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Covering peak loads in district heating networks using ground source heat pumps: potentials and challenges

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Abstract

Decarbonizing the building stock will require a significant increase in district heating, particularly in urban areas. Key challenges for rapid expansion include meeting peak loads with renewable sources and addressing the growing demand for cooling. This project investigates the potentials of decentralized, ground-coupled heat pumps using either geothermal probes or groundwater to address these issues. The simulation-based analysis relies on case studies to derive practical insights for future district heating development.
As demonstrated in former research, e.g. the 'HP-source' project the total length of geothermal probes can be significantly reduced when used solely for peak load rather than full load coverage. In residential buildings, the winter peak load often roughly matches summer cooling demand. In this setup, district heating supplies the winter base load, while ground-coupled heat pumps cover peaks. In summer, the heat pump and the probes cover the cooling demand.
This paper presents interim results, focusing on two case studies, aiming to initiate discussion on the topic. Case study 1 deals with the integration of decentralized borehole fields in a district-heating-and-cooling network currently under development. It focuses on different topologies and considers existing waste heat sources and demand for heating and cooling. Case study 2 is related to the integration of a borehole field into the existing technical infrastructure of a hospital, currently supplied by district heating. Different integration variants, including system sizing and coverage of summer cooling needs, are analysed.

Keywords: district heating; peak load coverage; cooling, borehole heat exchanger; geothermal probes

1. Introduction

District heating networks can significantly contribute to decarbonizing the built environment, especially in densely populated areas. By 2050, their role could nearly triple, reaching 15 TWh in Switzerland. Recent investments in infrastructure emphasize this growth, with technology based on "warm" networks operating around 70°C, which are proven worldwide. However, three main challenges remain: reliance on fossil peak supplies due to capacity constraints, difficulty expanding existing networks when pipes are fully utilized, and the inability to provide increasing cooling demands. The project HP-Source [1] demonstrates that borehole heat exchangers (BHX) are cost-effective for peak load coverage in multi-family houses. The size of BHX needed for peak load coverage can be reduced over-proportionately to the extraction power delivered when compared to a BHX used as the sole source in a heat pump system. The Fig. 1 shows the design graph developed in HP-Source [1] for peak load borefield systems. It illustrates the relationship between the relative BHX length (compared to a monovalent BHX system) and the peak load share of existing multi-family

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buildings. Due to the comparatively small energy extraction from the probes compared to the monovalent system, the ground regenerates almost completely over the summer.

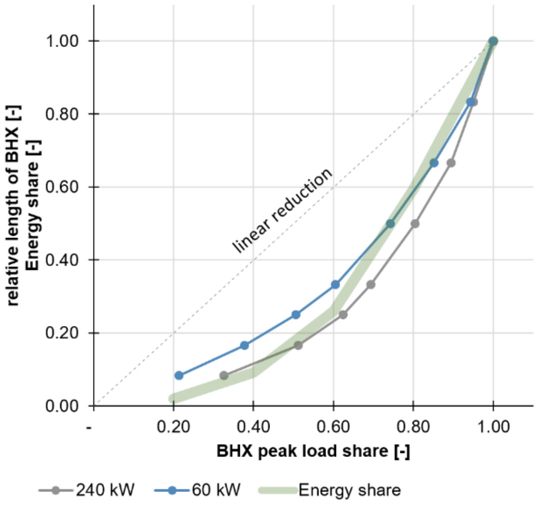

Figure 1. Dimensioning of BHX for peak load coverage of existing multi-family buildings [1]

Decentralised BHX in district heating (DH) systems can address peak demand, reduce infrastructure strain, and provide local cooling, enhancing overall efficiency and sustainability. Fig. 2 shows the cumulative frequency of the heat demand in the district heating network as an example of the opportunities the PeaknCool-concept offers in district heating systems.

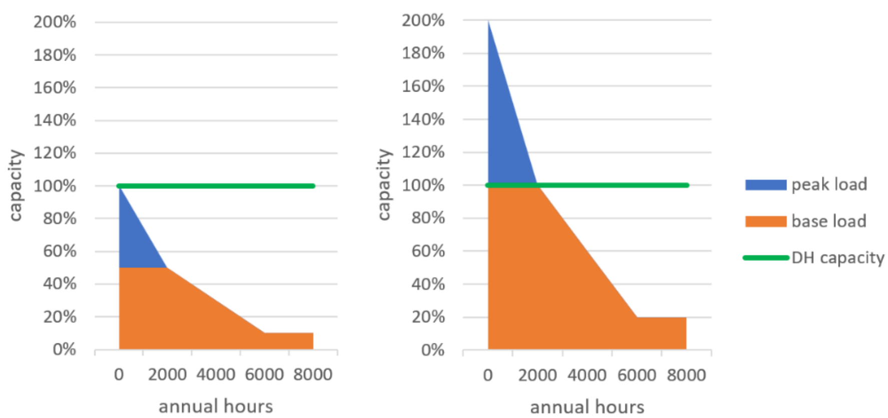

Figure 2. Cumulative frequency of heat demand in the district heating network. On the left: the total capacity is supplied from the district heating network. On the right: 50% of peak load is generated decentrally, directly at the building site. This allows the base load heat amount to be doubled.

Many thermal networks rely on fossil fuels, such as gas or oil, to cover peak loads. The BigStoreDH [2] project assessed the use of thermal storage as an alternative, finding that daily storages are cost-effective for small to medium networks but still require additional heat generators for peak coverage. In large networks, seasonal storage systems that fully meet the winter peak demand can be economically beneficial, though their space requirements cause challenges in the urban environment. Expanding district heating necessitates network upgrades and better utilization of existing heat sources, such as waste incineration, groundwater, or wastewater heat, which are often underused. Studies like IceGrid [3] show that increased peak coverage with ice storage can significantly expand the service area of wastewater treatment plants.

Projected climate change and modern construction will substantially increase building cooling demands, although heat remains dominant in dense areas. A complete transition to a heat supply solely via BHX is not feasible, as excessive heat demand risks ground overcooling. Estimates from DeCarbCH [4] indicate that future cooling needs may reach around 10-20% of future heating demand, with cooling energy playing a subordinate role and often not justifying dedicated low-temperature or “anergy” 5th generation district heating and cooling

networks. Combining cooling with peak heat coverage can balance energy flows for sustainable operation. However, rising cooling needs may lead to clients disconnecting from networks and pursuing individual solutions, thus threatening economic viability.
The investigations are conducted based on real case studies provided by industry partners involved in the project. These case studies serve as a foundation for the simulation analyses. From these, recommendations are derived regarding the sizing and integration of decentralized borehole heat exchanger fields into district heating networks, as well as the calculation of heat and cooling generation costs.

2. “Thusis” case study

The case study "Thusis" focuses on the integration of new ground heat exchangers into the existing technical systems of a hospital. It is currently connected to an existing district heating network which uses wood as an energy source, with a connected load of 260 kW for heat. Domestic hot water preparation is carried out using two heat pumps with a total installed thermal capacity of 142 kW which utilize waste heat from the air conditioning and process cooling (40%), and through direct electric heating (60%). In the summer, not all waste heat can be used, and the remainder is released to the environment via a dry cooler with a capacity of 240 kW at 50/42°C.

The hospital has potential to install around 20 BHX on its premises, these could supply process and climate cooling in summer and source heat in winter to cover peak loadsing mode The base load heat supply is still obtained from the existing district heating network. The main emphasis is on designing the borefield and assessing its contribution towards reducing demand on the district heating network.

2.1. Method

In this case study, technical concepts are developed to combine peak load coverage by ground heat exchangers with district heating for base load supply, considering requirements for cooling use and potential heat feed-in back into the network. These concepts define the specification of the simulation models. Initially, synthetic hourly load profiles are created, based on daily real heat and cold consumption over several years. The synthetic load profiles were generated using standardized weather data [5] and nPro [6].

Simulation studies investigate the integration of the BHX into the existing technical system in the hospital. Key questions are the sizing and contribution of the BHX for peak load coverage and cooling supply. Various integration concepts, ranging von minimal utilization to maximum area usage and network feed-in, will be investigated. Effects of different climate conditions (beyond the alpine location) will be investigated by variation of he load profiles.

The simulation studies will be carried out later in the project using Matlab Simulink and the Carnot-blockset [7]. The dynamic simulation model of the BHX is based on the Huber model [8] with a resistance model for the near field and the g-function for the far field. Initial simulation studies presented in this paper were conducted using the software "EWS" by Huber Energietechnik [9], using the Huber model for the BHX.

2.2. Results

Daily values of heat and cold generation from 2022 to 2024 were analysed, providing the basis for creating artificial load profiles using [6] (Fig. 3), compared to measured data in Table 1.

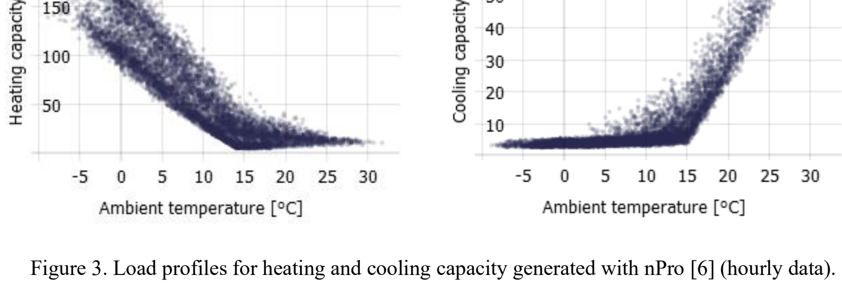

Figure 3. Load profiles for heating and cooling capacity generated with nPro [6] (hourly data).

Table 1. Energy values of the artificial load profile compared to measurement data

	nPro	Measurements		
	Load profiles	2022	2023	2024
Heating energy [MWh]	596	601	576	583
Cooling energy [MWh]	90	95	74	48
Ratio cooling to heating energy	15%	16%	13%	8%

Based on these load profiles, the following integration and sizing variants are examined:

- V1: Minimal solution with few boreholes, dimensioned for cooling demand. In active cooling mode (using the HP to lift the temperature) the numbers of boreholes is defined by the maximum allowed BHX inlet temperature. In passive cooling mode, due to the lower BHX inlet temperature than in active cooling mode, more probes are necessary.
- V2: Boreholes dimensioned for the maximum capacity of the heat pumps.
- V3: Additional regeneration of the borefield by the network using waste heat. This option is not relevant in this case study, as the heat needs to be produced separately at the central plant; however, it may be relevant for networks with waste heat sources (e.g. waste incineration plants).

An initial potential assessment was conducted for the integration concept V2 using the software «EWS» [7], with the artificial load profile and a base load of 130 kW from district heating. The heat demand for heating and domestic hot water was combined, and the base load was subtracted. The missing capacity is supplied by the heat pump. The cooling capacity is also generated by the heat pump.. The heating and cooling capacities required from the heat pump are summed monthly (Fig. 4) and annually (table 2). Peak load and cooling energies are used as input parameters into «EWS». The injection to extraction ratio is around 141 % which means, more waste heat from cooling is injected into the borehole than extracted for heating purpose. The heat produced from simultaneously needed cooling is also subtracted, as it does not appear in the BHX balance

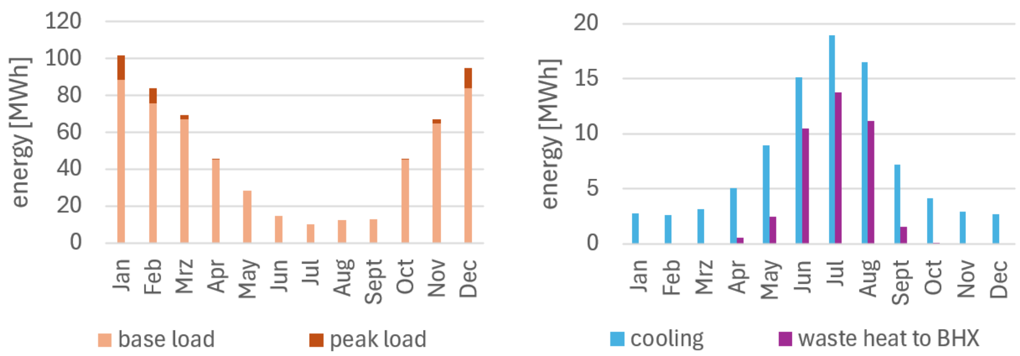

Figure 4. Monthly summarized energy for heating (left) and cooling (right). During winter time, all cooling waste energy can be used to produce heat.

Table 2. Annual sum of the energy input values for «EWS». The capacities and energies relate only to the peak of heat production and the total cooling production, the heating base load is not listed. COP and EER are defined as constant values for the first simulations.

		Heating:	*total load*	*base load*	*peak load*	***Cooling**: total load*
Capacity		kW	257	130	129	67
Annual sum	heating / cooling energy	MWh	587	549	38	90
Full-load hours		h	2284	4223	294	1343
Ratio to total load		%		94%	6%	
COP / EER		-			4	5
Annual sum	BHX balance injection resp. extraction	MWh			28	40
Ratio	BHX injection / extraction	-			141%	

Following soil parameters have been set for the simulations:

- thermal conductivity of backfill: 2 W/(mK)
- soil thermal conductivity: 2.4 W/(mK)
- soil density: 2600 kg/m³
- specific heat capacity of soil: 1000 J/(kgK).

The hospital is situated on a steep slope, facing south east. Below the parking lot is an underground hospital (bunker facility). Therefore, the possible area for drilling boreholes is limited to a narrow strip along the road (red-bordered area, see Fig. 4). In this area, two borefield arrays with seven 200 m deep boreholes are defined. In the «distributed» field, the boreholes are spaced as far apart as possible; in the «compact» field, boreholes are drilled with a minimum 5 m distance between them.

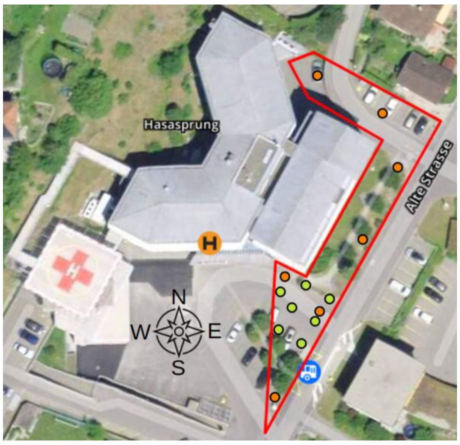

Figure 4. «Distributed» (orange) and «Compact» (green) borefield

Simulations were performed for both fields – with and without a stress test, defined as 2-day continuous operation at the end of February. Fig. 5 shows the fluid temperatures for the «distributed» variant with continuous operation at the end of February. The minimum fluid temperature stabilizes already in the first operational year and does not decrease further. However, if cooling operation is turned off, meaning the borefield is not regenerated, the temperature would decline over 50 years to -4.1 °C instead of -3 °C when cooling operation is activated. This effect is relatively modest compared to monovalent BHX systems, indicating that regeneration has little impact when operated with only a few full-load hours. One possible explanation for this is that due to the relatively low amount of energy extracted from the BHX, that the natural regeneration is sufficient. A clear influence is observed from the stress test involving two days of continuous operation. During this period, the bore temperatures drop significantly. To achieve the same minimum temperature of 1.1 °C in the distributed field as without the stress test, the boreholes would need to be extended from 200 m to 265 m. The «compact» field shows a minimum supply temperature of -5.7 °C for the simulation including the stress test, 2.6 K colder than the «distributed» field. Without the stress test, the difference between the fields is only 0.2 K. The comparison between the two fields, with and without the stress test, demonstrates that the stress test plays a significant role in the design process. During the stress test, the boreholes are subjected to high loads, which can lead to more intense and localized cooling of the surrounding soil in the short term. This effect must be taken into account in the design and will be further investigated in the course of the project.

For comparison, a simulation was performed with a monovalent BHX system, without district heating connection, also with 2 days of continuous operation at the end of February. The cooling is still used directly wherever possible. Nineteen boreholes, each 290 m long (spacing 10 m), are necessary to prevent the minimum entrance temperature from dropping below -3 °C over 50 years. Without bore regeneration via waste heat, the boreholes would need to be drilled to 305 m. The total bore length required for peak load operation amounts to 20% of that needed for a monovalent system.

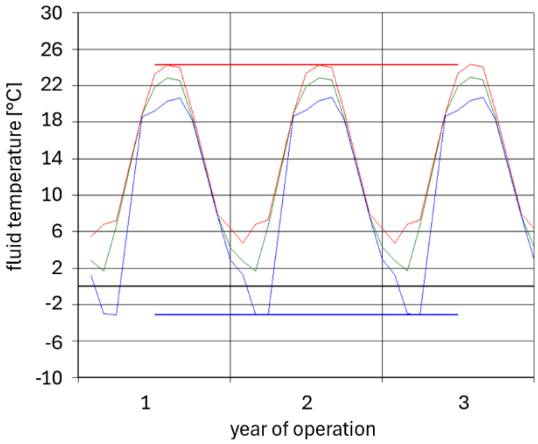

Figure 5. Borehole inlet temperatures (blue), outlet temperatures (red), and average temperature (green) for the distributed field with continuous operation over 2 days at the end of February.

During the summer months, heat is still needed from the DH (District Heating). This is because, in the simplified calculation, the heat pumps only activate when the heating output exceeds the DH connection capacity. This behavior will be optimized in further simulations so that in summer, the heat pumps contribute more to space heating. This makes sense in a DH system running on wood, as it directly saves fuel. However, if waste heat (e.g., from a waste incineration plant) is available, managing the probes as in this initial study may be beneficial.

3. “Wallisellen” case study

The Wallisellen municipal utilities aim to establish a district heating network in their gas supply area, exclusively utilizing renewable energy sources, with wood regarded as exhausted. The initial situation is challenging because little waste heat from industry is available in winter, whereas in summer, a significant amount of waste heat from a nearby waste incineration plant is available. Planning the district heating system on a "greenfield" site allows for testing and implementing new concepts. This case study focuses on the broader integration of decentralized ground source heat exchange fields into a larger district heating network, considering existing waste heat sources for base load and regeneration. The emphasis lies on network analysis and the large-scale subsurface effects, such as the mutual influence of boreholefield clusters. Potential locations for peak load boreholefields are analyzed based on known clusters of waste heat sources (e.g., industrial areas).

3.1. Method

In the case study of Wallisellen, a series of simulations were conducted utilising Polysun software [10]. This program is a planning software for energy systems which applies a time stepping algorithm and dynamically calculates all relevant system parameters. The mathematical model of the geothermal probe was adopted from the EWS program by Huber Energietechnik AG [8]. With this background model, probes are characterised using the g function according to Eskilson.

The heating and cooling requirements for the network development area in Wallisellen were taken from an existing feasibility study (RegEWS, [11]) and converted into high-resolution annual profiles using the nPro tool Klicken oder tippen Sie hier, um Text einzugeben.[6]. These profiles are compared with profiles from an Excel-based tool for dimensioning energy storage created as part of the SwissSTES project [12]. The daily load curves for space heating in the Excel tool were determined using gas data from the city of Zurich. In this tool, the daily distribution of domestic hot water (DHW) and space heating (SH) can be changed using a factor, where 0 is normal, factor 1 is completely smoothed over the day, and -0.5 has even more extreme peaks.

The DHW profile from nPro corresponds very closely to the VDI 6002 [13] profile used in the Excel tool as in Fig.6. In the SH profile, however, the morning peaks from nPro are very pronounced, even more than the Excel tool profile with an amplification factor of -0.5. It can therefore be seen that the profiles automatically generated with nPro show a very high degree of daily fluctuations.

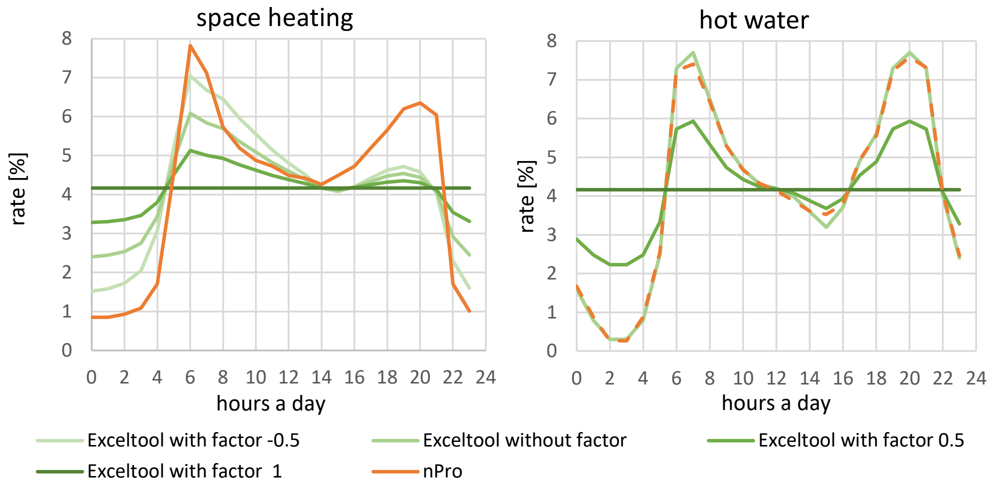

Figure 6. Comparison of the daily distribution of space heating and domestic hot water within the Excel-tool and its different factors, as well as profiles generated with nPro.

The feasibility study developed an innovative concept for supplying heat to the network area, which was adopted here as the basis for integrating decentralised boreholes (see Fig. 7). The concept is based on the use of waste heat from the Hagenholz waste incineration plant (more than 10 MW), which is available in surplus during the summer months at very favourable prices. During the summer months, this waste heat is used directly to cover heating requirements and to regenerate a central BHX with 192 boreholes (240 m deep) to 70 °C. In winter, demand is met by a central HP (up to 10 MW), which uses the BHX or, if outside temperatures are sufficient (at 3°C), outside air as its source. Peak loads are covered in the concept by peak boilers powered by biogas. The cooling demand in the network region is not considered in the RegEWS analysis.

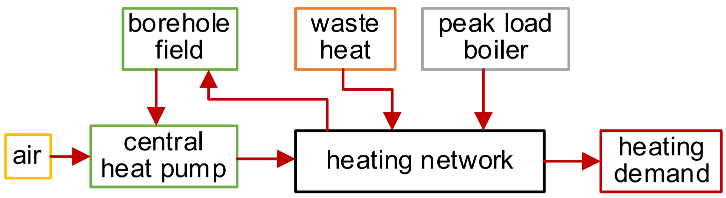

Figure 7: Concept of the heating network from the feasibility study (RegEWS).

In this analysis, the focus is set on different possibilities to integrate the cooling demand into the DH system. A schematic overview of the four different variants simulated can be seen in Fig. 8.

- One possibility proposed is to install decentralized geothermal heat pumps together with BHX close to buildings with a relevant cooling demand. These geothermal systems can then be used not only for climatization, but also be integrated in the thermal grid and substitute peak load burners needed in the original RegEWS system.
- Another possibility is to provide cooling in the network area and to use the central heat pump as chillers and install an additional cooling network for the building with cooling demand. This cooling network would not have to cover the whole network area, as buildings with the major cooling demands (mainly commercial buildings) are mainly located in one area of the network.
- During the analysis of the cooling and heating requirements in Wallisellen, many existing geothermal probes were identified including one large field of 232 BHX connected to a small low temperature DHC network in the “Richti Areal”. These were seen as offering great potential and therefore an additional variant was proposed, which uses existing BHX to provide cooling and heating peaks. In order to connect these BHX systems to the cooling demands, a cooling network is needed for this case. Furthermore, the building which are served by these existing systems have to connect to the network and this heating and cooling demand were added to the network demand profiles for this variant.
- For comparison a variant with the original RegEWS heating network and separated cooling systems cooling system was added.

The main characteristics of the networks heating and cooling demand are given in Table 3 for the original network and including the demand of the buildings with geothermal systems in the network area.

Table 3. Heating and cooling demand and parameters of existing boreholes of the largest decentral borehole fields.

	demand	demand with buildings with existing boreholes
cooling [MWh]	9’016	9’137
power [kW]	7’185	7’341
heating [MWh]	42’419	49’400
power [kW]	16’924	18’757

In order to analyse the potential of decentralised geothermal probes in supporting the DHN during peak load times, dynamic annual simulations were carried out using Polysun software [10]. One simulation template (see Appendix) was used to simulate the four variations by adapting the control strategy and the sizing of different components. The simulation template is based on the following simplifications:

- The heat demand and the heating network were simplified and combined in a sink.
- The integration of cooling into the simulation was achieved through a "multiplier" mechanism, thereby enabling the simulation of either a large central chiller or numerous small decentralised systems.
- The components of the cooling generation are dimensioned, controlled differently depending on the variant.
- As a simplification a number of 5-17 equal, middle sized decentral systems are used to represent a more complicated reality with different decentral systems. Boreholes and heat pump were sized to meet the cooling demand.
- All decentral BHX are supposed to have a length of 240 m length due to depth limitations and a temperature limit of 35°C for the regeneration was induced.
- The number of decentral boreholes as well as the power of the chiller are adapted to the cooling demand resulting in 408 probes for the variant with new geothermal probes.
- For the analysis with existing boreholes, only large systems with more than 20 boreholes (except for the Richti Areal) were considered resulting in a total of 350 BHX.

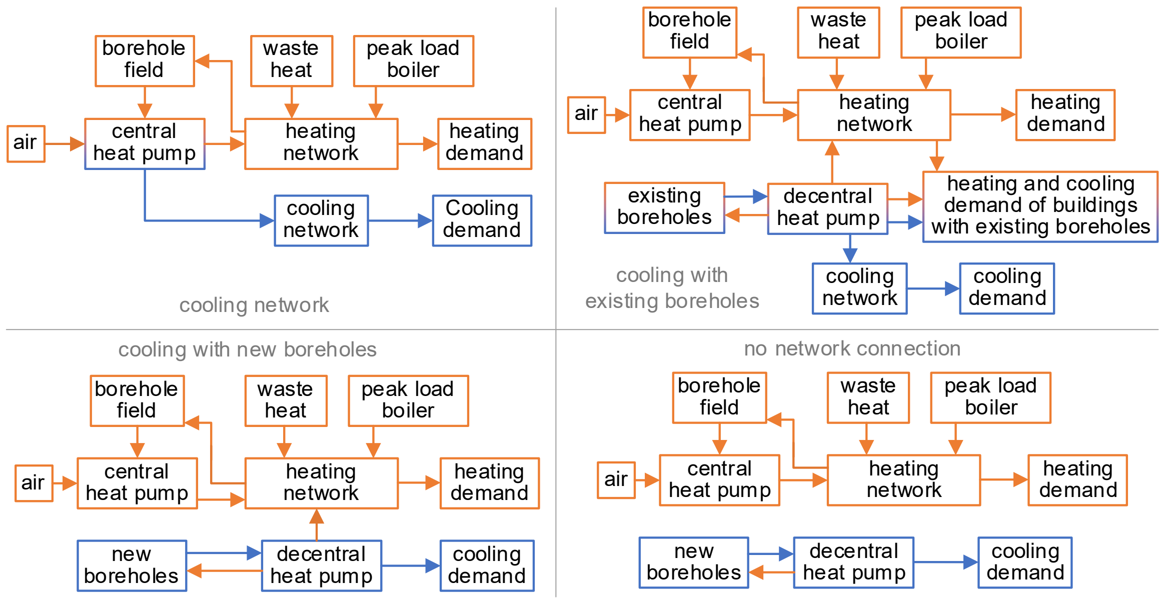

Figure 8. Schematic of the four simulated variations “cooling network”, “cooling with existing boreholes”, “cooling with new boreholes” and “no network connection”.

3.2. Results

Fig. 9 shows the annual heat supply in the DHN from the different sources of all four simulated variations. Only the direct coverage of demand is shown here; regeneration is not shown. The regeneration consists of approximately 19 GWh in summer and comes mainly from waste incineration plant and partly from cooling waste heat in summer for the corresponding variant. The heat imbalance (losses) at the decentral boreholes ranges from 13 % to 33 %. The variant ‘cooling with existing boreholes’ has more energy usage due to the energy coverage of additional buildings with these existing boreholes.

In all variations except ‘cooling network’, waste heat directly covers approximately one third of the energy demand in the summer half-year. The GSHP covers 17 to 24% depending on the variation, and the air source heat pump (ASHP) covers approximately 23 to 39%. If the chiller can feed the waste heat into the grid as in the ‘cooling network’ variant, it can cover around 17% of the heat demand, especially in summer, thereby reducing the proportion of waste heat used from the waste incineration plant. In the variants with decentralised BTES, the heat from the decentralised HP/chiller can cover around 30% of the demand. These decentralised HP also lead to a reduction in gas consumption from around 8% in the ‘no network connection’ and ‘cooling network’ variants to just around 1%.

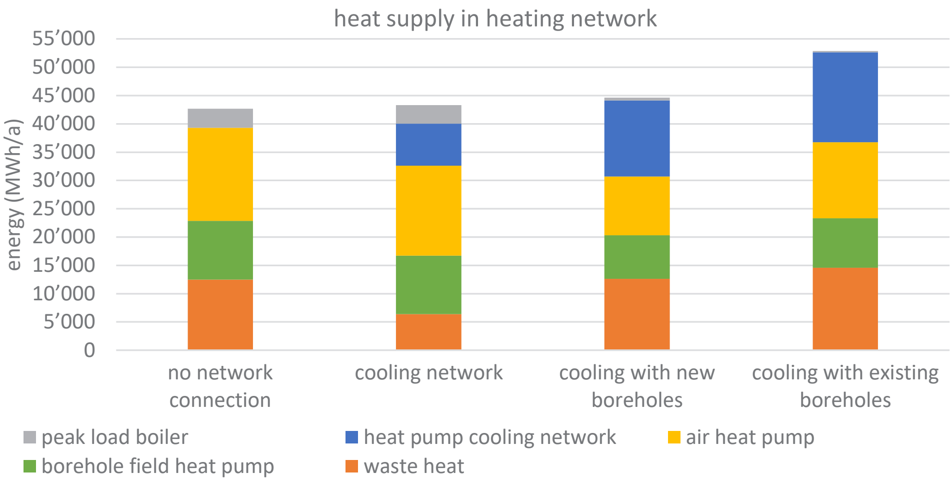

Figure 9. Annual heat supply in the heating network for the different variants and different energy sources without regeneration.

The reduction in gas consumption is visible in Fig. 10 as well. There, the heat generation of the different sources in the course of one year is shown. The waste heat covers the demand in summer (the regeneration of the central borehole fields is not displayed) and in winter the heat gets generated by air and borehole HP (the central HP) as well as the cooling network HP, which is replacing almost all of the peak load and some of the central HP.

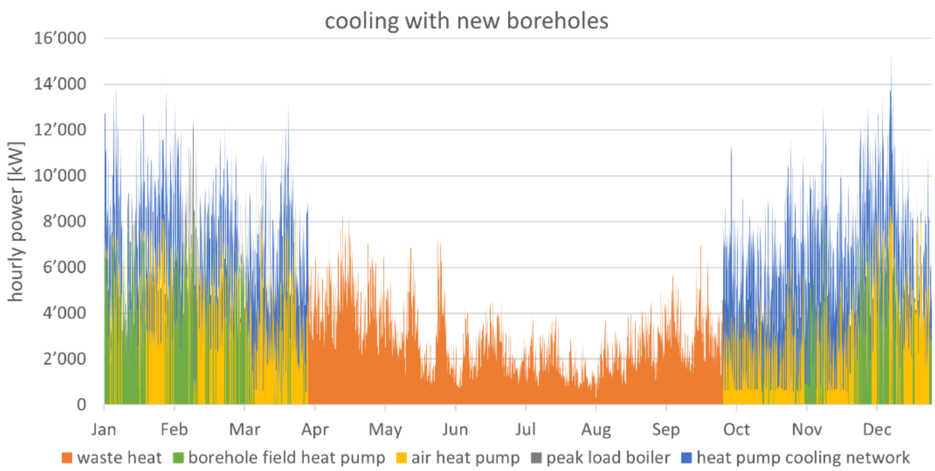

Figure 10: hourly heat generation over a year (without Regeneration of central borehole field) from the different heat sources of the variant ‘cooling with new boreholes’.

This evaluation of the annual energy balance shows that decentralised cooling with HP, chillers and boreholes can also contribute significantly to peak load coverage. With the ‘PeakNCool’ concept for covering the existing cooling demand in the grid area, the share of the peak load boiler can be reduced from approx. 8% to approx. 1%. These initial simulations demonstrate the energy potential of the approach. The numerous geothermal probes already existing in the grid area could, if necessary, be connected to the grid and operated as ‘PeakNCool’ systems.

4. Conclusion and Discussion

The Thusis-Study shows, that a significant reduction of boreholes can be achieved if only used for peak load covering. The effect of regeneration, although the injected energy is higher than the extracted energy, is almost negligible. However, a significant influence is observed from the arrangement (compact vs. distributed) and the stress test. The compact field experiences higher cooling than the distributed field, as the boreholes mutually influence each other, while regeneration has only a limited effect. It is, however, assumed that larger fields, especially in confined spaces where boreholes spacing is limited, will be more affected by regeneration impacts. These effects will be further examined through parametric simulation studies in the course of the project. Additionally, the influence of the stress test on the dimensioning will be analyzed in more detail, and strategies will be developed to manage extended periods of maximum heat demand.

In the Wallisellen case study, it was demonstrated that decentralised heat pumps for cooling can significantly reduce peak fuel demand. A survey of existing large-scale GSHP systems indicates that there are already sufficient decentralised boreholes to cover most winter peak loads when interconnected within a thermal grid and operated with appropriately sized heat pumps. Depending on the cooling concept, the heat rejection temperature can be increased for BHX field regeneration or reach up to 70 °C when rejecting heat into the network, which results in a substantial reduction in chiller efficiency. Further analysis will address the trade-off between chiller efficiency, an optimized sizing of the components and their integration and operation and compare economic key performance indicators.

Acknowledgements

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Appendix

1. heat generation (borehole HP), 10 MW
   central borehole field
2. waste heat, 10 MW
3. heat generation (air HP), 10 MW
4. peak load boiler
5. heat demand
6. cooling system (HP cooling network), ~10 MW
   decentral boreholes
7. cooling demand

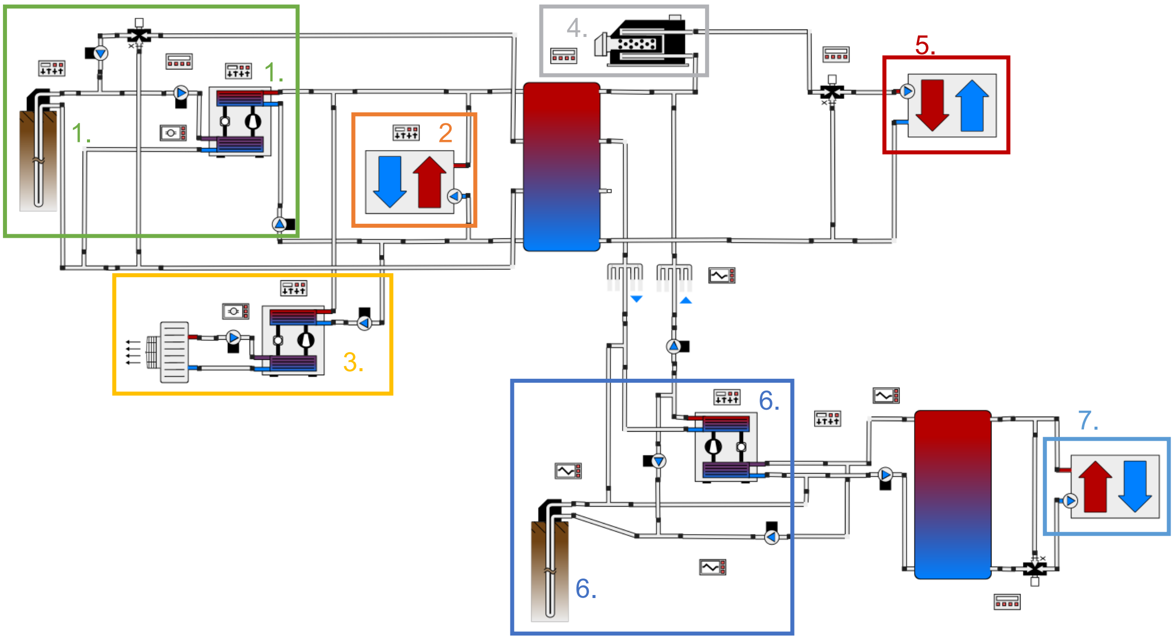

Figure 11: Diagram of the heating network above and the cooling network below in the ‘existing boreholes’ variation.