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Research Paper

Performance evaluation and control scenarios for targeted heat injection and extraction in an existing geothermal borehole field in Norway

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A R T I C L E I N F O

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Geothermal simulation
Borehole field sectioning
BTES operation

A B S T R A C T

This work presents the calibration, validation, and analysis of a borehole thermal energy storage (BTES) in building performance simulation using operational data from an existing borehole field in Kalnes, Norway. The data used in this study comprises the results of a thermal response test as well as operational data from the borehole field, which is used to cover the heating and cooling load of a hospital complex. The first part of this study focuses on the calibration and validation of the borehole field model using the IDA ICE software. Then, the validated model is used to explore the impact of different operational strategies in which the charging/discharging of the three sections of the borehole field are prioritized in different orders and compared to the most recent operational strategy. This analysis is carried out on a single year and a 20-year perspective to evaluate long-term temperature trends. This investigation aims to evaluate the current and future impacts of the existing operational strategy and whether it could be improved given that the real-life system struggles with below zero brine temperature at the end of the heating season. The simulation results show that the outgoing brine temperature in each borehole section is strongly dependent on the mass flow rate used in the BTES but that the temperature in an individual section had little impact on the neighboring one. When a section was prioritized by the control logic for heat extraction or injection (both in terms of order and mass flow), there was a notable increase or decrease in the outgoing brine temperature, indicating that it was possible to have targeted heat injection/extraction. In the 20-year operational horizon, the simulation results predicted a gradual warming trend of the outgoing brine temperature of approximately 1 °C due to the additional heat injected in all three sections and regardless of the scenario. The study shows that the most recently implemented operational strategy, in which all sections are charged and discharged simultaneously, is the most viable operation scenario for the borehole thermal energy storage at Kalnes, thus confirming previous findings in literature. Since none of the sections had a superior storage or heat regeneration capacity, prioritizing sections would only lead to more significant temperature swings in the ground. On the other hand, the current operation strategy leads to an overall higher temperature in the ground and reduces the risk of low outgoing brine temperatures.

1. Introduction

Buildings are responsible for 40% of the total energy consumption and 36% of total CO_2 emissions in the EU [1], which makes them a key target for carbon emission reduction in the larger context of the European Union's goals of net-zero balance greenhouse gas emissions and building a climate-neutral economy by 2050 [2]. Due to the wide availability of hydropower, about 80% of the heating demand in Norwegian buildings is covered by direct electric heating or heat pumps. The energy performance of buildings directive (EPBD) requires new buildings and buildings that undergo major renovations to be nearly zero energy buildings [3]. One of the main measures to promote the decarbonization of buildings suggested in the EPBD is to use renewable energy sources. Energy storage technologies are seen as tools for efficiently using renewable energy resources and balancing energy production and demand [4]. Thermal energy storages (TES) are necessary to support the use of electricity and heat generation from intermittent renewable energy sources because they help to overcome daily or seasonal mismatches between generation from renewable energy sources and building heating demands.

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Acronyms

BTES	Borehole Thermal Energy Storage
CM	Cooling Machine
GSHP	Ground Source Heat Pump
HP	Heat Pump
LHC	Local Heating/Cooling
MAE	Mean Absolute Error
MBE	Mean Bias Error
RMSE	Root Mean Square Error
TES	Thermal Energy Storage
TRT	Temperature Response Test
TSP	Temperature Setpoint

1.1. Borehole thermal energy storage behavior and simulation

Borehole thermal energy storages (BTES) are seasonal energy storages usually connected to a ground source heat pump (GSHP) used to further raise the temperature of the fluid exiting the borehole field before it is delivered to a building. The stored heat can originate from high-temperature sources (>40 °C), like solar thermal collectors, industrial waste heat or combined heat and power plants [5–8]. Alternatively, it can originate from low-temperature sources, where heat from cooling processes in buildings with high cooling loads (e.g., data centers or hospitals) can also be absorbed by a BTES seasonally. The suitability of the heat sources depends on the BTES storage temperature, and the type of collector used. Thermal balancing of the ground, i.e., obtaining at least a yearly balance between the amounts of heat extracted and injected into the ground, is essential to ensure the long-term performance of a GSHP or a BTES. However, this balance is challenging to reach in strongly heating-dominated regions like Scandinavia and may lead to a gradual reduction of the average temperature in the borehole field and a poorer thermal performance over time.

Most existing studies in the literature have focused on optimal design solutions for BTES, considering among others (i) the existing ground and climate conditions [9–11], (ii) the occurring heating and cooling demands [11,12], (iii) the integration of a BTES with other systems [9,13–15], (iv) key parameters for optimal (dis-)charging [16–18], and (v) advanced materials in the borehole grouting to improve heat storage [19]. In contrast, there has been little focus on evaluating existing BTES and considering strategies to improve their operation. For example, Nilsson and Rohdin [20] found that post-implementation evaluations of BTES were rare. According to Rapantova et al. [10], only a handful of studies have investigated the long-term operational behavior of BTES fields. In spite of this, studies have shown that there are potential benefits to reap from exploring different types of strategies for charging and discharging in large sectioned BTES [5]. These studies seem particularly interesting for large BTES fields divided into several sections (where one section consists of several boreholes connected in parallel) because one can choose to prioritize the order of the section(s) to charge or discharge and optimize heat storage management. Evaluating the potential of prioritizing BTES sections is relevant given that, in practice, most system operators charge all boreholes simultaneously - even when the BTES has

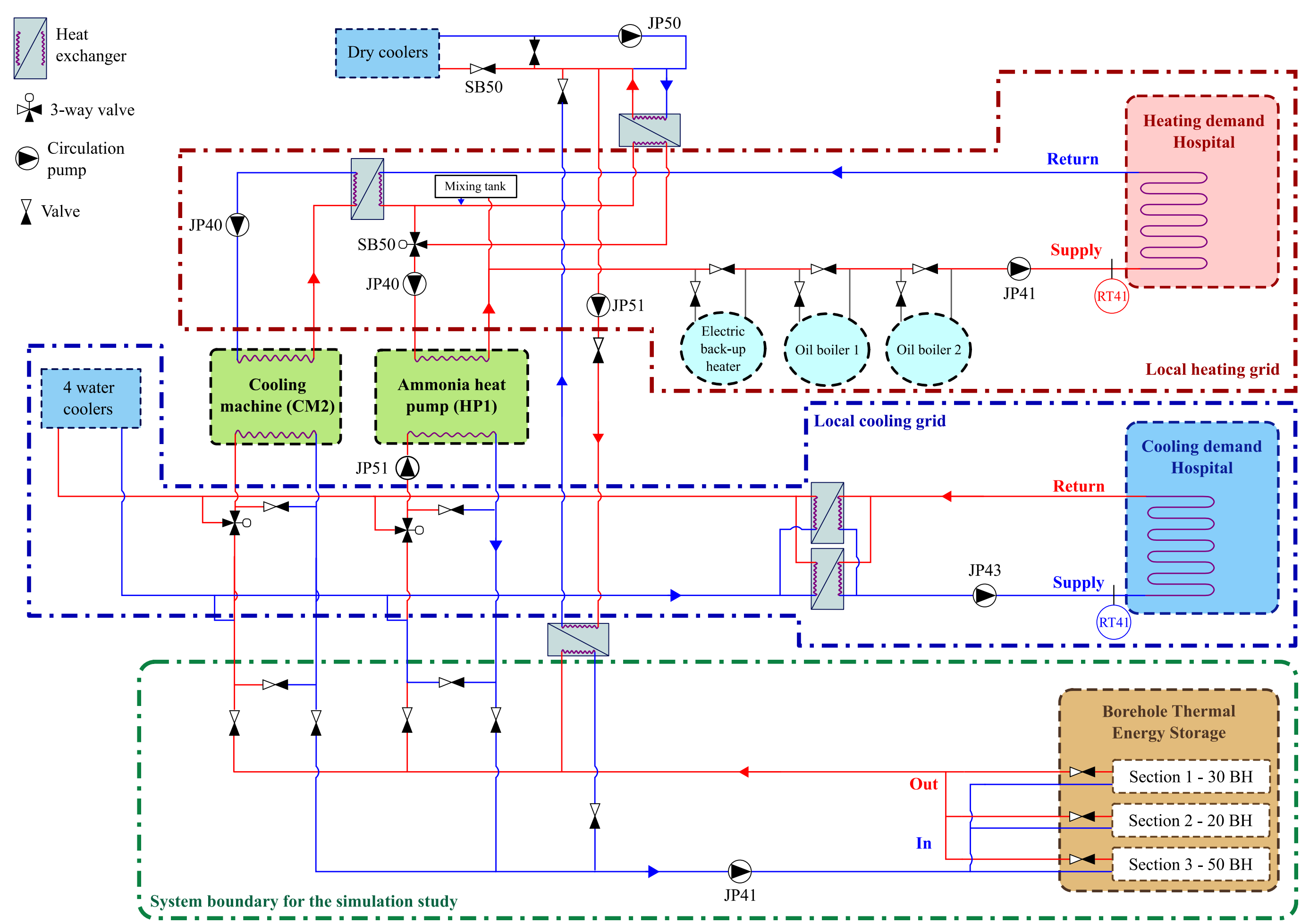

Fig. 1. Schematic of the energy system at Kalnes and boundary for the simulation study.

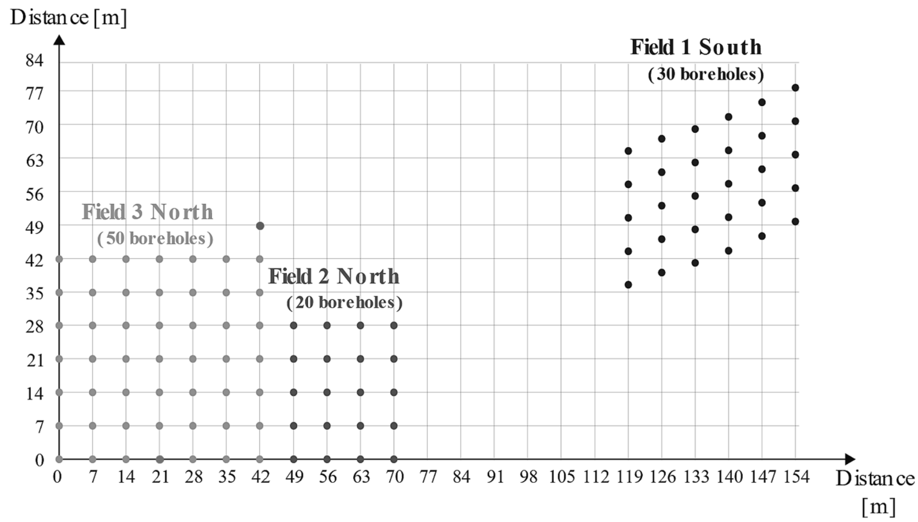

Fig. 2. The coordinate system with the layout of the BTES field at Kalnes. The response test was carried out in two points in red on the map.

multiple sections – for lack of experience or knowledge of alternatives.

Dynamic simulation tools offer the opportunity to investigate the thermal behavior of BTES fields in a numerical environment. This allows estimating the long-term effects of different control strategies on the evolution of ground temperatures before testing them in a real system. Dynamic simulation of boreholes is possible with multiple tools (e.g., EED, IDA ICE, TRNSYS, ComSol, GroundLoopDesign), but not all models provide the same functionalities. For instance, for BTESs, it is crucial to consider the possibility of parametrically calibrating/validating models with information from thermal response tests (TRT) to correctly define the relevant ground properties used in simulations in the design and evaluation processes. The importance of this functionality is shown in studies by Rabani et al. [21] and by Nádas [22]. They used the dynamic building simulation tool IDA ICE to study a BTES and used the parameters of the ground model based on the TRT to calibrate and validate their models. Xue et al. [23] validate 3D numerical models developed in IDA ICE 4.8 and COMSOL for a large-scale asymmetric borehole field consisting of 74 groundwater-filled boreholes with average depth of 310 m in Finland. They show that the IDA ICE model can estimate the BTES inlet and outlet brine temperatures as accurate as the COMSOL model. The average inlet and outlet brine temperature differences against the real-life measurement data in the IDA ICE and COMSOL models were both within 1 °C.

1.2. Main contributions of the study

The literature study shows that there is limited dissemination of real-life experiences regarding the operation of large BTES. This study provides insights into the operation of a real-life application which can help optimizing future BTES designs and operational practices to enhance the overall system performance. By providing a performance evaluation, model validation, and practical insights, this work contributes to the understanding and advancement of the BTES technology. It is important to note that the intention is not solely to introduce theoretical control strategies but rather to emphasize a real-world operational context. In collaboration with the BTES operator, control strategies are deliberately selected that align with their operational capabilities and constraints. These strategies are chosen based on their practical relevance, and the objective is to gain insights into their potential impacts on system dynamics. The ultimate aim remains the enhancement of geothermal energy storage solutions, driving efficiency, reliability, and sustainability in practical applications.

The main contributions of this paper are (i) the calibration and validation of a model describing the yearly evolution of the brine temperature in a large BTES field with 100 boreholes in a heating-dominated climate, and (ii) an evaluation of the impact of prioritizing different sections in a BTES on the thermal balance and overall performance of a borehole field with three sections, using the validated model of the case study developed in (i) and considering a 20-year operation horizon for the BTES.

The remainder of the article is structured as follows: Section 2 describes the methodology of the work, introduces the overall procedure, describes the energy system and the modelling of the BTES using IDA ICE, and elaborates on the prioritization strategies used. Results for the validation and the scenario modelling are presented in Section 3. The discussion of this work is developed in Section 5, and the conclusions are drawn in Section 5.

2. Material and methods

2.1. Presentation of the case study

2.1.1. System description of the test site and the BTES at Kalnes

The BTES is connected to the local heating/cooling (LHC) grid of the Kalnes Østfold Hospital, an 80 000 m^2 building complex located close to Sarpsborg in Southern Norway (59° North). The hospital, which started operating in 2016, uses a central reversible brine-water heat pump (HP1) and a heat pump used as a cooling machine (CM2). Heat Pump 1 (HP1) has a nominal capacity of 1.3 MWt_h (ammonia heat pump) and Cooling Machine 2 (CM2) has a capacity of 1.4 MW_{th} (R134a heat pump). HP1 and CM2 provide space heating, domestic hot water, process cooling and space cooling. The energy system offers the possibility to dissipate excess heat in the system either via dry coolers or by injecting it into the BTES. Additionally, there is one electric boiler and two oil boilers for backup heating and four cooling machines for backup cooling. Fig. 1 shows a schematic view of the energy system and the boundaries for the simulation study.

The BTES field has 100 boreholes, each ca. 250 m deep, and is divided into three parallel sections of 30, 20 and 50 boreholes, which are also connected in parallel within each section (Fig. 2). The collector in the borehole field is made of polyethylene (PE) and the fluid used is ethanol-based (HX I-35 – 35% ethanol and 65% water) with a freezing point of −17.5 °C (flashpoint 27 °C, boiling point 78 °C).

2.1.2. Performance of the BTES and previous operational strategies

The performance of the real-life borehole field is briefly described in this section to better understand the measurement data for the year 2020. This data is used to validate the simulation model that is the input

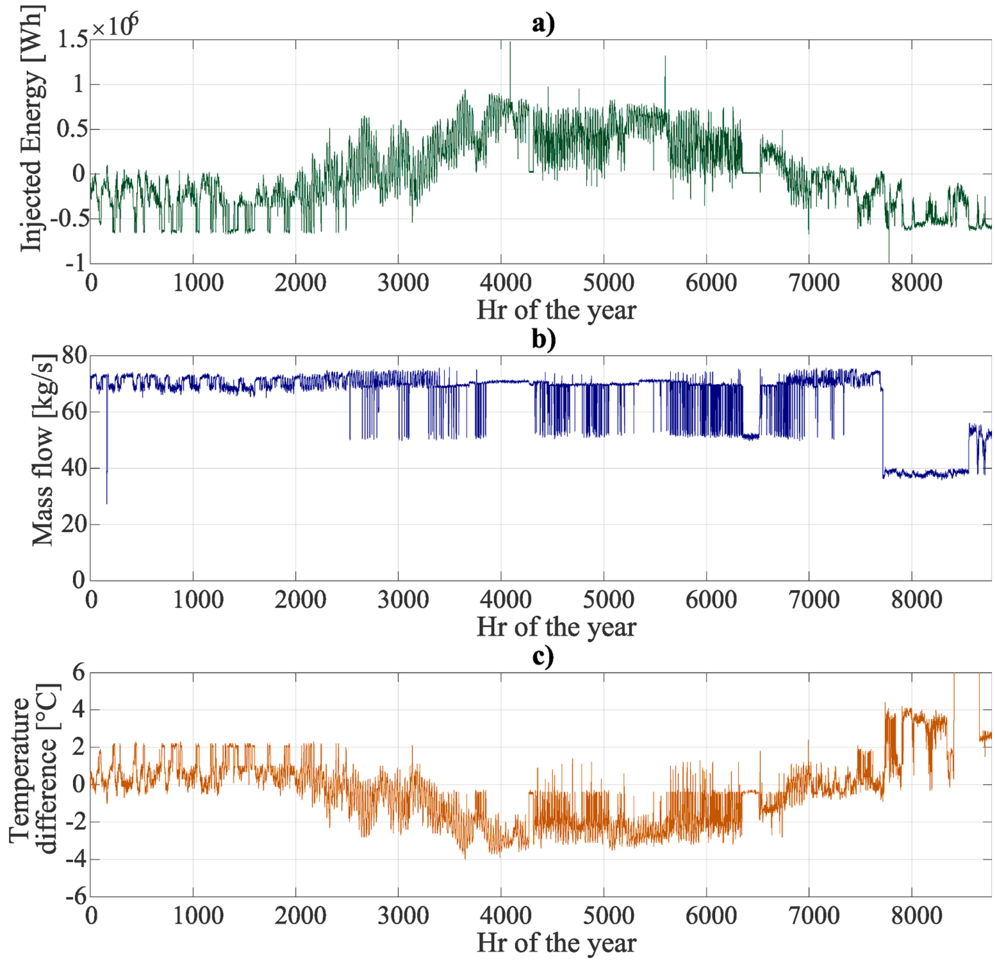

Fig. 3. BTES-related measurements for (a) hourly injected energy [Wh], (b) mass flow [kg/s] and (c) difference between outgoing and ingoing brine temperature in 2020 at the Kalnes test site. Regarding (c), notice that the temperature difference is higher at lower mass flows.

for the 20 years simulation.

Since the hospital started operating in 2016, there have been three different operational strategies used for the BTES. The BTES was only used intermittently in the first year and then primarily used as a ground source heat pump without storage (Strategy 1). Then the BTES was run with the idea that sections 2 and 3 (70 boreholes) would be used for heating and the 30 boreholes in section 1 would be used as a cooling reserve (Strategy 2). During this time, surplus heat from the hospital started getting reinjected in sections 2 and 3 of the borehole field for storage after study [24] pointed out the risk of depleting the ground seeing the increasingly low return temperatures of the brine at the end of the winter. The details about these two strategies, the interplay with HP1 and CM2, and their impacts are not described in this work as they are outside its scope. However, the model validation work considers the global trends of their impacts. The current operational strategy of the borehole field (Strategy 3) has been implemented in the end of 2019. It increasingly uses the borehole field as a BTES by making surplus heat reinjection in the BTES the main priority and only using dry coolers for the surplus heat that cannot be sent to the BTES because of temperature restrictions on the circulating fluid (risk of evaporation). The charging/discharging strategy was also modified to extend to all three sections of the BTES field, meaning all sections were charged parallelly with a mass flow proportional to the number of boreholes. Finally, in late 2020, the operator of the borehole field also explored reducing the mass flow rate from its maximum and maintaining the same energy output by allowing more heat to be extracted at once (see Fig. 3). This resulted in a higher temperature difference between the ingoing and outgoing brine temperatures. The decision to reduce the mass flow was likely based on the finding that the potential energy available to charge the boreholes is larger than estimated in the planning of the BTES. Another benefit of reducing the mass flow is a reduced pressure loss in the heat exchanger pipes. With the current energy situation in Europe, the reduction of electrical demands related to a reduced pressure loss may not be negligible.

The yearly heating load for the hospital has been decreasing over time and was at its lowest so far in 2020, when it amounted to 7.3 GWh compared to a projected 9 GWh/year. On the other hand, the yearly cooling demand has been above the projected value, varying between 5.8 and 4.6 GWh/year, while it was expected to be 4 GWh/year. The operation of the energy system as well as performance monitoring results for several years of operation are outlined in more detail in [25]. Fig. 3 shows the data used for the simulation analysis developed in this paper. Note that there was a sensor measurement error late in 2020 for the temperature difference as is visible in Fig. 3c. Due to this error, the last 15 days of data for the year were omitted in the simulations. Furthermore, there was a scheduled one-week maintenance period for HP1 during autumn (approximately hours 6350–6500 in Fig. 3). Hence, the injected energy to the BTES is 0 Wh. However, the system operator chose to continue circulating the brine through the BTES. The inclusion of this scenario is intended to highlight a real-world operational condition and its potential impact on system dynamics.

Table 1
Measurement results from thermal response test at the test site [28].

Input data	Thermal response test
Measurement period	22–25.08.2011
Heating power	8600 W
Brine mass flow rate	0.60 l/s
Borehole depth	Approximately 250 m
Undisturbed ground temperature	8.1 °C
Borehole resistance	0.09 (mK)/W
Ground thermal conductivity	3.38 W/(mK)

2.2. Modelling of BTES in IDA ICE

The software tool used for this study is IDA ICE version 4.8. IDA ICE is a validated equation-based dynamic building performance simulation tool [26]. The IDA ICE borehole model employs the finite difference method to compute multiple temperature fields, which are subsequently combined via superposition to produce a 3-D field in the ground. The IDA ICE borehole model allows for detailed modelling of an arbitrary combination of boreholes of equal length. The entire system (ground-borehole-pipe) is divided into several layers, and the temperatures of the borehole and brine fluid are assumed to be uniform within each layer. The model considers U-pipe heat exchangers and a constant borehole resistance along the borehole depth [27]. It does not consider groundwater flow movement. The model takes into account the heat transfer between the U-pipe, upward and downward brine fluid, borehole filling material, ground, ground surface, and ambient air. The calculation considers the thermal mass of the brine fluid and the borehole filling material, excluding the U-pipe. The actual temperature of the ground at the borehole wall is determined through superposition or multiple boreholes, the thermal behavior of the ground around each individual borehole is initially calculated. Then, the collective influence of all boreholes on the ground temperature is determined through summation using superposition. It is possible to define the x- and y-coordinates as well as the leaning angle of each borehole in a borehole field. The borehole model is based on the superposition of cylindrical 2D fields around each borehole as well as a 1D vertical field for the undisturbed ground temperature. Importantly, the model also considers the thermal influence related to the position of individual boreholes and their proximity to one another both within a section and in between two different sections. For a detailed description and validation of the IDA ICE borehole model, the reader is directed to Xue et al. [23].

2.2.1. Calibration and validation of the thermal response test

Onsite geological and hydrogeological conditions influence the utilization of a BTES as the specific properties affect the heat transfer characteristics of the ground. The thermal response test (TRT) performed at the Kalnes site in August 2011 for a single borehole [28] concluded that the undisturbed ground temperature in the area is 8.1 °C. The groundwater level was measured to be between 12 and 17 m for the two test drillings. It is assumed that the groundwater level is similar in the whole area of the BTES. The prevailing rock environment consists of

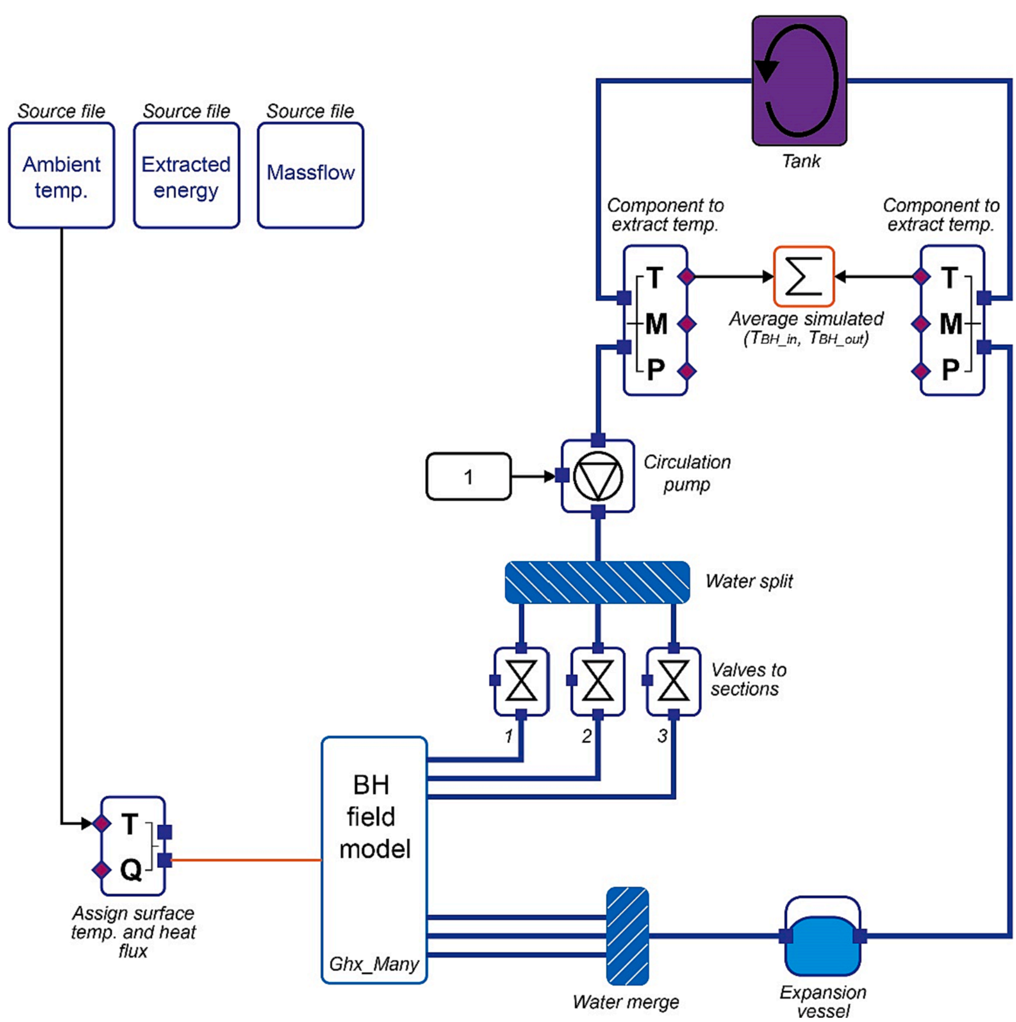

Fig. 4. Interface of the default model of the BTES in the IDA ICE simulation environment.

Table 2
Default and calibrated parameters of the IDA ICE ground model.

Parameter	Initial value	Range	Resolution	Calibrated value
Ground heat capacity [J/(kg·K)]	840	[800 900]	50	858.4
Ground density [kg/m^3]	2880	[2600 3100]	50	2941.2
Ground thermal conductivity [W/(m·K)]	3.38	[3 6]	50	3.625
Temperature gradient [°C/m]	0.0174	[0.008 0.02]	50	0.01299
Borehole resistance [(m·K)/W]	0.09	[0.05 0.10]	50	0.09122
Cumulative error [Kh]	**297.9**			**47.69**

several types of sedimentary rocks, including granite, mica schist and granitic gneiss. The rock environment lies at a depth of 2.5–3.5 m. The ground thermal conductivity is approximately 3.4 W/(m.K). Other TRT information is presented in Table 1.

For the TRT simulation in IDA ICE, the measured parameters used as input for the calibration were: (i) the supply and return brine temperature, (ii) the heat power and (iii) the mass flow rate of the brine. The TRT calibration procedure in IDA ICE was carried out as described by Rabani et al. [21] and Nadas [22] and used the single objective genetic optimization algorithm GenOpt [29]. GenOpt applies particle swarm optimization (PSO) and a generalized pattern search (GPS) to find the optimum solution.

2.2.2. Description of the procedure for calibration of the BTES model

As for the TRT validation, real-life measurement data from the test site is input to the simulation model in the form of time series. The developed default model, shown in Fig. 4, contains one circulation pump that is responsible for the fluid flow in the entire BTES. The real-life BTES is divided into three sections with different numbers of boreholes and the flow in each section is proportionally to the number of

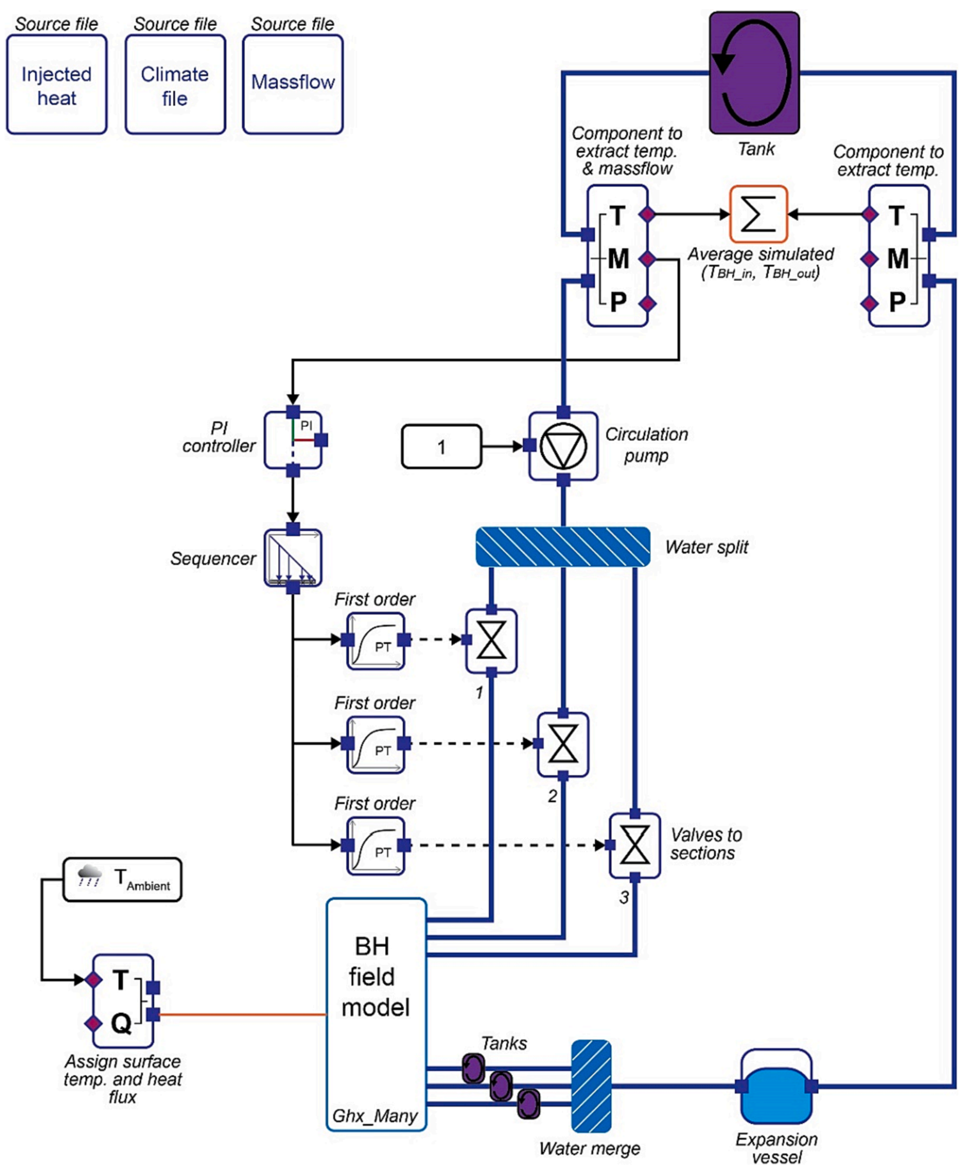

Fig. 5. Sequenced valve control to make use of the BTES sectioning in IDA ICE.

boreholes in the specific section. This means that the highest mass flow is in section 3 (50 boreholes and 50% of the total mass flow rate), followed by section 1 (30 boreholes and 30% of the total mass flow rate) and finally section 2 (20 boreholes and 20% of the total mass flow rate). In the simulation tool, the three mass flows are then fed to the BTES component ("Ghx_Many" in Fig. 4). It is possible to assign each borehole to one of the three sections within this component model. For the validation, the total amount of heat injected or extracted from the BTES is fed to the 1-node tank model in the form of a time series that contains hourly measurement data from 2020. The real system charges and discharges all three sections simultaneously.

For this work a two-step model development is performed:

1. Firstly, the IDA ICE ground model is calibrated against the Kalnes TRT to establish values for several ground property parameters (Table 2).
2. Secondly, the TRT-calibrated model is validated against hourly operational data from 2020. The simulation model is validated using hourly operational data from 1.1.2020 to 15.12.2020. It was not possible to use data for one full year because the sensor that measures the outgoing brine temperature was misplaced on 15.12.2020. During the model validation, the initial ground temperature is adjusted iteratively to decrease the offset between the actual ground temperature on 1.1.2020 and the simulated ground temperature. This adjustment can be seen as a second calibration step and was necessary as the operational strategies of the real system have varied over time since 2016.

2.3. Prioritization scenarios for (dis-)charging of the borehole field

As mentioned previously, the current operational strategy of the BTES is to prioritize heat storage and use all three sections of the BTES as one (this strategy is hereon by referred to as the business-as-usual or BAU strategy and was in place in the most recent year of data collection). This work investigates the impact of using the BAU strategy year after year for the next 20 years and evaluates its expected impact on each section's temperature in the BTES. This article also then investigates the impact of an alternative strategy, in which we prioritize charging and discharging specific sections of the BTES in a given order and compares the compares the impact of these two strategies on the ground temperatures in the BTES with a 20-year operational horizon.

The default borehole model (Fig. 4) is extended with a PI-controller and a "sequencer" to adjust how the mass flow is distributed to the different sections of the BTES (Fig. 5). When using a sequencer, the maximum mass flow to the valves needs to be set in the model. In this work, the mass flow for each section is predetermined and based on the hourly measurement data (Fig. 3b). In 2020, the maximum measured total mass flow in the BTES was 75.8 kg/s, which corresponds to 22.74 kg/s, 15.16 kg/s and 37.9 kg/s for Sections 1–3, respectively. The PI-controller adjusts the mass flow to meet the energy balance required at that timestep. The sequencer then decides how to distribute the mass flow to each borehole section based on the order of prioritization. When Section 1 is prioritized, the sequencer-component keeps the valves for Sections 2 and 3 closed until the maximum mass flow in Section 1 is reached. It then opens the second valve and then the third. Whether valves are opened or how much they are opened depends on the total mass flow rate required to meet the amount of energy to be extracted or injected. "First order" components are used to smoothen the numerical simulations. The largest difference between this type of control and the BAU is that not all sections of the BTES are used when the required mass flow is below the maximum.

Regarding the prioritization of the sections, different scenarios are chosen based on discussions with the system operator of Kalnes:

- ***BAU Business-as-usual:*** For this case, all three sections are charged and discharged simultaneously as in 2020. Regarding the average outgoing brine temperature from the BTES, the outgoing brine temperature is the mass-flow averaged brine temperature over all sections. This scenario corresponds to the current operation strategy (Strategy 3 described in Section 2.1.2).
- ***123: Order of Section priority 1-2-3:*** The sequencer controls the flow towards each section as explained earlier and prioritizes Section 1, then Section 2, then Section 3.
- ***321: Order of Section priority 3-2-1:*** Prioritizing Section 3 is chosen as it is the biggest section, and it is assumed that it covers most of the heating demands. Section 2 is in closest proximity to Section 3 and is therefore set as the second priority. Section 1 has the lowest priority and is charged/discharged only if the two other sections cannot cover the demands/loads. Note that this strategy is most similar to Strategy 2 which is described in Section 2.1.2 previously.
- ***312: Order of Section priority 3-1-2***: Similar to Case 3-2-1, prioritizing Section 3 due to size. Section 1 is prioritized over Section 2 as it contains 10 more boreholes than Section 2.
- ***This leads to the following research questions:***
  - o ***RQ1: What was the temperature distribution in the different borehole sections in 2020?***
  - o ***RQ2: What are the long-term trends of the temperatures in the different sections of the borehole fields given the current operational strategy and a 20-year horizon?***
  - o ***RQ3: Can the sectioning of the borehole field be used so that it is possible to target heat extraction/injection in sections of different sizes?***
  - o ***RQ4: Is the current operational strategy adapted to the BTES and viable for the future***?

The evaluation is based on the comparison of the outgoing brine temperatures in each section of the BTES compared to the BAU case.

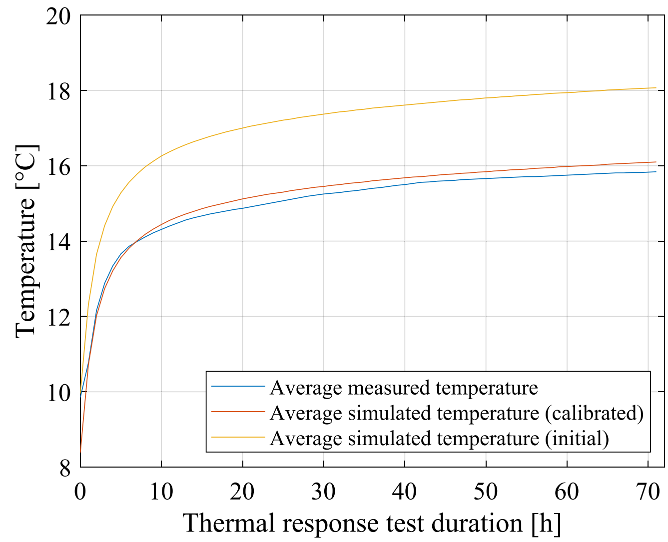

Fig. 6. Simulated and measured average temperatures with the calibrated model parameters.

3. Results

3.1. Results of the TRT model calibration

During the calibration, GenOpt minimizes the cumulative error between the simulated and measured brine temperatures (calculated using the arithmetic average of the supply and return brine temperature). The described procedure aims at getting values for these ground parameters that lead to a better fit of the model compared to the real measurements. The resulting values of the parameters included in the calibration are

Table 3
Key indicators for model accuracy evaluation. (MAE: mean absolute error, MBE: mean bias error; RMSE: root mean square error).

Case	Indicator								
	MAE [°C]			MBE [°C]			RMSE [°C]		
	Whole year	1.1–14.4. & 15.9–31.12	15.4–14.9.	Whole year	1.1–14.4. & 15.9–31.12	15.4–14.9.	Whole year	1.1–14.4. & 15.9–31.12	15.4–14.9.
Initial (before validation)	**2.84**	2.79	2.94	**2.84**	2.79	2.94	**4.58**	5.31	2.97
Validated (after validation)	**0.97**	0.99	0.95	**−0.06**	0.36	−0.85	**1.08**	1.10	1.04

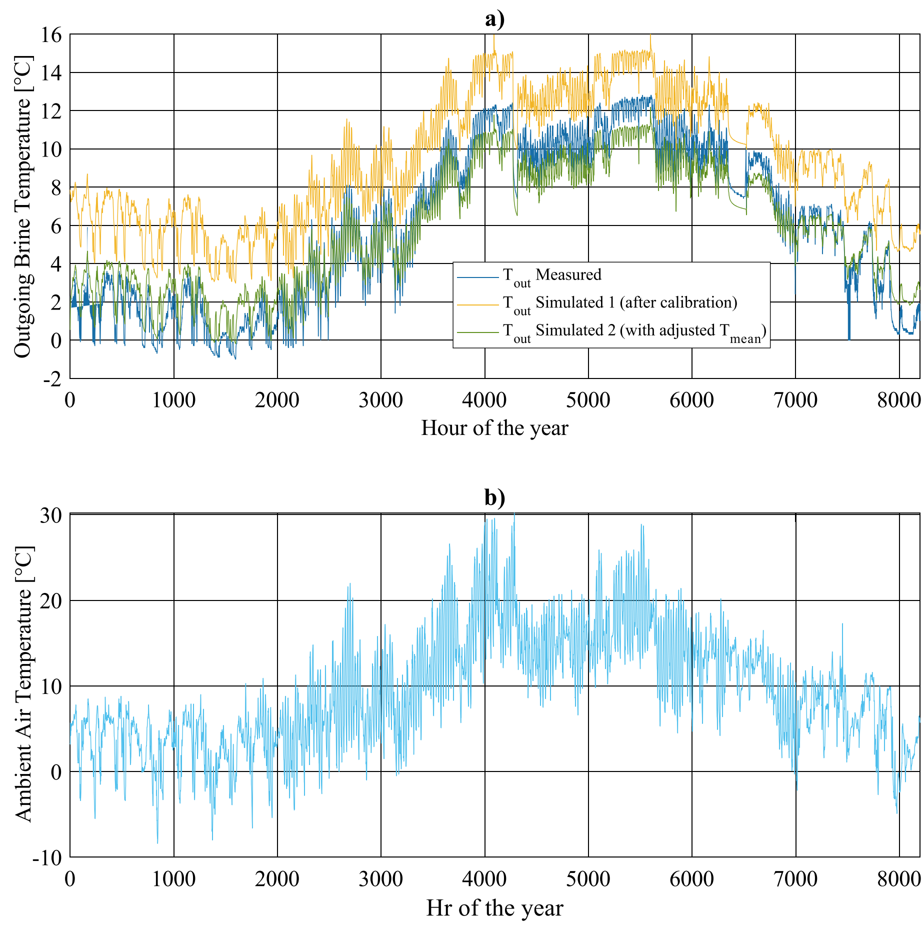

Fig. 7. (a) Visual model validation based on hourly outgoing brine temperature from the btes in 2020 (considered period until the beginning of december 2020 due to a malfunctioning sensor for measuring the outgoing brine temperature) and (b) ambient air temperature at the location.

shown in Table 2. The total cumulative error is given in degree-hours [Kh].

The results of the simulated values before and after calibration compared to measured average brine temperatures (hourly average of supply and return temperature) are shown in Fig. 6.

3.2. Results of the model calibration and validation of the BTES model

There is an initial mismatch between the simulated outgoing brine temperature for 2020 and the measurements due to the model being initially calibrated with the TRT results from 2013. This incurs the need for a second parameter fitting to account for the fact that more heat has been extracted than injected in the BTES between 2016 and 2019. Therefore, the ground surface temperature in 2013 (when the TRT was performed) and in the beginning of 2020 (used hourly measurement data) is different. A fit-for-purpose procedure is applied, where the IDA ICE model parameter for the "mean surface temperature, Tmean", is adjusted iteratively and a reasonable Tmean is chosen based on the MBE, MAE and RMSE of the simulated and measured outgoing brine temperature. In reality, the state of the ground after several years of operation cannot be assimilated to a uniform change in the ground temperature. An annual simulation is run for different Tmean-values in the model and the metrics shown in Table 3 are calculated. Based on the results for the error metrics, a Tmean of 4.0 °C is chosen. A Tmean of 4.0 °C may not be the numerically optimal solution, but a small error for Tmean is tolerated, as this work focuses on the evaluation of control strategies, where the objective is to see whether the model can predict similar changes in the outgoing brine temperature compared to the measurement data from the real system. It may not be the numerically optimal solution because no dedicated numerical optimization was performed to determine a Tmean of 4 °C. Different values for Tmean were investigated in an iterative manner adjusting Tmean in steps of 0.5 K in a range between 3 °C and 7 °C.

As can be seen in Fig. 7, the validated simulation model (in yellow)

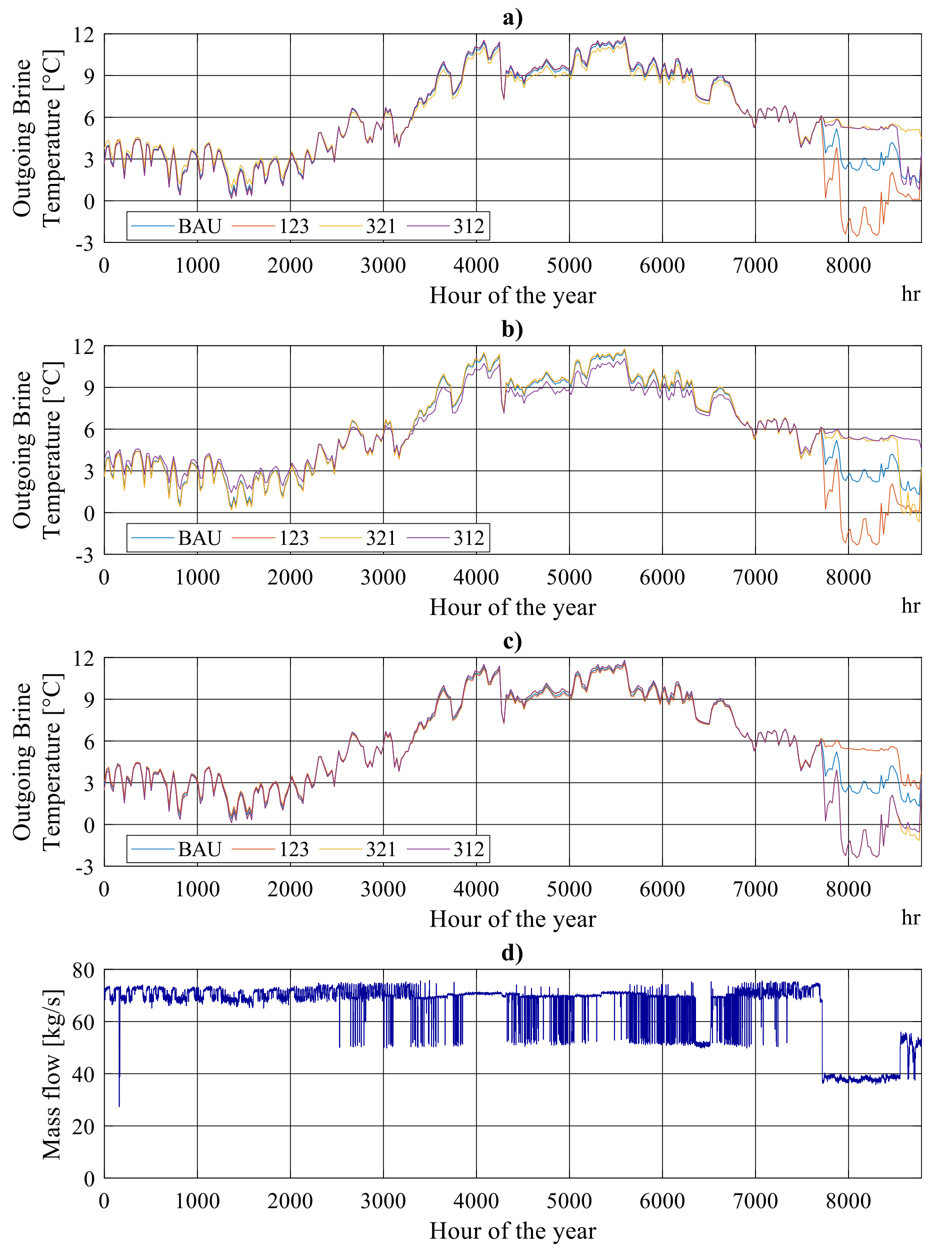

Fig. 8. Daily-averaged outgoing brine temperatures for four investigated control scenarios for (a) Section 1, (b) Section 2 and (c) Section 3. (d) shows the total mass flow in the system for improved clarity of the trends in (a–c).

overestimates the outgoing brine temperature during wintertime. In contrast, it predicts a lower outgoing brine temperature during summertime compared to the measured values. Despite this, the model follows the general hourly trend of the measurements, meaning the results visually capture the dynamics of the system correctly.

Since there is no approved guideline that determines acceptance criteria for model calibration with respect to temperatures in BTES, several indicators as well as visual evaluation are used as quantitative and qualitative measures in this work. Table 3 summarizes the error indicators. The equations used are given in the Appendix.

The mean absolute error (MAE) is 0.97 °C and is displayed as the difference between the yellow and blue lines in Fig. 7. A mean bias error (MBE) of −0.06 °C means that there is almost no difference between the measured and simulated values, but that, on average, the model tends to slightly underpredict the temperature. A deviation of ca. 1 °C corresponds well to the findings from Xue et al. [23], who also validated an IDA ICE borehole model with real-life measurement data.

3.3. Simulation results after one year of operation

Fig. 8 shows the daily-averaged outgoing brine temperature for all four scenarios for the first year of operation. The BAU uses the real mass flow measured at the test site in 2020 and the actual amounts of energy injected and extracted from the borehole field during this period. The three other scenarios use the same time series for injected and extracted energy, but the total mass flow in each section is distributed according to the capacity of each section and the order of priority. This allows using only certain sections of the BTES when the mass flow required is not near the maximum, e.g., in the last part of 2020.

Four general findings are apparent from Fig. 8:

1. When all sections are used together with the near-maximum mass flow rate, there is little difference between each section's temperatures (up until hour 7700). This means that the sections mostly behave similarly from the heat storage/extraction point of view

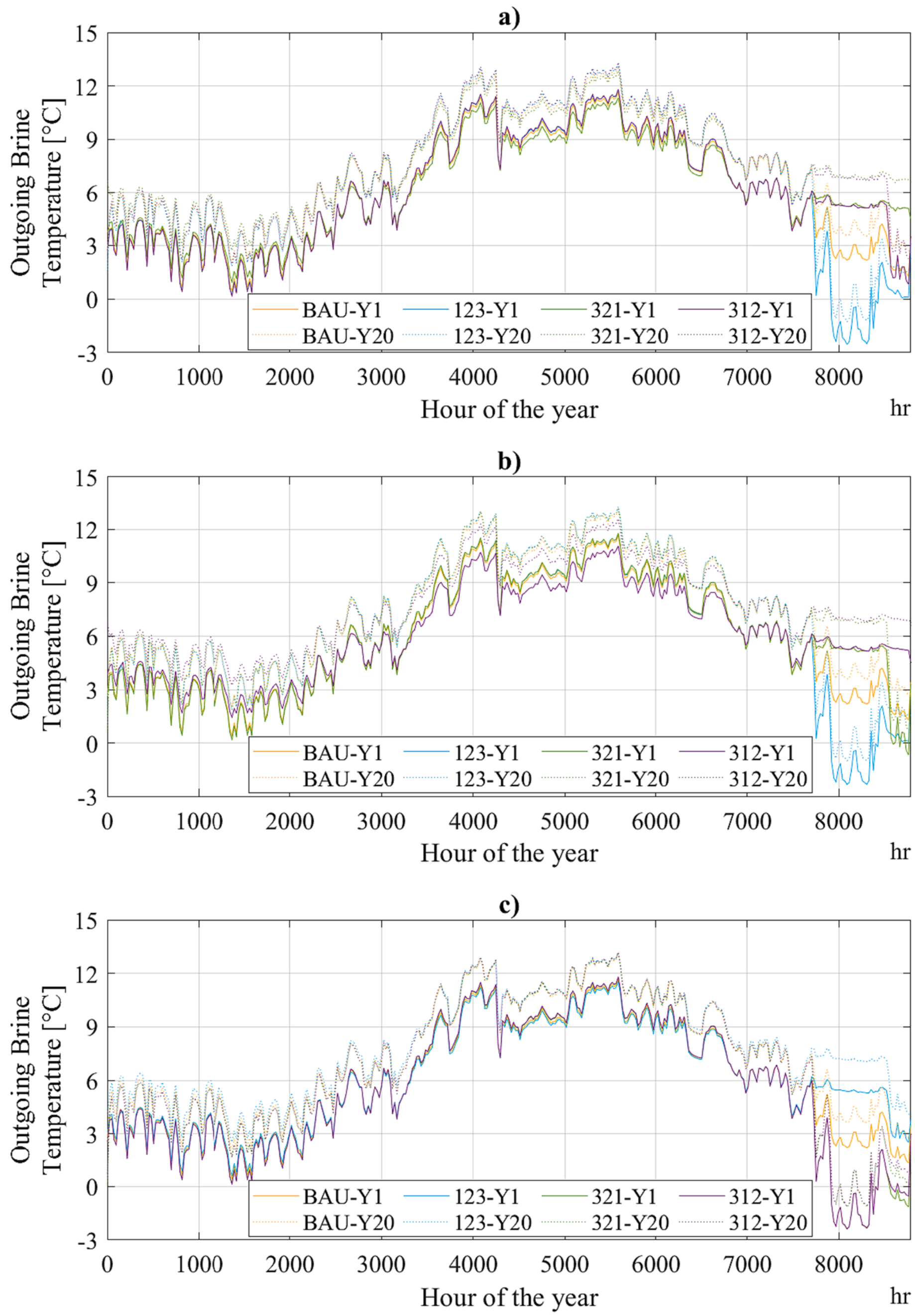

Fig. 9. Daily-averaged outgoing brine temperatures for four investigated scenarios for (a) Section 1, (b) Section 2 and (c) Section 3, where Y1 is the first year of operation, and Y20 is the 20th year of operation.

despite section 1 not being in the direct vicinity of sections 2 and 3. The average temperature of all sections (BAU case) is also representative of the temperature in each section when the system is operated this way.

2. As expected, the section with the highest priority has a lower outgoing brine temperature during times of heat extraction, whereas a high priority during times of heat injection leads to a higher outgoing brine temperature. This is visible in cases 312 (Fig. 8b) and 321 (Fig. 8a) and very clear after the mass flow is reduced at hour 7700. However, these temperature differences between the sections are very similar regardless of the proximity of the sections to one another.
3. The total mass flow for all three sections significantly influences the short-term evolution of the outgoing brine temperature. During most of the simulation period, when the imposed total mass flow rate is close to 75 kg/s, two out three sections run at their maximum mass flow rates while the third one will have a lower mass flow rate, and so less heat is extracted from this section.
4. The combination of borehole field dimensioning and total mass flow are important. From hour 7700 to approximately hour 8500, the total mass flow in the system was reduced to approximately 35 kg/s (Fig. 3b). This had a direct impact on the outgoing brine temperature of prioritized sections. A mass flow of 35 kg/s corresponds to the maximum flow rate in Section 3 of the BTES, meaning that if section 3 had the highest priority, the heat demand could be covered by this section alone. This led to a lower outgoing brine temperature in section 3 (see, e.g., case 321 Fig. 8c) and relatively higher brine temperatures in sections 1 and 2 (see, e.g., case 321 Fig. 8a and b). A similar behavior is seen for case 123, where the total mass flow of 35 kg/s is approximately the sum of the maximum combined mass flows

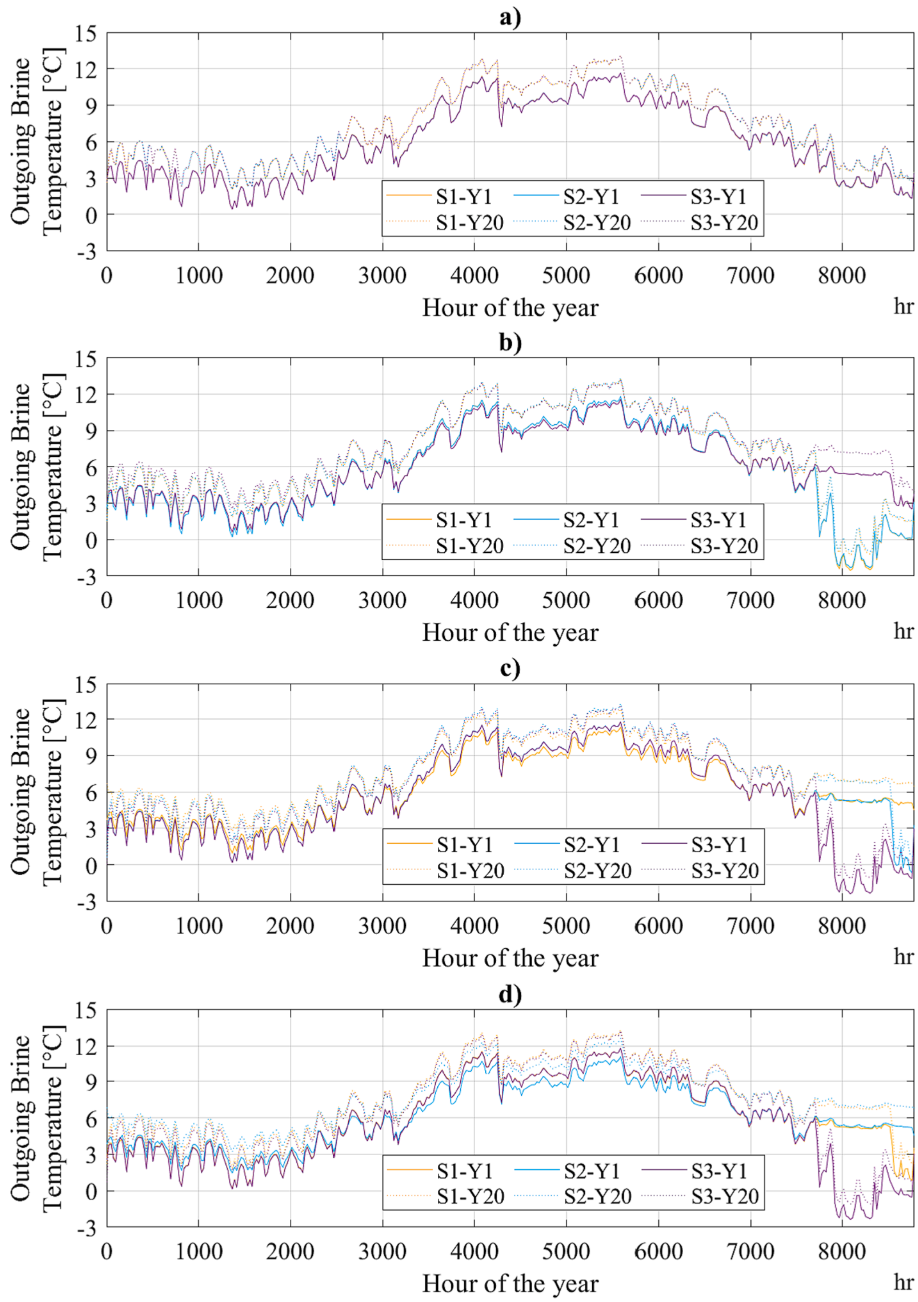

Fig. 10. Daily-averaged outgoing brine temperatures for each section for the different prioritization scenarios (a) BAU, (b) 123, (c) 321 and (d) 312. Y1 is first year of operation, Y20 is last year of operation.

of sections 1 and 2. Heat is extracted from sections 1 and 2 only, hence the higher temperature in section 3. The outgoing brine temperature for the BAU case is between the other cases for all three sections, as heat is always extracted from all three sections simultaneously. As soon as the total mass flow is increased from 35 kg/s to approximately 50 kg/s, heat is extracted from all three sections for each scenario, except for scenario 312, where the heat demand is met by sections 3 and 1 (Fig. 8b).

3.4. *Brine temperature evaluation per section for all scenarios over 20 years*

Fig. 9 shows the daily-averaged outgoing brine temperature for the four investigated prioritization scenarios and is used to evaluate the influence of the prioritization scenario on the outgoing brine temperature for each section. Over a 20-year period. the outgoing brine temperature slightly increases (by about 1 °C) in all three sections. The lowest daily-averaged outgoing brine temperatures are approximately −2 °C for all three sections during the first simulated year. The lowest temperatures in sections 1 and 2 occur for Scenario 123 (Fig. 9a and b), whereas in Section 3, the lowest temperatures occur for Scenarios 321 and 312 (Fig. 9c). This finding is consistent with the results of the one-year simulation.

3.5. *Brine temperature evaluation per scenario for all sections over 20 years*

Fig. 10 shows the daily-averaged outgoing brine temperature in the three sections for the four investigated scenarios. There is one subplot per prioritization scenario to visualize the outgoing brine temperature in each section. A similar upward trend over a 20-year period, as shown in Fig. 9, can be seen regardless of the scenario selected. However, there are some notable differences in the ranges of the temperatures. The BAU scenario shows a minimum outgoing brine temperature above 0 °C, compared to a minimum temperature of approximately −2 °C for all the three other scenarios. A bigger temperature drop in the prioritized section is also evident in Fig. 10b–d.

4. Discussion

This study indicates that the order of prioritization of the sections at Kalnes has little impact if the BTES runs at near-maximum mass flow rates. The outgoing brine temperatures were similar for all sections when all sections are used simultaneously. In fact, the temperature only seems to depend on the total mass flow in the system, which makes it possible to proportionally distribute the heat outtake or input across sections (RQ1).

When it comes to the evolution of the outgoing brine temperature for the investigated scenarios, this study shows that the section with the highest priority has a lower outgoing brine temperature when heat is extracted. The prioritized section has a higher outgoing brine temperature when heat is injected than the BAU scenario. This is regardless of the distance between the sections. This means that it is possible to have targeted heat extraction/injection from specific sections, and there is minimal interference between sections (RQ3).

The expected impact of the current operational strategy of the BTES in a 20-year perspective is an increase of the outgoing brine temperature over time (RQ2). This is true for the BAU case but also for each section in all scenarios. In the BAU case, the temperature in each section will be well above freezing, according to the simulation. Given that the model slightly overestimates this temperature in the heating season, the real system may not be as warm. However, this is still a positive and promising finding since the studied BTES has previously had issues with low brine temperatures.

When it comes to the viability of the different strategies for the BTES, it appears in this case that the BAU strategy is the most sustainable for the borehole field at Kalnes (RQ4). If a section could regenerate faster than another or store heat more efficiently, targeted heat injection/extraction would have been an interesting approach. However, in this case, all borehole sections behave similarly (at proportional mass flow rates) and targeting any section depletes it more than it would in a BAU strategy. This creates larger temperature swings without benefitting the rest of the system. One way to improve the heat storage would have been to plan the BTES with a different geometry. The investigated system has two rectangular and one trapezoid borehole sections. These geometries lead to higher energy losses to the ambient rock formation compared to a concentric circular shape, which allows dividing the sections as rings. In that way, the mid-section would allow for heat storage at higher temperatures, and the outermost section would have the relatively lowest temperatures, thus reducing energy losses to the ambient ground. This type of zoning would also be favorable to establish dedicated sections for heating or cooling and to achieve higher temperatures in the core. Furthermore, for both systems (real and simulated), there seems to be a lack of thermal interference between the three sections. From the measurements it is not possible to conclude on a clear thermal interference between boreholes within one section, but it is expected that the boreholes within each section interact thermally due their close distance towards each other. This could be expected as a typical radius of thermal influence of a single borehole in the ground per year is six to seven meters [30], which is about the physical distance between the boreholes at Kalnes (Fig. 2).

Finally, it is worth noting some of the limitations of this study due to assumptions made. For the modelling of the outgoing brine temperature over a 20-year period, the same hourly input data for the total mass flow in the borehole field as well as the injected and extracted energy to and from the borehole field were used for each year. This is not entirely representative of reality if the year 2020 is not an average operational year for the system and can lead to bias in the 20-year projection. In reality, different hourly energy demands depend on weather conditions, and further work should consider using a weather file, which may be more representative of a standard year and morphed version of this file to consider the impacts of climate change on the heating and cooling demand of the hospital.

Future work on this borehole field will focus on evaluating less restrictive assumptions on the selected mass flow rates (e.g., letting the system decide a flow rate based on the energy requirement alone), evaluating more time varying prioritization strategies (e.g., seasonal), and consider more realistic energy load profiles and weather patterns for the long-term evaluations.

5. Conclusion

This study investigates the impact and viability of different operational strategies for targeted heat injection and extraction from a large borehole field which is used as a BTES. The borehole field is connected to the Kalnes hospital complex in southern Norway. A model in the dynamic simulation software tool IDA ICE is developed to simulate the outgoing brine temperature from the BTES over a 20-year period.

Regarding model validation, the ground parameters in the model are first calibrated and validated using measurement data from the initial thermal response test carried out in 2013. Then the model is slightly recalibrated and validated again with hourly measurement data from Kalnes for the year 2020. In this second calibration, the initial ground temperature of the model is adjusted to fit the hourly measurements from 2020. An MAE of ca. 1 °C shows a satisfactory accuracy of the model. Visual validation of the model predictions and measurements shows that the model predicts slightly higher outgoing brine temperatures during the heating season and lower temperatures during the cooling season compared to the measurements from the real-life system. The model is then used to evaluate the outgoing brine temperature in each of the three sections of the BTES at Kalnes under the operational conditions in 2020 and over a 20-year horizon. The investigation compared the impact of the current operational strategy of the BTES to alternatives in which specific sections of the BTES are prioritized for heat extraction/injection. For this, three different scenarios that prioritize the three sections of the borehole field in a different order are compared to a business-as-usual scenario from 2020 in which all three sections are charged/discharged simultaneously.

The results of the simulation show that the outgoing brine temperature is strongly dependent on the mass flow rate used in the system and that all sections have very similar behavior. When a section is prioritized for heat extraction or injection, the temperature in this section would notably increase or decrease, which indicates that it was possible to have targeted heat injection/extraction. When considering a 20-year perspective, the average temperature of the outgoing brine temperature increases slightly (by about 1 °C) in all three sections in all scenarios. Comparing the four investigated scenarios for each borehole section separately, there is only very little difference between the scenarios as long as the total mass flow rate in the BTES is close to the design mass flow rate of 70 kg/s. The difference of the simulated temperatures among the four scenarios is smaller than the RMSE, or in the same order of magnitude. The RMSE of the model is the same for all investigated scenarios, thus a relative comparison of the strategies is done with the same RMSE. Therefore, the reliability in terms of simulating the real-world performance of the BTES system is the same for each of the scenarios. However, it is also shown that the most viable scenario for the BTES at Kalnes is the so-called BAU scenario in which all sections are charged and discharged simultaneously. This is because none of the sections has a superior storage or heat regeneration capacity and prioritizing sections only leads to more significant temperature swings in the ground. The BAU operational strategy allows having a higher temperature in all sections and reduces the risk of low brine temperatures in the system. This study therefore confirms

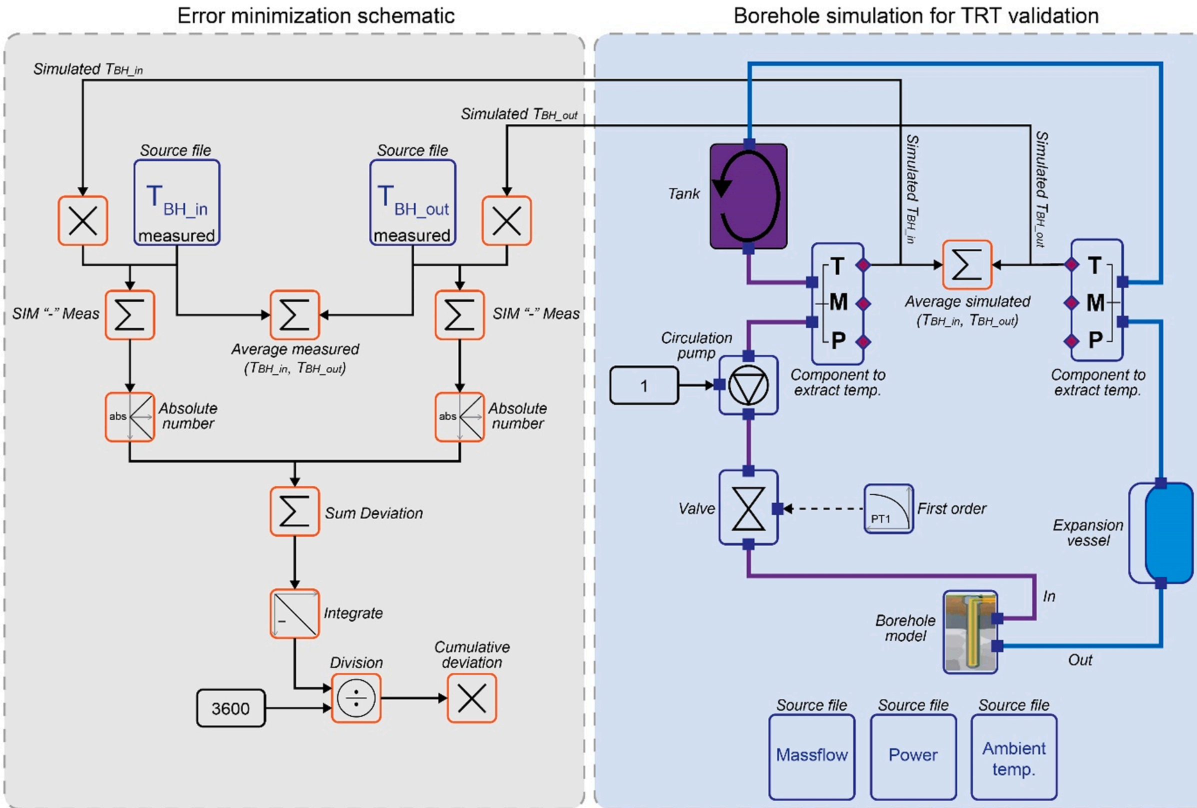

Fig. A1. Error minimization process implemented in IDA ICE.

previous findings from other studies. This study shows that the system can be controlled in the current way (BAU-case) in the next few years without risking too low ground temperatures adhering to the given ambient conditions.

Further work should investigate different prioritization scenarios, where the mass flow rates are not predetermined as in this study and where the model can select which section of the BTES to use based on the energy demand and the current temperature in each section. In this way, the order of prioritization would not be predetermined and possibly allow for more rotation of the prioritized section to not deplete the ground as much.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix

TRT calibration method

The error minimization process applied for this work in IDA ICE is presented in Fig. A.1. The right part of the figure includes the simulation of the borehole for the TRT validation, whereas the left part of the figure shows the schematic for the calculation of the cumulative error between the measured and simulated brine temperatures.

Measurement data from the real-life TRT is fed to the simulation model in the form of time series, e.g., for the mass flow [kg/s], the heat injected into the borehole [W], the ambient air temperature [°C], the brine temperature into the borehole [°C] and the brine temperature out of the borehole [°C]. The simulation loop includes an expansion vessel, a 1-node tank model, a circulation pump, a valve for flow control and the borehole model. PMT-sensors measure pressure, mass flow and temperatures of the brine at the supply and return side of the BTES field. The circulation pump gets a signal of "1″, meaning that it is switched on all the time. The valve is used to control the mass flow of the brine using the logged mass flow from the real-life TRT as inputs. The "expansion vessel" is included as it helps to get a more stable simulation and thus to avoid/reduce the risk of numerical errors. The "tank" is included as a component because the source file for "Power" which contains the TRT measurements for the heat injected into the borehole is connected to the power output parameter of the tank component. The tank has a volume of 10 L, which can be considered negligible compared to the total volume in a borehole of 250 m depth.

Error calculation

The mean absolute error (MAE) is an arithmetic average of the absolute error between a predicted/simulated and measured value. It is calculated as:

$$MAE = \frac{\sum_{i=1}^{n} |\hat{y}_i - y_i|}{n} \quad (A1)$$

The mean bias error (MBE) gives an indication of the total difference between the measured and the predicted value from the simulations [18] and is calculated by

$$MBE = \frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)}{n} \quad (A2)$$

with $\hat{y}_i$ and y_i being the simulated and measured value at instance i, and n being the number of instances used in the calibration. The root mean square error (RMSE) is calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{n}} \quad (A3)$$

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