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GOES-CH
Geothermal based Optimized Energy Systems

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Zusammenfassung

Das Hochtemperatur-Erdsondenfeld (HT-BTES) auf dem Empa-Campus in Dübendorf, Schweiz, ist ein innovatives Pilotprojekt, das darauf abzielt, Technologien zur geothermischen Energiespeicherung voranzutreiben. Das System, das in die Fernwärmenetze des Campus integriert ist, besteht aus 144 Erdsonden, die mit einer Vielzahl von Messsensoren ausgestattet sind, welche umfangreiche Daten zur Leistungsüberwachung liefern. Diese Sensoren sind entscheidend, um die betriebliche Effektivität des Systems zu bewerten und Erkenntnisse zu gewinnen, die zukünftige Geothermieprojekte in der Schweiz beeinflussen werden. Das Pilotprojekt ist auch von zentraler Bedeutung, um den plattformbasierten Designansatz (PBD) zu testen und zu validieren, der darauf abzielt, die Einführung von geothermischen Energiesystemen in der Schweiz zu vereinfachen und zu standardisieren.

Das HT-BTES-System auf dem Empa-Campus dient als flexible experimentelle Plattform, auf der verschiedene numerische Modelle sowohl für Entwurfs- als auch für Steuerungszwecke getestet werden. Diese Modelle bewerten den Einfluss von Speicherkapazität, Wärmeübertragung, Temperatur- und Betriebseffizienz auf das System und optimieren gleichzeitig die Interaktionen zwischen dem HT-BTES und den Wärmepumpen sowie Kühlsystemen des Campus. Es werden auch steuerungsorientierte Modelle zur dynamischen Steuerung der Massenströme im BTES entwickelt und um die verschiedenen Durchflussvarianten der Einspeisung in die Erdsonden (z.B. in Serie oder parallel) zu optimieren. Eines der Hauptziele ist es, diese Modelle zu vereinfachen, ihre Komplexität zu reduzieren und dabei die Genauigkeit beizubehalten, um sie auf andere geothermische Energiesysteme in der Schweiz besser anwenden zu können.

Die Umsetzung des HT-BTES-Systems stieß jedoch auf mehrere Herausforderungen. So wurde ein paralleles Projekt gestartet, um die Auswirkungen des HT-BTES auf den Untergrund zu untersuchen. Diese erforderte die Erfassung von Parametern aus dem thermisch ungestörten Erdreich, d.h. es mussten Messreihen durchgeführt werden, bevor man den Speicher ein erstes Mal geladen hat. Diese führte zu Verzögerungen bei der Inbetriebnahme. Darüber hinaus führte ein noch unbekannter Fehler während der Vorabtests zu einem Brandvorfall, bei dem Pumpen und Ventile beschädigt wurden. Dieser Unfall hat die Inbetriebnahme des Systems weiter verzögert, sodass die erste Betriebssaison nun voraussichtlich auf das 2. Quartal 2025 verschoben wird. Trotz diesen Herausforderungen hat das Pilotprojekt wertvolle Lehren und Erkenntnisse geliefert, insbesondere in der Aufbauphase. Diese Lehren, die in diesem Bericht detailliert beschrieben werden, werden entscheidend sein, um das Design und den Betrieb des HT-BTES-Systems zu verbessern und die PBD-Methodik weiter zu verfeinern.

Résumé

Le système de stockage d'énergie thermique par sondes géothermiques à haute température (HT-BTES) sur le campus de l'Empa à Dübendorf, en Suisse, représente un projet pilote innovant visant à faire progresser les technologies de stockage d'énergie géothermique. Le système, intégré aux réseaux de chauffage urbain du campus, se compose de 144 sondes équipées de divers capteurs de mesure qui fournissent des données étendues pour le suivi des performances. Ces capteurs sont essentiels pour évaluer l'efficacité opérationnelle du système et recueillir des informations qui guideront les futurs projets géothermiques en Suisse. Le projet pilote est également essentiel pour tester et valider l'approche de conception basée sur une plateforme (PBD), destinée à simplifier et à standardiser l'adoption des systèmes d'énergie géothermique en Suisse.

Le système HT-BTES du campus de l'Empa sert de plateforme expérimentale flexible où différents modèles numériques seront testés à la fois pour la conception et pour le contrôle. Ces modèles évaluent l'influence de la taille du stockage, du transfert de chaleur, de la température et de l'efficacité opérationnelle sur le système, tout en optimisant les interactions entre le HT-BTES et les pompes à chaleur ainsi que les refroidisseurs du campus. En plus de leurs capacités axées sur la conception, des modèles orientés vers le contrôle ont été développés pour gérer des conditions opérationnelles

dynamiques, telles que les débits massiques et les configurations de sondes (en série ou en parallèle). L'un des principaux objectifs est de simplifier ces modèles en réduisant leur complexité tout en conservant leur précision, afin de les rendre plus applicables à une adoption plus large dans d'autres systèmes géothermiques en Suisse.

Cependant, la mise en œuvre du système HT-BTES a rencontré plusieurs défis. Un projet parallèle a été lancé pour étudier l'effet du HT-BTES sur le sol environnant, ce qui a nécessité la collecte de mesures de référence dans un sol non perturbé. Cette exigence a contribué aux retards dans la mise en service. De plus, lors des tests préliminaires, une défaillance d'un composant a provoqué un incendie, endommageant des pompes et des vannes. Cet incident a encore retardé la mise en service du système, la première saison d'exploitation étant désormais reportée au deuxième trimestre 2025. Malgré ces défis, le projet pilote a fourni des enseignements et des informations précieuses, notamment au cours de la phase de mise en service. Ces leçons, détaillées dans ce rapport, seront essentielles pour améliorer la conception et le fonctionnement du système HT-BTES et pour affiner la méthodologie PBD.

Summary

The High-Temperature Borehole Thermal Energy Storage (HT-BTES) system at the Empa campus in Dübendorf, Switzerland, represents an innovative pilot project aimed at advancing geothermal energy storage technologies. The system, integrated with the campus's district heating networks, consists of 144 boreholes equipped with a variety of measurement sensors that provide extensive data for performance monitoring. These sensors are crucial to assessing the system's operational effectiveness and for gathering insights that will inform future geothermal projects in Switzerland. The pilot is also key to testing and validating the platform-based design (PBD) approach, which is intended to simplify and standardize the adoption of geothermal energy systems in Switzerland.

The HT-BTES system at the Empa campus serves as a flexible experimental platform where different numerical models will be tested for both design and control purposes. These models evaluate the influence of storage size, heat transfer, temperature, and operational efficiency on the system while also optimizing the interactions between the HT-BTES and the campus’s heat pumps and chillers. In addition to their design-oriented capabilities, control-oriented models have been developed to manage dynamic operational conditions, such as mass-flow rates and varying borehole layouts (in-series or in-parallel). One of the key goals is to streamline these models by reducing their complexity while retaining their accuracy, making them more applicable for broader adoption across other geothermal energy systems in Switzerland.

However, the implementation of the HT-BTES system has encountered several challenges. A parallel project was initiated to study the effect of HT-BTES on the surrounding ground, which necessitated the gathering of baseline measurements from undisturbed soil. This requirement contributed to delays in commissioning. Furthermore, during preliminary testing, a component failure resulted in a fire incident, damaging pumps and valves. This accident has further postponed the system's commissioning, with the first operational season now delayed until Q2 2025. Despite these challenges, the pilot project has provided valuable lessons and insights, particularly in the commissioning phase. These lessons learned, detailed in this report, will be critical in improving the design and operation of the HT-BTES system and in refining the PBD methodology.

Contents

Abbreviations

STES: seasonal thermal energy storage

BTES: borehole thermal energy storage

CHP: combined heat and power

HT: high-temperature

DTS: Distributed Temperature Sensing

PBD: platform-based design

GHX: ground heat-exchanger

MPC: model predictive control

RBC: rule-based control

MHMPC: multi-horizon model predictive control

HVAC: heating, ventilation, and air conditioning

KPI: key performance indicators

MPC: model predictive control

TES: thermal energy storage

SPF: seasonal performance factor

1 Introduction

1.1 Background information and current situation

Space heating accounts for 33.8% of the total energy consumption in Switzerland, with almost two third of this supplied by fossil fuels [1]. Increasing the share of renewable energy generation within the heating and cooling sectors is therefore crucial to hit the national decarbonisation targets [2]. However, the seasonality of both energy demand and generation poses significant challenges. Seasonal thermal energy storage (STES) addresses this mismatch by storing excess of energy generated during low-demand periods, e.g. summer, and released during high-demand periods, e.g. winter. Among the different types of STES, borehole thermal energy storage (BTES) is a promising and cost-effective technology to store thermal energy underground using boreholes [3]. Such a technology is particularly attractive for its potential to store large amounts of energy over long periods with minimal environmental impact.

Historically, BTES systems were integrated into large-scale solar thermal plants designed to operate at high temperatures and supported district heating networks. Examples of such systems are the Drake Landing solar community in Canada [4], and the solar district heating in Crailsheim, Germany [5]. Overall, such systems achieved good results in terms of solar fraction, but the overall efficiency of the storage was generally lower than expected at the design stage. Consequently, BTES systems are now generally operated at lower temperatures [3], to reduce heat losses to the surrounding ground and to enable the integration of low-temperature waste heat sources. However, high-temperature (HT) BTES possess the key advantages of higher energy density, integration with a broader range of thermal processes and improved heat transfer efficiency. Currently, none well-instrumented HT-BTES that could serve as a research platform to test data-driven characterization methods and operational strategies (e.g. the effect of varying the operational storage temperature, or the plumbing configuration) is present [6]. Benchmarking modeling methods and novel control strategies with experimental data can ensure to achieve the required accuracy and ultimately to improve performance. This is particularly important for BTES systems, as they are heavily affected by boundary conditions, and the performance of experimental implementation does not always match with the design expectations. Several numerical models have been developed to support energy system design [7], and few of these studies included BTES systems [8–10]. Further, a limited number of studies consider optimal control of seasonal thermal storage, such as [11], where a Model Predictive Control (MPC) approach targeting the Drake Landing solar community was proposed or by Fiorentini and Baldini [12], using the design of the Empa campus as a case study. However, no efforts have been made so far to validate these models with experimental results and to calibrate these models to reduce the mismatch in predictions between design and operational phases.

All in all, the current design and operation approaches struggle to deal with the high complexity of decarbonized energy systems, resulting in low deployment rates of innovative technologies such as geothermal reservoirs. Hence, the standardization of the design process is required to accelerate and facilitate the successful scaling of geothermal-based projects to substitute the current fossil fuel-based energy system elements with renewable solutions. To overcome this challenge, this project proposes the use of the platform-based design (PBD) as methodology to design energy systems including geothermal reservoirs. The PBD methodology manages and de-risk the complexity of integrated energy system design, leading to affordable, reliable and fit-for-purpose solutions [13].

1.2 Purpose of the project

The GEOTHERMICA GOES project aims to drive the transition to renewable heating and cooling through geothermal-based optimized energy systems. This international effort employs a Platform-Based Design (PBD) approach to create standardized and scalable tools for integrating geothermal energy across subsurface, city, and building scales. The project involves partners from Switzerland, Denmark, Austria, and the USA. The work packages of the GEOTHERMICA GOES project are structured as follows:

- **Work Package 1** deals with **subsurface energy storage** and is led by the **Lawrence Berkeley National Laboratory (LBNL)**, focusing on assessing geothermal heat and cold storage potential and developing surrogate models for application across project scales.
- **Work Package 2** deals with the **Technology and Building scale** and is led by the **Karlsruhe Institute of Technology (KIT)**, aiming to predict the limitations and potential of energy conversion and storage technologies at the building level.
- **Work Package 3** deals with the **Neighborhood and City scale** and is led by the **Austrian Institute of Technology (AIT)**, producing energy demand maps and conducting techno-economic analyses to support urban planning.
- **Work Package 4** deals with **Integration** and is led by **Empa**, focusing on defining standardized interfaces based on the PBD approach and coordinating information exchange between models and tools across the project scales.
- **Work Package 5** deals with **Pilot Sites and Case Studies** and is led by **Aalborg University (AAU)**, testing the integrated models and tools at selected pilot sites and case studies to validate their practical application.

The integration of a high-temperature borehole thermal energy storage (HT-BTES) system at the Empa campus is one of the selected pilots for the GEOTHERMICA GOES project. This report details the activities related to HT-BTES integration at Empa.

The overarching goal of the project is to develop a holistic framework for integrating geothermal-based energy systems across different sectors, utilizing a platform-based design (PBD) concept [13]. Such a framework is designed to accelerate and facilitate the uptake of geothermal energy solutions in Swiss energy systems. The project relies on a flexible experimental platform at the Empa campus to develop and validate models for a high-temperature borehole energy storage system. Consequently, the main contributions of the Swiss pilot to the GEOTHERMICA GOES project are twofold:

(i) **Testing of the PBD Framework**: Optimizing energy system designs at neighborhood and city scales, standardizing geothermal technology models, integrating technologies into representative sites, and developing simplified surrogate models to support city-scale energy planning.

(ii) **Utilization of the HT-BTES at Empa Campus**: Employing the HT-BTES system as a research platform to test numerical models, control strategies, and design choices. The well-instrumented BTES system allows for benchmarking models and novel control algorithms using experimental data. Ultimately, the insights gained will improve both the design and operation of HT-BTES.

1.3 Objectives

In agreement with the project's purpose stated in section 1.2, the specific objectives of the project can be summarized as follows:

1) How can geothermal technologies be optimally integrated into energy systems, and what is their potential impact in the Swiss context? Can a structured platform with standardized modeling and interface methods help this decision-making at different scales?
2) What are the critical parameters to be identified on a new potential site for using geothermal energy, and how can the assessment be standardized?
3) How can simplified surrogate models be developed to aid the concept transfer between different sites, thus supporting city planners and governmental agencies?

4) How can seasonal storage technologies be operated more efficiently through optimized management?

5) How can the proposed platform and demonstration activities support knowledge transfer to different sites?

Additional objectives are set to evaluate the specific benefits of integrating an HT-BTES in the Empa campus:

a. Quantification of reduction of fossil fuel consumption and annual emissions on the Empa/EAWAG site through seasonal heat storage and by means of temperature gradients in the HT-BTES.

b. Quantification of additional waste heat recovery obtained from seasonal thermal storage and long-term heat losses from the storage.

c. Detailed monitoring and understanding of the temperature distribution in the different HT-BTES rings.

d. Influence of the different backfill materials used during the construction on the temperature profiles of the HT-BTES.

2 Description of facility

The HT-BTES is located in Dübendorf and is connected to the Empa campus. The system is built partly below the newly built parking garage. The connections of the HT-BTES system with the campus district network are situated in the underground intermediate basement between the parking garage and the multifunctional building. A rendering of the HT-BTES is reported in Figure 1, along with the soil composition.

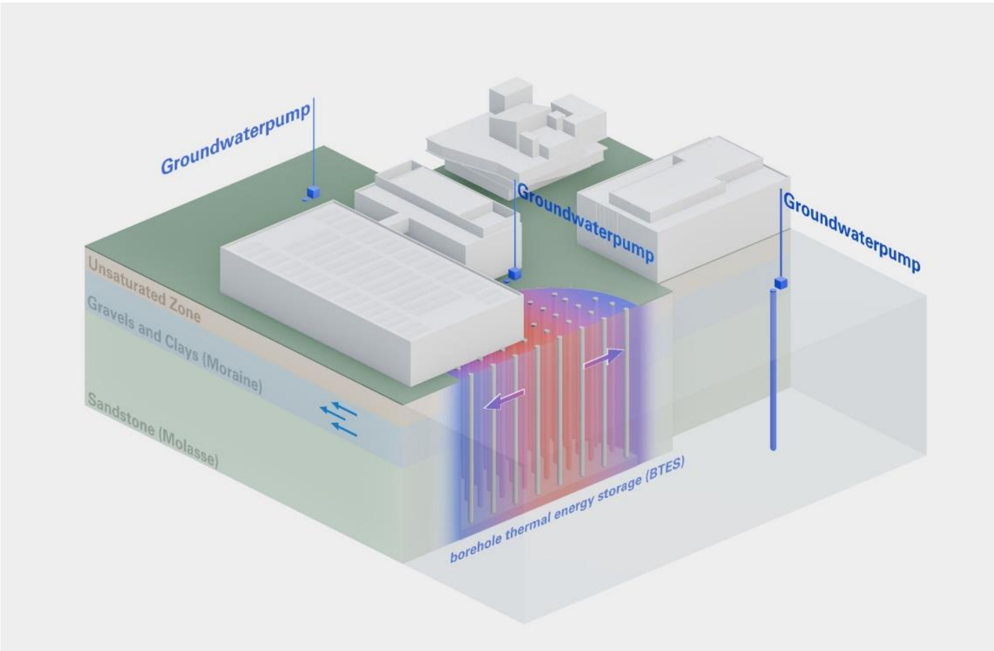


Figure 1 Rendering of the HT-BTES at the Empa campus.

The HT-BTES system consists of 144 boreholes, each drilled to a depth of 100 meters with a diameter of about 140mm. These boreholes are positioned to maximize the thermal interaction with the surrounding ground, as can be appreciated in Figure 2. Specifically, the outer rings of the configurations provide insulation to the inner ones, which can then be used to store high-temperature heat. The storage system is charged and discharged via the district heating network of the Empa campus (see Table 1). This relies on three different temperature levels: the HT network at ≈65 °C, the medium-temperature (MT) level at ≈35 °C and the low-temperature (LT) level at ≈7 °C. Concerning the charging of the HT-BTES, this is made via the HT network during summer and is mainly driven by the waste heat recovered from electrically driven cooling machines. While the design charging temperature is, as mentioned, of ≈65 °C, a maximum soil temperature of 50 °C is envisioned [12]. The boreholes are equipped with U-tube heat exchangers that circulate a heat transfer fluid to store thermal energy in the subsurface during periods of excess heat production and retrieve it when needed. The outer ones are made of PE-100 RC, and the inner ones are made of PE-100RT to withstand higher temperatures (up to 65°C).

Table 1: Operating phases over the year

1) In the steady state of the storage tank operation. It Is reached after approx. 6 years.

2) Depends on the direct ambient temperature of the ground heat exchanger.

Operating phase	**Nominal input temperature**	**Nominal return temperature**	**Nominal energy flow to/from BTES**	**Direct use mid-temperature network**
Summer (Charging)	35° - 65°C	22°C - 40°C 1)	450-600 kW 2)	-
Winter (Discharging)	25°C - 8°C	12°C - 45°C 1)	450 kW 1)	100 kW 1), 2)
Spring (Charging)	35°C	22°C - 28°C 1)	450-800 kW 2)	300 kW 1), 2)
Autumn (Charging)	45° - 65°C 1)	33°C - 40°C 1)	450-500 kW 2)	-

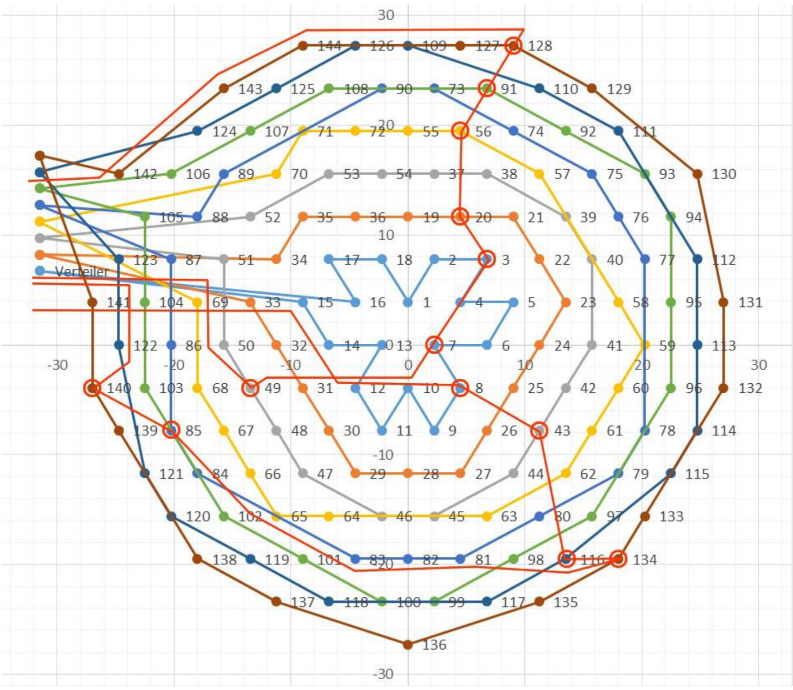


Figure 2 Structure of the geothermal probe field. The 8 concentric rings with 18 probes each are visible (144 probes in total). The probes that have been equipped with fibre optics for temperature measurement with laser are marked in red.

Figure 3 illustrates the P&ID of the HT-BTES system. This diagram provides a detailed view of the various components, including pumps, valves, sensors, and heat exchangers, and their interconnections. The 144 boreholes are represented in the light blue box on the right-hand side of the figure and are connected to a series of valves that ensure flow regulation, as well as can be used to define the types of operation of the boreholes between in-series and in-parallel operation. That is, The HT-BTES can be operated in a configuration with eight in-series circuits including 18 GHXs each, a configuration of all the GHXs connected in parallel, or any combinations between these two extremes. The different operational types are key to achieve desired storage, as well as discharging temperatures. Each one of the circuits is instrumented with bi-directional energy meters, measuring the HTF flow and inlet and outlet temperature from the field, as detailed in [14].

For serial operation, it is necessary that the flow direction of the water flowing through the BTES can be reversed. In summer (charging period), Water initially flows through the inner rings, followed by the outer rings. During winter, the operation is reversed, with water flowing first through the outer rings and then through the inner ones. This makes it possible to achieve high temperatures in the center of the storage in summer. In winter, low feed-in temperatures at the edge minimize overall heat losses and the return temperature to the heat pump is increased. This is achieved with the 4 valves, which are placed between the storage interface and the heat exchanger group.

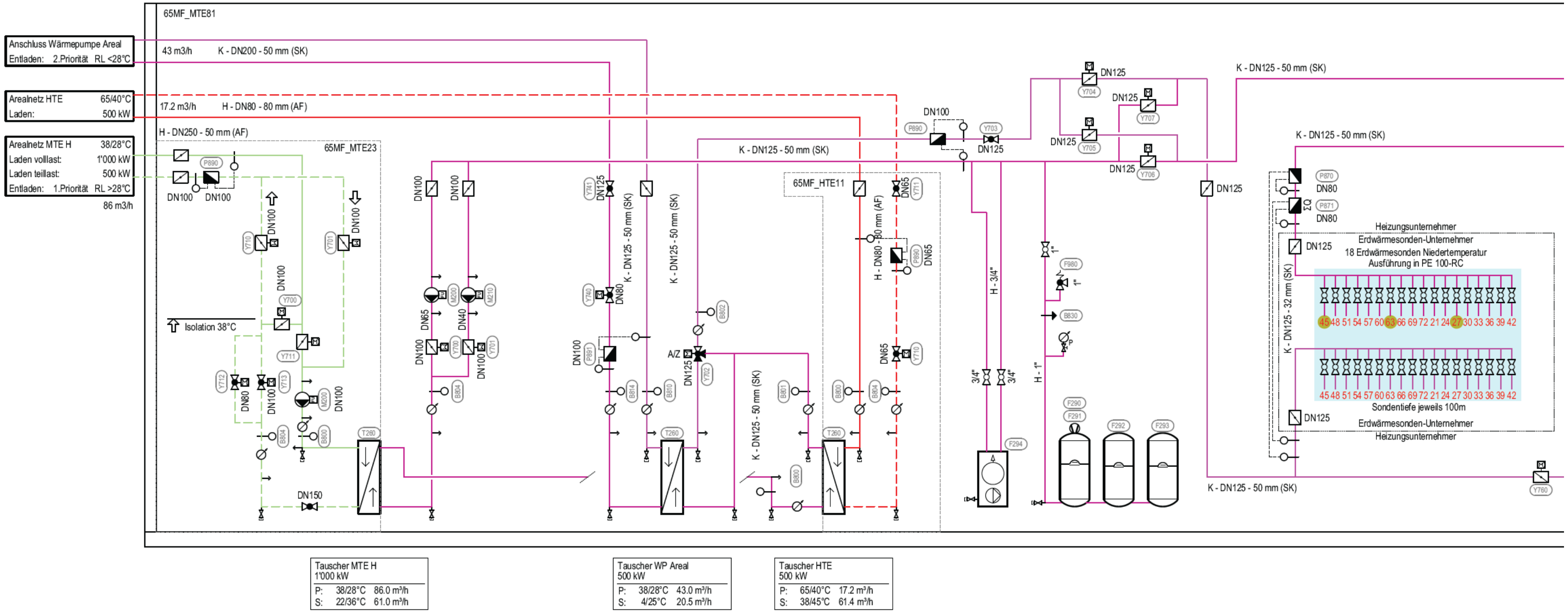


Figure 3. P&ID scheme of the HT-BTES system at Empa.

The integration of the BTES system with the Empa campus is depicted in Figure 4. Here, the generations and short-term storage units (water tanks) of the district heating networks are represented, with the relative sizes and capacities reported in Table 2. During periods of high demand, the key generation units are the combined heat and power (CHP) units sourced by gas, as well as gas burners. Both heat pump and chiller units are used to upgrade and downgrade heat between the different temperature levels of the network. During summer, the waste heat from the chiller units will be directed to the HT-BTES and is expected to constitute the majority of the charging heat for the storage system [15].

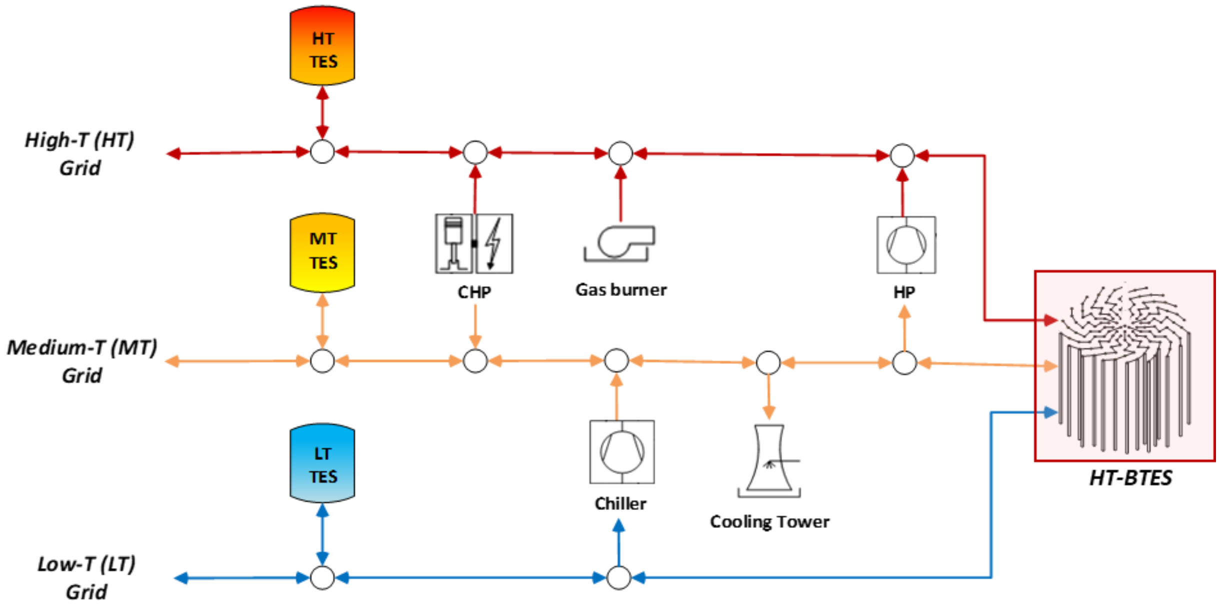


Figure 4. Schematic of the HT-BTES system within the Empa campus.

Table 2 Sizes of the key conversion units of the Empa campus.

HT network

Device	Size [kW]
Heat pumps	500
Gas boiler 1	900
Gas boiler 2	2000
CHP	577
Total	3977

MT network

Device	Size [kW]
Network	300
Heat pump	429
Exhaust condenser CHP	149
Total	878

LT network

Device	Size [kW]
Chiller 1	630
Chiller 2	630
Chiller 3	630
Total	1890

3 Procedures and methodology

3.1 The platform-based design methodology

One of the overarching goals of the project is to support the development of the Platform-Based Design (PBD) approach to facilitate the adoption of geothermal energy systems in Switzerland. The PBD approach draws inspiration from industries like semiconductors and automotive, employing a digitalized and modular design strategy. PBD separates functions from architectures, identifies abstraction levels for analysis and optimization, and allows component repurposing at all levels. This methodology enables holistic energy system designs from single buildings to city scales, fostering innovation, scalability, and improved performance across the energy sector. A detailed explanation of the PBD approach and its conceptual application to energy systems can be found in [13].

Within the GOES project, the HT-BTES at the Empa campus constitutes one of the case studies to implement and test the PBD approach, as depicted in Figure 5. The Empa case study focuses on the lowest levels of abstraction of the design problem, specifically at the building and equipment scales. Here, it is crucial to ensure reliable information exchange between system design, equipment, installation, and envisioned system operation. Models to support the design decision-making process will be tested, aiming to achieve a meet-in-the-middle approach between these different levels of abstraction. A key aspect is, therefore, the interconnection between these levels, with the aim of standardising such interconnections to automate and simplify the holistic design process. Efforts made in this direction are summarised in Section 4.1.

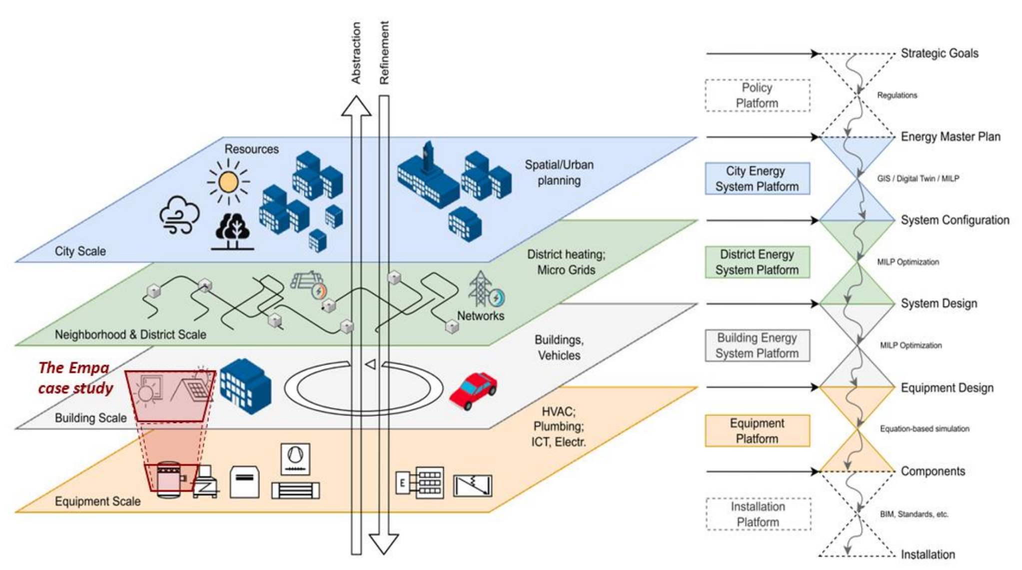


Figure 5 Spatial scales of decentralized energy systems from [13] with representation of the Empa case study. On the right, the different scales are assigned to their corresponding platforms. The tools mentioned on each platform are exemplary.

3.2 Numerical modelling

Within the GOES project, several numerical models will be validated against the collected experimental results. The overarching goal is to define the accuracy of the models, calibrate these models to improve accuracy, and identify if adopted assumptions lead to significant errors and, thus, poor design and operational choices. The numerical models to be tested are categorized into two main groups [16]:

(i) **Design-oriented modelling**: these models focus on selecting the layout, technology assets, and sizes for the energy system to meet goals such as minimal total cost or emissions or maximized energy efficiency. Consequently, these models are generic, capturing a broad range of technologies and sizes. A common assumption for design-oriented modelling is perfect knowledge of the system boundary conditions, which might not fully represent real system operations post-construction. Tools used in this context include BEMS (Building Energy Modelling and Simulation), TRNSYS, and the Ehub tool [17].

(ii) **Control-oriented modelling:** these models aim at optimizing the operation of an energy system, targeting goals like minimizing operational costs, emissions, and energy waste. Control-oriented models are specific to the energy system under analysis, referring to a fixed layout, technologies, and sizes. They require a higher modelling level of fidelity compared to design-oriented models. Due to the increased specificity of the physical systems treated, model calibration is possible. Key additional features to consider for control-oriented models are energy supply security and the uncertainty in demand and RES availability forecasts. Control-oriented models utilize tools and methodologies specific to the control of integrated systems, such as Modelica, often requiring sophisticated algorithms like model predictive control (MPC) [11].

As reviewed in [16], these modeling types are often treated separately. Consequently, the lessons learned during the operation of the energy system are not transferred back to the design tools, leading to future poor design choices. We, therefore, aim at testing and comparing the performance (accuracy, interpretability, and computational costs) of a model repository for HT-BTES systems and to provide insights into key modelling features during the different design and operational stages. The model repository that will be tested in the course of the project is detailed in section 4.2.

3.3 Design steps for the HT-BTES at Empa

This section summarizes the design steps and decisions that led to the final configuration of the HT-BTES system. These design choices will be compared with the final recommendations from the PBD. The overarching goal is to determine what could have been done better and, thus, how the PBD methodology can facilitate the implementation of geothermal energy systems. Reporting and analyzing these design steps is crucial for identifying common mistakes, areas for improvement, and often overlooked critical factors.

In 2008, Empa and Eawag decided to seek an innovative solution for the future energy supply of the site in order to reduce CO_2 emissions. After cogeneration with wood gasification of waste wood had failed, it was decided in 2013 that waste heat should be used. The concept included waste heat storage using a geothermal borehole field (BTES) based on the ETH Hönggerberg model. Due to the planning of a new building for the chemistry laboratory, the detailed planning of this BTES was delayed until 2017, as the positioning of the building and the BTES had to be coordinated. However, this delay also made it possible to question once again whether the reduction of energy and CO_2 emissions should be the sole criteria.

Based on simulation results [15], it was recommended to the management that a geothermal borehole field should be built that allows higher storage temperatures than the undisturbed ground temperature. Hence, the HT-BTES. As previously mentioned, the advantage of this would be that a higher efficiency of the heat pumps could be achieved in winter (additional criterion of grid serviceability). However, this would result in poorer efficiency and a longer running time for the heat pump in summer. On the other hand, the positive aspect is that electricity produced in summer has considerably lower CO_2 emissions than in winter. This results in a kind of electricity storage. Simulations have shown that a reduction in total annual CO_2 emissions is possible in this way.

The proposal for an HT-BTES was approved but demanded that if the research idea failed, the storage facility could still be operated conventionally (lower storage temperature). This led to a somewhat more complex design for the power supply to the storage facility. The HT-BTES was planned in such a way that operation with uniformly higher temperatures, operation with a temperature gradient, and conventional operation were all possible. Simulation results then showed that operation with a temperature gradient (warm in the center, cooler at the edge) has the best chance of success [12], as the heat losses are low, and the temperature increase in the center is relatively high. A simulation tool was also adopted to determine the dimensions of 144 probes at a depth of 100 meters each.

According to the simulation results, the optimum distance between the boreholes would have been around 4 meters. However, due to safety considerations during drilling, the distance was increased to 4.5 meters. The closer the boreholes are placed to each other, the more likely it is that an existing pipe could be damaged if the drill slips underground.

During the construction of the BTES in January 2022, inspections revealed that the minimum requirements for the thermal conductivity of the backfill used at the beginning were not being met. High thermal conductivity is desired so that the temperature difference between the pipe surface and the ground remains as small as possible, especially at high power levels. The initially adopted filling material showed a thermal conductivity of only approx. 1.05 W/(mK) instead of the required 1.6 W/(mK), and below the manufacturer value of approx. 1.8 - 2.0 W/(mK). This backfill material was used for approx. 30% of the probes before the discrepancy in thermal conductivity was noticed. Therefore, the backfill material used was changed for the remaining probes. The new backfill material was tested with a thermal conductivity value of approx. 1.8 W/(mK).

As the HT-BTES was intended as a research project, a large number of sensors were planned. It was requested fiber optic sensor cables be installed with the geothermal probes at selected points. The idea was to record temperature profiles along the entire length of selected geothermal heat exchangers. However, one fiber of the originally planned boreholes (No. 85) was destroyed during installation, so a replacement (No. 79) had to be selected. With the approval of the GOES project and the associated need to better understand the processes on the ground, it was decided to operate a DTS (Distributed Temperature Sensing) on a permanent basis.

As a final note, it must be pointed out that communication between researchers and planners was not always optimal. The entire construction project was handed over to a general contractor, and the building services planner had never contacted the researchers. As a result, the planner was not aware of the researchers' purposes. For example, the heat exchangers were designed with a poor heat transfer rate. However, a prerequisite for the project to be completed successfully is that the thermal losses are minimal. These heat exchangers and the associated pipe diameters of the supply lines, which were too small, had to be exchanged with larger ones.

3.3.1 Delayed commissioning of the borehole thermal energy storage

The commissioning of the storage facility was postponed several times. Following the change in the energy supply concept in 2013, it was assumed that the storage facility would be in operation by 2018 at the latest. When it became clear that the storage facility was to be constructed together with the new buildings, it was assumed that the storage facility would be ready for operation in 2022. Due to the coronavirus and delays in the approval process, the aim was for the storage facility to start operating in July 2023.

However, it became clear as early as January 2023 that the water protection authorities would not grant the operating license if the consequences of the high operating temperatures for the groundwater and the subsurface were not investigated at the same time. Therefore, the ARTS (Aquifer Reaction to Thermal Storage) research project was initiated. Such a project is carried out by Eawag and funded by various cantons and the federal government. The approach chosen is to use additional observation boreholes to investigate changes in the groundwater. However, this required measurement for the undisturbed ground. It was, therefore, necessary to wait until the preparations of the ARTS project were completed before commissioning the HT-BTES system.

However, ARTS also faced unforeseen disruptions, and the commissioning of the storage facility was further delayed. To enable continuous water sampling at ARTS, the walls of the boreholes were supported with a perforated stainless steel or plastic pipe. Despite this, clay entered the middle borehole together with water and filled the borehole so that the measuring probes could no longer be inserted. The problem was rectified, and measurements of the undisturbed soil are now underway. Commissioning of the reservoir has, therefore, been scheduled for July 15th, 2024.

On June 29, 01:00, the fire department was called out because the fire alarm went off in the pump control centre of the geothermal storage system. Due to a faulty manipulation of the pumps, one pump had been working against closed valves for 18 hours. This resulted in very high temperatures and pressures, which caused the pump to leak. The leaking water destroyed the electronics of the other pumps in the room and caused a fire. The damage to the pumps and remotely controlled valves cannot be estimated in detail at the moment. It is also completely unclear how the faulty manipulation occurred and why the safety routines did not kick in. The necessary repairs cannot begin before mid-September 2024, as the spare parts cannot be delivered before then. If the repair work is delayed any further, the start of charging operation for the storage facility this year is in doubt and will have to be postponed to the heating period of 2025.

3.4 Key Performance Indicators

To describe the performance of the storage facility, various success factors were proposed and discussed in the measurement concept submitted to the SFOE [14]. The summary of these indicators can be seen in Table 3.

Table 3: Key performance indicators.

Q indicates heat, ϑ indicates temperature, E is electrical power, and m indicates mass.

KPI	Formulas
Heat capacity BTES	$C_{BTES} = \frac{Q_{BTES}}{\vartheta_{BTES} - \vartheta_{undisturbed}} = c_{p,Ground} \cdot m_{BTES}$
Annual heat loss	$Q_{loss,year} = \sum_{year} Q_{charging} - \sum_{year} Q_{discharging} + C_{BTES} \cdot \Delta\vartheta_{year}$
SPF charging and discharging of the storage	$SPF_{charging} = \sum_{year} Q_{charging,heat\ pump} / \sum_{year} E_{charging,heat\ pump}$ $SPF_{discharging} = \sum_{year} Q_{discharging,heat\ pump} / \sum_{year} E_{discharging,heat\ pump}$
Efficiency as an electrical seasonal storage	$Eff_{el.storage} = \frac{\sum_{discharge} E_{el_{HP},LT-BTES} - \sum_{discharge} E_{el_{HP},HT-BTES}}{\sum_{Charge} E_{el}}$
Proportion of heat with direct charging and discharging	$Direct\ charging[\%] = \frac{\sum_{year} Q_{direct\ charging}}{\sum_{year} Q_{total\ charging}} \cdot 100$ $Direct\ discharging[\%] = \frac{\sum_{year} Q_{direct\ discharging}}{\sum_{year} Q_{total\ discharging}} \cdot 100$
Ratio waste heat utilisation	$Ratio_{waste\_heat}[\%] = \frac{\sum_{year} Q_{BTES\ discharging}}{\sum_{year} Q_{waste\ heat\ produced\ on\ site}} \cdot 100$
Reduction of CO_2 emissions	$Reduction_{CO_2}[\%] = \frac{Emission_{without\_HP\&BTES} - Emission_{with\_HP\&BTES}}{Emission_{without\_HP\&BTES}} \cdot 100$

4 Activities and results

4.1 Platform-based design: connecting different levels of abstraction

To ensure a flexible and fast modelling of various energy systems, the GOES consortium agreed for the use of Modelica as modelling environment. Modelica can indeed use a vast range of libraries, such as [18], with the key advantages of:

- rapid prototyping, design and analysis of new control systems for buildings and districts;
- testing of integrated energy systems and products to reduce their risk prior to deployment,
- controls development, specification, verification, and deployment within a model-based design process,
- analysis of the operation of existing building systems and improvements of operation;
- export of digital twins to support operation for functional testing, verification of control sequences, energy-minimizing controls, fault detection and diagnostics.

Library [18] already contains a vast catalogue of sub-systems, such as HVAC, storage solutions, standardized control schemes, heat transfer interaction among rooms and environment, etc. Within this library, efforts have been made to the standardization of borehole walls and their interface to the ground, as can be appreciated in Figure 6.

The modelica models of a specific site are connected to subsurface models and overarching linear system design models via the PBD approach. Empa is responsible for the conceptualization of the PBD approach for energy systems, with the contributions made reported in publication [13]. Furthermore, Empa is responsible for the coordination of the efforts made within the GEOTHERMICA GOES for the application of the PBD approach to energy systems design and integration of geothermal energy.

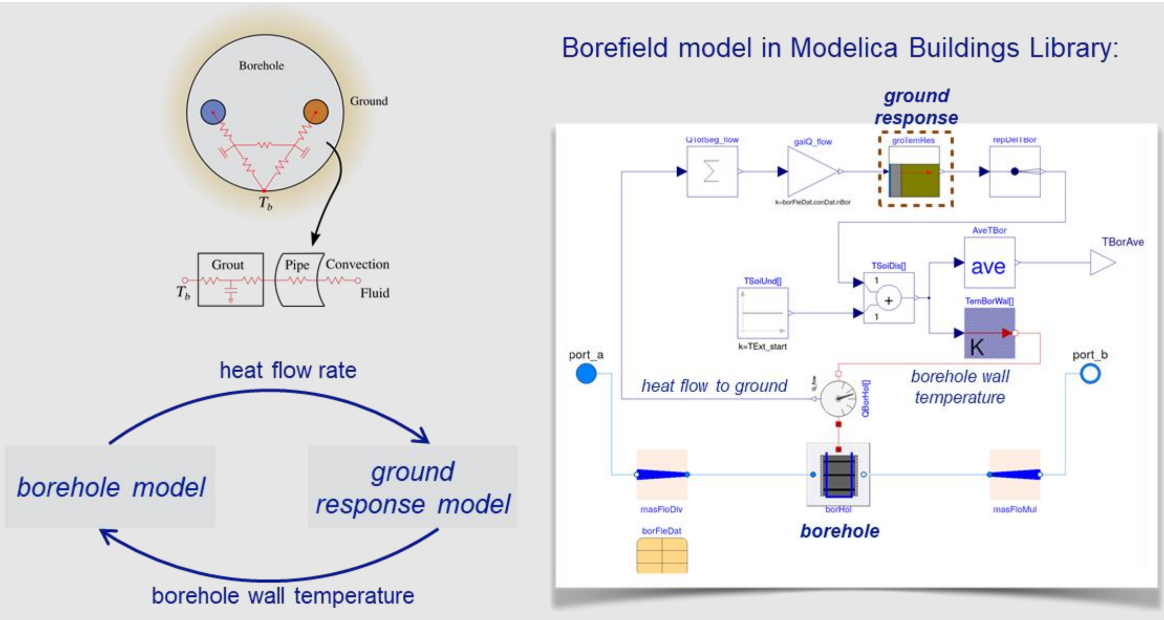


Figure 6 Standardized interface between the borehole model and the ground response model for the Modelica library [18].

4.2 Modelling repository for HT-BTES system

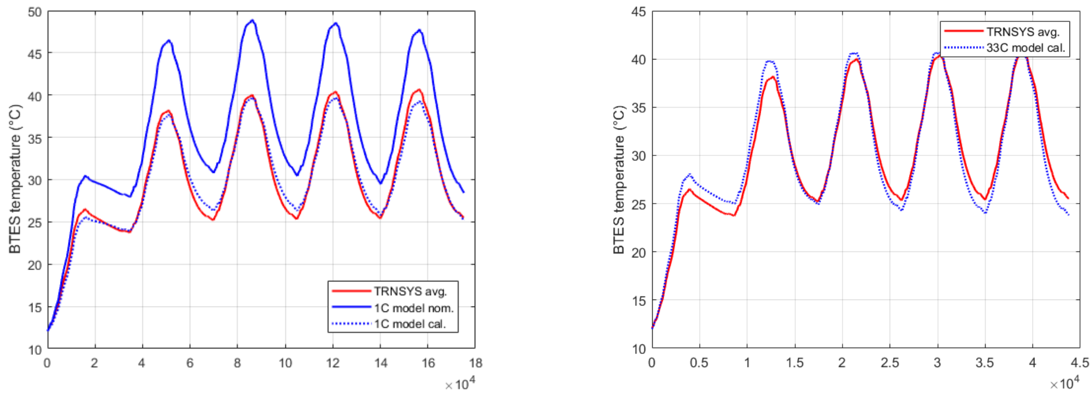
A summary of the modelling repository for design and control of HT-BTES is reported in Table 4. Three models, namely the 1C (capacitance), the 33C and the TRNSYS models have already been developed and published in journal papers. The 1C model was adopted in publications [19,20] and relied on a MILP approach to optimize the layout and sizing of an energy system adopting HT-BTES. The term 1C refers to the fact that a single borehole is treated as a long cylinder with a radius set by the distance between adjacent boreholes. In this way, a simple modelling of the seasonal storage is achieved, but at the expense of a poor representation of specific configurations. In publication [12], a control-oriented model was developed that targeted the specific design of the HT-BTES at the Empa campus, a R-C grid was developed to account for the mutual influence of the different probes. Finally, the TRNSYS [15] adopts superposition models that allow for an accurate representation of convective and diffusive heat transfer.

Table 4 Modelling repository for HT-BTES systems.

Model name	Design/control oriented	Advantages	Disadvantages	Environment	Status
1C model	Design	Simple and computationally cheap	Poor representation of spatial behaviour, and inability to handle in-series plumbing configuration.	Python	Completed, published in [19], [20]
33C model	Design and control	Suitable for control. Allows for both in-parallel and in-series pipes and Can capture influence of mass flow rate.	Assumes BTES cylindrical, uniform ground properties, and no groundwater flow.	Python	Completed, published in [12]
TRNSYS model	Design and control	The most accurate representation of convective and diffusive heat transfer	Computationally expensive and requires more detailed characterization of soil properties	TRNSYS	Completed, published in [15]
Modelica model	Control	Suitable for control and for rapid prototyping thanks to the models library.	Tbd, issues related to timestep are envisioned.	Modelica	On-going, based on [21]
ehubX model	Design	Simple and computationally cheap. System integration of STES.	Poor representation of spatial behaviour, and inability to handle in-series	Python	On-going, based on [17]

			plumbing configuration.		

For the three developed models, the BTES temperature predictions were compared. Overall, the analysis showed a temperature overestimation for uncalibrated 1C models against the TRNSYS model, which was considered as a benchmark approach in the comparison. Interestingly, calibrated 1C models lead instead to small errors and to a slight underestimation of the BTES temperature. This ultimately highlights the importance of calibrated input parameters. By increasing the number of slices considered to approximate the cylindrical borehole, i.e., 33C model, similar errors are obtained, but the behavior slightly differs, with higher temperatures predicted compared to the TRNSYS model.



(a) (b)

Figure 7 Model comparison over five-year operation including initial thermal transient for: (a) TRNSYS and 1C and (b) TRNSYS and 33C.

Concerning the control of seasonal storage, the vast majority of these systems are operated using rule-based controllers (RBC). This approach has the drawback that the controller must be manually tuned, and that human intervention is often necessary if the operating conditions change. In contrast, MPC solutions have been proposed to optimize the control input with respect to cost. However, current implementations either use a large sampling time, in which case it can only be used for high-level planning and not for direct control, or they consider short prediction horizons which don't capture the seasonal behaviour. This is because the long prediction horizon needed to optimize the yearly operation makes the problem computationally intractable. To solve this issue, a multi-horizon MPC (MHMPC) approach was investigated which significantly reduces the dimensionality of the optimization problem. The key results obtained are summarized in [22]. Additionally, temporal aggregation methods were used to mitigate the negative effects of large sampling intervals used in the baseline MHMPC. The applicability of the proposed control method to the Empa campus was studied by comparing the control performance to both RBC as well as to different MPC schemes. We show that the MHMPC scheme together with temporal aggregation has one of the lowest ideal operational costs of the compared controllers, while simultaneously performing well in terms of transient behaviour and effectively adapting to changes in operating conditions. To explore the concept of MHMPC, the work adopted the 1C model due to its simplicity and ease of integration. Future efforts will extend the use of MHMPC with more detailed modelling tools, such as the 33C model.
The models listed in Table 4 are contributions from Empa. The Modelica model mentioned will rely on the buildings library [18]. However, the available models will need to be calibrated or adapted to fit the specific case of the Empa campus.

4.3 Lessons learned during installation

In the document [6], chapter 3.2, a very comprehensive list of learnings about underground heat storage is provided. Most of the findings from [6] can also be applied to Empa's HT-BTES storage. Nonetheless, there are a few deviations or additions that should also be mentioned.

In Empa's feasibility study, simulations were carried out in 2016 using measured values of the site's cooling and heating requirements. For safety reasons, it was assumed that these values could increase by around 30% by 2030. Today, we know that the heating requirement is declining despite the construction of new buildings, but the cooling requirement has already risen to 200% by 2023. As the cooling requirement was the minimum energy factor, the dimensioning from 2016 was already too small from today's perspective.

During the planning phase, a borehole was created with exact profiling of the subsoil (minerals, groundwater) and an additional enhanced Thermal Response Testing (e-TRT) test was carried out to clarify whether flowing groundwater could lead to problems. No flow could be detected. In the final planning, the field was shifted by approx. 100 meters, and it turned out that even this small distance from the original measurement brought us into a zone with weakly flowing groundwater. It also turned out that the stratification of the minerals had changed considerably. The subsoil can therefore change quickly locally.

The pipe material in the boreholes was optimized with the help of simulations. In the "Heatstore" project [6], PEX pipes were identified as optimal. However, simulations showed that for our expected temperature range, the materials PE 100RC (for the outer area) and PE 100 RT for the inner area have higher creep rupture strengths. In order to guarantee good heat transfer from the pipes to the ground, a thermal conductivity of >1.6W/(mK) was required for the grouting. It turned out that various grouting products with high thermal conductivities are advertised on the market. However, measurements showed that products without carbon additives could hardly meet this requirement.

Fiber optic fibers are used for small-scale temperature measurement in the underground. These fibers are sunk into the borehole with the water pipes. However, there is a risk of fiber breakage. When implementing this technology, sufficient reserve fibers should be provided.

Figure 8: HT-BTES during the construction phase. The heads of the boreholes are clearly visible. Also visible, one third of the BTES is situated below the new parking slot. Picture from Kevin Olas.

4.3.1 Measuring concept

For the sake of conciseness, the measuring concept is not entirely reported in this document. A detailed description of the measuring concept can be found in [14]. A snapshot of the temperature measurements from the fiber optic cables placed along the probes can be appreciated in Figure 9. The temperature drops represent the different boreholes, with, at the moment when the snapshot was taken, higher temperature measured at ground level.

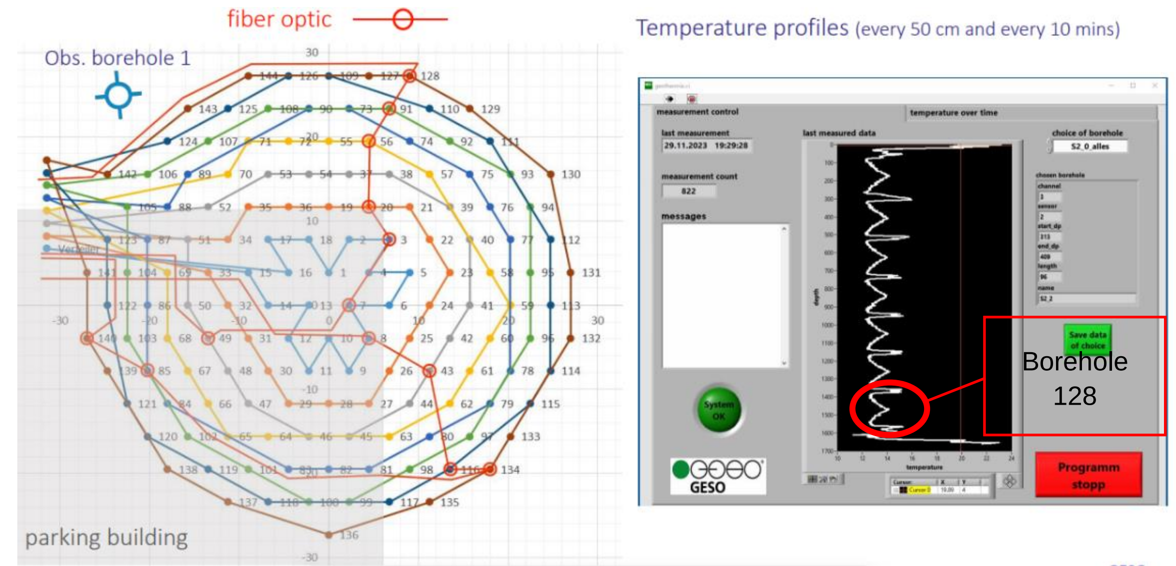


Figure 9: On the left side the orange line marks the path of the fiber optic. There are two lines, which with both ends are connected to the evaluation unit. On the right side, the thermal results form 29.11.2023 of the upper fiber are presented.

5 Evaluation of results to date

The results to data are evaluated under the three main topics of PBD development, development of modelling tools and HT-BTES implementation as follows:

- **PBD development**: important steps have been made in the conceptualization of the PBD approach for energy systems and in the definition of standardized interfaces between different level of abstractions. Concerning the equipment scale, it was decided to adopt Modelica as environment for the development of control-oriented models. This decision facilitates the use of modelling libraries, and thus allows for a fast prototyping and evaluation of design concepts. The preparation of a Modelica model for the HT-BTES system at Empa is on-going.
- **Modelling tools for HT-BTES**: Significant effort has been placed in the development of design and control-oriented models for HT-BTES systems, as can be appreciated in [12,15,19,20,22] The efforts made targeted an increasing modelling level of fidelity and increased specificity on the HT-BTES installed at the Empa campus. An initial comparison between the models capability and limitations was made and reported in section 4.2. Overall, the models well represent the expected behavior of the system and, when modelling complexity was increased, they were able to capture different operational behaviors for the HT-BTES system. However, the validation of predictions against experimental data will be crucial to fully assess these models.
- **HT-BTES system implementation:** the commissioning of the HT-BTES took place with a 1-year delay compared to what initially planned at proposal stage (summer 2023). This delay is due to several factors: (i) the construction of a new laboratory at Empa, which was coupled with

the HT-BTES construction, (ii) the interest in the measurements of undisturbed soil to understand the biological and mineralogical impact of HT-BTES, which led to the ARTS project (funded by BFE), for which an experimental campaign took place in 2024, (iii) delay of the ARTS project due to clogging of the main borehole, (iv) and a fire that destroyed the circulation pumps and control valves in the distribution central of the HT-BTES in July 2024. Overall, despite the accumulated delay, significant experience was gained during the design and commissioning of the HT-BTES. The lessons learned are well-documented in this report and will constitute a basis for understanding how the design process of energy systems integrating geothermal storage can be enhanced.

6 Next steps

A fire accident happened during preliminary testing of the system, and the necessary components replacement is planned to be delivered in mid-September 2024. It is not known though, at the moment of writing, the date for the installation of these replaced components. Obviously, this leaves little time to exploit the cooling season to charge the HT-BTES. Consequently, while a few preliminary tests might be performed, the first charging season for the HT-BTES will be delayed until summer 2025.

As a consequence of this delay, some adjustments in the planned activities have been made compared to the proposal:

(i) Efforts towards modelling activities have been extended. The goal is now the generation of a high-fidelity tool in the Modelica language to be used to perform design verification. The Modelica model will also be used to derive optimal operational strategies, as initially planned, and compared to other modelling tools reported in Table 4;

(ii) Given the shorter time for data collection, the validation of the models will be mainly directed to the accurate representation of the district, modelling of auxiliaries and validation of the HT-BTES charging process. The validation of the discharging process will necessitate longer data collection periods and will not be carried out within this project.

Initially, the HT-BTES system will be operated manually. In particular, given the initial thermal transient typical of large-scale BTES systems [19], the system will be charged as much as possible with waste heat from the Empa campus during the first year of operation. The soil temperature is not predicted to increase significantly, leading to poor discharging potential for the first discharging season (Q4 2025 and Q1 2026). Nonetheless, tests will be performed to collect data and have a better understanding of the system operation. The data will be constantly measured and collected in the Empa database.

In parallel to the start of the measurement campaign, a control-oriented model in the Modelica environment will be developed. This model, along with the other models listed in Section 4.2, will be validated against the experimental data collected within the first years of operation and will be used to improve the operation of the HT-BTES system in the following years, in relation to objectives 1) and 4) listed in section 1.3. The validation process will start during the first charging and discharging seasons, however, it will continue in the future to ensure good fidelity of the modelling tools also for long-term (several years) predictions. This is particularly important to assess influence of inertia and ageing factors on the system.

By means of numerical and experimental results comparison, the modelling tools will also be simplified to only consider features that have the largest influence on the system behavior, in close relation to objective 3) of section 1.3. The exact features that will be considered will be driven by the findings of the project and recommendations will be provided regarding range of validity of assumptions made. These efforts are directed to providing tools with limited computational cost that can still produce accurate results and can be used at the different scales considered within the GEOTHERMICA GOES project.

Table 5 Adapted Gantt-chart related to the HT-BTES operation and modelling. First Charging season for the storage is envisioned to start in Q2 of 2025.

	2022	2023				2024				2025				2026			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Installation																	
Measurements																	
Modelling																	
Validation																	

7 National and international cooperation

- Collaboration with Aalborg University and Berkley University in the development and application of modelling tools for HT-BTES systems. This will contribute to open-access models for energy technologies [18].
- Collaborations with the all organizations involved in the GOES project for the development and application of the platform based design approach. These collaborations are detailed in the international mid-term report.
- Collaboration with the project SWEET PATHFNDR, contributions to the database for techno-economic parameters for energy technologies published in [23].
- Collaboration with the NCCR automation for the development of control strategies for seasonal storage [22].
- Application of modelling tools for BTES systems developed in the framework of the SWEET DeCarbCH project [19].

8 Communication

The dissemination activities made in framework of the GOES project are listed in the project website (www.goes-project.info). Below, is a list of dissemination activities undertaken:

Activity	Location / Date	GOES participants	Type of dissemination
Participation in the exhibition: Metropolis – Sustainable Futures Under Construction	San Francisco (US) / Nov 6-9, 2023	M. Sulzer M. Wetter	Poster presentation and video sharing
Participation in the 15th Modelica conference	Aachen (DE) / Oct 9-11, 2024	A. Maccarini, M. Sulzer, M. Wetter	Oral presentation (A. Maccarini)
Webinar	Online / Feb 28, 2024	All GOES partners	A 1.5-hour webinar featuring five presentations related to the GOES project.

Additional dissemination activities can be found in the international midterm report.

9 Publications

The following publications were made available in the first half of the project:

- Sulzer M, Wetter M, Mutschler R, Sangiovanni-Vincentelli A. Platform-based design for energy systems. Appl Energy 2023;352:121955. https://doi.org/10.1016/j.apenergy.2023.121955.
- Florian Wirth, multi-horizon MPC for operation of seasonal thermal energy storage, Semester project, ETH Zurich.

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