D4.5 – Helsingborg Energy Centre design

Renewable and Waste Heat Recovery for Competitive District Heating and
Cooling Networks

REWARDHeat

Project Title: Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks

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List of acronyms

API	Application Programming Interface
BTES	Borehole Thermal Energy Storage
COP	Coefficient of Performance
DH	District Heating
DHC	District Heating and Cooling
DHW	Domestic Hot Water
EED	Earth Energy Designer
GHE	Ground Heat Exchanger
GSHP	Ground Source Heat Pump
HP	Heat Pump
HX	Heat Exchanger
PLC	Programmable Logic Controller
PV	Photovoltaic
SC	Space Cooling
SCADA	Supervisory Control and Data Acquisition
SCOP	Seasonal Coefficient of Performance
SH	Space Heating
TES	Thermal Energy Storage
TRT	Thermal Response Test

1 Introduction

Integrating heat pumps (HPs) and thermal storage tanks into district heating and cooling (DHC) systems enhances thermal regulation at substations. Heat pumps elevate low-grade thermal energy from the district heating (DH) network to higher temperatures required for domestic hot water (DHW) and space heating (SH) [1] [2], improving system efficiency and reducing thermal losses [3]. Thermal storage tanks ensure on-demand heat availability, bolstering system reliability and stability.

Advanced monitoring and control systems optimize substation performance by dynamically adjusting operations to match real-time demand, thereby enhancing energy efficiency, reliability, cost-effectiveness, and sustainability [4] [5]. Rigorous performance analysis of substations, focusing on operational stability, efficiency, and energy loss identification, is essential for identifying energy-saving potentials and informing system upgrades and maintenance strategies [6].

A major obstacle to developing a comprehensive energy assessment for real DH substations is the lack of detailed system information and the use of limited sensors solely for system control. Energy disaggregation, which involves breaking down total energy consumption into the consumption of individual components, offers a more detailed understanding of energy use characteristics. This approach allows for a more accurate assessment of the energy performance of the substations [7].

This report provides a descriptive analysis of the Energy Centre set up at the Drottninghög neighbourhood in Helsingborg, focused on defining standardised HP packages adapted to be connected to DH networks. This report offers a comprehensive overview of the design principles, components, and operating conditions, including heat generation, distribution, and regulation.

To introduce the demo site, we first outline the overarching objectives of the construction project. Following, we provide a general overview of the Energy Centre and its role in meeting the demands for DHW, SH, and SC for end-users, along with an explanation of its main components and control system. We then delve into the operational principles of the Energy Centre.

2 Description of demo case

2.1 Construction project

Tornet specializes in the construction and management of rental properties, with a strong commitment to energy efficiency, responsible material utilization, and sustainable product choices. Their latest initiative focuses on developing affordable rental apartments within multifamily houses in Helsingborg, a city in Sweden experiencing a significant shortage of available homes. The primary objective of this project is to provide economical housing solutions for individuals with limited incomes in the Drottninghög neighborhood.

Figure 1 illustrates the initial state of the building blocks, offering insights into the construction project. The images provide a visual representation of the efforts in the building block. Moreover, the surrounding area, known as Infanteriet, is undergoing transformation to accommodate new offices, garages, and gardens. This holistic approach reflects Tornet’s commitment not only to housing development but also to the overall enhancement of the urban environment.

The following sections will delve into specific aspects of the project, detailing the strategies employed for energy efficiency, resource utilization, and sustainable construction practices.

Figure 1. Building blocks before implementation of construction project (Left) and render of newly constructed blocks post-implementation (Right)

The Infanteriet neighborhood (Figure 2) comprises two 5-story and two 7-story buildings, with a total heated floor area of 7,795 m^2, included in a communal yard. This yard is equipped with amenities such as bicycle parking, a playground, and patios designated for the ground-floor apartments. Adjacent to the eastern side of the building blocks, a park is slated for development, establishing a connection to a more extensive park area situated to the north. This layout ensures a thoughtfully designed and integrated living space with a focus on both residential comfort and community amenities.

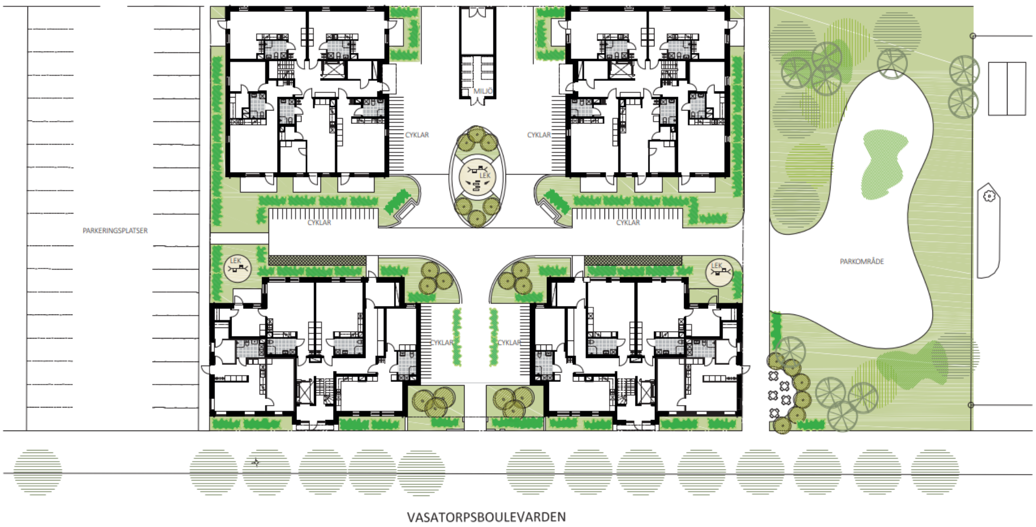


Figure 2. Layout of the construction project

The collaborative project involves two key partners: ARVALLA, overseeing construction management, and INDEPRO, tasked with strategic planning. The project aims to achieve the following objectives:

- Installation of a standardized substation: streamlining construction processes through the deployment of standardized substations.
- Integration of a geothermal HP in the substation aimed to minimise the import of energy from the district heating network.
- Integration of diffuse PV-Thermal (PVT) hybrid panels, reducing electricity consumption from the grid and charging the boreholes field in summer.
- Smart monitoring and control implementation:
    1. Integrating state-of-the-art smart monitoring and control hardware and software.
    2. Selecting the most effective way of sourcing heat for the buildings - between the DH system and the borehole field- according to actual electric and thermal energy prices.

The outlined goals reflect a comprehensive approach to construction and energy supply.

2.2 Energy Centre configuration

The Tornet Energy Centre consists of a thermal substation and a low-temperature network designed to cover the demands for DHW, SH, and SC. It is designed to supply heat using a DH system and a HP. Additionally, the plant is equipped with hybrid PVT modules installed on the roofs of the buildings, contributing to a partial provision of heat and electricity to the energy system. A field of borehole thermal energy storage (BTES) is also coupled to the HP to cover SC and heat demands.

Figure 3 shows the layout of the Energy Centre including HXs, valves, piping, heat and flow meters, temperature sensors, pumps, storage tanks, HP and BTES.

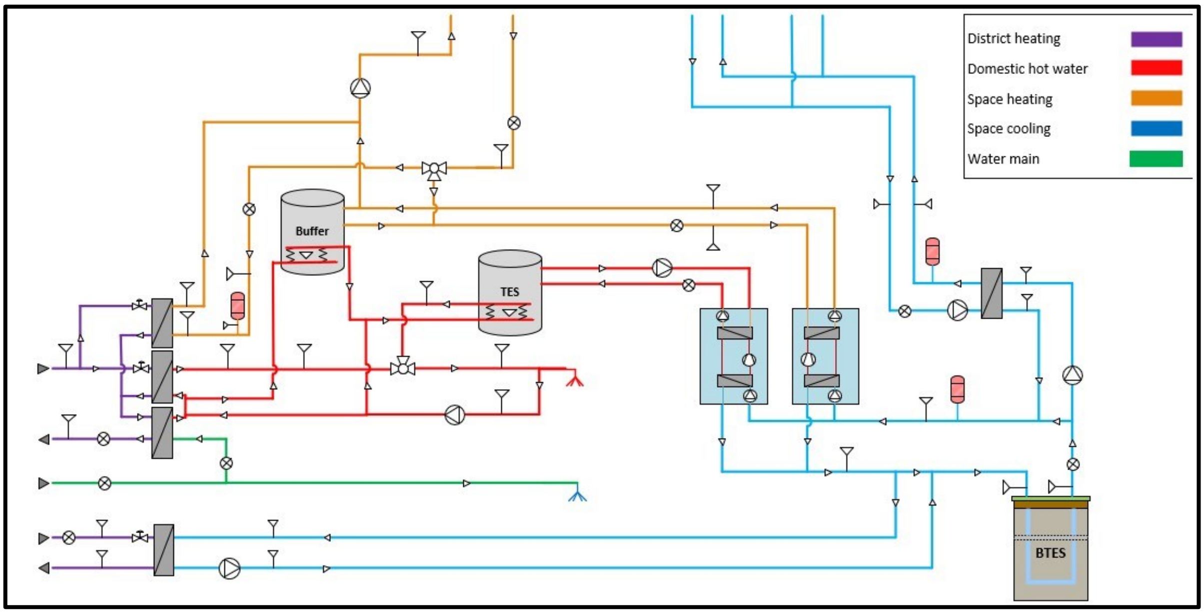


Figure 3. Layout of the Tornet Energy Centre in Helsingborg

The energy system integrates with the DH network (depicted by purple lines) via two counter-flow HXs: one dual-stage HX to meet DHW demands (shown by red lines) and one for SH demands (depicted by orange lines). The dual-stage HX is represented by two separate HXs to show how water undergoes preheating and further heating. The DHW system is modelled as a lumped hot water tap for the entire building blocks. Similarly, the SH system is represented by a single user.

There are two identical hot water storage tanks each with a capacity of 750 L: a high-temperature tank (TES) dedicated to meeting DHW demand, and a low-temperature tank (Buffer) used for SH and preheating the high-temperature tank. These tanks are utilized to address the heat demand for DHW and SH in winter. During heating season, a combination of ground heat exchangers in boreholes and a ground source heat pump (GSHP) are deployed, supplemented by the DH network. Since the HP features a two-stage compressor, it is represented as two separate HPs for clarification. The ground acts as a thermal reservoir, maintaining a relatively stable and higher temperature compared to the ambient air. This configuration is expected to enhance the seasonal coefficient of performance (SCOP) of the HP, targeting an average SCOP of 3, which is superior to conventional air-to-water HPs.

However, continuous heat extraction from the boreholes poses a risk of reducing the ground temperature, which could decrease the SCOP and increase power consumption over time. To mitigate this potential issue, a recharging strategy for the geothermal installation is devised to operate during non-winter periods. To optimize the system’s efficiency and maintain the borehole temperature within acceptable limits, hybrid PVT panels are employed to capture solar energy. This thermal energy contributes to recharging the BTES system, is upgraded by the HP, and is stored in buffer and TES tanks for SH and DHW applications. The connection between the BTES and PVT systems, while not depicted in the simplified illustration, plays a crucial role in maintaining the thermal balance and enhancing overall system efficiency.

During summer, the BTES system is reversed and functions as a reliable heat sink to meet the SC demand (represented by blue lines). The heat rejected from the SC system is redirected to the ground, aiming to achieve free cooling. The primary challenge lies in balancing free cooling and recharging the BTES through PVT panels within summer timeframe. Alternatively, the exhausted heat from the SC system can be upgraded by the HP for DHW or simultaneous SH demands.

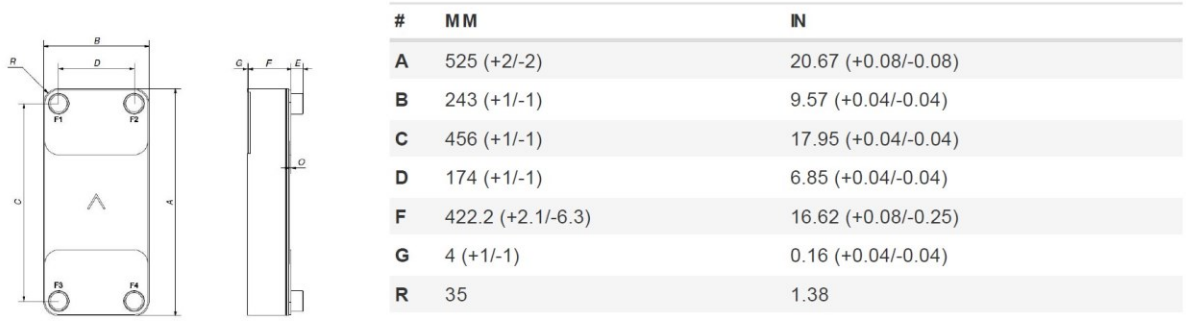
The HX at the bottom left of the layout connects the DH network to the BTES system. This setup effectively bridges the temporal gap between heat supply and demand, allowing for the storage of heat during summer and its retrieval during winter when the demand for heat increases. As mentioned, the BTES system can be also used to store the heat from hybrid PVT panels during summer, improving the electricity production efficiency of panels by reducing the panels' temperature using the ground thermal capacity. Although the connection between the DH network and BTES system is currently non-operational due to regulatory restrictions, one of the study objectives on the Tornet Energy Centre is to demonstrate the advantages of BTES coupled with DH in terms of primary energy consumption and cost savings.

The following subsections elucidate further details of the main components and control system of this thermal energy system.

2.3 Heat exchangers

The SWEP B120THx180/1P heat exchanger [8], designed for efficient heat transfer, features 180 plates made of 316/316L stainless steel with copper brazing. The unit's dimensions are 52 mm x 24 mm x 45 mm with the heat transfer area of 23.5 m^2 and a hold-up volume of 21.4 dm^3 on circuit 1 and 21.6 dm^3 on circuit 2. The HX operates with a maximum heat load of 130 kW. It supports a counter-current flow direction, which enhances heat transfer efficiency.

The thermal length is 2.9 on side 1 and 1.6 on side 2. The mean temperature difference between the fluids is 4.4 K and the overall heat transfer coefficient is 1260 W/(m^2.°C). The pressure drop across the heat exchanger is 6.9 kPa on side 1 and 13.9 kPa on side 2. The connections are 2" ISO-G ports. The dimensions of the unit are illustrated in Figure 4.



#	MM	IN
A	525 (+2/-2)	20.67 (+0.08/-0.08)
B	243 (+1/-1)	9.57 (+0.04/-0.04)
C	456 (+1/-1)	17.95 (+0.04/-0.04)
D	174 (+1/-1)	6.85 (+0.04/-0.04)
F	422.2 (+2.1/-6.3)	16.62 (+0.08/-0.25)
G	4 (+1/-1)	0.16 (+0.04/-0.04)
R	35	1.38

Figure 4. SWEP B120THx180/1P heat exchanger with connections and dimensions

2.4 Dual-stage heat pump

The Thermia Mega XL [9] is a commercial HP designed for maximum performance and economy. It features an inverter-controlled two-stage compressor with a power range from 21 kW to 88 kW. The Mega XL uses R410A refrigerant with a Global Warming Potential of 2088. Two levels of operation allow for more efficient energy use and better comfort control because the HP can adjust more precisely to temperature demands, leading to less electricity use. The HP has a nominal heating output of 79 kW under average climate conditions and a SCOP of 4.13.

2.5 Geothermal system: Layout and schematic

As illustrated in Figure 6, the Tornet Energy Centre incorporates a closed-loop shallow geothermal system. The borehole filed, nearly rectangular and measuring 22 m by 24 m, consists of 12 U-tube ground heat exchangers (GHEs), each with a depth of 200 m and spaced 9 m apart. The boreholes are designed to continuously deliver 60 kW of thermal energy.

Based on the results from a Thermal Response Test (TRT) and simulations conducted using the Earth Energy Designer (EED) software (detailed in the Appendix), the continuous heat flux of each borehole has been calculated to be 25 W/m, with the potential to reach up to 75 W/m during peak demand. This design ensures efficient thermal energy extraction and storage, contributing to the overall energy performance and sustainability of the Energy Centre.

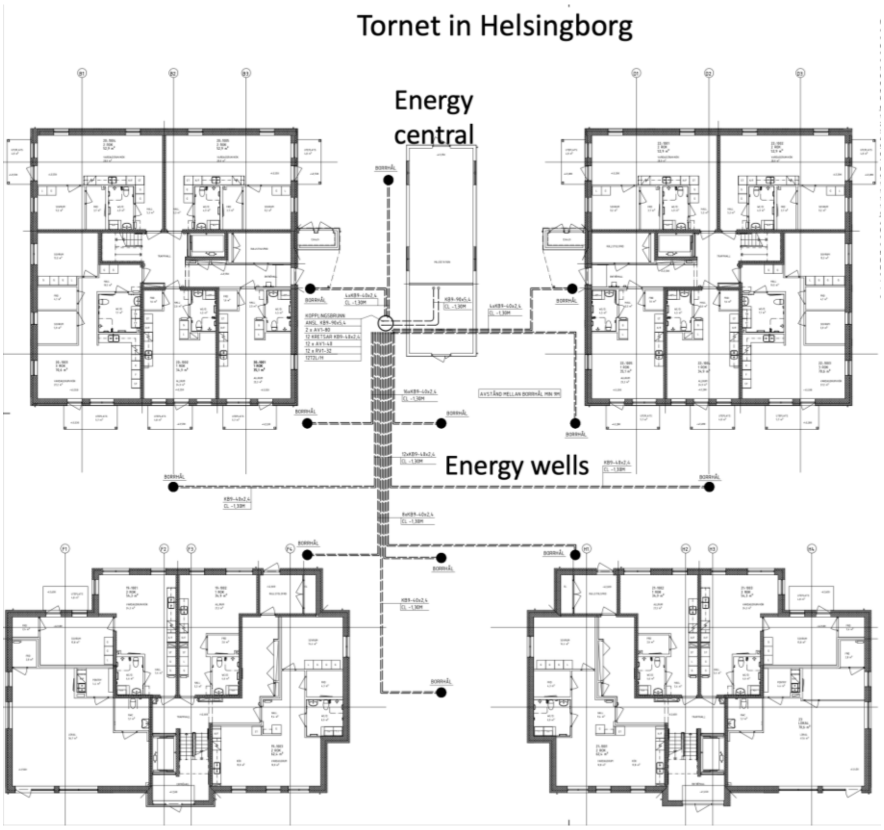
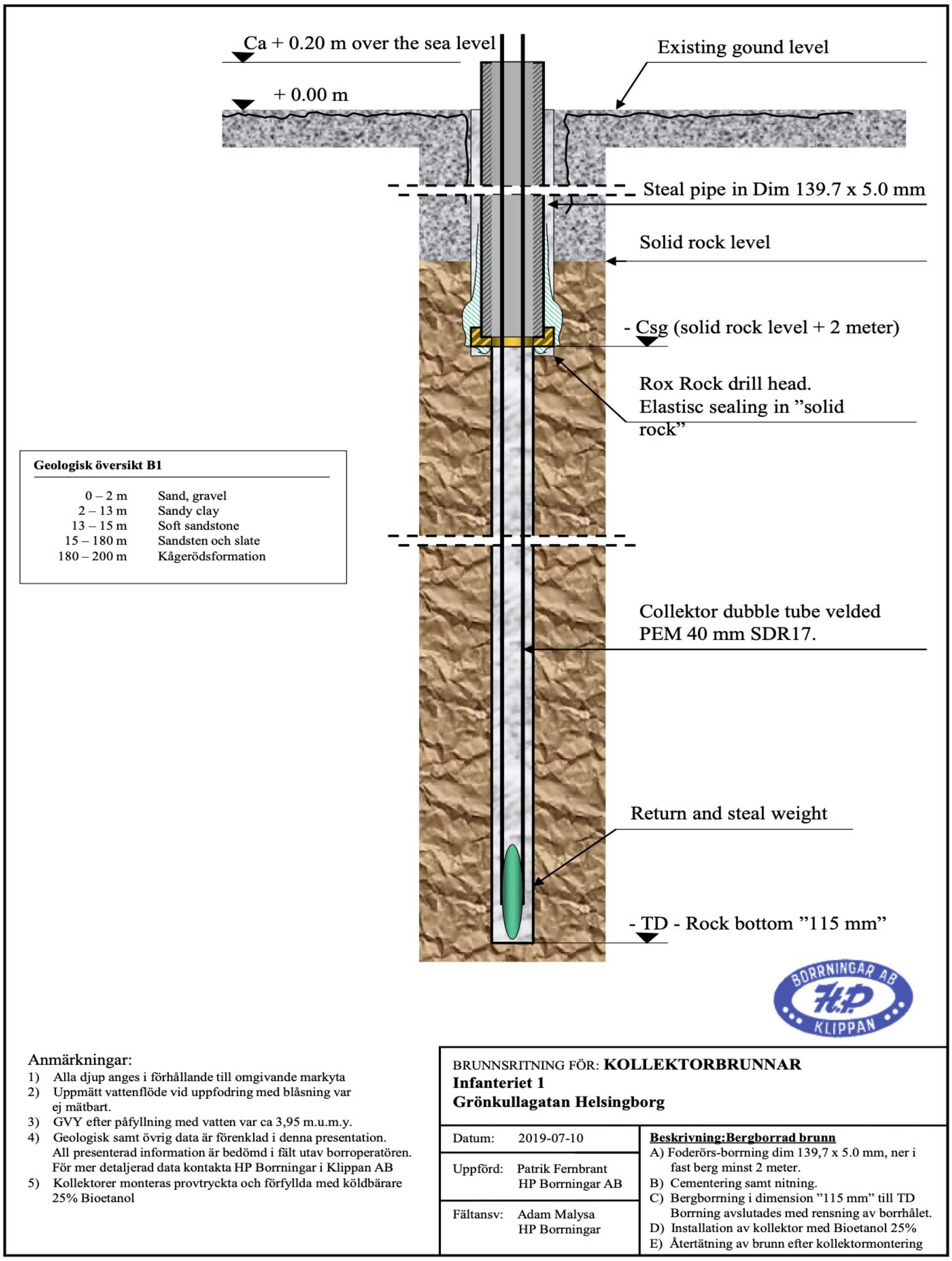


Figure 5. Layout of the borehole field in the Energy Centre

Figure 7 illustrates the drilling view of a U-tube heat exchanger situated within a borehole. This diagram is informed by comprehensive field exploration and local hydrogeological data, providing a detailed account of the material composition and depth of each geological layer. The GHE employs a coaxial structure, with water serving as the circulating refrigerant.

Heat transfer within the borehole encompasses several processes: convection due to the refrigerant flowing downward through the annulus and upward in the inner pipe, conduction between the refrigerant in the inner and annular pipes, as well as between the grout filling and the coaxial tube. Outside the borehole, the heat transfer process includes convection and thermal dispersion from groundwater seepage, and conduction through the surrounding strata.



Geologisk översikt B1

0 – 2 m	Sand, gravel
2 – 13 m	Sandy clay
13 – 15 m	Soft sandstone
15 – 180 m	Sandsten och slate
180 – 200 m	Kågerödsformation

Anmärkningar:

1) Alla djup anges i förhållande till omgivande markyta
2) Uppmätt vattenflöde vid uppfodring med blåsning var ej mätbart.
3) GVY efter påfyllning med vatten var ca 3,95 m.u.m.y.
4) Geologisk samt övrig data är förenklad i denna presentation. All presenterad information är bedömd i fält utav borroperatören. För mer detaljerad data kontakta HP Borrningar i Klippan AB
5) Kollektorer monteras provtryckta och förfyllda med köldbärare 25% Bioetanol

BRUNNSRITNING FÖR: **KOLLEKTORBRUNNAR**
Infanteriet 1
Grönkullagatan Helsingborg

Datum: 2019-07-10

Uppförd: Patrik Fernbrant
HP Borrningar AB

Fältansv: Adam Malysa
HP Borrningar

Beskrivning:Bergborrad brunn

A) Foderörs-borrning dim 139,7 x 5.0 mm, ner i fast berg minst 2 meter.
B) Cementering samt nitning.
C) Bergborrning i dimension ”115 mm” till TD Borrning avslutades med rensning av borrhålet.
D) Installation av kollektor med Bioetanol 25%
E) Återtätning av brunn efter kollektormontering

Figure 6. Schematic of the U-tube borehole heat exchanger and existing ground layers

2.6 Hybrid PVT panels

The Samster KALL SOLHYBRID 395W [10] is a high-performance hybrid solar panel with a thermal collector on the back. It delivers up to 20% more electrical output than a standard solar panel and increases the efficiency of heat pump systems. The panel provides thermal energy year-round, heating cold boreholes and borehole storage systems.

Key specifications of this module include a fluid volume of 1.5 L, using propylene glycol as the fluid, with a maximum operating temperature of 40 °C and a maximum operating pressure of 10 bar.

The pressure drop per panel is 20 kPa at a flow rate of 0.03 L/s. The thermal collector is connected hydraulically via a 12 mm connection. Overall, 60 panels, each covering an area of 1.95 m^2, are mounted on the building roofs.

2.7 Control system

The monitoring and control system of the Energy Centre is pivotal in ensuring the efficient, reliable, and safe operation of the heating network. By precisely managing the flow and temperature of the heating water, the control system optimizes energy use, enhances system reliability, and improves user comfort. The following subsections provide descriptions of the hardware and software components of the control system.

2.7.1 Hardware components

The hardware components of the Energy Centre's control system include sensors that measure parameters such as temperature and flow rates. These sensors provide real-time data to programmable logic controllers (PLCs), which execute control algorithms to maintain desired setpoints. The data collected primarily consists of temperature, flow rates, and energy at a frequency of 5 minutes.

Communication devices, both wired and wireless, enable data transmission between the substation and central monitoring stations. Additionally, a supervisory control and data acquisition (SCADA) system facilitates data acquisition, monitoring, and analysis.

The following list details the equipment of the Tornet Energy Centre's control system:

- Temperature sensors located at the supply and return of the DH network, outflow and inflow of BTES, HP, hot water storage tanks, and HXs to control and monitor the temperature distribution in the entire system.
- Flow meters located at the water main's entrance, supply and return of the DH network, outlet and inlet of BTES, HP, hot water storage tanks, and HXs to control the DHW, SH and SC demands.
- Variable speed pumps to meet the heating load and three-way valves located at the DHW loop, SH network (secondary side), and the BTES loop.
- Expansion vessels located at the flow from BTES to HP and SH network (secondary side) to maintain the pressure within an acceptable range.

In addition to the above components, heat meters—comprising two temperature sensors and a flow meter—are deployed. The specific locations of these meters are detailed in Subsections 3.1 to 3.4. While the inclusion of this equipment is generally sufficient for fault detection and issue diagnosis within the substation, there are notable gaps in the data required for a comprehensive analysis of its energy performance.

Specifically, the electricity consumption of individual circulation pumps and HP compressors is not recorded, nor is the cumulative electricity consumption of the substation. Furthermore, the DHW circuit lacks both a temperature sensor to measure the main water temperature and a flow meter to monitor the recirculation flow rate. Additionally, the BTES system is devoid of flow meters necessary for monitoring groundwater velocity.

2.7.2 Software component

The software component incorporates control algorithms designed for fault detection and diagnostics, which optimize performance and efficiency by adjusting system parameters based on real-time monitoring data. FastAPI [11], a modern web framework for building Application Programming Interfaces (APIs) with Python, is employed to develop web applications that interact seamlessly with the control system. This integration ensures precise control and monitoring of the DH substation, thereby enhancing energy efficiency, system reliability, and user comfort.

3 Operational schemes

To gain a comprehensive understanding of the operations within the thermal energy system, we systematically disaggregated it into smaller operational schemes, each designed with focused, lower-level objectives. These schemes were then grouped based on their shared objectives. This method of disaggregation allows for a clearer comprehension of the system's overall functionality, thereby enhancing the clarity of our analysis. The following subsections detail these operational schemes and describe the heat meters' allocation.

3.1 DHW provision using DH and HP

The primary objective of this scheme is to ensure the supply and recirculation of DHW. Figure 8 features a direct system, meaning there is no water tank; all heat demand must be met instantaneously using DH and its corresponding two-stage HX. This sub-scheme integrates hydraulic separation of the buildings' circuit from the network through this HX. This separation protects the buildings facilities from potential leakage from the DH network and reduces maintenance issues. In this configuration, the water from the DH system heats the domestic cold water via the HX. The DHW is then distributed to various taps in the buildings through the substation and a recirculation circuit.

Figure 9, on the other hand, employs buffer and TES tanks to supply DHW. The heat stored in these tanks is provided by two HPs on their condenser sides. By storing DHW in the tanks, demand variations can be balanced, and peak demands can be reduced. However, storing hot water increases the risk of Legionella growth, necessitating a higher temperature than required for instant DHW heating.

In DHW provision using DH, the integration of two temperature sensors, which measure the supply and return temperatures to/from the hot tap water, and a flow meter, functioning as a heat meter, facilitates the calculation of heat flux on the primary side of the district heating's HX. Additionally, the flow meter on the water main, combined with the temperature readings of the water main and the delivered DHW, contributes to the energy analysis of the secondary side of the HX.

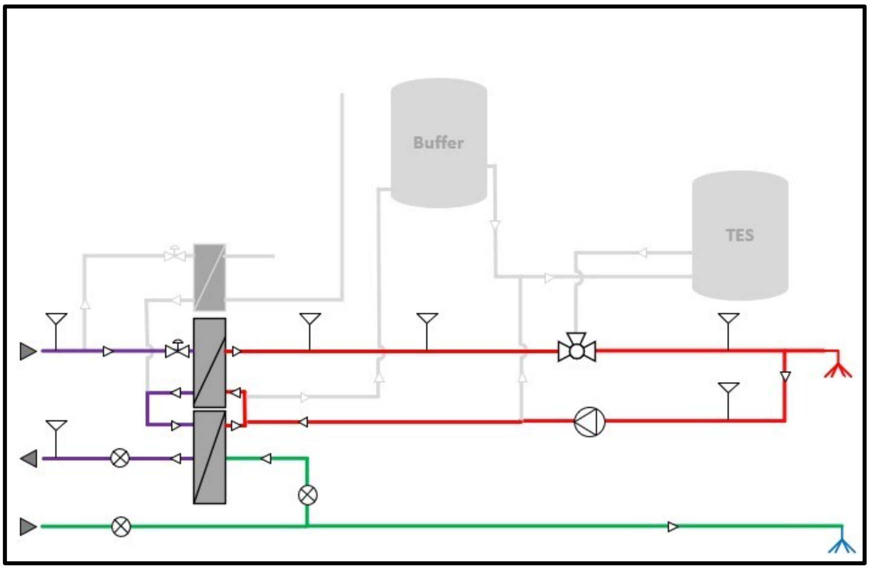


Figure 7. Supply of domestic hot water and recirculation using district heating system

As shown in Figure 9, the DHW is provided using the heat stored in buffer and TES tanks, which are charged by the HP. The calculation of the output heat flux to DHW in this sub-scheme follows a similar approach to that employed in the previous sub-scheme. The switch between these two sub-schemes depends on the balance between DH and electricity prices. During the summer, when DH is cheaper, the former is operative. In the cold season, priority is given to HP due to the lower electricity price compared to DH, resulting in the operation of the latter.

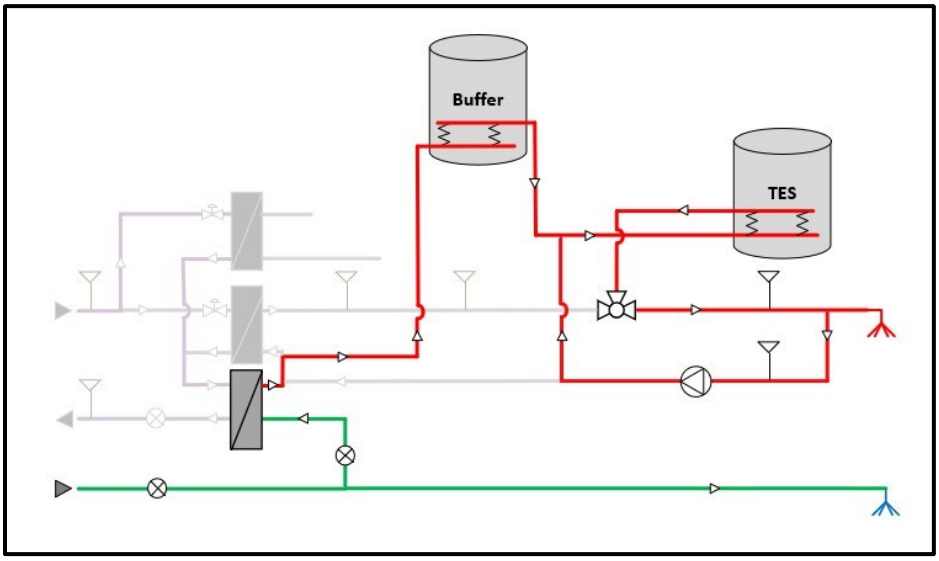


Figure 8. Supply of domestic hot water and recirculation using the Buffer and TES

3.2 BTES exploitation for SC and/or charging TES

The overall objective of this scheme is to utilize BTES and HP to provide SC and/or to charge TES for DHW applications. The first sub-scheme (illustrated in Figure 10) is specifically designed to deliver SC by exploiting the stable, cool temperatures found at certain ground depths, which remain unaffected by seasonal variations. The elevated return temperature from the cooling unit is directed to the HP's evaporator, which subsequently charges the TES. This setup, when combined with a storage tank, allows for a more efficient heat transfer process, minimizing the energy required to elevate the water to the desired DHW temperature and enhancing the operational efficiency of the HP.

Key components in this sub-scheme include the HP, BTES, and HX. The input and output heat flux from the HP are essential parameters. On the HP's condenser side, in addition to the dedicated flow meter, two temperature sensors installed in the HP unit are required for the calculation of the heat flux to the TES. Moreover, the heat flux on the primary side of the HX can be calculated using the dedicated two temperature sensors and the flow meter. Similarly, the heat flux to the BTES is computed utilizing the two installed temperature sensors and the flow meter. To determine the heat flux into the evaporator, temperature sensors positioned before and after the HP's evaporator, along with the flow meter in the circuit, are employed.

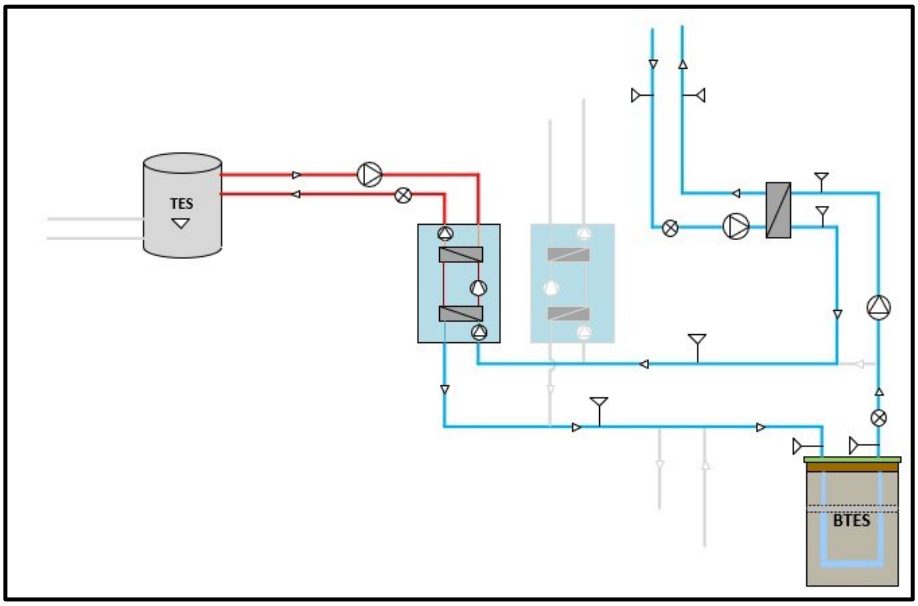


Figure 9. Space cooling and charging the thermal energy storage using the heat pump and borehole field

Figure 11 depicts the second sub-scheme which is specifically designed to charge the TES for DHW application. To optimize cost savings, the activation of the HP is scheduled to happen during the cold season when electricity rates are typically lower than the DH prices. The implementation of a smart control system is crucial in this context. This system intelligently switches between the DH and HP based on real-time factors such as demand, temperature conditions, and energy costs. This dynamic control mechanism ensures efficient operation and maximizes the benefits of both heating methods.

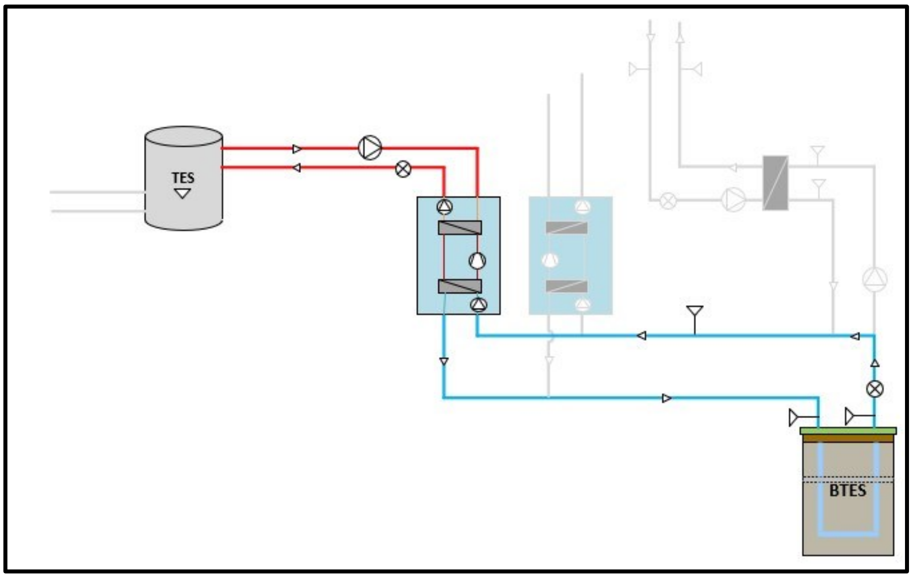


Figure 10. Charging the thermal energy storage using the borehole field and heat pump

Figure 12 illustrates the process during the warmer months. When the ground is cooler than the ambient air, the borehole field provides heat transfer at a relatively stable temperature, typically around 10 to 15 °C. During this period, the HP can be bypassed, and the heat exchange fluid circulates through the ground via the BTES system.

This process collects heat from the building and deposits it into the ground for extraction in the next winter. Known as free cooling, this method contrasts with conventional cooling through chillers or reversible heat pumps, and results in substantial cost savings. However, several critical factors such as the quantity and arrangement of boreholes, the choice of heat exchange fluid, control strategies, and the thermal properties of the ground. By addressing these considerations, the free cooling system can achieve high efficiency and substantial cost savings, making it a viable alternative to conventional cooling methods.

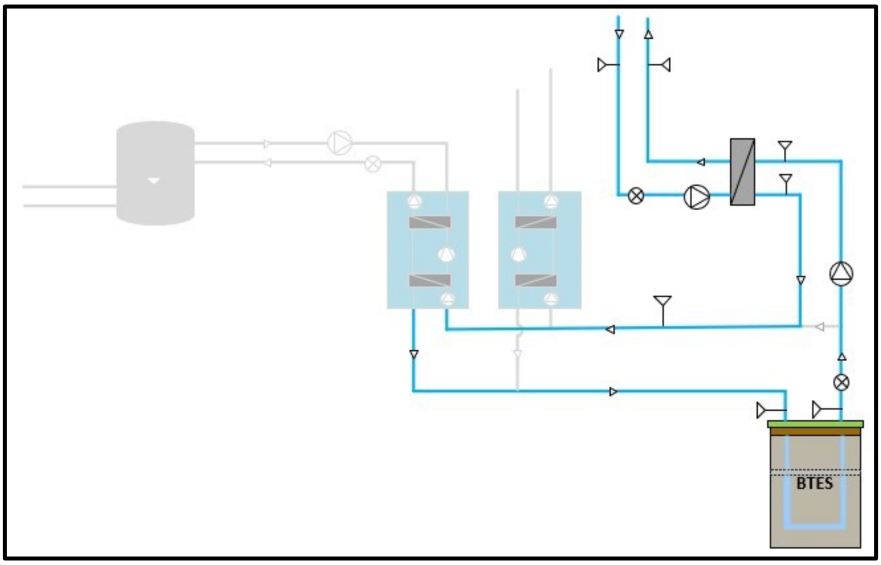


Figure 11. Free cooling using borehole field

3.3 BTES exploitation for SH and SC

The aim of this scheme is to use the GSHP to cover SC and to charge the buffer for SH purposes. During the transitional seasons (spring and fall), there might be a simultaneous need for both SC and SH in different parts of the buildings. The first sub-scheme, as illustrated in Figure 13, operates in a mixed mode during these periods. The heat rejected from the user's SC side is utilized by the HP to the buffer. This stored heat is subsequently employed for SH purposes.

The heat flux from the HP to the buffer can be determined using two temperature sensors and a flow meter, integrated as a heat meter. Additionally, the heat flux to the users for SH can be known based on the monitored supply and return temperatures and flow rate. Furthermore, with the temperatures and flow rates to/from the buffer known, its stored energy can be calculated as the difference between the heat flux from the HP and the heat flux to the SH.

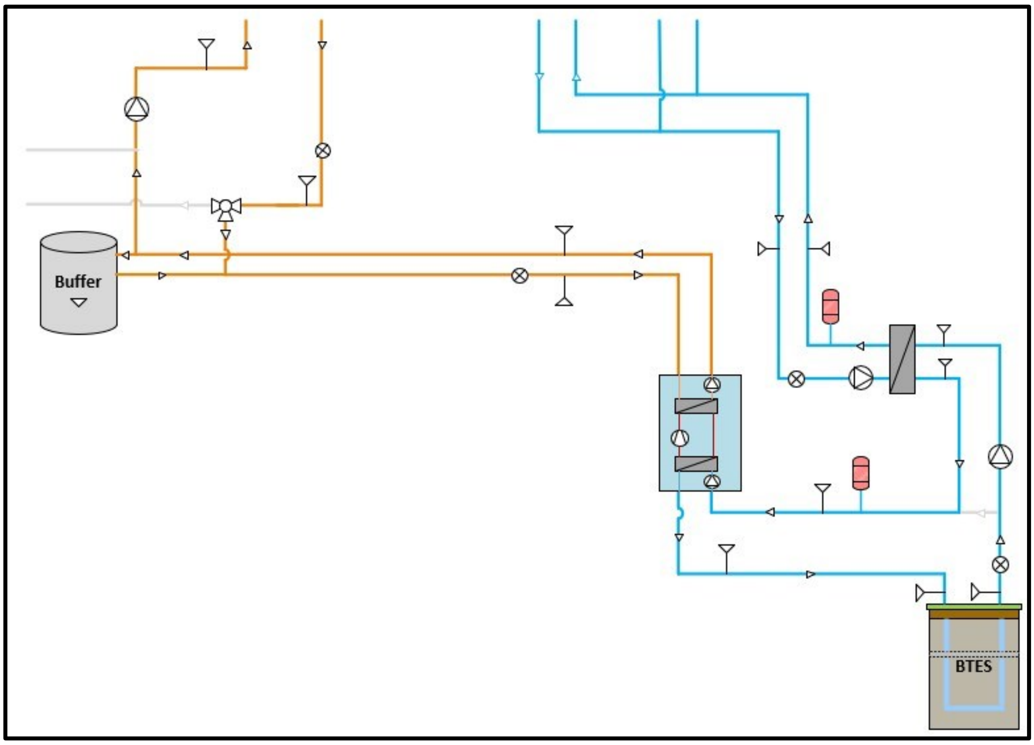


Figure 12. Space heating and cooling using the borehole filed and heat pump

As illustrated in Figure 14, the other sub-scheme is dedicated to meeting SH demand using a GSHP system. Technical considerations, including borehole configurations and control strategies are equally applicable to this sub-scheme.

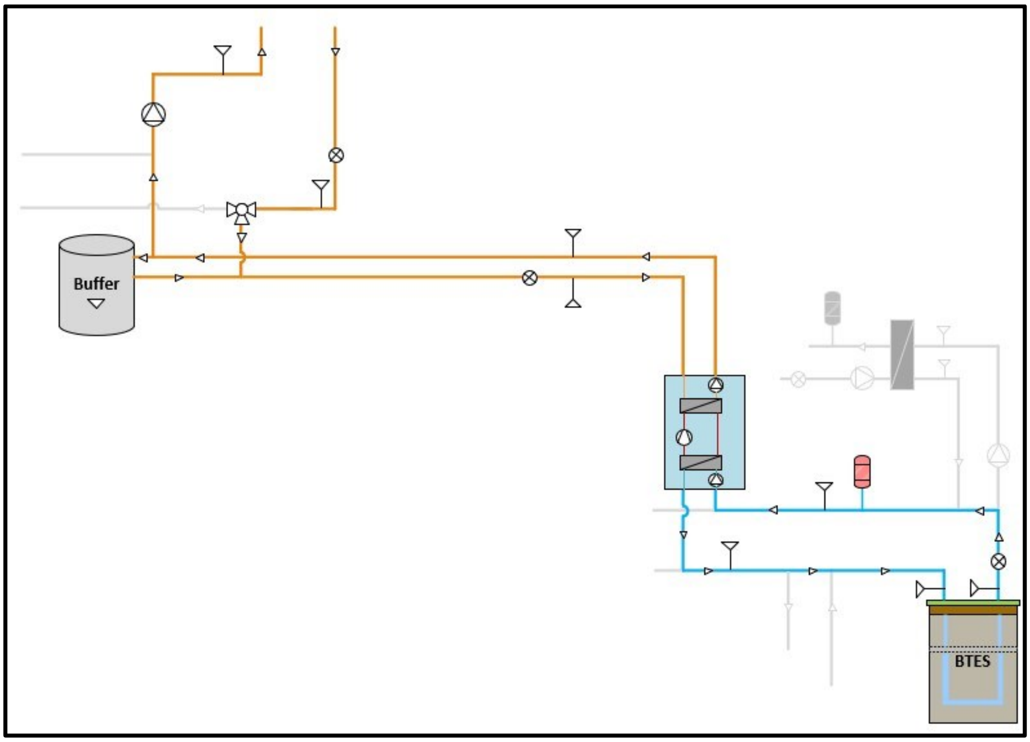


Figure 13. Space heating using the borehole field and heat pump

3.4 SH provision using buffer and DH

The primary function of this scheme, as depicted in Figure 15, is to deliver SH utilizing the buffer and/or DH system. In this scheme, the provision of SH primarily leverages the stored heat within the buffer, which is replenished by the HP. Consequently, DH serves as a contingency source when the buffer's stored heat is depleted. The transition between these sub-schemes, or their modulation, is facilitated by the existing diverter valve.

For the first sub-scheme, analyzing the buffer's discharge to supply SH necessitates access to the temperatures entering and exiting the buffer, as well as the flow rate recorded by a dedicated heat meter. In the second sub-scheme, the primary side involves monitoring two temperature sensors and a flow meter to calculate the heat flux delivered to the HX. On the secondary side—the load side of the HX—both the SH supply and return temperatures to the users, along with the flow rate, are measured by dedicated sensors and meters.

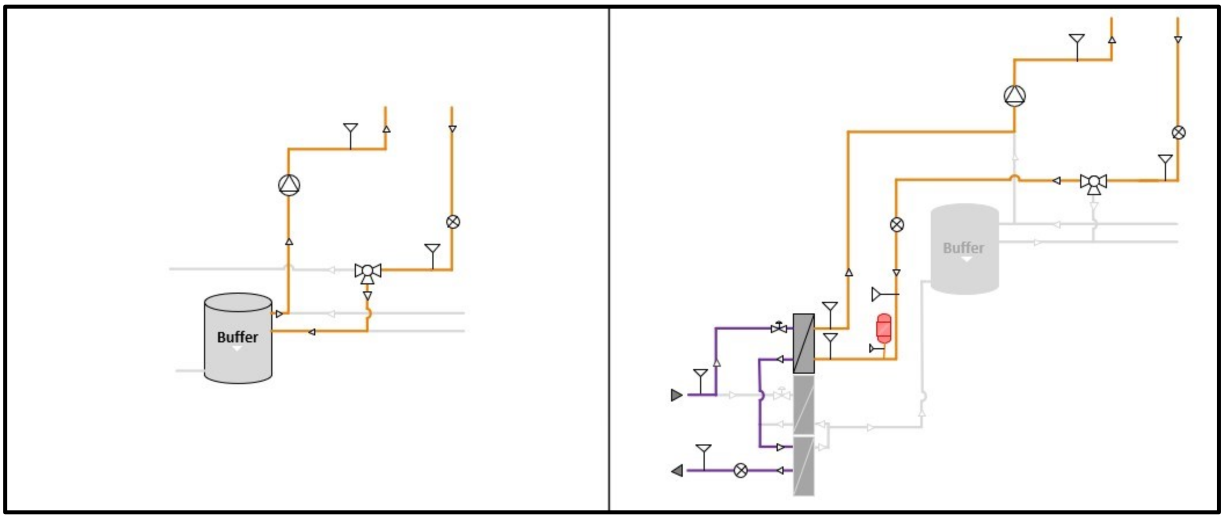


Figure 14. Space heating using the buffer (Left) and using the district heating system (Right)

4 Conclusions

The Tornet Energy Centre, a decentralized district heating and cooling substation in Helsingborg, Sweden, has shown significant advancements in sustainable energy systems. This report outlines the design and operation of the Energy Centre, highlighting the following key takeaways:

1. Integration of renewable energy sources: The Energy Centre effectively integrates a ground source heat pump and hybrid photovoltaic-thermal panels. These components play a crucial role in enhancing the overall energy efficiency and sustainability of the system. By utilizing low-grade thermal energy from the district heating network and upgrading it to higher temperatures, the heat pump reduces dependency on conventional energy sources and decreases thermal losses.
2. Thermal energy storage tank and borehole thermal energy storage: The incorporation of these components provides substantial benefits in balancing supply and demand by storing excess thermal energy during low-demand periods and utilizing it during peak demand. This approach ensures a stable and reliable energy supply while mitigating the risk of decreased performance due to continuous heat extraction from boreholes. Notably, the higher fluid temperatures resulting from EED software simulations suggest an increase in the SCOP of the heat pump, indicating reduced electricity consumption over time.
3. Advanced monitoring and control system: The deployment of a sophisticated monitoring and control system, incorporating sensors, programmable logic controllers, and a SCADA system, ensures optimal performance and reliability. This system improves energy efficiency and user comfort, while also supporting fault detection and diagnostics, enabling proactive maintenance and system optimization. Yet, this analysis identifies room for improvement, as monitoring focuses mostly on thermal energy fluxes, while electric uses are disregarded. These should be taken into account in newly bult systems in order to easily calculate HP’s COP and maintain auxiliaries’ electricity consumption under control, hence to optimize their performance over a continuous commissioning process.
4. Operational schemes and flexibility: The disaggregation of the Energy Centre operation into multiple schemes allows for targeted management of space heating, space cooling, and domestic hot water demands. The flexibility to switch between different schemes based on real-time energy prices and thermal demand conditions optimizes the use of both DH heat and electricity, enhancing cost-effectiveness and energy efficiency.

The concluding remarks derived from these analyses lay the groundwork for developing control algorithms for simulation-based assessments. Utilizing monitoring data from the demo site, a meticulously calibrated substation model has been created to predict the system’s energy performance.

5 Appendix

5.1 Thermal Response Test

Since the initial introduction of thermal response tests (TRTs) with mobile measurement devices in Sweden and the USA in 1995, the method has been developed and adopted widely across North America and Europe. TRTs are primarily used for in situ determination of design data for GHE systems, but they also evaluate grout material, HX types, and groundwater effects. This method assesses thermal conductivity and borehole thermal resistance, both of which are essential for designing efficient GSHP systems.

The Swedish response test apparatus TED (a new mobile thermal response test equipment) has been in use since 1998 [12]. Its main purpose is to determine in situ values of effective ground thermal conductivity, including the effects of groundwater flow and natural convection in boreholes. This test indicates that convective heat transfer may significantly influence the thermal behaviour of a groundwater filled GHE. The magnitude of the induced natural convection depends on the heat transfer rate and temperature level, which is minimal in grouted boreholes. To better understand the influence of groundwater flow on TRTs, software simulations are conducted to estimate the heat transfer effects of groundwater flowing near a GHE.

Groundwater flow can be represented in three ways: (1) flow through an equivalent porous medium, (2) flow through an impermeable medium with a porous zone, and (3) flow through an impermeable medium with a thin vertical fracture. Each representation results in significantly different temperature field patterns around the borehole, and all three cause lower borehole temperatures. Among these, the fracture flow model yields higher effective thermal conductivity compared to the continuum and porous zone models within a certain flow rate interval. This difference illustrates the efficiency of high flow velocity in the fracture and the substantial temperature gradient between the borehole and the fracture flow.

The influence of flow in the fracture or porous zone diminishes with distance from the borehole, yet even at distances of half a meter or more, the presence of a porous zone or fracture can significantly enhance heat transfer. Notably, even a relatively narrow fracture close to a borehole can result in greater effective thermal conductivity, despite continuum approach estimations potentially suggesting otherwise.

A TRT aims to induce thermosiphon flow due to the temperature difference between the borehole and its surroundings, resulting in an enhanced estimation of effective thermal conductivity. The enhancement of the effective thermal conductivity of the GHE depends on the injected power rate and flow resistance in fractures. The fracture flow resistance can be quantified in terms of hydraulic conductivity.

The EED software [13] has been used for designing GSHP systems and GHEs, as well as for sizing the borehole field. This software allows for the calculation and definition of various types of geothermal fields, including determining the optimal borehole perforation depth, to provide the best solution. It employs the thermal response factor technique, which is based on modelling and parameter studies using a numerical simulation model (Superposition Borehole Model). This results in analytical solutions for the heat flow with multiple combinations of borehole configurations and geometries. As an input, the EED tool requires TRTs to be conducted either before or after the design phase to obtain an accurate measure of the ground's thermal conductivity.

A 20-year simulation using EED was conducted for the conditions found in Helsingborg. Figure 16 presents the results, indicating a slight increase in borehole temperature of approximately 2°C over the years. The simulation also shows trends in fluid temperature, peak heat load, and peak cooling load. The higher fluid temperature results in an increased SCOP for the HP, which corresponds to a decrease in electricity consumption over the long term.

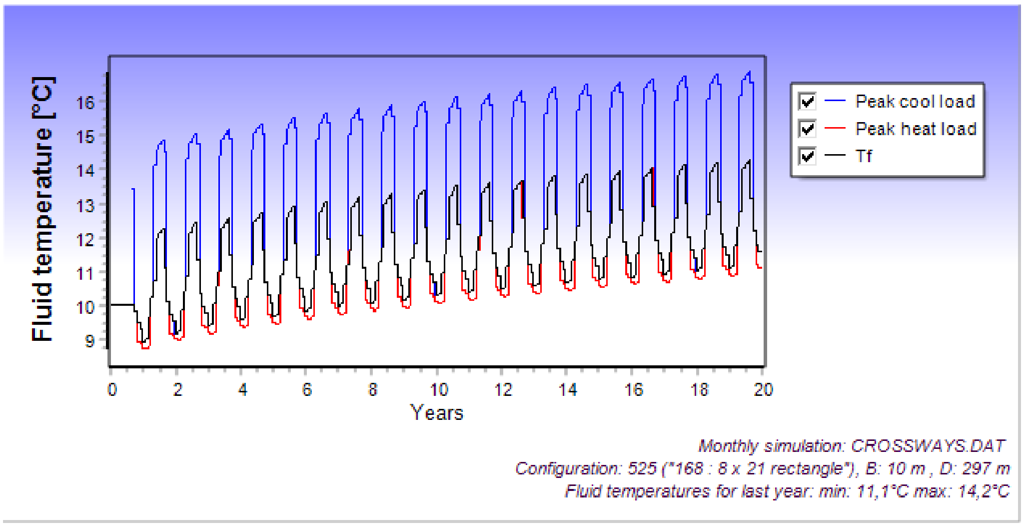


Figure 15. Simulated borehole temperatures throughout a 20-year period in EED software

To visualize the behaviour of the boreholes in the medium term, a simulation was conducted over a 12-month period. Figure 17 shows that the fluid temperature reaches its minimum value of around 2°C from December to March and its maximum temperature of 16-18°C between June and August. In this simulation, there is a simultaneous cooling and heating load from the perspective of the boreholes, meaning that during summer, heat flows into the boreholes.

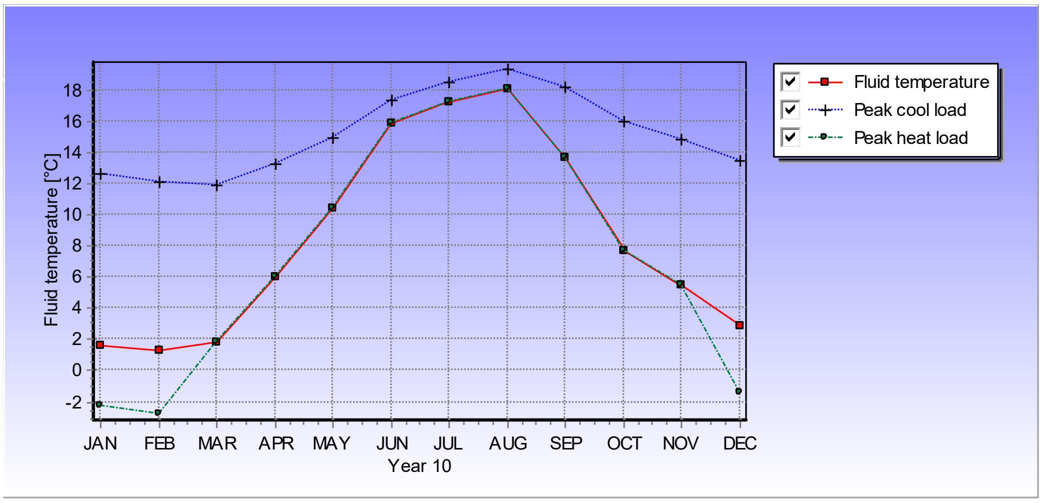


Figure 16. Simulated borehole temperatures throughout a 12-month period in EED software

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