole heat exchangers and 80 m² PVT collectors, B: 33 borehole heat exchangers and 690 m² PVT collectors.

The graph shows that solely increasing the PVT collector area is not a profitable option. Thus, for the most favorable number of boreholes, the minimum required collector is always the economically best option. The results show furthermore that variations with a small array of boreholes and a large PVT area are most cost efficient. However, it appears that at about 33 (interpolated) borehole heat exchangers, some sort of tipping point may be reached, beyond which further reduction will drive up the minimum required PVT area such that the Levelized Cost of Heat will be higher. The economically optimal variant is the one with 33 borehole heat exchangers and 690 m² PVT collectors at below 16.4 ct/kWh. At the current state of the planning process, it seems possible to install the optimal 690 m^2 of PVT collectors. If there appears an installation limit for PVT collectors below 690 m^2 in later stages of the planning or construction process it may be necessary to drill more boreholes.

5. Summary

This paper presents a case study for the sustainable, efficient and cost-effective dimensioning of a cold thermal network with borehole heat exchangers and PVT collectors as the source of a heat pump-based district heating concept with 37 multi-family houses. The results of the TRNSYS simulations can be summarized in the following three statements:

- Firstly, small BHE fields with high degrees of regeneration are more efficient than large fields with little regeneration. For the operation of the largest possible BHE field with 70 boreholes at least 80 m^2 of PVT collectors is needed. By using additional 610 m² of PVT panels, the number of boreholes can be reduced by 53 % from 70 to 33, and the 50-year average SPF_{H2+} is simultaneously rising from 3.1 to 3.27.
- Secondly, small numbers of BHE with large areas of PVT result in the lowest long-term cooling of the ground, and thus are the most sustainable option for using the ground as a heat source for district heating systems.
- Lastly, small BHE fields with minimal required regeneration represent the most cost-effective option. The lowest heat production cost of 16.4 ct/kWh is achieved for the variant with 33 boreholes and 690 m² of PVT collectors. Further addition of PVT collectors to increase system efficiency is not cost effective.

This concludes that saving boreholes by using regeneration should always be considered in the planning phase of large renewable heat supply solutions with heat pumps.

6. Acknowledgement

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