Borehole Thermal Energy Storage Systems for Storage of Industrial Excess Heat

Performance Evaluation and Modelling

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Linköping Studies in Science and Technology
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Sammanfattning

Ökad energieffektivisering inom industrin anses vara en nyckelkomponent för att minska koldioxidutsläpp och motarbeta klimatförändringar. För många industrier belägna i kallare klimat behövs under sommaren inte all den värme som alstras på anläggningen för att uppnå anläggningens värmebehov, och värmen avlägsnas därför till utomhusluften. Även om ett överskott av värme framförallt existerar under sommaren kan överskottsvärme även uppstå under vintern, till exempel under mildare vinterdagar eller högproduktionstimmar. Om överskottsvärmen istället för att avlägsnas till utomhusluften lagras till senare då den behövs skulle köpt energi till anläggningen kunna minskas. Ett sätt att åstadkomma detta är med hjälp av ett borrhålsvärmelager.

Ett borrhålsvärmelager lagrar energi direkt i marken med hjälp av ett flertal närliggande borrhål genom vilka en värmebärare, vanligtvis vatten, cirkuleras. Hittills har borrhålsvärmelager med syfte att leverera värme framförallt använts för lagring av termisk solenergi. Borrhålsvärmelager har då ingått i solvärmesystem för uppvärmning av enstaka bostadskvarter, för att på så vis minska den säsongsbaserade missanpassningen mellan solinstrålning och värmebehov och öka värmesystemets solfraktion. För denna applikation av borrhålsvärmelager kan energimängder för lagring kontrolleras av storleken på solfångarkollektorytan. För industriella borrhålsvärmelagertillämpningar däremot, bestäms energimängder som kan lagras av den tillgängliga överskottsvärmen vid anläggningen. En industri har dessutom vanligtvis ett flertal energianvändande processer, vilka på grund av tidsvarierande drift och olika kvalitet på den alstrade värmen ger upphov till alternativ för vilka processer som bör integreras i värmeåtervinningssystemet och hur själva borrhålsvärmelagret bör utformas. För beräkning av värmemängder tillgängliga för lagring vid en industriell anläggning krävs dessutom mätdata för de individuella värmeströmmar som ska ingå i lagerprocessen, vilket betyder att detta måste genomföras mer fallspecifikt för industriella borrhålsvärmelagertillämpningar än för borrhålsvärmelager för lagring av solenergi, där historisk solinstrålningsdata för beräkning av detta är direkt tillgänglig för de flesta platser.

För prediktioner av prestandan av borrhålsvärmelager användandes för både lång- och korttidslagring behövs dessutom modeller som kan hantera effekterna från korttidslagringen, vilket traditionella modeller för borrhålsvärmelagerprediktioner inte gör.

Trots att storskaliga borrhålsvärmelager har byggts sedan 1970-talet finns lite data publicerat över hur olika systemparametrar så som borrhålsavstånd och borrhålsdjup påverkar lagerprestandan, särskilt med avseende på industriella borrhålsvärmelagertillämpningar. De flesta studier i litteraturen kopplat till utformning av borrhålsvärmeväxlersystem avser traditionell bergvärme där värmepumpen arbetar mot marken vid sin naturliga temperatur och enbart ett fåtal borrhål används.

I det här arbetet genomfördes först en utvärdering av det första borrhålsvärmelagret för lagring av industriell överskottsvärme i Sverige med avseende på lagrets första sju år i drift. Borrhålsvärmelagret, vilket har använts för både lång- och korttidslagring, modellerades sedan

i IDA ICE 4.8 med målet att återskapa lagrets utfall. Slutligen användes den validerade borrhålsvärmelagermodellen för en parameterisering av lagret, där påverkan på inladdad och urladdad energi och borrhålsvärmelagerverkningsgrad från bland annat borrhålsavstånd och temperatur och storlek på flödet till lagret vid laddning studerades.

Från uppföljningen av lagrets utfall konstaterades det att lägre än uppskattade mängder överskottsvärme och/eller kvalitet på överskottsvärmen, resulterande i lägre än uppskattade framledningstemperaturer till lagret vid laddning, har hindrat lagret från att nå temperaturer nödvändiga för att väsentliga mängder energi ska kunna hämtas upp från lagret. Baserat på det på årsbasis cykliska beteende noterat för lagret för de sista åren av utvärderingen är rimliga långsiktiga värden för urladdad energi och borrhålsvärmelagerverkningsgrad cirka 400 MWh/år respektive 20%.

För jämförelsen mellan predikterad och uppmätt lagerprestanda, vilken avser en period om tre år, avvek predikterade värden för inladdad och urladdad energi från uppmätta värden med mindre än 1% respektive 3%. Värden för predikterad och uppmätt inladdad och urladdad energi följde dessutom varandra väl under de tre åren. Vidare var den genomsnittliga relativa skillnaden för lagertemperaturerna för valideringsperioden 4%. En tidsstegsanalys bekräftade att modellen hade fångat upp effekterna av den intermittenta driften av lagret, inträffande vid intervall ned till halva dygn, då prediktioner blev felaktiga när simuleringstidssteget överskred tiden för vilka ändringar mellan laddning och urladdning av lagret ägt rum.

Huvudsakliga resultat från parameterstudien inkluderar att 1) för undersökta flöden till lagret vid laddning var en hög temperatur viktigare än ett stort massflöde för att uppnå en hög årlig urladdning av energi och 2) den mängd energi som på årsbasis kan hämtas upp från lagret sjönk hastigt när borrhålsavståndet minskades från det avstånd som resulterade i att mest energi kunde laddas ur, medan en långsam minskning sågs när borrhålsavståndet ökades från denna punkt. Ytterligare en slutsats kopplat till påverkan på lagerprestanda från ingående systemparametrar är att möjligheter för utformning av ett lågtemperaturlager bör beaktas vid planering av byggande av borrhålsvärmelager. Genom att reducera lagrets arbetstemperatur kan mer energi laddas in i lagret, vilket i sin tur innebär att mer energi kan laddas ur. En lägre arbetstemperatur innebär även lägre värmeförluster från lagret till dess omgivning.

Abstract

Improving industrial energy efficiency is considered an important factor in reducing carbon dioxide emissions and counteract climate change. For many industrial companies in cold climates, heat generated at the site in summer will not be needed to fulfil the site heat demand during this time, and is thus removed to the outdoor air. Although a mismatch between heat generation and heat demand primarily being seasonal, a mismatch may also exist at times in the winter, e.g. during milder winter days or high production hours. If this excess heat instead of being sent to the outdoors was stored for later use when it is needed, purchased energy for the site could be decreased. One way to do this is by the use of a borehole thermal energy storage (BTES) system.

A BTES system stores energy directly in the ground by using an array of closely drilled boreholes through which a heat carrier, often water, is circulated. So far, BTES systems used for heating purposes have mainly been used for storage of solar thermal energy. The BTES system has then been part of smaller district solar heating systems to reduce the seasonal mismatch between incoming solar radiation and heat demand, thus increasing system solar fraction. For this application of BTES systems, energy for storage can be controlled by the sizing of the solar collector area. At an industrial site, however, the energy that can be stored will be limited to the excess heat at the site, and the possible presence of several time-varying processes generating heat at different temperatures gives options as to which processes to include in the heat recovery process and how to design the BTES system. Moreover, to determine the available heat for storage at an industrial site, individual measurements of the heat streams to be included are required. Thus, this must be made more site-specific as compared to that of the traditional usage of BTES systems where solar thermal energy is stored, in which case long-time historic solar radiation data to do this is readily accessible for most locations. Furthermore, for performance predictions of industrial BTES systems to be used for both seasonal and short-term storage of energy, models that can treat the short-term effects are needed, as traditional models for predicting BTES performance do not consider this.

Although large-scale BTES systems have been around since the 1970's, little data is to be found in the literature on how design parameters such as borehole spacing and borehole depth affect storage performance, especially for industrial BTES applications. Most studies that can be found with regard to the designing of ground heat exchanger systems are for traditional ground source heat pumps, working at the natural temperature of the ground and being limited to only one or a few boreholes.

In this work, the performance of the first and largest industrial BTES system in Sweden was first presented and evaluated with regard to the storage's first seven years in operation. The BTES system, which has been used for both long- and short-term storage of energy, was then modelled in the IDA ICE 4.8 environment with the aim to model actual storage performance. Finally, the model was used to conduct a parametric study on the BTES system, where e.g. the impact on storage performance from borehole spacing and characteristics of the storage supply flow at heat injection were investigated.

From the performance evaluation it could be concluded that lower than estimated quantities and/or quality of the excess heat at the site, resulting in lower storage supply flow temperatures at heat injection, has hindered the storage from reaching temperatures necessary for significant amounts of energy to be extracted. Based on the repeating annual storage behavior seen for the last years of the evaluation period, a long-term annual heat extraction and ratio of energy extracted to energy injected of approximately 400 MWh/year and 20% respectively are likely.

For the comparison of predicted and measured storage performance, which considered a period of three years, predicted values for total injected and extracted energy deviated from measured values by less than 1 and 3% respectively, and predicted and measured values for injected and extracted energy followed the same pattern throughout the period. Furthermore, the mean relative difference for the storage temperatures was 4%. A time-step analysis confirmed that the intermittent heat injection and extraction, occurring at intervals down to half a day, had been captured in the three-year validation. This as predictions would become erroneous when the time step exceeded the time at which these changes in storage operation occur.

Main findings from the parametric study include that 1) for investigated supply flows at heat injection, a high temperature was more important than a high flow rate in order to achieve high annual heat extractions and that 2) annual heat extraction would rapidly reduce as the borehole spacing was decreased from the one yielding the highest annual heat extraction, whereas the reduction in annual heat extraction was quite slow when the spacing was increased from this point. Another conclusion that came from the performance evaluation and the parametric study, as a consequence of the Emmaboda storage being designed as a high-temperature BTES system, intended working temperatures being 40–55 °C, was that the possibility of designing the BTES system for low working temperatures should be considered in the designing of a BTES system. Lower storage operation temperatures allow for more energy to be injected and in turn for more energy to be extracted and reduces storage heat losses to the surroundings.

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List of papers

This thesis is based on the work presented in the two papers listed below. The papers are referred to in the thesis by Roman numerals and are appended at the end of the thesis. Co-author statements for the papers are presented in chapter 1.3.

- I. Nilsson, E., Rohdin, P. Performance evaluation of an industrial borehole thermal energy storage (BTES) project – Experiences from the first seven years of operation. *Renewable Energy* 2019, 143, 1022-1034.
- II. Nilsson, E., Rohdin, P. Empirical Validation and Numerical Predictions of an Industrial Borehole Thermal Energy Storage System. *Energies* 2019, 12, (2263).

Other publications by the author of this thesis that are not included in the thesis:

- Nilsson, E., Andersson, E., Rohdin, P., Thollander, P. Benchmarking of space heating demand for a sample of foundries in Nordic climate. In *Proceedings ECEEE Industrial Summer Study*, 2018.

Thesis outline

Chapter 1 introduces the overall research field and motivates the research of the thesis. The chapter presents the thesis research questions, the research scope and its limitations, and co-author statements of the publications on which the thesis is based.

Chapter 2 starts with a brief review of the excess heat potential for delivery to the district heating network for Sweden and the EU27 countries, followed by a short description of some prominent methods for long-term storage of thermal energy. The chapter then ends with a more detailed overview on BTES system technique and BTES systems reported in the literature.

Chapter 3 presents the research design and the methods used to conduct the research.

Chapter 4 describes the industrial site and BTES system used as study object for the research.

Chapter 5 outlines input data and assumptions for conducted model validation and parameterization.

Chapter 6 summarizes results from appended papers relevant to the thesis research questions.

Chapter 7 presents main conclusions and findings from the research and final thoughts are given. The chapter ends with suggestions for future research.

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1 Introduction

This chapter starts by introducing the overall research field and motivating the research of this thesis. This is then followed by the thesis aim and research questions, the research scope, and finally an overview of the papers on which the thesis is based.

For many industrial companies in cold climates there are times when heat generated from processes at the site is not needed in order to fulfill the site heat demand, and is thus wasted to the outdoor air. This mismatch between heat generation and demand will primarily take place in the summer, but could also occur in the winter, e.g. during milder winter days or high production hours. If this excess heat instead of being wasted to the outdoors is stored for later use when it is needed, energy purchased for the site can be reduced. One way to do this is with the use of a borehole thermal energy storage (BTES) system.

A BTES system stores energy directly in the ground using a number of closely drilled vertical boreholes through which a heat carrier, usually water, is circulated. Full-size BTES systems have been built since the 1970s [1] and Gao et al. [2] report that the number of BTES boreholes in use in the Netherlands is estimated to have increased from 18,000 to 22,500 between 2006 and 2007 and that similar growth can be seen in other European countries. In 2015, the estimated number of BTES systems in Sweden with 10 or more boreholes was around 650 [3]. BTES systems have commonly been used within smaller district solar heating systems to compensate for the seasonal mismatch between incoming solar radiation and space heating demand, thus increasing the system solar fraction. Examples of such systems for seasonal storage of solar thermal for which detailed storage performance is reported are the BTES systems at Anneberg, Sweden [4], The Drake Landing Solar Community in Okotoks, Alberta, Canada [5], and Neckarsulm, Germany [6].

For the traditional use of BTES systems where solar energy is stored, year-round historic solar radiation data to calculate the quantities of energy that can be stored is often readily accessible. To determine the available heat for storage at an industrial site, however, individual measurements of the heat streams to be included are needed, and must thus be made more site-specific than for the aforementioned usage of BTES systems. Differences in the temperature of the heat generated from various processes at an industrial site also give alternatives as to which processes to include in the storage system and what temperature levels to design the storage for. Moreover, for an industrial BTES system, the performance will be based on the quantity and quality of the excess heat present at the site, whereas sizing of the solar collector area makes this parameter controllable to a greater extent for a solar thermal BTES system.

Post-implementation evaluations are a way to identify design and operation weaknesses, calibrate models, and report real system performance. A literature review shows a handful of publications presenting and evaluating the performance of BTES systems, which includes

aforementioned publications [4-6]. With the exception of one evaluation, [7], presenting a BTES system for storage of heat from combined heat and power, these consider BTES systems for storage of solar thermal energy. In Chifeng, China, a BTES system is in part used for storage of heat from a copper plant. Long-term performance predictions of the BTES system for two district heating solutions were carried out by Xu et al. [8]. However, as the storage has only recently been put into operation, data of its performance is not yet available.

For a BTES system that is not only used for seasonal storage of energy but also for short-term storage, more requirements are placed on design and control systems and thus also on the ability to numerically model these factors. To the best of author's knowledge, no publications prior to this work have validated a numerical model for large-scale BTES systems used for both long- and short-term storage of energy. Furthermore, most studies investigating the influence on system performance from ground heat exchanger design consider traditional ground source heat pump systems, generally utilizing only one or a few boreholes. Little is to be found in the literature on how the performance of BTES systems, utilizing an array of boreholes with the objective to store energy, is affected by various system parameters, especially with regard to BTES systems for storage of industrial excess heat.

1.1 Aim and research questions

The aim of this thesis is to present and analyze the performance of the first and largest BTES system for storage of industrial excess heat in Sweden with respect to its first seven years in operation and compare measured storage performance to that obtained when the storage is modelled using a commercial borehole system software. With the use of the validated model, the impact on the storage's performance from various design parameters will also be investigated, for example being of value for actors interested in designing industrial BTES systems. The industrial BTES system used as a case study in this work is located at Xylem's production site in Emmaboda, Sweden.

The thesis will answer the following three research questions:

- 1) How has the industrial BTES system at Xylem, Emmaboda performed in terms of ground temperatures and heat injected into and extracted from the storage during its first seven years of operation?
- 2) With what accuracy can the performance in terms of injected and extracted energy and ground temperatures of a BTES system used for both seasonal and short-term storage of energy be modelled using a commercial software for ground heat exchanger calculations?
- 3) How is the performance, especially annual heat extraction, of the BTES system at Emmaboda affected by design parameters such as borehole spacing and storage supply flow characteristics at heat injection?

Research question 1) is treated in appended Paper I and research questions 2) and 3) are treated in appended Paper II.

1.2 Scope and delimitations

The scope of this thesis is BTES systems for storage of industrial excess heat, and more precise, to model and evaluate the performance of the first and largest industrial BTES system in Sweden. The system boundary of the study is the industrial site at which the studied BTES system is located, where the BTES system is used to deliver energy at the site, with the aim of reducing purchased energy for the site. The study does not include the possibility for the site to deliver energy to the district heating network. These conditions also correspond to those that have applied for Xylem, Emmaboda. Furthermore, the study will only look at the effects from using a BTES system on purchased energy for the site, and not on the effects on global greenhouse gas emissions.

Due to software memory limitations, the comparison of measured and modelled storage performance was done for a period of three years.

1.3 Paper overview and co-author statement

This thesis is based on the two papers listed below.

Paper I

Nilsson, E.; Rohdin, P., Performance evaluation of an industrial borehole thermal energy storage (BTES) project – Experiences from the first seven years of operation. *Renewable Energy* 2019, 143, 1022-1034.

The paper presents and analyses the first and largest BTES system for storage of industrial excess heat in Sweden, located at Xylem's production plant in Emmaboda, with respect to how it was integrated to the site and how it has performed during its first seven years of operation. Basis for the evaluation are on-site measurements and design documents from Xylem. Parameters being evaluated are for example storage heat injection and extraction, the effective ground thermal conductivity, short-term storage, and pump electricity to operate the BTES system.

Main contribution was made by the author of this thesis. Associate professor Patrik Rohdin supervised the work. Analysis was conducted by both authors.

Paper II

Nilsson, E.; Rohdin, P., Empirical Validation and Numerical Predictions of an Industrial Borehole Thermal Energy Storage System. *Energies* 2019, 12, (2263).

In this paper, the large-scale industrial BTES system at Xylem, Emmaboda is modelled in the IDA ICE 4.8 environment using the GHX module and compared to three years of measured storage performance. The model is also used to investigate how the storage would be affected by parameters such as borehole spacing, borehole depth, and temperature and flow rate of

the storage supply flow during heat injection, with focus being on their effect on annual storage heat extraction.

Main contribution was made by the author of this thesis. Associate professor Patrik Rohdin supervised the work. Analysis was conducted by both authors.

2 Theoretical background

The scope of this thesis is recovery of energy from industrial excess heat by the use of BTES technology. This chapter first introduces the term industrial excess heat and options for how it can be recovered. This is then followed by a presentation of prominent thermal energy storage methods other than BTES technology. Finally, a theoretical background on BTES system technique is provided, introducing concepts and parameters relevant to the research of the thesis.

2.1 Industrial excess heat

Improved industrial energy efficiency is considered a key component in the work against climate change, and industrial companies implementing energy efficiency measures could attain a competitive advantage e.g. due to decreased production costs following from this. Globally, around 30% of the total energy end-use originates from the industry sector [9], and in Sweden, this number is around 40% [10]. Central to the concept of industrial energy efficiency is industrial excess heat. Industrial excess heat is an industrial process by-product characterized by lower exergy than that of the energy initially used in the process, arising due to machine inefficiencies. Industrial excess heat can be defined as heat, bound in liquids, gases, or hot materials, generated in an industrial process and currently not used within the process [11]. Applications for industrial excess heat has been studied by e.g. Thekdi and Belt [12], who furthermore propose a step-by-step procedure for the order in which options for excess heat recovery should be considered for improving energy efficiency:

- 1) Reduction – reduce the amount of excess heat through efficient use of heat within the process
- 2) Recycle – use the excess heat within the process in which it arose
- 3) Recovery – use the excess heat in other parts of the industrial plant or externally
- 4) Recovery – use the heat for power conversion

In this thesis, energy recovery from industrial excess heat with regard to the first part of point 3), concerning usage of excess heat at the industrial plant is considered, in which case energy storage can be used to accomplish this in case of a time-based mismatch existing between heat generation and heat demand. For the latter part of point 3), aggregated potential assessments for recovery of industrial excess heat have been more extensively reported, and following some such potential assessments for Sweden and the EU27 countries are summarized:

Cronholm et al. [13] estimate the theoretical industrial excess heat potential for delivery to the district heating network in Sweden to be between 6.2 and 7.9 TWh/year and up to 100% higher than the actual heat recovery as of today. Persson and Werner [14] estimate the EU27

industrial excess heat recovery potential for delivery to the district heating network if best Member State practice is applied at 119 TWh/year, which would mean an increase of around 113 TWh/year compared to the current heat recovery within EU27 calculated by the authors. Connolly et al. [15] determine the industrial excess heat potential for district heating delivery for the EU27 countries at 753 TWh/year, where estimations are based on European emission data and assumptions for carbon dioxide emission factors and heat recovery efficiency.

2.2 Seasonal thermal energy storage

Common methods for seasonal storage of thermal energy include hot water thermal energy storage (HWTES), gravel water thermal energy storage (GWTES), aquifer thermal energy storage (ATES), and borehole thermal energy storage (BTES). HWTES and GWTES systems store energy in water and a water and gravel mixture respectively, contained in artificial, insulated tanks. The mixture is a practice to overcome the high costs of water and the lower volumetric heat capacity of rock as compared to water [16]. HWTES and GWTES systems may both be located above ground or be fully or partially buried in the ground.

ATES and BTES systems store energy using the natural formations of the ground. For ATES systems, this is done by the use of layers of water-saturated porous media, known as aquifers, where two wells have been drilled into the aquifer at some distance from each other. During charging, ground water is extracted from one of the wells, collects heat from the heat source, and is then sent back to the aquifer through the second well, eventually resulting in a cold and hot well being obtained. During discharging, the flow direction is reversed. For an aquifer to be suitable for energy storage, the layer above and below the aquifer should be impermeable and groundwater flows at the location should be low [17]. For a BTES system, being the storage method studied in this work and explained in detail in the next section, energy is stored directly in the ground by the use of several closely drilled vertical boreholes through which a heat carrier is circulated.

The high volumetric heat capacity of water means that HWTES systems require the smallest volume of the methods to achieve the same storage capacity. Compared to HWTES systems, a volume of 1.3–2 times, 2–3 times, and 3–5 times are needed for GWTES, ATES, and BTES systems respectively to achieve the same storage capacity [18]. The insulated storage boundaries for HWTES and GWTES also results in a higher energy recovery, i.e. more of the energy injected into the storage can be recovered, as compared to ATES and BTES systems. Benefits for ATES and BTES systems, on the other hand, include that large storage capacities can be achieved without the need for construction of costly tanks. One specific advantage for BTES systems is that the storage volume can easily be extended by the drilling of additional boreholes. One drawback, however, is that a startup time of 3–4 years is required before it can be operated at full performance [4,18], whereas this can be achieved already in the first year for the other storage methods. ATES systems generally have higher recovery efficiencies than BTES systems, but BTES systems are not as limited to certain ground formations and thus more universally applicable [19].

2.3 Borehole thermal energy storage

2.3.1 Overview of BTES techniques and reported BTES systems

A BTES system stores energy directly in the ground using an array of vertically drilled boreholes in which a heat carrier is circulated. Most commonly, the heat carrier is circulated using a single or double U-pipe inserted into the borehole. However, BTES installations using co-axial ground heat exchangers, where the heat transfer fluid is in direct contact with the ground, also exist. In the case of U-pipes being used, the boreholes are backfilled with a grouting material, e.g. bentonite, quartz sand, or water. Thermally enhanced grouts have been developed to achieve higher fluid-to-ground heat transfer rates. The heat transfer properties of grouted boreholes have been studied theoretically in e.g. [20,21] and by in-situ measurements in e.g. [22,23].

Boreholes are usually positioned within a regular shape at a distance of 3–4 m from each other [16] and drilled to a depth of 30–200 m. The surface towards the atmosphere confining the borehole field is insulated to reduce heat losses. Geological formations that are suitable for a BTES system include soil and rock [2,17]. Unsaturated ground formations may result in higher storage performances than saturated ground formations due to a lower thermal conductivity [24,25]. Groundwater flows at the storage location are preferred to be low as these may transfer heat away from the storage region. A schematic showing the geometrics and physics associated with a BTES system is shown in Figure 1.

Figure 1. Schematic of geometrics and physics associated with a BTES system, considering single U-pipes as ground heat exchangers.

For a BTES system, the highest temperatures will be achieved at the storage centre and decrease with the distance away from it. The storage volume of a BTES system is usually presented as the approximate volume confining the borehole field. However, the useful storage

capacity is given by the volume holding a temperature higher or equal to that of the minimum temperature wanted at extraction, which must not be limited to the volume taken up by the borehole field. The overall performance of a BTES system is often described by the amount of useful energy that can be extracted from the storage, or by the ratio of heat extracted from and injected into the storage, known as the BTES efficiency (Equation 1).

$$BTES\ efficiency = \frac{Heat\ extracted}{Heat\ injected} \quad (1)$$

If the storage volume of a BTES system is for example described by the ground volume taken up by the borehole field, the energy balance for the BTES system can be written according to Equation (2):

$$E_{injected} + E_{extracted} = E_{stored} + E_{losses} \quad (2)$$

where $E_{injected}$ and $E_{extracted}$ are the energy injected into and extracted from the BTES system respectively, E_{stored} the energy accumulated within the BTES system, and E_{losses} the energy lost from the BTES system to the surrounding ground and atmosphere due to heat transfer by conduction and convection.

For the closed-loop U-pipe ground heat exchanger, the heat transfer rate, Q (W) between the heat transfer fluid and the ground during storage heat injection or extraction can be written according to Equation (3):

$$Q = \dot{m}_{fluid} \cdot C_{p,fluid} \cdot (T_{fluid,in} - T_{fluid,out}) \quad (3)$$

where $\dot{m}_{fluid}$ (kg/s) is the heat transfer fluid mass flow rate, $C_{p,fluid}$ (J/(kg·°C)) the heat transfer fluid specific heat capacity, and $T_{fluid,in}$ and $T_{fluid,out}$ (°C) the heat transfer fluid temperature at the borehole heat exchanger inlet and outlet respectively. Traditionally, Q has been solved for in models for ground heat exchanger systems by relating it to an effective fluid-to-borehole wall thermal resistance, R_b , which is further explained in section 2.3.2.

Commonly, BTES systems have been used to assist either with both heating and cooling of buildings, or with only heating [26]. When used for both, the storage is operated so that low ground temperatures are achieved before the summer months. Heat injected into the ground during summer, as a consequence of cold being extracted, is then used for space heating in winter. Ground temperatures may be around 5 °C before the summer and reach around 20 °C in the winter. When used for heating only, which will be the typical application when used for storage of industrial excess heat, the storage is actively charged with heat with the aim of using the heat later when it is needed. The BTES system then collects heat from somewhere other than the building itself, or collects heat from the building but works at temperatures that are too high to efficiently provide space cooling (the storage temperature being higher than that of the outdoor air), thus making heating its main purpose. In the former case (cooling and heating),

because of low storage operating temperatures, a heat pump is needed for the extraction in the winter, whereas in the latter case (heating only), the storage may be designed for either direct extraction or extraction using a heat pump.

Full-size BTES systems have been built since the 1970s [1] and Gao et al. [2] report that the number of BTES boreholes in use in the Netherlands is estimated to have increased from 18,000 to 22,500 between 2006 and 2007 and that similar growth can be seen in other European countries. In 2015, the number of BTES systems in Sweden with 10 or more boreholes was around 650 [3]. Until now, BTES systems used to assist with space heating alone have mainly been used for storage of solar thermal energy. BTES systems have then been used within smaller district solar heating systems to compensate for the mismatch between incoming solar radiation and space heating demand, thus increasing the system solar fraction. Examples of such systems for which detailed storage performance is reported are the BTES systems at Anneberg, Sweden [4], The Drake Landing Solar Community in Okotoks, Alberta, Canada [5], and Neckarsulm, Germany [6].

For the Anneberg storage, which is designed as a low temperature storage, with an intended mean working temperature of 30–45 °C, the BTES efficiency and annual heat extraction after five years in operation were estimated at around 50% and 500 MWh respectively. The evaluation, which considers the storage's first two years in operation, concludes that several parts of the BTES-integrated solar heating system seem to work less efficient than predicted but that the overall system idea works as intended. [4]

For the storage at Drake Landing, around 2020 MWh was injected into the storage during its third to fifth year in operation, for which a repeating annual storage behaviour was seen. The total BTES efficiency for the three years was approximately 42%. During these years, the core temperature of the borehole field varied between approximately 40 and 65 °C. Overall, actual storage performance regarding heat injection, heat extraction and BTES efficiency correlated well with the five-year projection that was done prior to the construction of the storage. [5]

The BTES system at Neckarsulm was put into operation in 1999. However, heat extraction first took place in 2002 since the storage needed to reach useful temperatures. Within the period 1999–2002, however, the borehole field was extended, during which time heat injection was paused. A cycling annual storage behaviour can be seen from 2004. From the beginning of 2004 and approximately 4.5 years onward, approximately 1840 MWh of energy was extracted and the BTES efficiency for the period was around 55%. During this period, storage temperatures reached maximum values of around 65 °C, which was approximately 20 °C lower than what was expected. A smaller than planned solar collector area is given as one reason for this. [6] It should be noted that the BTES system at Neckarsulm makes use of heat pumps for heat extraction, whereas direct heat exchange is used for heat extraction for the storages at Anneberg and The Drake Landing.

Some data for aforementioned three BTES systems can also be seen in Table 1, which furthermore shows some key parameters for a few other well-known BTES systems for storage

of solar thermal, briefly presented in the literature. Most of these systems incorporate a water tank, used for short-term storage. A short-term storage can for example be added to handle peak loads.

For increased understanding of the performance of large-scale geothermal technologies, the project Annex 52 [27] is currently under way. In this project, measurements are conducted on geothermal installations serving commercial, institutional and multi-family buildings, with the objective of reporting realistic system performances and giving guidelines on the instrumental set-up and analysis of these systems. The project will continue until 2021 and the participating countries are Finland, the Netherlands, Sweden, the UK and the USA. The BTES system at Xylem's production plant in Emmaboda, Sweden, which is studied in this work, is one of the case studies in Annex 52.

Table 1. BTES-incorporated solar heating systems.

Site	Year put into operation	Served area	Heat demand of served area [MWh/year]	Design system solar fraction [-]	BTES volume [10^3 m^3]	Design BTES working temperatures [$^{\circ}\text{C}$]	Extraction method	STTES (water)	Reference
Groningen, Netherlands	1984	Residential area	n/a	0.65	23	n/a	n/a	n/a	[28]
Treviglio, Italy	1985	Residential area	n/a	0.70	43	n/a	HP	n/a	[28]
Neckarsulm, Germany Phase 1 (Phase 2)	1997	Six multi-family houses, school, etc. total of 20,000 m^2	1700	0.50	20 (63) (528 BHE)	Up to 85	HP	Yes	[29], [6]
Attenkirchen, Germany	1999	30 houses, total of 6200 m^2	500	0.55	9 90 BHE, 30 m deep	n/a	HP	500 m^3	[29]
Anneberg, Sweden	2002	50 residential units, total of 6000 m^2	600	0.80	60 100 BHE, 65 m deep	45/30 start/end of extraction season	Direct extraction (low temperature DHS)	Yes	[4]
Crailsheim, Germany	2006	260 apartments, sports hall, school, total of 40,000 m^2	4100	0.50	38 80 BHE, 55 m deep	n/a	HP	580 m^3	[30]
DLSC, Okotoks, Canada	2007	52 houses	700	≥ 0.90	34 144 BHE, 35 m deep	Up to 80	Direct extraction	240 m^3	[5], [16]
Brødstrup, Denmark	2013	1500 households	45,000	0.20	19 48 BHE, 45 m deep	Down to 16	HP (1.2 MW)	7500 m^3	[31]

2.3.2 Predictions of ground heat exchanger systems

Conventionally, the way to decompose the thermal processes associated with a ground heat exchanger is with regard to the borehole radius [32]. The thermal process within the borehole is assumed to be at steady state, described by an effective borehole thermal resistance, R_b , whereas the thermal process outside of the borehole is considered time-dependent, being described by a G-function. The formulation of G-functions, which can both be calculated using numerical and analytical methods, originate from the works by Ingersoll [33] and Eskilson [34]. Some typical analytical formulations of the G-function are presented and discussed in [32]. The mathematical expressions for these are based on the borehole being represented by a cylinder or, because of the small borehole diameter compared to the length, as a line, and the ground

as an infinite medium or a medium limited by the ground surface. The effective borehole thermal resistance, R_b , describes the fluid-to-borehole wall resistance at steady-flux state, which is a state where the temperature difference between fluid and borehole wall is constant. Steady-state flux can be considered reached at a constant heating or cooling load occurring for a time longer than $5t_b$, where t_b , being the time scale associated with the borehole diameter, is in the order of one hour [32], [35]. The effective borehole thermal resistance, R_b ((m·°C)/W) can be related to the heat transfer rate per unit length, q (W/m), the simple mean fluid temperature, T_{fluid} (°C), and the borehole wall temperature, T_{bw} (°C) according to Equation (4) [36]:

$$q(t) = \frac{T_{fluid}(t) - T_{bw}(t)}{R_b} \quad (4)$$

For heat loads varying at shorter intervals than a few hours, the heat capacity of the backfill material becomes relevant in determining the fluid-to-borehole wall heat transfer. In recent years, a number of analytical and numerical methods to handle these short-term thermal responses have been proposed. However, these studies have been limited to only one ground heat exchanger, due to the purpose being to improve predictions of ground source heat pump systems. To the author's best knowledge, no publications prior to this work have attempted to model the performance of a BTES system utilizing intermittent heat injection and extraction, in which case the possibility to predict the effects of rapid changes in heat load is relevant.

2.3.3 *Earlier studies investigating the influence of various system parameters on BTES performance*

Although BTES systems have been constructed for some time now, little is to be found in the literature regarding the impact of various system parameters on the overall system performance, especially for industrial BTES applications. However, this lack of representation in the literature has begun to receive attention and below are some recent studies on the subject presented. These studies presented below are not based on industrial BTES systems, unless otherwise stated.

In [37], the impact on storage performance from e.g. borehole depth, borehole spacing, number of boreholes, and fluid inlet temperatures was investigated. Conclusions included that there exists an optimal borehole spacing at which the highest heat extraction rates and BTES efficiencies are achieved. The impact on BTES performance from borehole field arrangement and borehole inclination was analyzed in [38]. Results for example showed that for one specific borehole field arrangement, an inclination of 60° from a case of no inclination would result in an increase and decrease in injected and extracted energy of 49% and 80.7% respectively for the considered time of 15 years. The impact of groundwater flow and ambient air temperature variations on storage performance was analyzed in [39]. It was concluded that the combined effect of these parameters can significantly reduce BTES performance. In [7], cycles of heat injection and extraction for a BTES system used for storage of industrial excess heat were

optimized with the objective to maximize long-term BTES efficiency. A feasible long-term BTES efficiency of 65% was predicted.

3 Research design and methods

This chapter starts with a presentation of the overall research design and objective, which is then followed by the methods that were used to conduct the research.

A schematic of the overall research design and research objective can be seen in Figure 2. Firstly, a case study was conducted on the BTES system at Xylem, Emmaboda with the purpose to show and evaluate its performance (Paper I). The main contributions from the case study are 1) measured storage performance data, 2) identification of reasons for deviations in storage performance from predictions made prior to construction, and 3) design considerations. The measured storage performance data can e.g. be used by other researchers developing models for predictions of BTES system performance, and the identification of reasons for performance deviations and design considerations can aid in the designing of that of future BTES implementations.

Storage performance data collected in the case study was then used to model the Emmaboda storage (Paper II). Main outcomes from the modelling are 1) the model validation itself and 2) the modelling approach, both which can be of use for researchers and actors constructing BTES systems wanting to do BTES system performance predictions. Moreover, the modelling results together with the empirical data from Paper I can be used for comparison of performance predictions to that of other models. Finally, the validated model made it possible for a parametric study to be conducted on the Emmaboda storage (Paper II). The parametrization included varying of borehole spacing and borehole depth, for which the impact on BTES performance are scarcely represented in the literature. The main contributions from the parametric study are 1) ideas on the influence of system parameters such as borehole spacing and borehole depth on BTES heat injection and extraction and BTES efficiency, and 2) ideas for beneficial system design in order to achieve high storage heat extraction.

Figure 2. Schematic of overall research design and research contribution.

The overall scope of the research project, see Figure 3, is to study how the use of a BTES system can affect purchased energy for the site, especially with regard to energy purchased for the site for heating purposes. This is indicated by the boundary marked with an A. However, with a few exceptions, the study only concerns the BTES system itself (boundary B), where the flows into and out from the BTES system are heat injected into and extracted from the storage respectively.

Figure 3. The studied system and considered energy flows.

3.1 Case study layout

The case study on the BTES system at Xylem, Emmaboda was guided by the framework on case study research by Yin [40]. The case study was made in an explorative manner, i.e. without the stating of hypotheses with the objective to generalize its results to some broader theory. However, some results from the case study could likely be used for replication of findings within future research with the aim of doing so. In why/how format, the research questions were e.g. “How has the BTES system at Xylem, Emmaboda performed in terms of e.g. energy injected into and extracted from the storage?” and “Why, if this being the case, has the BTES system performed differently from its design values?”. The reason for choosing the BTES system at Xylem, Emmaboda for the case study was that it to the authors’ best knowledge was the only existing large-scale BTES system for storage of industrial excess heat.

3.1.1 Data collection

To describe technical features of the BTES system, the case study made use of design documents, on-site visits, and the evaluation reports by Nordell et al., [41] and [42], evaluating the storage with regard to its first three and five years in operation respectively. Data to describe storage performance in terms of ground temperatures and storage heat injection and

extraction was collected from the site's monitoring system. The sensors used for monitoring of the BTES system are explained in detail in conjunction with Figure 7, showing the BTES system layout.

3.2 Modelling

The BTES system at Xylem, Emmaboda was modelled in the IDA ICE 4.8 environment, where the BTES system itself was represented by the GHX module, being described in detail below. Based on the law of conservation of energy, storage supply flow data was used as model input, whereas energy injected into and extracted from the storage and ground temperatures were used as parameters to validate the model against. An error assessment for measured storage heat injection and extraction and ground temperatures for the considered three-year validation period can be found in Paper II. BTES system design parameters used as input for the model validation are given by section 5.1, and the parametric study setup is given by section 5.2.

A field that has been extensively studied with regard to system modelling is that of energy performance of buildings. A categorization of model validation methods for building energy performance predictions is given by Ryan and Sanquist [43]. Ryan and Sanquist [43] state that model validation for building energy performance predictions in general make use of three different methods for comparison, being analytical solutions, peer models, and empirical data. The authors describe the methods as follows: Analytical solutions provide comparison to the exact solution of a problem and can be because of this useful when describing the behavior of single components, but may be less useful for validating coupling of model components and entire systems. For peer model validation, model predictions are compared to predictions made by other models for some specific case, using the same input parameters. Peer model validation thus relies on the accuracy of the models for comparison. Model validation by comparison to empirical data allows, within the uncertainty of the measurements, for an "absolute truth standard" to be achieved, but can be time-consuming and expensive. The authors furthermore make a distinction between idealized and realistic validation studies. Idealized validation studies are limited to parameters related to the building structure, which includes the architectural layout, the building materials and the HVAC equipment, whereas realistic validation studies in addition to this considers building occupancy, which includes the intended use of the building and the behavior of the occupants. In the idealized case, controlled test cells are typically used, whereas the idealistic case makes use of actual metering and auditing data from residential and commercial buildings. Using the categorization by Ryan and Sanquist [43], the model validation carried out in this work can be considered an empirical, realistic validation with regard to that the validation is carried out on an actual BTES system operating at its normal conditions.

3.2.1 IDA ICE ground heat exchanger module

For the modelling of the performance of the Emmaboda storage, a model was set up in the IDA ICE 4.8 environment. IDA ICE 4.8 is a simulation tool with focus on dynamic modelling of thermal systems such as heating, ventilation, cooling and generic functions for buildings and industries. IDA ICE is included in the general-purpose environment IDA, where all models are available as NMF (Neutral Modelling Format) source code [44]. The simulation environment has been validated and is found in the BESTEST Library [45]. In IDA ICE, ground borehole systems are described with the GHX module. The GHX module uses superposition of 2-D temperature fields, calculated around each borehole using the finite difference method, to generate a 3-D temperature field in the ground. The module can be used for an arbitrary configuration of boreholes of the same depth. The ground is homogenous, which means that it is modelled using average properties for e.g. thermal conductivity, density and heat capacity. However, separate properties may be assigned the top layer in which the borehole casing is placed. Only U-pipes can be used as borehole heat exchangers and groundwater flow is not explicitly considered. Ground surface boundary conditions are given by the outdoor air temperature, which may vary with time. Heat transfer fluid mass flow rate and temperature at the borehole heat exchanger inlet are used as model input. For each borehole, the following temperature fields are calculated [46]:

- One-dimensional heat transfer between downward and upward going flow
- One-dimensional heat transfer between the grout (backfill material), liquid and ground
- Two-dimensional heat transfer around the borehole and between the grout and the liquid, using a mesh of cylindrical coordinates

The combined thermal influence on the ground from multiple boreholes is obtained by superposition. To describe the undistributed ground temperature, a one-dimensional vertical field, interacting with the ground surface, is used. The thermal processes between fluid, grout and borehole wall are dynamic, i.e. they account for the thermal mass of both the fluid and the grout. However, the thermal mass of the pipe itself is neglected. The energy balance of downward and upward flow are described by Equations (5) and (6) [46,47]:

$$\begin{aligned} & MC_{p,Liq} \cdot dT_{d,i,j}/dt \\ &= m_i C_{p,Liq} \cdot (T_{d,i,j-1} - T_{d,i,j}) + K_{LiqGrout,i} \cdot (T_{Groutd,i,j} - T_{d,i,j}) \\ &+ K_{LiqEarth,i} \cdot (T_{i,j} - T_{d,i,j}) \end{aligned} \quad (5)$$

$$\begin{aligned} & MC_{p,Liq} \cdot dT_{u,i,j}/dt \\ &= m_i C_{p,Liq} \cdot (T_{u,i,j+1} - T_{u,i,j}) + K_{LiqGrout,i} \cdot (T_{Groutu,i,j} - T_{u,i,j}) \\ &+ K_{LiqEarth,i} \cdot (T_{i,j} - T_{u,i,j}) \end{aligned} \quad (6)$$

where $MC_{p,Liq}$ (J/°C) is the absolute heat capacity of the upward or downward flow in node j at borehole i , $T_{d,i,j}$ (°C) and $T_{u,i,j}$ (°C) are the temperature of the downward and upward flow respectively in node j at borehole i , m_i (kg/s) is the mass flow rate at borehole i , $C_{p,Liq}$ (J/(kg·°C)) is the specific heat capacity of the fluid at borehole i , $K_{LiqGrout,i}$ (W/°C) is the heat transfer coefficient multiplied by area between grout and fluid at borehole i , $T_{Groutd,i,j}$ (°C) and $T_{Groutu,i,j}$ (°C) are the grout temperature around the downward and upward flow respectively

in node j at borehole i , $K_{LiqEarth,i}$ (W/°C) is the heat transfer coefficient multiplied by area between the fluid and borehole wall at borehole i , and $T_{i,j}$ (°C) is the borehole wall temperature in node j at borehole i .

To describe the energy balance of the filling material, Equations (7)–(9) are applied [46,47]:

$$\begin{aligned} & MC_{p,Grout2} \cdot dT_{Grout,i,j}/dt \\ &= K_{GroutGrout} \cdot (T_{Groutd,i,j} - T_{Groutu,i,j} - 2T_{Grout,i,j}) \\ &+ K_{GroutEarth} \cdot (T_{i,j} - T_{Grout,i,j}) \end{aligned} \quad (7)$$

$$\begin{aligned} & MC_{p,Grout1} \cdot dT_{Groutd,i,j}/dt = K_{GroutGrout} \cdot (T_{Grout,i,j} - T_{Groutd,i,j}) + \\ & K_{LiqGrout,i} \cdot (T_{d,i,j} - T_{Groutd,i,j}) + K_{RingEarth} \cdot (T_{i,j} - T_{Groutd,i,j}) \end{aligned} \quad (8)$$

$$\begin{aligned} & MC_{p,Grout1} \cdot dT_{Groutu,i,j}/dt = K_{GroutGrout} \cdot (T_{Grout,i,j} - T_{Groutu,i,j}) \\ &+ K_{LiqGrout,i} \cdot (T_{d,i,j} - T_{Groutu,i,j}) + K_{RingEarth} \cdot (T_{i,j} - T_{Groutu,i,j}) \end{aligned} \quad (9)$$

where $MC_{p,Grout2}$ (J/°C) and $MC_{p,Grout1}$ (J/°C) are the absolute heat capacity of the outer and inner grout respectively, $T_{Grout,i,j}$ (°C) is the temperature of the outer grout in node j at borehole i , $K_{GroutGrout}$ (W/°C) is the heat conductivity coefficient multiplied by length between the grout ring and outer grout, $K_{GroutEarth}$ (W/°C) is the heat conductivity coefficient multiplied by length between grout and ground, and $K_{RingEarth}$ (W/°C) is the heat conductivity coefficient multiplied by length between grout ring and ground.

The heat resistances, R (m²·°C/W), related to the heat transfer/conductivity coefficients, K (W/°C), and heat capacities, MC_p (J/°C) used to calculate the thermal processes within a borehole are shown in Figure 4. Calculations furthermore consider a heat transfer coefficient, α (W/(m²·°C)) between the fluid and the inner U-pipe surface. Heat resistances, R used to calculate the heat transfer/conductivity coefficients, K , are either entered directly or calculated by giving an effective borehole thermal resistance, R_b (m·°C)/W. The effective borehole thermal resistance, R_b is the thermal resistance between the heat transfer fluid and the borehole wall at steady-flux state [32]. A more detailed description of the model is found in [47].

Figure 4. Heat capacities and thermal resistances considered in the IDA ICE GHX module for calculation of the thermal processes within a borehole. [47]

4 Xylem, Emmaboda and the studied BTES system

This chapter describes the studied BTES system and the site Xylem, Emmaboda at which the BTES system is located. The chapter for example shows how the BTES system was integrated to the site's heat recovery system, the BTES system design, the sensors used for data collection, and results from exploration drillings conducted prior to the construction of the BTES system.

Xylem Water Solutions is a global company offering water-saving technologies and solutions, and at the production site in Emmaboda the focus is mainly on manufacturing submersible pumps. The site has an indoor area of approximately 110,000 m² and has around 1100 employees, of whom 750 work in production. Annually, around 45,000 MWh of electricity and 5000 MWh of district heating are purchased for the site. A BTES system was put into operation at the site in early summer 2010, with the main purpose to recover energy from excess heat present in the summer for usage of the energy in the winter when it would be needed, thereby reducing purchased district heating for the site. However, some energy was also expected to be injected into the BTES system in the winter, e.g. during milder winter days. The BTES system was connected to the site's existing heat recovery circuit, which was already recovering 4000 MWh of energy annually to be used directly for ventilation and space heating. An overview of the site is shown by Figure 5. Heat at the site is mainly recovered from its foundry, much due to two high-temperature furnaces that are placed in the building. Because of the space required for the BTES system, it was located opposite the factory area on the other side of a river that crosses the site. Technical information about the BTES system at Xylem, Emmaboda presented in this chapter is based on design documents from Xylem, on-site visits, and Nordell et al. [41,42].

Figure 5. Site overview of Xylem, Emmaboda. Reprinted from Nilsson and Rohdin [48].

The BTES-integrated heat recovery circuit is shown in Figure 6. Heat is extracted both directly from the high-temperature furnaces and via a cooling tower water basin. Heat is also extracted directly from the site's compressor centre. Heat from the water basin, the foundry ventilation air and a few other processes is recovered with the use of a heat pump, seen at the top centre of Figure 6. The heat pump was implemented to the heat recovery circuit in conjunction with the integration of the BTES system to include heat sources otherwise being at too low a temperature (20–30 °C) to be used at the site's internal heat distribution network, having a return temperature of 35–40 °C. The heat pump is designed to increase the temperature of the low temperature heat to that obtained from the high-temperature furnaces and the compressor centre, around 55–70 °C. Because of the large quantities and high temperatures of the estimated excess heat, the BTES system was designed to exchange heat with the internal heat distribution network through direct heat exchange.

Figure 6. Simplified graphic of the BTES-integrated heat recovery system at Xylem, Emmaboda. Energy is injected into and extracted from the BTES through direct heat exchange. Reprinted from Nilsson and Rohdin [48].

The BTES system was designed using the Duct Storage Model (DST) [21]. Simulations were carried out for various borehole setups, including borehole spacing, borehole depth, and number of boreholes, and considered a constant supply flow temperature at storage heat injection of 60 °C. For the chosen BTES system design, annual heat injection and extraction at storage annual steady state were estimated at 3600 and 2500 MWh respectively, where energy during the year would initially be extracted at 55 °C and finally at 40 °C. Annual steady state was predicted to be reached in the storage's second to third year in operation. For the injected heat, 1200 MWh was expected to be recovered from the high-temperature furnaces, 2200 MWh from the ventilation air and 200 MWh from remaining processes. However, as calculations only considered seasonal storage of energy and some energy also was expected

to be injected into the storage in the winter, annual heat extraction was expected to somewhat exceed 2500 MWh [42].

The chosen BTES system, shown in Figure 7, consists of 140 boreholes placed in a rectangular manner. The boreholes are drilled to a depth of 150 m and are placed at a distance of 4 m from each other. From ground to atmosphere, the top surface area confining the borehole field is covered with 0.15 m sand, 0.40 m foam glass, thermal conductivity of 0.11 W/(m·°C), and 0.20 m soil. The storage has been divided into seven sections, A–G, each with their own connection to the main supply and return manifold connecting the storage to the site's internal heat distribution system via a heat exchanger. This segmentation makes it possible to choose which parts of the storage to charge and discharge. For example, at times when heat for storage is available at temperatures close to that of the storage centre, it may be injected at only the outer sections where the ground temperature is lower. Each section contains 20 boreholes, connected in series of two and two, as shown in Figure 7 for section C. The supply flow to an open section is around 3 l/s and is distributed evenly across a section's boreholes. Pipe lengths for the BTES circuit can be found in Paper I.

Figure 7. Design of the BTES system at Xylem, Emmaboda. The storage has been divided into seven sections, A–G, each covering 20 boreholes. The sections can be charged and discharged separately through a shut-off valve leading to each section. GT1–GT4 are temperature sensors located in the ground for controlling and monitoring the storage. Reprinted from Nilsson and Rohdin [48].

The monitoring system at the site includes a large number of temperature and pressure sensors, allowing the BTES side of the heat exchanger to operate automatically according to the factory side of the heat exchanger. Ground temperatures are obtained from four temperature sensors, GT1–GT4 (see Figure 7). GT1 and GT2 are located within the borehole field at a depth of 117 m and 70 m respectively, GT3 10 m outside the south-west border of the borehole field at a depth of 100 m, and GT4 just beneath the insulation covering the top of

the storage. GT1–GT3 are placed in inactive boreholes, used during the design of the storage, whereas GT4 is positioned between boreholes. This means that no temperature sensor is in direct contact with the heat transfer fluid. The temperature sensors are Pt100 sensors from Pentronic (four-wire connection, wire wound, class AA according to IEC 60751:2008). With the exception of GT1, for which temperatures are measured every five minutes, ground temperatures are recorded every six hours. Energy injected into and extracted from the storage are determined from the flow temperature and mass flow rate at the storage entrance and exit. Also in this case, temperatures are measured using Pt100 sensors from Pentronic. The mass flow rate is calculated from the pressure differential, which is measured using a pressure differential meter from TA Hydronics (TA Link 0–10 V/4–20 mA) with an accuracy of less than 1 kPa. Flow data is recorded at five-minute intervals.

The borehole heat exchanger, illustrated in Figure 8, is of an open type. It consists of a double pipe, a DN 40 pipe placed within a DN 90 pipe, positioned in line with the borehole's centre point. The heat carrier, being a mixture of groundwater and externally added water, is transported within the DN 40 pipe and the annular space between the DN 90 pipe and the surrounding rock. In the space between the pipes, water is confined by the use of swelling rubber at regular intervals along the borehole heat exchanger length, with the purpose to limit heat transfer between upward and downward going flows. At heat injection, downward flow travels within the tube and upward flow in the annular, whereas the opposite is true for heat extraction. The idea of this is that heat transfer in the direction desired at the time will be benefitted. This function is why the heat carrier can go in two directions, as shown in Figure 7. The open borehole heat exchanger design is made possible by a nearby dam, see Figure 5, which keeps the groundwater level at approximately 2 m below ground level year-round. For the distance between ground and groundwater level, the borehole is separated from the surrounding rock by a steel pipe. Because of this and due to the fact that the pipe system ends at a depth of 146 m, the length of a borehole heat exchanger is 144 m.

Figure 8. Schematic of the borehole heat exchanger. The open borehole heat exchanger design means that the heat transfer fluid, being a mixture of groundwater and externally added water, is in direct contact with the borehole wall. Reprinted from Nilsson and Rohdin [49].

For site investigations prior to the construction of the BTES system, two exploration boreholes, TH1 and TH2, were drilled, each to a depth of 150 m. The positions of TH1 and TH2 are given by the positions of temperature sensors GT3 and GT1/GT2 respectively, see Figure 7. Rock samples showed a bedrock primarily consisting of granodiorite. However, for both drillings, a few 2–5 m thick layers of amphibolite were also encountered. In TH1, a fracture zone showing groundwater movement was identified at a depth of 29–33 m, whereas TH2 showed a minor fracture zone close to ground level. The exploration drillings together with a pumping test confirmed a larger fracture zone with groundwater flow, dipping towards west, at the west border of the planned storage location [42]. The fracture zone passes through a well a few metres west of TH1 within a depth of 70 m and a well located just on the opposite side of the river within a depth of 90 m [50]. Figure 9 shows a schematic of the estimated ground composition at the storage location. From a thermal response test (TRT), conducted in TH2, the effective ground thermal conductivity and effective borehole thermal resistance were determined at 3.0 W/(m·°C) and 0.02 (m·°C)/W respectively. Furthermore, from the site investigations the unaffected ground temperature was determined at 8 °C.

Figure 9. Schematic of the ground composition at the storage location [42]. A larger fracture zone passes through the storage location, including the west borehole field border. Reprinted from Nilsson and Rohdin [48].

5 Model validation and parametric study setup and assumptions

This chapter first describes input parameters and assumptions used in the model validation, which is then followed by a presentation of the parametric study setup, including e.g. investigated parameters and parameter ranges and conditions for heat extraction and simulation stop.

5.1 Model validation setup

The majority of the model input parameters have been compiled in Table 2. Borehole spacing, borehole depth, number of boreholes and the connection of boreholes were modelled according to the actual design. The distance between the surface level (0 m) and the top of the ground heat exchangers (approximately -2.8 m) was modelled as one layer with the weighted average properties of the individual layers. The outdoor air temperature for the considered period was given by data from a nearby weather station, located in Kosta, Sweden, approximately 30 km from the site. Ground volumetric heat capacity and unaffected ground temperature were set according to site investigations prior to the construction of the BTES system, meaning a value of $2.2 \text{ MJ}/(\text{m}^3 \cdot ^\circ\text{C})$ (granodiorite) and $8 \text{ }^\circ\text{C}$ respectively. The effective ground thermal conductivity was set to $6 \text{ W}/(\text{m} \cdot ^\circ\text{C})$, which was calculated from measured storage performance using steady-state heat transfer through cylindrical shells. A detailed description of the calculations can be found in Paper I as well as Paper II. Since IDA ICE GHX is limited to closed-loop borehole heat exchangers, the open borehole heat exchanger was modelled as a single U-pipe. The inner radius of the U-pipe was set to 16 mm and water was used as backfill material, both of these properties being common for ground heat exchanger applications. The borehole diameter was set to the same as for the actual case (115 mm). Due to the modelling of the open borehole heat exchanger as a U-pipe and the effective borehole thermal resistance determined from the TRT prior to the construction of the BTES system being based on the calculated effective borehole thermal resistance from the same test, simulations were carried out for various values of the effective borehole thermal resistance. Values for the effective borehole thermal resistance were limited to 0.05, 0.10, and $0.15 \text{ (m} \cdot ^\circ\text{C})/\text{W}$, on the basis of $0.10 \text{ (m} \cdot ^\circ\text{C})/\text{W}$ being a common value for U-pipe ground heat exchangers [36]. Good agreement between modelled and measured storage performance was achieved when R_b was set to $0.15 \text{ (m} \cdot ^\circ\text{C})/\text{W}$.

Table 2. Input data model validation.

Input parameters	Input parameter values
Borehole field	
Borehole spacing, borehole depth, number of boreholes, borehole connection	4 m, 144 m, 140, serial two by two
Top layer and top surface boundary conditions	
Top layer thickness, volumetric heat capacity, ground thermal conductivity	2.75 m, 2.16 MJ/(m ³ ·°C), 0.53 W/(m·°C)
Boundary conditions surface towards atmosphere	Mean daily outdoor temperature, weather station Kosta, Sweden
Ground properties	
Ground volumetric heat capacity and effective thermal conductivity	2.20 MJ/(m ³ ·°C), 6 W/(m·°C)
Natural ground temperature	8 °C
Borehole heat exchanger	
Type and pipe and borehole diameters	Single U-pipe, 32 mm inner pipe diameter, 115 mm borehole diameter
Backfill material and its properties	Water, specific heat capacity 4.18 kJ/(kg·°C), density 1000 kg/m ³ , thermal conductivity 0.6 W/(m·°C)
Effective borehole thermal resistance	0.05/0.10/0.15 (m·°C)/W
Storage operation	
Open storage sections heat injection	All
Open storage sections heat extraction	Three inner sections, C–E

The operation of the storage at heat extraction was restricted to the three inner storage sections, which resembles the actual operation of the storage where this most of the time has been the case. For heat injection, which mainly takes place with four and five storage sections open, the operation of the storage was approximated by letting the flow be evenly distributed across all the boreholes. Measured storage supply flow data used as model input is shown in *Figure 10*. In the model, a resolution of one hour was used for the storage supply flow data. Since the storage was put into operation in June 2010, but detailed data for storage heat injection and extraction and ground temperatures is missing until March 2012, the model was initiated to correspond to the storage status as of March 2012. However, the temperature measured by sensor GT4 is strongly affected by the outdoor climate as the sensor is placed just below the storage insulation. A figure showing the model layout, including explanations for some main components, can be found in Paper II.

Figure 10. Measured storage supply flow temperature (a) and mass flow rate (b) at weekly mean values. Reprinted from Nilsson and Rohdin [49].

5.2 Parametric study setup

The performance of the Emmaboda storage was investigated in terms of annual heat injection and extraction as well as BTES efficiency by varying storage supply flow characteristics at heat injection, borehole spacing, borehole depth, ground thermal conductivity, and minimum useful storage temperature. Parameterization of borehole spacing and borehole depth was carried out for six combinations of the storage supply flow at heat injection, being multiples of the actual supply flow. The analysis of ground thermal conductivity and minimum useful storage temperature was limited to the actual storage supply flow at heat injection. The considered storage supply flows at heat injection, denoted Cases 1–6, where Case 6 is the actual supply flow, are shown in Table 3. The flows were chosen in order to be able to study how storage performance is affected by both mass flow rate and temperature of the supply flow at heat injection. The overall parametric study setup is shown in Table 4.

Table 3. Storage supply flows at heat injection considered in the parametric study, Cases 1–6. The actual storage supply flow at heat injection, Case 6, has been marked in bold. Mass flow rate (kg/s) and flow temperature (°C) are yearly mean values.

Case	Mass Flow of Actual (%)	Flow Temperature of Actual (%)	Mass Flow Rate (kg/s)	Flow Temperature (°C)
Case 1	75	200	10	80
Case 2	150	150	20	60
Case 3	100	150	13	60
Case 4	75	150	10	60
Case 5	150	100	20	40
Case 6	100	100	13	40

Table 4. Parametric study setup. Bold print denotes actual design and geological values for the BTES system at Xylem, Emmaboda.

Parameter	Values	Case
Borehole spacing (m)	1, 2, 3, 4 , 5, 6, 7, 8	1–6
Borehole depth (m)	84, 114, 144 , 174, 204, 234, 264, 294, 324	1–6
Modelled ground thermal conductivity (W/(m·°C))	1, 2, 3, 4, 5, 6 , 7, 8	6
Minimum useful storage temperature (°C)	30, 35, 40 , 45	6

Calculations consider that energy is extracted from the BTES system during the heating season whenever heat is not injected and the BTES system can deliver the minimum useful temperature to the internal heat distribution network. A supply flow temperature of a minimum of 40 °C is needed to be supplied to the internal heat distribution network for existing heat exchangers. It is assumed that all energy extracted from the BTES system can be used at the site. Heat extraction takes place at maximum flow rate, where the actual maximum flow rate, being approximately 20 kg/s, is used together with Case 6. The mass flow rate at heat extraction for Cases 1–5 have been scaled from that used together with Case 6 in accordance to the scaling of the supply flow rate at storage heat injection from Case 6. During both heat injection and extraction, the flow is evenly distributed over all the boreholes. The heating season for Emmaboda is September 15 – May 15.

Simulations were carried out for a long enough time for the BTES system to reach an annual steady state, i.e. storage performance is repeated for subsequent years. Annual steady state was considered reached when annual storage heat injection for the following year differed by no more than 5% and the ground temperatures, as measured by GT1–GT4, at the beginning and the end of the years differed by maximum 1% and showed the same patterns throughout the year. The criterion for annual steady state by considering one temperature point is illustrated in Figure 11, in which case annual steady state is considered reached in year six.

Figure 11. Illustration of the criteria for storage annual steady state: (a) ground temperatures and (b) annual injected energy. In this case, annual steady state is considered reached in year six. Reprinted from Nilsson and Rohdin [49].

For the simulation period exceeding the three-year validation period, storage supply data at heat injection for the last year was repeated for following years. For all investigated cases, annual steady state was reached in 2–4 years from that storage supply flow data was repeated. Based on results from the model validation, presented later, the parametric study was conducted using daily averages for the supply flow data used as model input. Remaining model input parameters for the parameterization were the same as used for the model validation.

6 Results and analysis

This chapter presents selected results from the research related to the thesis research questions, starting with results from the case study, which includes storage performance data and reasons for deviations in storage performance from predictions made prior to construction, followed by results from the model validation, and lastly by results from the parametric study.

6.1 Performance evaluation of the BTES system at Emmaboda

6.1.1 Storage heat injection and extraction and ground temperatures

The Emmaboda storage was put into operation in June 2010, but detailed data of storage heat injection and extraction and development of ground temperatures are missing until March 2012. As of March 2012, no energy had yet been extracted from the storage, but almost 2500 MWh of energy had been injected. This heat injection increased the temperature of the ground from around 8 °C to around 23 °C as measured by temperature sensors GT1 and GT2, located within the borehole field at a depth of 117 and 70 m respectively, and to around 16 °C as measured by GT4, located just beneath the insulation covering the borehole field. The temperature measured by sensor GT3, located 10 m from the south-west border of the borehole field at a depth of 100 m, had increased to approximately 14 °C. The positions of GT1–GT4 can be seen in Figure 7.

The development of heat injection and extraction and ground temperatures from March 2012 and onward is shown in Figure 12. Storage temperatures increased steadily on an annual basis until summer 2014, as more energy was injected into the ground. From here, however, annual peak temperatures only increased by 1–2 °C, which may partially be explained by the fact that heat was extracted hereon. In total, around 15,700 MWh of heat was injected into the storage from when it was put into operation in late summer 2010 until early summer 2017. During this time, 870 MWh of heat was also extracted from the storage, contributing to less district heating being purchased for the site.

However, predictions made at the design stage showed an annual heat injection and extraction of 3600 MWh and 2500 MWh respectively from the storage's second to third year of operation. Moreover, due to the storage being easier to charge at lower temperatures, heat injection for the first year was estimated at 6000 MWh. This means that the storage has not performed as expected.

Figure 12. Outcome of the Emmaboda storage with regard to ground temperatures (a) and storage heat injection and extraction (b) from March 2012 to June 2017. Reprinted from Nilsson and Rohdin [48].

For the storage's first years of operation, the lower than expected heat injection can primarily be explained by problems with gas in the system circuit, which prevented the heat carrier from being circulated. In autumn 2011, vacuum pumps were installed at the main supply and return manifolds to degas the system, and have since autumn 2012 been sufficient to keep the system running without interruptions. The source of the formation of the gas is still unknown but could be due to a leakage in the pipe system. The main reason, however, for the lower heat injection is lower than estimated quantities and/or quality of the excess heat for storage, which has resulted in a lower storage supply flow temperature. Flow temperatures from the factory during storage heat injection have on a weekly basis been in the range 40–50 °C instead of its expected value of 60 °C. The lower heat injection from this results in lower than estimated storage temperatures being reached and thus a lower heat extraction. The difficulty to charge the storage becomes prominent in 2015 and 2016 as storage temperatures and the temperature of the storage supply flow approach each other. In 2015 and 2016, 2300 and 2250

MWh respectively were injected into the storage, which can be compared to a heat injection of 3000 MWh in 2014. The reason that the heat injection in 2014 was higher than in 2013 (2350 MWh) is explained by the fact that some more processes were added to the heat recovery circuit in 2014, e.g. the server rooms at the site. It should be noted that design values considered heat injection at higher temperatures than at which the storage has operated, meaning that actual values for annual heat injection are further from predicted values than a comparison in absolute values suggests.

In order to see whether the lower than predicted storage performance also was a result of less favourable ground conditions, the effective ground thermal conductivity was calculated. This was done using steady-state heat transfer through cylindrical shells. The argument for the chosen method was the slow ground temperature changes seen at the storage location and that the heat transfer from the vertical borehole field border to the surrounding ground will be distributed over a larger area as the distance from the borehole field border increases. The effective ground thermal conductivity could be determined at around $6 \text{ W/(m}\cdot\text{°C)}$, which is quite a bit from the $3 \text{ W/(m}\cdot\text{°C)}$ that was used in the designing of the storage. An explanation for this difference in effective ground thermal conductivity could be the water-bearing fracture zone identified at the western storage border, see Figure 9, transporting energy away from the storage location and that these effects were not captured by the thermal response test as it was conducted at some distance away, near the eastern storage border. It is also possible there are other groundwater flows at the storage location that the TRT did not capture, carrying energy away from the storage region.

For the considered performance evaluation period of the Emmaboda storage, the highest heat extraction was achieved in 2016, where around 430 MWh of energy was extracted. In this year, also the highest ratio of heat extracted to heat injected was achieved, being approximately 19%. Since the storage temperatures were approximately the same at the start and end of the year, circa 40 °C as given by GT1 and GT2 and 30 °C as given by GT4, this is likely an approximate annual heat extraction and BTES efficiency that the storage can perform at long-term.

6.1.2 *Short-term storage*

BTES systems have commonly been used for long-term storage of solar energy to compensate for the seasonal mismatch of incoming solar radiation and building heat demand. However, industrial companies in cold climates with production year-round may also have a mismatch between heat generation and heat demand periodically in the winter. The alternating heat injection and extraction during a week in October 2015 and its effect on the temperatures in the ground is shown for the Emmaboda storage by the storage supply and return flow temperatures in Figure 13. The storage flow rate for the period was in the interval 10–15 l/s. During the week, around 53,500 kWh was injected into the storage and 12,500 kWh extracted. As in the case of the illustrated example, changes between heat injection and extraction have mostly occurred over the course of a few days. The shortest changes noted have been around

10 hours. The design idea for storage of energy in the winter was that it would primarily be injected at the storage centre to be extracted at higher temperatures and used as peak load.

Figure 13. Intermittent heat injection and extraction illustrated by the storage supply and return flow temperature, October 2015. Flow and ground temperatures shown in the figure are hourly mean values. Reprinted from Nilsson and Rohdin [48].

6.2 Modelling of the BTES system at Emmaboda

6.2.1 Model validation

For the three-year comparison, modelled values for total injected and extracted energy deviated from measured values by less than 1 and 3% respectively, and graphs for modelled and measured values followed the same patterns throughout the years (Figure 14). The same patterns between modelled and measured values were also seen for the ground temperatures (Figure 15). Both for GT1, GT2, and GT3, which are all located at considerable depths (70–117 m), the mean relative difference between modelled and measured values for the period was about 4%. For GT4, located just beneath the insulation covering the borehole field, this value was approximately 13%. Both for modelled and measured data, the BTES efficiency for the whole period was 2%.

The larger temperature changes seen for modelled values of GT2 as compared to measured values suggest a ground composition in the model at this location of lower heat capacity than that of the actual ground composition. Although site investigations showed a bedrock mainly made of granodiorite, it also showed some 2–5 m thick layers of amphibolite, which has slightly higher heat capacity than that of granodiorite. For ground formations, geological properties may be different at various depths. For example, dependent on e.g., porosity and water content, the ground thermal conductivity can range from around 1 W/(m·°C) up to 7 W/(m·°C), showing the importance of site investigations before the construction of the BTES system. For

GT4, the temperature difference between the modelled and measured values as of March 2012 is nearly 15 °C and the slower temperature changes seen for the modelled values suggest that the climate has a smaller impact on GT4 in the model. Reasons for this could be an overprediction of the thermal resistance of the layer covering the borehole field, as well as climate data limited to outdoor temperature. For example, heat transfer from the region could be affected by rain permeating the ground. However, the difference in temperature at GT4 has little effect on storage performance. One-dimensional steady-state heat conduction through the layer covering the borehole field, from the position of GT4 to the atmosphere, gives a storage heat loss of 255 MWh and 225 MWh respectively for modelled and measured temperatures for the three-year period, corresponding to about 3% of the total injected energy.

Figure 14. Injected (a) and extracted (b) energy, modelled versus measured. Reprinted from Nilsson and Rohdin [49].

Figure 15. Ground temperatures, modelled versus measured: (a) GT1, (b) GT2, (c) GT3, and (d) GT4. Reprinted from Nilsson and Rohdin [49].

The significance of a small time step for predicted storage performance was seen from a time step analysis. Figure 16 shows predicted heat extraction for a time step of one hour, 12 hours, one day, and one week. Predictions become erroneous when the time step exceeds the period at which changes between storage heat injection and extraction occurs, taking place at intervals down to around half a day. Averaging storage supply flow data for periods containing both heat injection and extraction will result in the storage either only being charged or discharged during the respective period. In Paper II, the impact of simulation time step on heat injection and ground temperatures GT1–GT4 can be seen. These parameters were little influenced by choice of time step. Since the energy quantities related to the intermittent storage operation are small compared to the total injected energy, this means that the choice of time step had little influence on storage performance for periods of heat injection only.

Figure 16. Modelled extracted energy for a time step of one hour, one day, one week and one month. Reprinted from Nilsson and Rohdin [49].

6.2.2 Parametric study

6.2.2.1 Borehole spacing

A parameter of interest to investigate with respect to the performance of a BTES system is the borehole spacing as this will affect the volume into which energy is injected and the thermal interaction between the boreholes. In Figure 17, annual heat injection and extraction as function of borehole spacing is shown for the six combinations of the storage supply flow at heat injection presented in detail in Table 3, where Case 6 contains the actual flow rate and flow temperature. From Figure 17 a), it can be seen that for all flows the amount of energy that can be injected increases with increasing borehole spacing. This outcome is expected because an increased borehole spacing means that energy is injected into a larger ground volume, i.e. the heat capacity of the volume confining the boreholes is increased, resulting in a higher temperature difference between the ground and the heat transfer fluid. It is visible that the increase in injected energy for each increment in borehole spacing reduces as the spacing becomes larger. The curves will continue to flatten out as a spacing is approached at which the heat transfer process around a borehole is negligibly affected by that of any other borehole. From a spacing of 7 to 8 m, the increase in injected energy for considered flows is 3–6%. A

logarithmic curve fit shows that at a borehole spacing of 15 and 30 m, this increase from an increment (1 m) in spacing is less than 1 and 2% respectively.

Figure 17. Annual injected energy (a), extracted energy (b) and BTES efficiency (c) plotted against borehole spacing. Values presented in legend parentheses are the mass flow rate and temperature of the supply flow at heat injection respectively. The actual borehole spacing measures 4 m. Reprinted from Nilsson and Rohdin [49].

A too large borehole spacing means that storage temperatures necessary for energy to be extracted are not reached, whereas a too small spacing means that potential energy that could have been stored and recovered is lost. This existence of an optimum borehole spacing for heat extraction is also in agreement with findings by Welsch et al. [37]. In this case, a borehole spacing of 4 m yields the highest heat extraction for Cases 1–3, whereas 3 m gives the highest value for Case 4. At these spacings, the annual heat extraction is 3080, 2060, 1680, and 1380 MWh for Cases 1, 2, 3 and 4 respectively. Overall, the reduction in extracted energy is higher when the spacing is decreased as opposed to increased from this point. For the considered flows, the energy that can be injected and extracted at the same borehole spacing is in descending order first linked to the flow temperature and secondly to the flow rate. The actual flow temperature, used in Cases 5 and 6, is not sufficient for the storage to reach the temperatures necessary for any noteworthy amounts of energy to be extracted.

From Figure 17 c), it can be concluded that the BTES efficiency does not necessarily reflect the storage performance in terms of heat extraction that the storage could have been designed for. For Cases 1–3, the BTES efficiency is about the same at a spacing of 2 and 4 m, despite annual heat extraction being considerably lower at the former. Furthermore, the highest BTES efficiency is achieved at a spacing of 3 m and not at 4 m, which yields the highest annual heat extraction. For Cases 1–4, BTES efficiencies of 40–50% are reached, whereas BTES efficiencies for Cases 5 and 6 are below 10%.

6.2.2.2. *Borehole depth*

As for the case of borehole spacing, borehole depth will affect the volume into which energy is injected, but in addition to this also the heat exchanger length. Figure 18 shows annual injected and extracted energy as function of borehole depth for the six constructions of the storage supply flow at heat injection, Cases 1–6. It can be seen that the amount of energy that can be injected increases with increasing depth. However, taking into account that Figure 18 starts at a borehole depth of 84 m, it is also seen that average injected energy per metre of borehole depth reduces with depth. The basis for this outcome is that the storage supply flow temperature at heat injection is at its highest at the borehole inlet, for example facilitating heat transfer between the fluid and the ground closer to this point. The lower heat injection per unit depth with increased depth results in lower storage temperatures, just as an increased borehole spacing does, giving a cut-off point of borehole depth for heat extraction. From this argument, it follows logically that the borehole depth yielding the highest annual heat extraction increases with heat injection rate, as seen here for Cases 1–4. Heat extraction is highest at a depth of around 264 m for Cases 1 and 2, at 234 m for Case 3, and at 204 m for Case 4. At these depths, around 3590, 3020, 2130, and 1530 MWh/year can be extracted for Cases 1, 2, 3, and 4 respectively. It should be noted, however, that in practice ground heat exchanger installations seldom exceed a depth of around 250 m due to the difficulty and cost of drilling at these depths. As also seen for the parameterization of borehole spacing, the BTES efficiency is insufficient as indicator for whether a BTES system has been appropriately constructed with regard to heat extraction. For Cases 1–4, BTES efficiencies reach around 35–50%.

Figure 18. Annual injected energy (a), extracted energy (b) and BTES efficiency (c) plotted against borehole depth. Values presented in legend parentheses are the mass flow rate and temperature of the supply flow at heat injection respectively. The actual borehole depth measures 144 m. Reprinted from Nilsson and Rohdin [49]

6.2.2.3. Ground thermal conductivity

Another important factor for the heat transfer process in the ground in the presence of a BTES system is the (effective) ground thermal conductivity. In Figure 19, annual injected and extracted energy and BTES efficiency are shown as function of ground thermal conductivity at storage annual steady state for the actual design and storage supply flow at heat injection of the Emmaboda storage. It can be seen that, independent of ground thermal conductivity, only a small amount of energy can be extracted, at most approximately 100 MWh/year. The reason for this, as supported by the almost linear relationship between storage temperature GT2 and ground thermal conductivity seen in Figure 20, is the limited storage supply flow temperature at heat injection, being on average around 40 °C. However, had there been a larger temperature difference between the minimum useful storage temperature (presently at 40 °C), and the storage supply flow at heat injection, the increase in heat extraction for lower ground thermal conductivities would likely have been more significant. The results shown in Figure 19 support, nonetheless, the concept of Başer et al. [24] that a BTES system installed in unsaturated ground formations may achieve higher performances than a BTES system

installed in saturated ground formations, because of the lower ground thermal conductivity of the former.

Figure 19. Annual injected and extracted energy (a) and BTES efficiency (b) as a function of ground thermal conductivity for the actual storage design and supply flow at heat injection, Case 6. Reprinted from Nilsson and Rohdin [49].

From GT3, located 10 m from the borehole field border at a depth of 100 m, it can be seen how the increase in temperature levels out with increasing ground thermal conductivity according to the logarithmic behaviour of heat transfer taking place radially, which was an expected outcome. The reason that around 170 MWh of heat could be extracted during the winter of 2014–2015 at a ground thermal conductivity of 6 W/(m·°C) in the model validation, Figure 14, is because heat extraction in that case was limited to the inner boreholes.

Figure 20. Ground temperatures as a function of ground thermal conductivity for the actual storage design and supply flow at heat injection, Case 6. September 15 and May 15 are the beginning and end of the building heating season respectively. Reprinted from Nilsson and Rohdin [49].

6.2.2.4. Minimum useful storage temperature

By allowing for heat extraction down to lower storage temperatures, amounts of energy that can be injected into the ground will increase due to the increased temperature difference

between ground and heat transfer fluid, in turn resulting in more energy becoming available for heat extraction. In Figure 21, the effect on heat injection and extraction and BTES efficiency from minimum useful storage temperature is shown for the actual design of the Emmaboda storage and the actual supply flow at heat injection, Case 6. When the useful storage temperature is decreased to 35 or 30 °C, it is predicted that 360 MWh/year and 800 MWh/year can be extracted respectively. Also the BTES efficiency increases as the minimum useful storage temperature decreases, reaching around 30% for a temperature of 30 °C of the latter. In both cases, it was observed that minimum useful ground temperatures are reached before the end of the heating season and that the temperature 10 m from the storage border, given by GT3, peaks at 25 °C during the year. This means that all the energy at the given heat extraction rate above 30 °C, until the date for which minimum ground temperatures are reached, can be extracted and that most of the energy above this temperature is found within the borehole field. The latter is also indicated by the almost linear relationship seen for extracted energy between 30 and 40 °C. However, the relation between annual heat extraction and minimum useful storage temperature, heat extraction rate aside, must not be linear but will depend on the minimum useful storage temperature as well as the temperature difference between the storage working temperatures and the storage supply flow temperature at heat injection. In this particular case, limited storage supply flow temperatures, being on average around 40 °C, allow for the same storage temperatures to be reached independent whether heating takes place from storage temperatures of 30 or 35 °C.

Figure 21. Annual injected and extracted energy (a) and BTES efficiency (b) vs. minimum useful storage temperature for the actual storage design and supply flow at heat injection, Case 6. Reprinted from Nilsson and Rohdin [49].

7 Concluding remarks

This chapter first provides a concluding discussion with regard to the thesis research questions. Then, based on the concluding discussion and limitations of the thesis, suggestions for future work are given.

7.1 Research question 1

How has the industrial BTES system at Xylem, Emmaboda performed in terms of ground temperatures and heat injected into and extracted from the storage during its first seven years of operation?

For the Emmaboda storage, it can be concluded that lower than estimated quantities and/or quality of the excess heat for storage, resulting in lower than expected storage supply flow temperatures at heat injection, is the underlying reason for the difference in actual and predicted storage performance. This shows the importance of accurately predicting excess heat available for storage, which in case of time-dependent differences in operation of involved processes for heat recovery can be quite a difficult task.

Today, the Emmaboda storage is operated using heat pumps for heat extraction. However, at the performance that the Emmaboda storage, based on the cycling storage behavior seen in 2016, could likely have been operated at long-term otherwise, the heat injection and extraction of 2250 and 430 MWh/year respectively would have meant an annual BTES efficiency of 19%. Predicted values for heat injection and extraction give a BTES efficiency of almost 70%. However, for one of the more successful BTES implementations with regard to BTES efficiency utilizing direct heat exchange for extraction, being the BTES in Alberta, Canada [5], the annual BTES efficiency for the storage's third to fifth years of operation, where a repeating annual storage behaviour was seen, was on average approximately 42%. This number for the BTES efficiency also corresponds to that seen from the parametric study conducted on the Emmaboda storage in this work, where values up to 40–50% were reached. It should be noted though that these predictions considered an effective ground thermal conductivity of $6 \text{ W/(m}\cdot\text{°C)}$, which in case of ground formations little influenced by groundwater flow is in the upper range. These findings may overall, however, suggest that BTES efficiencies higher than this range (40–50%) should not be expected.

But, as shown in this work, it is not necessarily reflected by the BTES efficiency whether a BTES system has been built as to benefit heat extraction. Because of this, cost versus performance assessments should not only use the BTES efficiency for describing BTES performance. However, for performance evaluations of a BTES system on a year-to-year basis as a first step to identify eventual system disruptions, the BTES efficiency can be a useful performance metric.

7.2 Research question 2

With what accuracy can the performance in terms of injected and extracted energy and ground temperatures of a BTES system used for both seasonal and short-term storage of energy be modelled using a commercial software for ground heat exchanger calculations?

For the three-year modelling of the performance of the Emmaboda storage, predicted values for total injected and extracted energy deviated from measured values by less than 1 and 3% respectively, and predicted and measured values for injected and extracted energy followed the same pattern throughout the period. Furthermore, for all ground temperatures measured at considerable depths (70–117 m), corresponding to GT1–GT3, the mean relative difference between predicted and measured values was about 4%. However, for GT4, located just beneath the insulation covering the borehole field, the mean relative difference was approximately 13%. An overprediction of the thermal resistance of the layer covering the borehole field and climate data in the model limited to outdoor air temperature were given in this work as possible reasons for this discrepancy. However, it could be shown that this difference in temperature at GT4 has little effect on the storage performance. Both for predicted and measured values of GT4, storage heat losses through the layer covering the borehole field could be determined at around 3% of the total injected energy for the validation period.

Through a time-step test, it could also be confirmed that the model had captured the short-term storage effects, as predictions (for heat extraction) would become erroneous when the time step exceeded the intervals at which changes in heat injection and extraction occur. From the time-step analysis, it could furthermore be seen that predicted storage performance was only slightly influenced when the time step was varied from one hour up to one month for periods with only heat injection.

7.3 Research question 3

How is the performance, especially annual heat extraction, of the BTES system at Emmaboda affected by design parameters such as borehole spacing and storage supply flow characteristics at heat injection?

One main outcome from the parametric study was that of the impact on storage performance from the storage supply flow temperature at heat injection. For the considered storage supply flows at heat injection, 10–20 l/s and 40–80 °C, a high temperature in the supply flow was more important than a high flow rate in order to achieve high annual heat extractions. In the context of BTES systems, the fact that heat transfer is facilitated by the temperature difference between the two objects that the heat transfer concerns will mean that the supply flow temperature has great impact. This because the increasing storage temperatures during charging will mean that also the ratio of the temperature difference between heat transfer fluid and ground between a supply flow temperature of higher and lower temperature will increase. With an increased storage supply flow temperature, heat injection can also continue for a

longer time as storage temperatures approach the supply flow temperature. Another main finding from the parametric study was that of the impact on storage performance from borehole spacing. Annual heat extraction would rapidly reduce as the spacing was decreased from the spacing yielding the highest annual heat extraction, whereas the reduction in annual heat extraction was quite slow when the spacing was increased from this point. The reduction in borehole field volume from a decreased borehole spacing, reducing amounts of energy that can be stored and recovered, can be compensated for with deeper boreholes. However, due to difficulties and costs drilling after some depth, taking place at circa 250 m, space restrictions could be the limiting factor for the potential of using a BTES system for energy recovery.

Furthermore, for designers of BTES systems, the possibility of designing the storage for low working temperatures should be looked into. What an increase in annual heat extraction with decreasing minimum useful storage temperature can look like has been demonstrated in this work. By decreasing the storage working temperatures, more energy can be injected into the storage, which in turn results in that more energy can be extracted from the storage. Another benefit of a decreased working temperature is lower storage heat losses to the surroundings. An opportunity for a low minimum useful storage temperature could be that of a high ventilation demand existing at the site and its close surroundings. However, if the low-temperature heat demand is small, the storage could work at low temperatures by using heat pumps for heat extraction. Noteworthy for this design is that based on the Carnot efficiency, a heat pump extracting energy from a BTES system could be operating at significant COPs. In reality, however, the COP is for example in the interval 4–6 for a source temperature of 30–40 °C at common delivery temperatures (50–60 °C), to be compared to a COP of around 3 for a heat pump working with the natural temperature of the ground. One benefit of using heat pumps for heat extraction is that storage performance will be less affected to deviations in predicted heat injection and could thus be a way to deal with possible difficulties when estimating heat available for storage at an industrial site.

7.4 Further work

One of the main reasons for the lower than expected storage performance of the Emmaboda storage was an overestimation of the quality and/or quantity of the excess heat for storage. In future work, procedures for determining amounts of energy that can be stored could be established. These plans could e.g. deal with averaging of measured data due to time-varying changes in operation of processes, logging duration and extrapolation of measured data, heat exchanger temperature differences, and influences on the overall heat recovery system from the addition of another heat sink (the BTES system).

To aid in decision-making with regard to energy efficiency measures, future work could map the energy-economic potential and effects on greenhouse gas emissions from using BTES systems for storage of industrial excess heat. The mapping could for example be done through categorization on industry sector or subsector by considering the typical company within the sector with regard to heat generation and heat demand characteristics. Such an assessment

could also include the willingness of the district heating owner to purchase energy from the industrial site, which could e.g. affect the economically and emission-based favorable sizing and operation of the BTES system.

Future work could also look at the effects on e.g. primary energy use, greenhouse gas emissions, and district heating delivery capacity from various integrations of BTES systems for storage of heat from the industry and the heat plants to the regional district heating network. For example, in the case of one or a few central BTES systems, one can benefit from increased BTES efficiency from storage size, whereas a number of smaller BTES systems, strategically located, could better aid in reducing bottlenecks in the district heating network.

References

1. Nordell, B.; Hellström, G. High temperature solar heated seasonal storage system for low temperature heating of buildings. *Solar Energy* **2000**, *69*, 511-523.
2. Gao, L.; Zhao, J.; Tang, Z. A review on borehole seasonal solar thermal energy storage. *Energy Procedia* **2015**, *70*, 209-218.
3. Gehlin, S.; Andersson, O. Geothermal Energy Use, Country Update for Sweden. In Proceedings of European Geothermal Congress 2016, Strasbourg, France.
4. Lundh, M.; Dalenbäck, J.-O. Swedish solar heated residential area with seasonal storage in rock: Initial evaluation. *Renewable Energy* **2008**, *33*, 703-711.
5. Sibbitt, B.; McClenahan, D.; Djebbar, R.; Thornton, J.; Wong, B.; Carriere, J.; Kokko, J. The performance of a high solar fraction seasonal storage district heating system - five years of operation. *Energy Procedia* **2012**, *30*, 856-865.
6. Bauer, D.; Marx, R.; Nußbicker-Lux, J.; Ochs, F.; Heidemann, W.; Müller-Steinhagen, H. German central solar heating plants with seasonal heat storage. *Solar Energy* **2010**, *84*, 612-623.
7. Rapantova, N.; Pospisil, P.; Koziorek, J.; Wojcinak, P.; Grycz, D.; Rozehnal, Z. Optimisation of experimental operation of borehole thermal energy storage. *Appl Energy* **2016**, *181*, 464-476.
8. Xu, L.; Torrens, I.; Guo, F.; Yang, X.; Hensen, J.L.M. Application of large underground seasonal thermal energy storage in district heating system: A model-based energy performance assessment of a pilot system in Chifeng, China. *Applied Thermal Engineering* **2018**, *137*, 319-328.
9. *Key world energy statistics*; International Energy Agency, France, 2019.
10. *Energy in Sweden 2019*; Swedish Energy Agency, Eskilstuna, Sweden, 2019.
11. Broberg, V.S. *System studies of the use of industrial excess heat*, Dissertation no. 1679; Division of Energy Systems, Department of Management and Engineering: Linköping, Sweden, 2015.
12. Thekdi, A.; Belt, C. *Waste heat reduction and recovery options for metals industry In: Energy technology 2011: Carbon dioxide and other greenhouse gas reduction metallurgy and waste heat recovery*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
13. Cronholm, L.-Å.; Grönkvist, S.; Saxe, M. *Spillvärme från industrier och värmeåtervinning från lokaler*, 2009:12; Swedish District Heating Association, Stockholm, Sweden, 2009.
14. Persson, U.; Werner, S. District heating in sequential energy supply. *Appl Energy* **2012**, *95*, 123-131.
15. Connolly, D.; Lund, H.; Mathiesen, B.; Werner, S.; Möller, B.; Persson, U.; Boermans, T.; Trier, D.; Østergaard, P.A.; Nielsen, S. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. *Energy Policy* **2014**, *65*, 475-489.
16. Rad, F.M.; Fung, A.S. Solar community heating and cooling system with borehole thermal energy storage - Review of systems. *Renewable and Sustainable Energy Reviews* **2016**, *60*, 1550-1561.
17. Pavlov, G.K.; Olesen, B.W. Seasonal solar thermal energy storage through ground heat exchangers – Review of systems and applications. In Proceedings of The 6th Dubrovnik conference on sustainable development of energy, water and environment systems, Croatia, Dubrovnik.
18. Hesaraki, A.; Holmberg, S.; Haghighat, F. Seasonal thermal energy storage with heat pumps and low temperatures in building projects — A comparative review. *Renewable and Sustainable Energy Reviews* **2015**, *43*, 1199-1213.
19. Lanahan, M.; Tabares-Velasco, P.C. Seasonal Thermal-Energy Storage: A Critical Review on BTES Systems, Modeling, and System Design for Higher System Efficiency. *Energies* **2017**, *10*.

20. Bennet, J.; Claesson, J.; Hellström, G. *Multipole method to compute the conductive heat flows to and between pipes in a composite cylinder*; 1987.
21. Hellström, G. *Ground heat storage: thermal analyses of duct storage systems*; Doctoral thesis, Lund University, Sweden, 1991.
22. Bose, J.; Smith, M.; Spitler, J. Advances in Ground Source Heat Pump Systems - An International Overview. In Proceedings of 7th IEA Heat Pump Conference, Beijing; pp. 313-324.
23. Austin, W.A. *Development of an In-situ System for Measurement of Ground Thermal Properties*; M.Sc. thesis, Department of Mechanical Engineering, Oklahoma State University, Stillwater, OK, USA, 1998.
24. Başer, T.; McCartney, J.S. Transient evaluation of a soil-borehole thermal energy storage system. *Renewable Energy* **2018**, 10.1016/j.renene.2018.11.012, doi:10.1016/j.renene.2018.11.012.
25. Choi, J.C.; Lee, S.R.; Lee, D.S. Numerical simulation of vertical ground heat exchangers: Intermittent operation in unsaturated soil conditions. *Computers and Geotechnics* **2011**, 38, 949-958.
26. Paksoy, H.; Snijders, A.; Stiles, L. State-of-the-Art Review of Underground Thermal Energy Storage Systems for Heating and Cooling Buildings. In Proceedings of World Energy Engineering Congress.
27. *Long-term performance measurement of GSHP systems serving commercial, institutional and multi-family buildings*; IEA HPT TCP, 2017.
28. Fisch, M.N.; Guigas, M.; Dalenbäck, J.O. A review of large-scale solar heating systems in Europe. *Solar Energy* **1998**, 63, 355-366.
29. Schmidt, T.; Mangold, D.; Müller-Steinhagen, H. Central solar heating plants with seasonal storage in Germany. *Solar Energy* **2004**, 76, 165-174.
30. Mangold, D.; Schmidt, T. *The next Generations of Seasonal Thermal Energy Storage in Germany*, Solites – Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems: Stuttgart, Germany.
31. Tordrup, K.W.; Poulsen, S.E.; Bjørn, H. An improved method for upscaling borehole thermal energy storage using inverse finite element modelling. *Renewable Energy* **2017**, 105, 13-21.
32. Li, M.; Lai, A.C.K. Review of analytical models for heat transfer by vertical ground heat exchangers (GHEs): A perspective of time and space scales. *Appl Energy* **2015**, 151, 178-191, doi:10.1016/j.apenergy.2015.04.070.
33. Ingersoll, L.R.; Zobel, O.J.; Ingersoll, A.C. *Heat conduction with engineering, geological, and other applications*; University of Wisconsin Press, 1954.
34. Eskilson, P. *Thermal analysis of heat extraction boreholes [PhD Thesis]*; Department of Physics, University of Lund, Sweden, 1987.
35. De Rosa, M.; Ruiz-Calvo, F.; Corberán, J.M.; Montagud, C.; Tagliafico, L.A. A novel TRNSYS type for short-term borehole heat exchanger simulation: B2G model. *Energy Conversion and Management* **2015**, 100, 347–357.
36. Patricia, M. *Modelling and monitoring thermal response of the ground in borehole fields*; PhD Dissertation, KTH Royal Institute of Technology: Stockholm, 2018.
37. Welsch, B.; Ruhaak, W.; Schulte, D.O.; Bar, K.; Sass, I. Characteristics of medium deep borehole thermal energy storage. *International Journal of Energy Research* **2016**, 40, 1855-1868, doi:10.1002/er.3570.
38. Woloszyn, J. Global sensitivity analysis of borehole thermal energy storage efficiency on the heat exchanger arrangement. *Energy Conversion and Management* **2018**, 166, 106-119, doi:10.1016/j.enconman.2018.04.009.
39. Nguyen, A.; Pasquier, P.; Marcotte, D. Borehole thermal energy storage systems under the influence of groundwater flow and time-varying surface temperature. *Geothermics* **2017**, 66, 110-118, doi:10.1016/j.geothermics.2016.11.002.
40. Yin, R.K. *Case Study Research: Design and Methods*, 5 ed.; SAGE Publications: 2013.

41. Nordell, B.; Liuzzo scorpo, A.; Andersson, O.; Rydell, L. *The HT BTES plant in Emmaboda - Report from the first three years of operation 2010-2013*; 2014.
42. Nordell, B.; Liuzzo Scorpo, A.; Andersson, O.; Rydell, L.; Carlsson, B. *The HT BTES plant in Emmaboda*; Div. of Architecture and Water, Luleå University of Technology: Luleå, 2016.
43. Ryan, E.M.; Sanquist, F.T. Validation of building energy modeling tools under idealized and realistic conditions. *Energy and Buildings* **2012**, *47*, 375-382.
44. Bring, A.; Sahlin, P.; Vuolle, M. *Models for Building Indoor Climate and Energy Simulation*; Dept. of Building Sciences, KTH Royal Institute of Technology: Stockholm, 1999.
45. Achermann, M. *VALIDATION OF IDA ICE, Version 2.11.06*; Hochschule Luzern: Luzern, Schweiz, 2000.
46. Fadejev, J.; Kurnitski, J. Geothermal energy piles and boreholes design with heat pump in a whole building simulation software. *Energy and Buildings* **2015**, *106*, 23-34.
47. *Description of the IDA ICE borehole model*; EQUA Simulation AB, 2018.
48. Nilsson, E.; Rohdin, P. Performance evaluation of an industrial borehole thermal energy storage (BTES) project – Experiences from the first seven years of operation. *Renewable Energy* **2019**, *143*, 1022-1034.
49. Nilsson, E.; Rohdin, P. Empirical Validation and Numerical Predictions of an Industrial Borehole Thermal Energy Storage System. *Energies* **2019**, *12*.
50. *BORRHÅLSLAGER ITT EMMABODA - Resulat av förundersökningar och projektering*; Sweco: Malmö, 2010.

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