

Seasonal Storage of Photovoltaic Energy

Seasonal energy storage in borehole thermal energy systems for load shifting potential through increased ground source heat pump efficiency

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Renewable energy systems
30 Credits

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Abstract

This thesis addresses the significant mismatch between solar photovoltaic (PV) energy production and the heating demands of Norwegian households, particularly in the context of the country's unique climate characterized by pronounced seasonal variations. In summer, solar production peaks while heating demand is minimal, leading to excess electricity generation that is often exported to the grid. Conversely, winter brings low solar output and high heating needs, resulting in substantial energy imports.

The study focuses on evaluating the viability of borehole thermal energy storage (BTES) systems for both single-family homes and larger-scale applications. To achieve this, the energy consumption was modeled for both types of scenarios: typical single-family homes, which utilize a single borehole, and for larger-scale applications that employ a borehole park consisting of multiple interconnected boreholes. The model aimed to determine the energy input and extraction from the borehole. By utilizing energy extraction data (EED), the study further analyzed temperature variations within the boreholes, offering insights into the system's effectiveness.

The results indicate that it is neither economically viable nor practical to store energy in a single borehole. This conclusion arises from the fact that added heat merely replaces the natural heat flux, leading to considerable heat loss to the surroundings.

In contrast, the findings indicate that larger-scale applications exhibit reduced electricity consumption in winter when storing surplus solar energy in summer. However, factors such as borehole depth, spacing, and energy inputs will influence the efficiency of the systems. The results provide a foundation for arguing both the practical and economic feasibility of BTES systems. Further research is recommended to validate these findings and to investigate the potential benefits of load shifting from the perspective of Distribution System Operators.

AI declaration

In this scientific work, generative artificial intelligence has been utilized. All data and personal information have been processed in accordance with the regulations of the University of Oslo, and we, as the authors of the document, take full responsibility for its content, claims, and references. An overview of the use of generative AI is provided below

- The GPT UiO service, developed by the IT department at UiO, has been used to improve the content of the thesis. Sections of the report have been given to the AI software and made to correct misspelling and to bring academic flow to the text. The proposed correction was then critically assessed and partially rewritten by the authors of this thesis. In no shape or form was Chat GPT used to generate text from blank.
- Chat GPT was used is assistance in data analysis and programming. AI was used to aid in generation of specific lines of codes, for example the Sankey diagrams. Additionally AI was used to make plots more visually appealing.
- Chat GPT was used as assistance in literature study. AI was given initial research questions to help the authors form a starting point of the literature study and to find relevant sources. From there AI aided in discussion around specific topics where all outputs were critically assessed and fact checked by the authors.

Preface

This thesis is a collaborative work between Thomas Kvalvågnes and Sveinung Lenes Aga. The entirety of the work has been completed in close collaboration. There are no parts of the thesis that have been strictly completed by either author alone. However, Thomas directed additional focus towards existing BTES systems, costs and understanding of the potential benefits of seasonal energy storage. Sveinung focused on energy system model, ground properties and energy well components.

This Master's thesis concludes the degree in Renewable Energy Systems at the University of Oslo (UiO). We are very appreciative for the knowledge and experience we have gathered with great professors and fellow students.

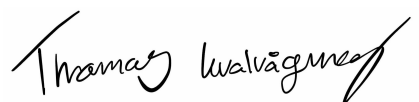
Over the past two years, we have gained a deep appreciation for the complexity and challenges involved in transforming energy systems to meet sustainability goals. There is no universal solution; instead, a successful transition requires a multifaceted approach in power generation, transmission, and changes in consumer behavior. While the total efforts required are substantial and often not immediately profitable, it is crucial that someone takes on the responsibility to drive these changes forward.

We would like to thank our supervisor, Josef Noll for guidance and informative discussions through weekly meetings.

Additionally, we would like to express our gratitude to our fellow students, informally known as the four leaf clover crew, for feedback and emotional support during the thesis.

Oslo, May 2025

Thomas Kvalvågnes & Sveinung Lenes Aga



Sveinung L. Aga

NDC	National determined contributions
VRES	Variable renewable energy sources
PV	Photovoltaic
CAT	Climate action tracker
BTES	Borehole thermal energy storage
DESSI	Distributed energy system security infrastructure
DSO	Distribution system operator
NGU	Norwegian geological investigation
GSHP	Ground source heat pump
ASHP	Air source heat pump
COP	Coefficient of performance
HSPF	Heating seasonal performance factor
SEER	Seasonal energy efficiency ratio
GAMS	General algebraic modeling system
EED	Earth energy designer

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1 Introduction

1.1 Context and motivation

Combating climate change is a complex and multi faced challenge. Achieving national and international greenhouse gas emission reduction targets requires a comprehensive transformation of the current energy system. Norway's national determined contributions towards the Paris agreement (NDC) aims to reduce the total emission by 55% by 2030 compared to 1990 levels [1]. Climate action tracker (CAT) states that with current policies and actions Norway will only achieve a 21% reduction in greenhouse gas emissions by 2030 [2].

Phasing out fossil fuels through increased electrification in the industrial and transportation sectors is a key strategy to meet climate targets by 2030 [3]. In the same time period the population is expected to grow by 3.6% according to SSB [4]. According to "kortsiktig markedsanalyse" from Statnett the increased electrification and population growth is expected to bring a 20 TWh increase in electrical consumption towards 2030. The increased electrification necessitates costly grid reinforcements and capacity expansion, totaling to between 60-100 billion NOK towards 2030 [5], [6].

While electrification is a positive step towards decarbonization, minimizing the need for large-scale grid investments is crucial. One promising solution is the implementation of decentralized energy systems, which integrate local energy generation and storage to address grid capacity challenges. [7], [8]. Decentralized energy systems offer both an environmental and socioeconomic benefit. Utilization of locally produced energy will minimize transport losses due to shorter transmission distances, additionally the surrounding transmission grid will get more free capacity. Decentralized energy system can provide peak shaving and load shifting through the integration of local storage and smart systems, thereby delaying or avoiding the need for expensive grid reinforcements [9]. By relying on locally produced energy, consumers can lower their energy costs and gain greater control over their energy supply. Increased energy independence is particularly valuable in the face of natural disasters, geopolitical instability, and supply chain disruptions which is an increasing risk today.

In Norway, the residential sector accounts for 130 TWh of electricity consumption in 2024, representing approximately 31.5% of the country's total electricity usage [10]. By transitioning to decentralized energy systems, the residential sector has the potential to reduce its reliance on the centralized grid, alleviating grid stress and facilitating a sustainable energy transition.

Solar photovoltaic (PV) systems and batteries are central components of decentralized energy

systems. In recent years, these technologies have seen substantial price reductions, a trend expected to continue [11]. Their affordability makes them viable for widespread adoption. However, the intermittent nature of solar power creates a mismatch between energy generation and demand. The mismatch can be combated by several measures, i.e seasonal energy storage, consumer flexibility, smart technologies. However, to achieve the best possible outcome, it is essential to employ all of these methods in unison, ensuring a comprehensive and robust solution.

Batteries serve as daily buffers, storing excess solar energy produced during the day for use during the night or cloudy periods. However, batteries are limited for longer-term storage. Seasonal variations in energy production can be managed using technologies such as energy wells, which utilize the stable temperature underground. Energy wells ensures a stable and reliable energy supply. There is also a possibility to store surplus energy generated during sunny months for use in colder, less sunny seasons in a borehole thermal energy storage system (BTES).

Recognizing the importance of local energy production, the Norwegian government has set a target of producing 8 TWh locally by 2030, which would equal 6.1% of the total electricity consumption in Norway. Reaching the target would require a 15-fold increase in the current installed capacity [12]. Research and project implementations by DNV and SINTEF have identified solar PV systems and geothermal storage as some of the most promising solutions for decentralizing energy systems to offload the grid [13].

Zooming in on the southern parts of Norway. Oslo and Akershus has the biggest power deficit in all of the Nordic, with a negative power balance of 16 TWh. The region is therefore totally dependent on power import from neighboring regions. Lillestrøm municipality have highlighted the need for decentralized energy systems, more locally produced power and grid expansions. Hence why Lillestrøm wants to expand on the already 11 MW installed rooftop PV and make use of the surplus power more efficiently [14].

1.2 Problem statement and scope

This Master thesis investigates the potential of BTES, and whether if it can improve local and regional energy systems. The thesis is limited to investigation of single borehole energy wells and borehole thermal energy storage system. The aim of the thesis is to develop recommendations to private consumers and commercial building owners helping them make an educated decision on seasonal storage. This master thesis aims to do this by answering the following research questions:

- What are the potential synergy between solar photovoltaics power production and heating

demand when utilizing seasonal energy storage?

- To what extent can seasonal BTES systems be economically viable for single-family homes with a single energy well?
- How do design parameters, such as borehole spacing and energy input ratio affect the energy storage performance of seasonal BTES systems?
- To what extent can thermal energy storage in multi-borehole systems help reduce electricity consumption in winter thereby alleviate pressure on the power grid?

1.3 Scientific method and content of thesis

To answer the research questions a comprehensive scientific approach was conducted. The work flow is represented in figure 1.1.

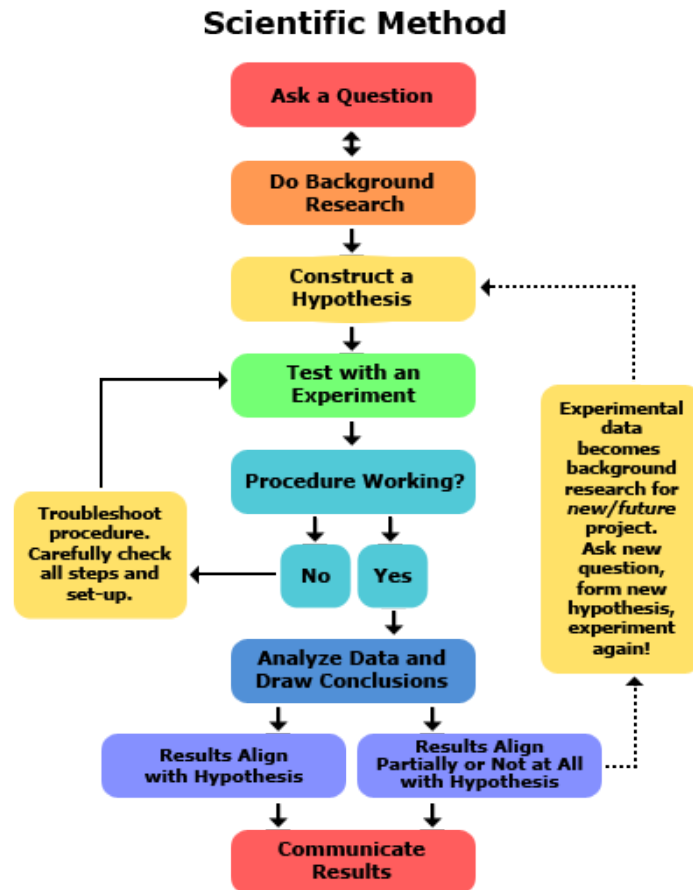


Figure 1.1: Schematic representation of the scientific approach applied to answer the research questions [15].

The starting point of this thesis was the inquiry into how to address the mismatch between PV production and heating demand. To explore this issue, an extensive literature review on

potential seasonal energy storage technologies was conducted, ultimately leading to a focus on BTES systems. Following this initial literature review, specific research questions were formulated. Subsequently, modeling and simulations were performed, during which initial results revealed certain shortcomings. These challenges were systematically addressed to the best of our capabilities. This methodological approach culminated in the presentation of the results detailed in this thesis. Finally, efforts were made to ensure that all research questions were thoroughly answered and communicated.

The thesis is structured in the following way. Section 2 describes the inherent mismatch between solar power production and energy consumption. The section describes typical PV power production and heating demand profiles in Norway. Furthermore, the sections go through the different components of the electricity bill.

Section 3 lays out the current state of energy well systems in Norway. The section also provides a detailed description of the components in energy wells and BTES and what the optimal configuration and operation looks like. Additionally the section explains the most important geothermal properties affecting the heat transfer in the systems.

Section 4 describes the methodology and the modeling tools used for the two different simulations. This section describes in detail how the energy system models is established and how the different modeling tools interact.

From here, Due to shortcomings in the initial approach. The thesis is divided into two main parts. Part I includes the simulations, results, discussion and conclusion for the single home energy system. Part II includes the same sections for the bigger scale BTES system.

The thesis concludes with section 8 presenting a personal evaluation of the research question along with a summary of all main section, providing the reader with the main take away from each section.

2 Mismatch between power production and consumption

In recent years, several factors have converged to make solar photovoltaic (PV) systems increasingly attractive for Norwegian households. Declining costs of solar modules, government incentives, and rising electricity prices have all contributed to a rapid growth in installations across the country. However, Norway's unique climate, characterized by significant seasonal variation in daylight and temperature, creates a pronounced mismatch between solar energy production and household heating demand. This section explores the dynamics of PV system production in the Norwegian context, the seasonal interplay with residential heating needs, and the implications for both homeowners and the power grid.

The price of PV systems has dropped the last decade, according to IRENAs report "renewable energy production costs" from 2023. The cost of crystalline solar PV modules sold in Europe declined by 93% between December 2009 and December 2023. Making solar energy more accessible [16]. Additionally, the Norwegian government has provided subsidies and grants, reducing the installation costs. For private households ENOVA grants between 7500 - 32 500 NOK depending on the size of the PV system. The rising electricity prices and energy crises in Europe over the last years have further increased the attractiveness of PV power for more self sufficient power as a cost-effective alternative [17]. These combined factors have increased PV system installations across Norway. The residential sector have over the past five years seen rapid increase in in PV system installations from 43 MW in 2020 to 254 MW in 2024, an increase of over 500% [18].

PV production in Norway is affected a lot by seasonal variations in solar irradiation. The highest producing month will produce approximately 25 times more electricity than the lowest producing month [18]. The average temperature difference from the coldest month to the warmest is 20°C in Oslo. The large temperature variation in Oslo affects the heating demand, resulting in a heating demand in winter four times greater than in summer [19].

During the summer, good solar conditions enhance the performance of the PV system resulting in higher energy production. At the same time the elevated ambient temperature reduce the demand for heating. As a consequence, during sunlit hours in summer, rooftop PV system produces more energy than is required for heating. The surplus then has to be exported to the grid. In winter, the PV production is low, while the heating demand is large, the deficit needs to be imported by the grid.

The Distributed Energy Systems and Security Infrastructure (DESSI) is a research initiative

conducted by the University of Oslo (UiO). This project serves as a reference system to illustrate the volumes of which electricity is being imported and exported in Norwegian homes. The aim of the project is to look at the potential of decentralized energy production, storage and consumption. One of the project targets is to contribute to the energy transition related to the mismatch in production and consumption in Nordic regions. The project collects data from private households, called pilot houses, to measure the energy balance. The figure 2.1 below is data gathered from one of the pilot houses [20].

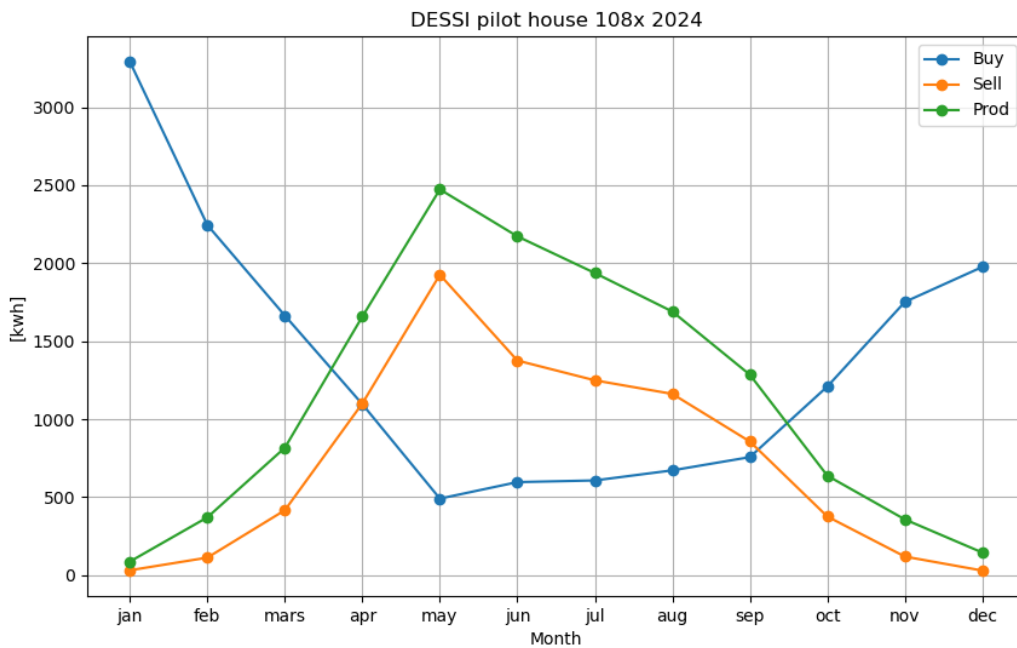


Figure 2.1: DESSI Pilot House 2024, highlighting the seasonal variation in import (blue) and export (orange) due to PV power production (green) and seasonal heating demand.

The figure presents the electricity import, export and PV production for the house at a monthly resolution in 2024. In January, the pilot house imports approximately 3 300 kWh while only generating around 100 kWh. In contrast, during the summer months, PV production ranges between 2 000 to 2 500 kWh. However, 3/4 of the energy is exported to the grid, with only 500 to 600 kWh imported. The total electric consumption in the pilot house in the summer months is approximately 1 000-1 500 kWh, less than half of the electricity consumption in January alone. This emphasizes the seasonal imbalance in electricity import and export for a private home with a PV system. Furthermore, it indicates that more than 2/3 of the electricity generated in the summer cannot be utilized on-site and consequently must be sold to the grid. In summary, during the winter months, electricity demand surpasses photovoltaic production, necessitating substantial imports. Conversely, in the summer, electricity generation exceeds consumption,

leading to significant exports.

2.1 Photovoltaic system production

Statistics from SSB indicate that the average installed capacity of solar PV systems on residential homes for plus-customers ranges between 9 and 10 kWp. Additionally, approximately 72% of all plus-customers are single-family homeowners, with the majority located in the south-west and south-east regions of Norway [21]. In general, a 10 kW photovoltaic system in Norway is expected to produce between 700 and 1 000 kWh per installed kW annually, resulting in a total estimated production of 7 000 to 10 000 kWh per year [22].

Consumers who want to achieve maximum utilization for their locally produced solar power needs to either store the surplus or sell it to the grid. To be able to sell surplus power to the grid, consumers at a residential scale needs to be registered as a plus-costumer. This is in principle a power agreement between the home owner and the DSO, allowing for bidirectional flow of electricity [23]. The plus-customer scheme offers several benefits, both for society and for the individual homeowner. First and foremost, homeowners are compensated for selling surplus energy back to the grid. Additionally, the Distribution System Operator (DSO) gains access to decentralized power capacity, which can help reduce grid losses. However, there is an inherent challenge. According to statistics from SSB, plus-customers often sell their excess power during periods of high production and low consumption [21]. From the DSO's perspective, this means that they receive a large amount of extra capacity when overall demand is low. The challenge will only grow larger as more PV systems are installed.

2.2 Heating demand in Norwegian homes

In the Norwegian climate, the typical year brings mild summers and long, cold winters, resulting in substantial energy requirements for heating during the colder months. This seasonal variation between energy production and energy consumption presents both challenges and opportunities for improving energy efficiency and resource utilization.

Norway is home to approximately 2.7 million households [24], each of which requires significant energy for heating and cooling throughout the year. The average Norwegian single home is 168m² [25]. Elvia, The DSO for eastern Norway, states that the average energy consumption in Norwegian single homes is 25 000 kWh, 17 000 kWh for flats and 11 000 kWh for apartments [26]. Of this, approximately 67% is used for spatial heating, 12% for hot water. The remaining 21% is used for lighting and electrical appliances [19]. Typically, the electric demand and hot water demand is independent of outside temperature and more dependent on time of day. Reaching its

peaks in morning and evening hours. Resulting in demand profiles that are stable throughout the year with hourly variations. The heating demand follows a profiles which is heavily dependent on the outside temperature and not the time of day. Meaning that the majority of the total energy demand is consumed in the winter time. Currently, most of the spatial heating demand is met through conventional heating methods, such as panel heaters and heating cables [27], highlighting significant potential for reducing energy consumption through increased efficiency.

Integrating more renewable energy sources (RES) and enhancing energy efficiency are considered among the most promising measures to decrease green house gas emissions. Efforts to improve energy efficiency have largely focused on the adoption of heat pumps, a technology that Norway has embraced more widely than any other country. In 2020, Norway had the highest concentration of heat pumps per capita [28]. As of 2021, approximately 1 million Norwegian households had installed heat pumps, primarily air-to-air systems. These systems are considered a viable investment for energy savings, achieving reduction in electricity consumption for heating by up to 65% [29].

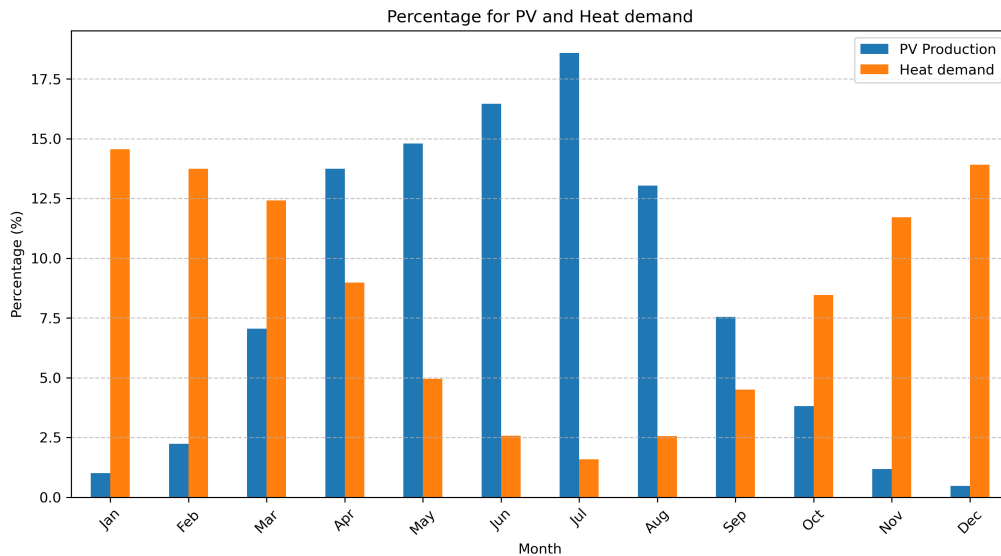


Figure 2.2: Aggregated monthly percentage of PV production (blue) and heating demand (orange). PV production is based on irradiation data in Oslo region. It peaks in the summer when heating demand is minimal, while in winter, PV output is low and heating demand is high.

Figure 2.2 shows the mismatch between solar PV power production and the heating demand for an average single home in Norway. In the reference system, 9 kWp is installed and the heating demand is applicable for a regular 168 m^2 single home in the Oslo region [25]. April through August accounts for approximately 3/4 of the total power production, while only 1/5 of the total heating demand is consumed in the same period. The opposite happens in winter. This seasonal

mismatch between PV generation and heating demand serves as the main motivation for this thesis: To explore seasonal energy storage solutions that can store excess energy generated in the summer for use in the winter months.

2.3 The power grid

As explained in Section 2, the mismatch between power consumption and production, combined with seasonal variations, creates challenges for the power grid. Surplus production during summer months can lead to curtailment, while increased heat demand in winter can push the grid towards saturation. In many cases, grid capacity becomes the main constraint in balancing the energy system. The power grid is designed to handle peak demand during the busiest hours. Additionally, the grid is dimensioned to transport electricity between regions to maintain balance across the system. As a result, the grid remains over-dimensioned for the majority of the year [30]. While over-dimensioning is essential for ensuring power security and system stability during peak periods, it is not efficient from a socio-economic perspective. It is both costly for private consumers and the power grid developer.

In 2012, NVE introduced requirements for power companies to share information about the current state of the power grid and future development plans. These power system assessments are compiled in PlanNett, which serves as a tool to support socially responsible and forward-looking energy system planning [31]. Additionally, a dynamic map of current and projected capacity at transformer stations is available through the WattApp user interface. According to the interface, there is limited capacity for new connections, both for consumers and producers in the Akershus region [32].

As detailed in Section 2.2, electricity consumption peaks in Norway are closely associated with the increased use of electric heating during colder periods. According to Statnett's System Development Plan from 2023, a reduction in electric heating demand in the order of 4–5 TWh could potentially free up approximately 2 000 MW of capacity in the NO1 across all levels of the electricity grid. In pursuit of this objective, the Norwegian government has established a target to reduce total energy consumption in buildings by 10 TWh by 2030 [31]. One proposed method for achieving this reduction involves the utilization of BTES systems to store surplus energy, as further discussed in Section 3.

Efforts to reduce peak electricity consumption are also efforts to mitigate the need for costly and space-demanding investments in the power grid. According to Elvia, a commonly applied heuristic for distribution-level grid investments estimates the cost of a new transformer station

(200 kW) at approximately NOK 750 000, and cable installation at around NOK 3 000 per meter¹. In addition, there are costs associated with digging and labor, planning and engineering etc. In cases where increased capacity is required due to general demand growth, the DSO typically covers the investment costs. However, when additional capacity is necessitated by new industrial or residential developments, the associated costs are generally borne by the developers. Ultimately, upgrades in the regional distribution grid is governed by the status and capacity in the other levels of the power grid.

While the costs of grid upgrades can be quantified, the broader value of releasing capacity through seasonal energy storage remains more difficult to estimate. Unlocking capacity on the power grid enables the integration of higher shares of VRES, thereby supporting a more sustainable and low-emission energy system. Additionally, it promotes more efficient utilization of existing energy resources, such as PV energy. Increased grid capacity also enhances system resilience by reducing the likelihood of congestion and outages. Furthermore, peak shaving to accommodate new connections offers a significantly faster and more flexible pathway to electrification compared to extensive infrastructure expansion. This will ultimately accelerate the transition towards a low-carbon society.

2.4 Electricity bill

The electricity bill consists of three main components, the spot price, the grid tariff and taxes. The spot price is the spontaneous price of electricity each hour, determined by supply and demand in the electricity market. In addition to the spot price, consumers have to pay taxes on the amount of electricity they use, equal to 25%. Historical hourly spot prices for each region can be obtained from Nordpool [33]. Spot price data from Nordpool in 2023 shows that the average price between May and September is 41% that of the price between October and April. The spot price is constantly varying and is considered a very unpredictable parameter in the future [6]. The changing state of the geopolitical tension between power producers and the introduction of more variable renewable energy sources (RES) are considered the main reasons to why the prices will be fluctuating in the upcoming years. The increased investments in solar PV will also potentially provide an even greater difference in electricity prices between summer and winter, limiting the profitability of PV installations.

Alongside the spot prices, the grid tariff consists of several flexibility sections, along with a predetermined monthly sum to cover expenses the DSO encounter to provide consumers with

¹Heuristics obtained from email by Per Edvard Lund from ELVIA at 11.04.2025

the basic required infrastructure and capacity. The flexibility sections is designed to make the consumers act more flexible. Both by shaving their consumption peaks and by shifting their demand to less busy hours. The flexibility is valued and calculated in two ways. The power section is calculated from the three highest consuming hours, and puts the consumer in the respective price category accordingly. For example, if the average of the three highest consuming hours is 4.89 kW, the consumer is placed in the price category 2, equaling to 215 NOK/month. The power tariff and energy tariff is gathered from ELVIA in February 2025 and can be seen in table 2.1 and 2.2.

Table 2.1: Power tariff price categories from ELVIA [34]. Calculated from the average of the three highest consuming hours in the month. The bigger the hourly peak consumption is the bigger the costs get, incentivizing flexible consumption through peak shaving.

Category	kW	Power tariff (NOK/month)
Step 1	0–2	135
Step 2	2–5	215
Step 3	5–10	350
Step 4	10–15	485
Step 5	15–20	620
Step 6	20–25	755
Step 7	25–50	1 425
Step 8	50–75	2 100
Step 9	75–100	2 775
Step 10	Over 100	5 605

Table 2.2: Energy tariff from ELVIA [34], incentivizing flexible consumption by load shifting.

Energy tariff (øre/kWh)	January – March	April – December
Daytime	42.50	51.43
Night/weekend	32.50	41.43

The energy section provided in figure 2.2 is dependent on the time of consumption. In addition to the spot price the consumer have to pay more for consumption during peak hours (weekdays between 06-22). The remaining hours of the week is considered less busy, consequently being cheaper. The price of consumption including fees in peak hours is 0.425 NOK/kWh and 0.325 NOK/kWh in weekends and nights [34].

Since the onset of the energy crisis in 2021, the Norwegian government implemented a power support scheme aimed towards private consumers. In recent years the amount of economic support issued by the state have decreased, however it is still a substantial contributor to lowering the energy bill. As of January 2025 the power support is designed to cover 90% of the total price when the spot price goes above the threshold of 0.9375 NOK/kWh including taxes [35].

Due to the inherent mismatch between solar power production and consumption, consumers need the ability to export excess electricity back to the distribution grid. When an entity both consumes and produces power at a capacity over 100 kW, they are classified as prosumers. To qualify as a prosumer, strict regulations must be followed. For private households with production below 100 kW, you are considered a plus-customer and generally less strict rules and regulations apply [36]. Registering as a plus-customer requires installing a bidirectional AMS meter to track both consumption and production sold to the grid. Between 2019 and 2021 the amount of plus-costumers in Norway increased from 2 500 to 6 100 costumers, an increase of 150%. Whereas 99% of these have installed solar PV on their roofs [21].

The sell-back price varies between power companies, meaning individual agreements must be established. However, Elvia offers 0.05 NOK/kWh as compensation for reduced grid losses [37]. Since DSOs benefit from reduced losses, the sell-back price is assumed to align with the spot price in the energy system models later described.

Profits up to 10 000 NOK is tax-free as of February 2025. If exceeded, 85% of the surplus is taxable after a standard deduction of 15%. Given the modest earning potential from selling electricity, most plus-customers will likely have a fully tax-free income in practice [38]. The greatest benefit of installing PV panels is therefore the cost saving potential, the individual contribution to a sustainable transition and power independency.

The main takeaways from the section 2 is the mismatch between solar PV production and heating demand in Norway and the significant seasonal variations between them. Approximately 75% of household heating needs occurs from October to March. During these months, electricity prices tend to be higher due to increased demand. Higher demand puts pressure on the power grid capacity, reaching its limits in the winter. Conversely, solar energy production is primarily concentrated in the summer months, leading to a surplus of generated electricity that typically exceeds household consumption, resulting in lower electricity prices during this season.

This seasonal imbalance creates a compelling need to explore methods for transferring the solar energy generated in the summer for use in the winter months. Implementing seasonal energy storage solutions becomes critical to effectively manage this mismatch between energy production and heating demand. However, the support scheme will have a negative effect on seasonal storage, lowering the potential savings.

Although several technologies can facilitate seasonal storage, including hydrogen and battery systems, both have limitations that make them less suitable for this purpose. Hydrogen is currently considered too costly and is not well-suited for small-scale applications. Additionally

the social acceptance remains a barrier to development of hydrogen systems. On the other hand, the cost of batteries remains prohibitively high for the large quantity of energy involved in seasonal storage, while the longer term storage potential is limited.

Geothermal energy storage remains relatively underexplored and may offer a promising solution worth further investigation. By leveraging geothermal resources for seasonal thermal energy storage, it could provide an effective way to balance the differences between energy supply and demand throughout the year.

3 Seasonal storage in Energy well

This section intends to investigate the potential of utilizing energy wells as a seasonal storage solution. It will also outline the main factors influencing the efficiency of such systems. However, to set a reference, the current status and operational characteristics of energy wells in Norway will be presented.

Energy wells utilize the constant temperature in the ground. In the first 10 to 20 meters, the temperature is influenced by seasonal variations, aligning closely with the average annual ambient air temperature. However, below this depth, the temperature stabilizes at around 5 to 7 °C, making heat extraction with a GSHP efficient [39]. The system consists of four main components; the borehole, heat carrier fluid, GSHP and the distribution system.

3.1 Energy well systems in Norway

Norway possesses potential for harnessing geothermal energy, particularly due to its favorable geological conditions, as discussed later in section 3.5. In principle, the entire heating and cooling demand of the country could be met by geothermal energy sources [40]. Although the initial investment costs for energy well systems are relatively high, there has been a notable increase in installations in recent years.

Over the past few decades, approximately 1 000 to 2 000 energy wells have been constructed annually for single-family homes in Norway. According to data from GRANADA, a total of 4 677 energy wells have been developed for single homes in the Oslo region alone as of 2024 [41]. In comparison, Sweden has demonstrated the broader potential of ground-source heating systems in the Nordic region, with over 300 000 households having installed such systems with an annual growth of around 30 000 installations [42].

The most used energy well system is a closed loop system. Meaning that the fluid on the evaporator side of the heat pump is constantly circulating from the heat pump to the bottom of the energy well and back, in a closed loop [40].

3.2 Components in energy well

This subsection aims to provide an overview of the key components in an energy well system, highlighting their functions and significance within the overall system.

3.2.1 Borehole

The primary function of a borehole in a geothermal system is to establish a large surface area for thermal exchange with the ground. Key parameters influencing the efficiency of a borehole include the thermal conductivity, specific heat capacity, and thermal diffusivity of the surrounding geological materials. There are two main installation practices: horizontal and vertical. In horizontal systems, often referred to as ground or earth heat systems, pipes are laid approximately two meters below the surface across a wide area. This method can be more cost-effective due to simpler installation techniques and less specialized equipment[43].

Vertical boreholes requires less land area compared to horizontal systems but involves a more complex and technically demanding process, typically utilizing rotary drilling equipment. Boreholes generally have a diameter ranging from 80 mm to 200 mm and a depth between 80 and 300 meters. In the Nordic region, boreholes are naturally filled with groundwater, which facilitates effective thermal exchange. However, in areas where the groundwater table is not accessible, the borehole must be filled with thermally conductive grout to enhance heat transfer efficiency[44].

Statistics from the Geological Survey of Norway (NGU) indicate that there are 4 677 registered energy wells for single-family homes in the Oslo region in 2024. Of these, approximately 75% have a borehole diameter of $115 \text{ mm} \pm 2 \text{ mm}$. The data also show that 70% of the boreholes have a depth of 200 meters or less, with 200 meters being the most common depth [41]. At this depth, the temperature remains relatively stable and is typically between $6\text{--}8^\circ\text{C}$, which is slightly higher than the average surface temperature. It is estimated that the subsurface temperature increases by approximately $25\text{--}30^\circ\text{C}$ per kilometer of depth. Excluding the influence of the water table and the unconsolidated surface layer, the geothermal gradient can be considered nearly linear, corresponding to an estimated temperature increase of 2.5°C to 3°C per 100 meters [45].

For shallow boreholes (100-300 meters), the cost per meter of drilling is typically regarded as constant. This implies that a borehole with a depth of 100 meters will cost half as much as a borehole that is 200 meters deep. More on specific costs will be presented in section 3.8. A balance between costs and energy extractions needs to be established at the specific site of installations. Depending on the size and application the depth is varying considerably as described in section 3.6. Digging deeper also carries significant risks, such as encountering underground water reservoirs or causing the bedrock to crack.

3.2.2 Collector pipes

The main objective of collector pipes is to efficiently conduct heat between the heat carrier fluid and the surrounding ground. Therefore, the collector pipe must be as conductive as possible while still be affordable and have structural strength. Today, the most used material is polymers due to their low cost and structural integrity[44].

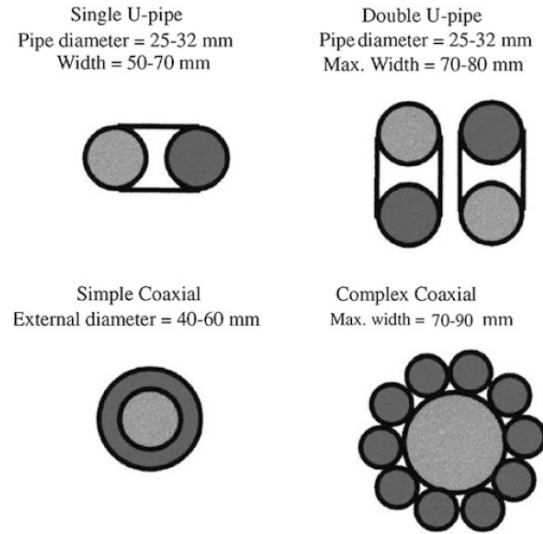


Figure 3.1: Different configurations of collector pipes [44].

Figure 3.1 shows different types of collector pipes. Single U-pipe is one set of pipes spanning the whole depth of the borehole. When extracting heat, cold fluid is pumped in from one side, when the fluid travels through the pipes it extracts geothermal heat. After a completed cycle, the fluid temperature is elevated. The U-type collector pipe configuration is the most widely used in the Norwegian market, due to its low cost and simplicity. Double U-type collector pipes have an additional set of u-type collector. These types typically have a 10-20% increased heat exchange compared to single u-type, however, investment costs are greater[46].

Simple coaxial and complex coaxial are different configurations of collector pipes. As the figure above shows they consist of multiple layers of pipes. The heat carrier fluid will flow down the center pipe and up the outer pipe in heat mode. Since the inflow and outflow from the heat pump is so close, the coaxial will have a lower efficiency compared to u-type. The coaxial pipe is advantageous due to its compact design. Therefore the borehole diameter can be smaller, saving expenses on drilling [46].

The size of the collector pipes also varies. Pipes with bigger diameter experience less head loss, therefore deeper boreholes need to use wider pipes to combat the increasing head loss. The most common size for a 200 meter borehole is 32-40 mm outer diameter with a thickness of 2-4

mm. The material is typically Polyethylene with a conductivity of $0.42 \text{ W/m} \cdot \text{K}$.

3.2.3 Heat carrier fluid

Heat carrier fluid is the working fluid, it transports the heat from the ground to the heat pump. The type of fluid depends on the temperature range in the energy well. Water is beneficial since it is cheap and environmentally friendly. However, water is prone to freezing in the northern climate. Common practice is to add antifreeze to prevent freezing and mechanical stress on the system. The most common antifreeze fluids according to GRANADA is a mixture of water and glycol or water and ethanol. Data records from NGU on existing borehole in the Oslo region shows that HX35 is commonly used as heat carrier fluid. HX35 is 35% ethanol by volume mixed with water. HX35 have a freezing point of -18°C [47].

The best possible heat extraction is achieved when the flow of heat carrier fluid is turbulent. Turbulent flow ensures proper mixing of the fluid allowing for even heat distribution. Even temperature distribution also lowers the fluids thermal resistance. Reynolds number is a unit less number describing the state of flow of a fluid, values above 2 300 are regarded as turbulent flows. However, to ensure turbulent flows in all parts of the pipe 4 000 is a common threshold.

3.2.4 Distribution system

From the heat pump, the heated fluid must be distributed throughout the house. Most systems supply the heat through an accumulator tank as a buffer, before its transported to the radiators or floor heating. Radiator heating requires higher temperatures, typically in the range of $40\text{--}60^{\circ}\text{C}$, while water borne floor heating typically requires temperatures in the range of $25\text{--}45^{\circ}\text{C}$ [48]. Circulation pumps are installed to ensure proper flow and mixing of the heat carrier fluid throughout the whole system. The heat pump efficiency will be affected by the choice of distribution system and will be further described in the following section.

3.2.5 Ground source heat pump

Ground source heat pump (GSHP) systems have demonstrated superior performance compared to air source heat pumps (ASHPs) for both heating and cooling applications. Studies have shown that GSHPs maintain higher and more consistent coefficients of performance (COP) across varying ambient conditions, since ground source heat pumps are subject to more consistent temperatures and less extremes [49].

Ground source heat pumps utilize the heat stored in the earth as a natural energy source while it can also use the earth as a reservoir to dissipate excess heat during the summer.

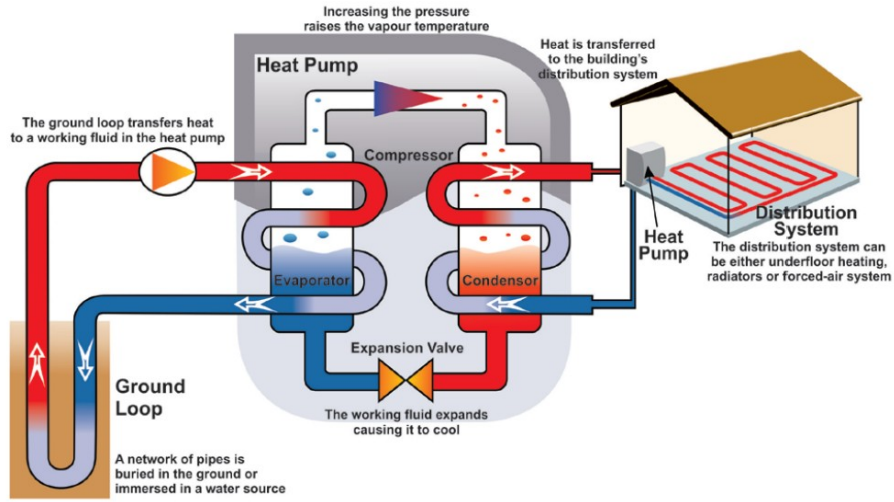


Figure 3.2: GSHP closed system in heating mode. GSHP extracts heat from the ground loop, elevating the temperature and distributes it to the distribution system. The heat carrier fluid is returned to the GSHP with lower temperature and dumped in the ground loop [50].

Figure 3.2 shows a schematic drawing of how a GSHP functions in heating mode. The ground loop is closed and heat carrier fluid flows through the heat pump and exchanges heat. Inside the heat pump the working fluid is being evaporated and compressed to increase its temperature. It then releases the thermal energy to the closed distribution system loop. The working fluid, which now has lower temperature then goes through an expansion to lower the temperature even more, before once again being exposed to the elevated temperature of the ground loop heat carrier fluid. Using this principle a ground source heat pump can make use of the slightly elevated temperature stored in the ground and transport the thermal energy from a place with lower enthalpy to a place with higher enthalpy against the natural flow of heat.

Common metrics to define the efficiency of a ground source heat pump are Coefficient of performance (COP), heating seasonal performance factor (HSPF) and seasonal energy efficiency ratio (SEER). COP factor describes the ratio of which the heat pump transfer electrical energy into thermal energy. The higher the temperature difference between the cold and hot side the lower the COP factor gets. Since the ground source temperature is higher and more stable compared to the average surface temperature, ground source heat pumps typically have a higher COP compared to a conventional ASHP. A typical COP factor for a GSHP is 3.5 to 5.0 [28].

The HSPF and SEER are seasonal performance factors describing the total heat/cool delivered throughout the year in respect to electricity consumption. HSPF describes the efficiency across the full heating season, while SEER describes the efficiency in cooling mode across the full cooling season. The seasonal metrics are also better for a GSHP compared to the conventional ASHP.

This is because the GSHP remains its efficiency even though the outside temperature drops with several degrees Celsius. In the summer, the ground temperature is lower than the outside temperature, elevating the natural flow of heat to achieve better cooling efficiency. For reference, studies have shown that the SEER could reach 8.0 for a typical summer day in Germany [51], highlighting the big potential in efficient cooling of houses.

3.3 Operation of energy well

In Norwegian single homes energy wells are traditionally used as a stable and tempered source of heat for heating applications. In a typical meteorological year in Oslo the average temperature in January is -3°C compared to 6-8°C in the boreholes ². This results in a temperature difference of 11 °C, enhancing the ground source heat pump efficiency.

During periods of cooling demand in the summer months, the borehole owner could also reverse the GSHP, dumping excess heat into the energy well. Cooling the house by using the energy well as a thermal sink will in principle mean that the energy well is being charged with heat. Charging the energy well will not only serve as a cheap way of cooling your house, but it will also elevate the temperature inside the energy well potentially increasing the heat pump efficiency in the upcoming heating season.

3.4 Borehole thermal energy storage

By storing excess energy produced in the summer in the borehole, the temperature of the working fluid will increase. This will make the temperature difference between the hot and cold side of the heat pump smaller, consequently enhancing the COP. For an optimal system, following the perfect Carnot cycle equation 3.1, a temperature increase from 6 to 7 °C in the sink, while keeping the outlet temperature at 45 °C will result in a 2.58% increase in COP.

$$\eta_{carnot} = \frac{T_H}{T_H - T_C} \quad (3.1)$$

However, real ground source heat pumps operate at just a fraction of the Carnot efficiency, because of pressure drop and losses related to compression and heat transfer. The COP for conventional GSHPs as a function of temperature difference between outlet and inlet is shown in figure 3.3.

²Average temperature is calculated from hourly temperature data in PROFet

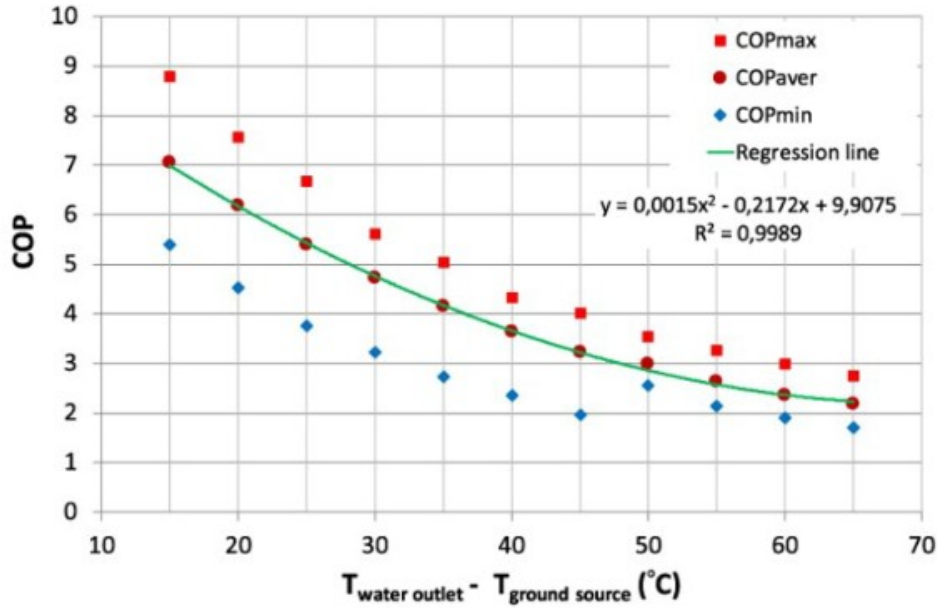


Figure 3.3: Graph showing the temperature dependency of GSHP the function is derived from tests of 122 commercialized GSHP models. Higher temperature differences between the inlet and outlet of the GSHP results in lower COP factor [52].

Figure 3.3 shows the polynomial function of GSHP COP in respect to the temperature difference between the outlet and the source. 122 different commercialized GSHPs were tested and was published in 2020 [52]. The figure shows that the higher the temperature difference, the lower the COP. Some variations in efficiency will occur from manufacturer to manufacturer, the average is represented by the green line. The graph highlights the potential of enhancing the temperature of the working fluid to achieve better efficiency. However, enhancement of the efficiency is dependent on the geothermal properties as described in section 3.5.

Additionally, it is important to highlight that the COP is not only affected by the temperature difference between the outlet and inlet, but also the range at which it operates. For example will a heat pump operating between 15 and 45 °C be more efficient than a heap pump operating between -5 and 25°C, even though the absolute temperature difference is the same. This can be proved by the following equations for a perfect Carnot cycle.

$$COP_{carnot} = \frac{T_{outlet}}{\Delta T} \quad (3.2)$$

$$COP_{carnot}^{15-45^{\circ}C} = \frac{318K}{318K - 288K} = 10.6 \quad (3.3)$$

$$COP_{carnot}^{-5-25^{\circ}C} = \frac{298K}{298K - 268K} = 9.93 \quad (3.4)$$

Naturally, the heat pump is using more energy to extract heat from a lower temperature reservoir, which is shown by the 6.3% decrease in heat pump efficiency.

3.5 Geothermal properties

Geothermal properties of the ground determine how heat moves through the surrounding rock. Heat is energy, and according to the first law of thermodynamics, energy cannot be created or destroyed, only transformed. In a Borehole Thermal Energy Storage (BTES) system, this means that the heat injected into the ground does not vanish, it simply moves based on the thermal characteristics of the subsurface. The recovery efficiency of a BTES system refers to the proportion of injected heat that can later be extracted. Any heat that is not recovered has simply migrated beyond the effective reach of the system.

The second law of thermodynamics states that heat always flows from hotter to colder regions in a material. If you consider a hot point in a material, the heat will spread from that point outward in every direction. Given a homogenous material, the heat will spread in a circular pattern away from the hot center.

Thermal conductivity measures how well a material can conduct heat. The unit is given in $[W/m \cdot K]$ and describes how easily heat moves through a material. For example, a thermal conductivity of 3 $[W/m \cdot K]$ means that 3 W will move through 1 meter of the material given a temperature difference of 1°C. Another way of describing the conductivity is in inverse relation to the thermal resistance.

$$R = \frac{d}{\lambda * A} \quad (3.5)$$

R = Thermal resistance $[K/W]$

d = Thickness of the material $[m]$

λ = Thermal conductivity $[W/(m \cdot K)]$

A = Area through which heat flows $[m^2]$

Thermal resistance measures how much a material resists heat flow. The unit describes how large the temperature difference needs to be to transfer 1 W heat through the material given its thickness and area. The different components in the system, such as the heat carrier fluid,

pipe, ground water and the ground provides different thermal resistances which all adds to the total thermal resistance to heat flow in the system.

A material with high thermal conductivity have a lower thermal resistance, therefore the heat will move easily through the material. If the rock mass around the borehole has a high thermal conductivity the heat extracted from the borehole can quickly be replenished, this will improve the efficiency of the system.

Heat capacity [J/kg·K] is another important parameter in BTES systems. It describes how much energy is needed to heat one kilogram of the given material with 1°K. Materials with higher heat capacity will therefore require more energy for the same temperature increase compered with a material with lower heat capacity. Heat capacity can also be described as the amount of heat that can be stored inside a material. The different heat capacities in the surrounding ground will influence the storage capacity and the temperature gradient.

Heat flux measure at what rate heat is transferred through a given material per surface area. There will always be heat flux between materials with different temperatures. Geothermal heat flux [W/m²] represents how much heat that flows from the earths hot core to the surface of the earth. It is the geothermal heat flux that is the reason to why the ground maintains stable and elevated temperatures. The Earth's interior essentially acts as an infinite heat source primarily due to the presence of a molten core within the Earth's crust. While the geothermal heat flux is relatively stable across much of the Earth's surface, it is significantly higher in volcanically active or geologically radioactive regions. In Norway, for example, the geothermal heat flux has been measured at approximately 55–65 mW/m² [53]. Heat flux is governed by Fourier's Law, which states that it is the product of a material's thermal conductivity and the temperature gradient, as shown in the equation 3.6.

$$q = -\lambda \frac{\Delta T}{\Delta z} \quad (3.6)$$

$$\begin{aligned} q &= \text{Heat Flux } \left[\frac{W}{m^2} \right] \\ \frac{\Delta T}{\Delta z} &= \text{Temperature gradient } [K/m] \\ \lambda &= \text{Thermal conductivity} \end{aligned}$$

From an energy well perspective, a higher geothermal heat flux is advantageous, as it results in a

greater potential energy yield. According to Fourier's Law, an increase in either the temperature gradient or the thermal conductivity of the surrounding material will lead to a corresponding increase in heat flux

Thermal diffusivity has the unit $[m^2/s]$ and describes how fast a heat moves through a material. Diffusivity is a product of thermal conductivity and heat capacity.

$$\alpha = \frac{\lambda}{\rho * C_p} \quad (3.7)$$

$$\begin{aligned} \alpha &= \text{Thermal diffusivity} \left[\frac{m^2}{s} \right] \\ \lambda &= \text{Thermal conductivity} \left[\frac{W}{m * K} \right] \\ \rho &= \text{Density} \left[\frac{kg}{m^3} \right] \\ C_p &= \text{Specific heat capacity} \left[\frac{J}{kg * K} \right] \end{aligned}$$

If two materials have the same conductivity, but different heat capacity, The material with lower heat capacity will transport heat faster, because the material require less energy to increase the temperature in the material. Therefore, the temperature difference will be greater.

The performance of a BTES system is heavily influenced by the geothermal properties of the surrounding ground. Key factors include thermal conductivity, thermal resistance, heat capacity, heat flux, and thermal diffusivity. Values gathered from NGU shows that the average thermal conductivity is 2.6 W/m·K and that a typical volumetric heat capacity is 2-2.8 MJ/ $m^3 \cdot K$ [54].

For an efficient BTES system, the ideal ground conditions are high thermal conductivity and heat capacity in the BTES domain, low thermal resistance between layers, and high geothermal heat flux, all of which contribute to effective heat storage and recovery. The clue is to minimize heat dissipation from the usable domain, while simultaneously allowing for external geothermal heat flux to the volume.

3.6 Existing BTES systems

As mentioned previously, using the constant and elevated temperature in the ground as a source of heat is the most common application for single homes. Storing excess energy in a BTES is more widespread for bigger scale applications.

BTES systems for seasonal heat storage are a well-established concept. Both national and international projects have demonstrated their efficiency in practical applications. One notable example is the Drake Landing Solar Community in Okotoks, Canada, which was considered a pioneering project in solar-assisted seasonal underground storage in North America at the time of its installation. The community consists of 52 homes connected to a centralized heating system powered by thermal energy stored in the ground and supported by solar collectors. The BTES system at Drake Landing includes 144 boreholes, each drilled to a depth of 37 meters with 2.25 meter spacing. Over the years, the community has achieved a solar fraction as high as 100 percent, meaning that all heating demand was met entirely by solar energy, either directly or through stored heat [55].

In Europe, and particularly in the northern regions, borehole thermal energy storage systems are becoming increasingly widespread due to favorable geological conditions. Norway offers several examples of well-functioning BTES installations, including those at Ljan Skole, Tømtebanen, and Fjell Skole.

At Ljan Skole, the energy system combines 1,400 square meters of solar collectors with 24 boreholes, each reaching a depth of 200 meters with 7 m spacing, along with heat pumps. This setup supplied a total of 157 000 kWh of thermal energy [56]

At Tømtebanen, the football field itself is utilized as a solar heat collector. The system includes 60 boreholes, each 100 meters deep with a spacing of 5 meters. The BTES system has successfully stored and delivered 720 000 kWh in 2023, keeping the field free of ice throughout the winter [57].

The BTES system at Fjell Skole comprises 100 boreholes with a depth of 50 meters located with a distance of 4 meters. This system is charged using both solar thermal collectors and solar photovoltaic panels, with heat pumps facilitating the transfer of energy. The installation has achieved an annual return of approximately 350 000 kWh [58].

All of these systems operate on the same fundamental principle: capturing excess energy produced during the summer months and storing it underground for use during periods of high heating demand. BTES systems increase energy self-sufficiency and reduce the dependence on imported electricity during the coldest hours of the year.

However, the depth and number of boreholes used in each BTES system vary significantly. Determining the most optimal configuration requires careful consideration of multiple factors, including geological conditions, energy demand, system design, and available surface area. Due

to the complex and interdependent nature of these parameters, there are no scientific standards. The following sections aims to describe the most important parameters of BTES systems.

3.7 Optimal configuration of BTES systems

Maximizing energy recovery efficiency in a borehole thermal energy storage system requires adherence to several key design and operational principles. First, BTES systems are inherently area-intensive, making borehole density optimization crucial within the constraints of the available surface area. Secondly, thermal interactions between boreholes must be carefully evaluated. Reduced spacing can lead to increased thermal interference, which may negatively impact system performance over time. The impact of borehole spacing will be outlined in section 3.7.2. Third, the energy storage capacity of the system is directly linked to the effective ground volume, making the relationship between borehole depth and surface area a critical design factor. Finally, the operational strategy of the BTES system plays a significant role in determining its long-term efficiency and heat recovery potential. The following section outlines the factors that contribute to an optimal configuration for BTES systems.

3.7.1 Configuration and Area

As described in section 3.5, to minimize heat loss through conduction the surface area in relation to the volume should be minimized. This is achieved when the boreholes are in a circular configuration. A circular configuration also captures the radially distribution of heat. Moreover, to maximize storage capacity, the diameter of the cylindrical volume should be equal to the width of the available area. To enhance the recovery rate even more, the depth of the wells should follow the simple form factor rule ($d/D = 2$), provided by “Improvement of borehole thermal energy storage design based on experimental and modeling results” [59].

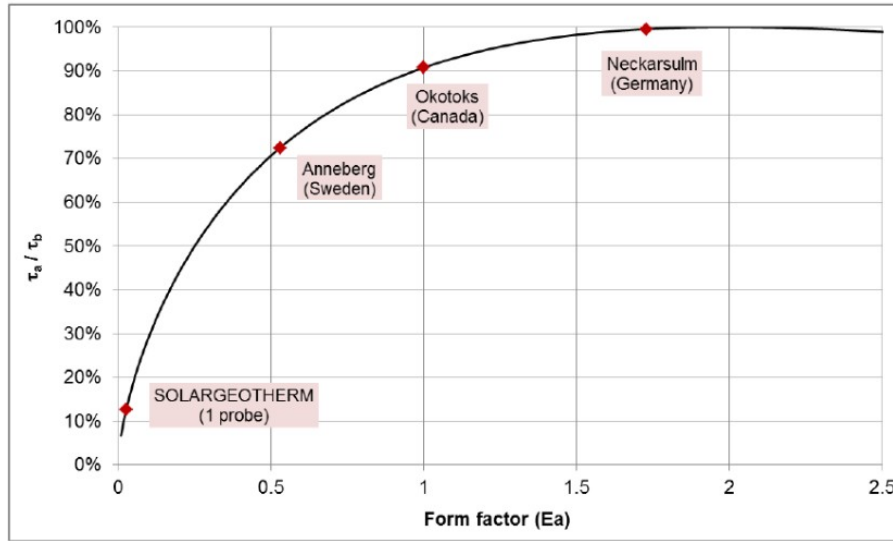


Figure 3.4: Form factor vs efficiency. When diameter of the well park is twice the depth the system experience its highest recovery efficiency [59]. Higher form factor insinuates a bigger area.

Figure 3.4 shows how different BTES systems perform giving different form factors. The graph clearly states that when the form factor is closing in on 2 the efficiency increases, meaning that the diameter is twice as big as the depth. Drakes landing in Okotoks have a form factor of 1 and consequently an efficiency of 90%. When considering lower form factors, the efficiency decreases. This reduction in efficiency is attributed to several factors, including vertical heat loss, increased heat diffusion beyond the well's domain, and the variability in borehole spacing. As the depth of the borehole increases, the likelihood of drilling perfectly straight diminishes. [59].

Borehole parks should be arranged in a circular configuration to optimize efficiency, and the wells should maintain a form factor of 2 to enhance energy storage capacity. However, it is important to note that effects flattens out at a certain point.

3.7.2 Borehole spacing

The spacing between boreholes is an important parameter regarding the efficiency of a BTES system. The closer the boreholes is placed the more thermal interference they will experience. With closer spaced boreholes, the system will occupy a smaller volume, lowering both the geo thermal heat flux and the total volumetric heat capacity.

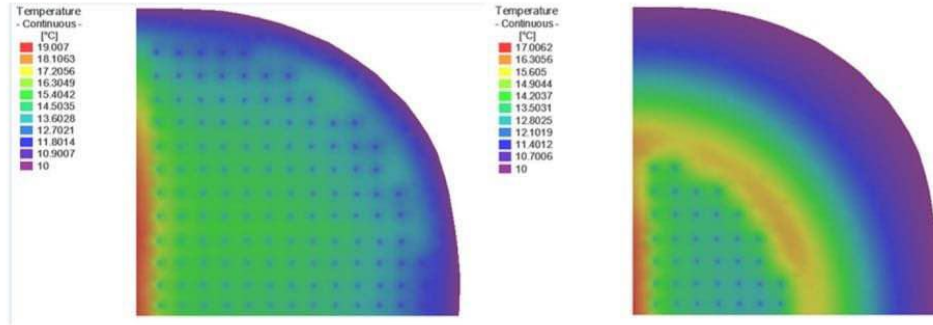


Figure 3.5: top-down view of BTES system showing that in a scenario with fewer boreholes the heat gets concentrated on the outer edge of the domain, highlighting that a bigger volume is favorable for energy storage. [60].

Figure 3.5 a shows how the heat is distributed in a BTES system for two different configurations. Scenario 1 have 127 boreholes and scenario 2 have 37 boreholes with 2.5 meter spacing in both cases [60]. From the plot it is clearly visible that the heat is more evenly distributed throughout the system in scenario 1 while the heat in scenario 2 moves beyond the usable domain. During a 30 years simulation scenario 1 achieved a maximum recovery efficiency of 65% while scenario 2 achieved a maximum recovery efficiency of 53%. This essentially means that more of the input energy could be recovered with more boreholes spanning a larger volume.

A study from the same article, compares BTES systems with 2.5 m and 10 m spacing between boreholes. 2.5 m spacing showed a recovery rate of 90% after a 3 year simulation, while the 10 m spacing showed a recovery rate of around 30%. When boreholes are in closer proximity the total volume of the BTES experience a more even temperature distribution, since the heat is injected in more points throughout the BTES. In the BTES with 10 m spacing the temperature can be seen to be more locally concentrated.

In summary, the findings suggest that closely spaced boreholes within a larger confined volume represent the most effective configuration for optimizing heat distribution and energy recovery in BTES systems. Ultimately leading to better performance in seasonal energy storage applications.

3.7.3 Operation of Energy Wells

Boreholes located with a distance of less than 7 meters from each other needs to be charged not to freeze and maintain the system efficiency [61]. In systems with boreholes in close proximity, the thermal zones of each borehole overlap, which means that they will influence each other. Moving above the 7 meter threshold means that the natural geothermal heat flux will charge the BTES. Charging the BTES externally could be done in a number of ways e.g by solar PV,

solar collectors, air-water heat pump and heat waste from ventilation.

When the spacing is less than 7 meters the charge and discharge rates need to be carefully assessed. Since the boreholes are interacting with each other, over-extraction of heat compared to injection can cause the BTES domain to go cold or in worst case freeze [62]. In fact, carefully determined flow rates could enhance the recovery efficiency greatly. In the initial years of operating a BTES, the energy input should exceed the energy extraction to build up equilibrium heat in the system. After a few seasons energy extraction can be increased while still achieving higher recovery efficiency. BTES systems typically achieve the highest efficiency after 10-30 years in operation [60].

As figure 3.5 shows the outer most boreholes, located closer to the external ground will be colder. This is an expected trend, but it highlights another important factor to consider, namely where the heat should be injected and extracted from the BTES. The operation of the BTES system at Fjell skole serve as an example of this and can be seen in figure 3.6. This system is both advanced and intricate; Four boreholes are connected in series, forming a network that utilizes layered temperature control throughout the well park. This configuration not only enables the extraction of varying temperatures, but also provides greater control over heat loss to the surroundings [63]. The inner layers are used for direct heating while the colder, outer layers is used indirectly with a heat pump.

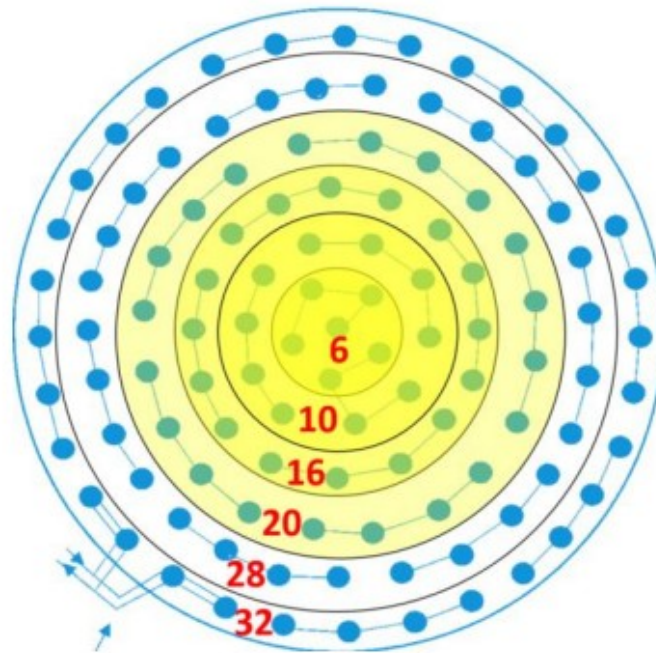


Figure 3.6: BTES configuration of Fjell school. The configuration consists of 6 layers, where four and four boreholes are connected in series. The yellow area represents where the majority of the heat is stored [63].

From the final report by Asplan Viak the operation of the BTES system at Fjell skole is described the following way: “Heat is supplied in the middle, and the collector fluid is cooled as it circulates through several series-connected wells towards the edge of the well park. When heat is to be extracted from the storage, the collector fluid circulates in the opposite direction and is heated towards the center of the storage” [63].

The injection of heat at the central layer of the BTES system, combined with the outward circulation of the heat carrier fluid, allows for the concentration of heat in the center of the borehole park. As a result, the temperature decreases towards the outer layers of the system. This operational approach ensures that a greater proportion of the heat remains within the usable domain compared to a strategy that disperses heat evenly across all boreholes. Our initial hypothesis is that this method will prove to be the most effective operational strategy.

3.8 Costs of energy wells

The costs of energy wells is mainly dependent on boring and heat distribution infrastructure. Costs of single energy well on resident scale can reach 100 000 - 300 000 NOK. In general, the bigger the heating demand is, the more profitable the investment gets [64].

Numbers from Aarsleff estimates that the price of a 300 meter energy well with piping and heat carrier fluid is 110 000 NOK excluded taxes. Heuristics states that you need 20 meters of depth per kW heat extraction. For the average Norwegian single home, this means that approximately 100 m of depth is required to deliver the peak demand. Rough estimates states that the price per meter of boring is 350 NOK and the price per meter of casing piping is 650 NOK. For a 100 meter energy well with 4 meter of casing pipe this result in a total price of 37 600 NOK. In addition comes costs related to ground source heat pump, internal distribution system, installation and labor. For a complete single well system the total price will approximately be 200 000 - 300 000 NOK, depending on heat pump size, depth and geological conditions³. Enova also provides economic support for such installations, however the exact amount is hard to estimate .

Investments in ground source heat pumps and energy wells is considered long term investments. The expected lifetime of the heat pump is 20-30 years while the boreholes could last for up to 100 years with minimal maintenance costs during operation.

The price of PV panels in 2024 is between 2 500- 4 000 NOK / m² with each PV panel delivering roughly 200 Wp / m². Solar PV panels has an estimated lifetime of 25-30 years [65]. Additionally

³Rough boring cost estimates is provided by Petter Aas from Aarsleff by email at the 31st of January 2025 and are compared and validated with other sources by the authors.

an inverter is required and usually brings a substantial investment. The costs vary significantly and specific numbers are hard to obtain. However, an inverter typically has a lifespan of 10-15 years, which implies that over the operational lifespan of the PV system, it is expected to replace the inverter at least once. When installed, PV systems typically exhibit minimal operational costs.

These rough cost estimates will be used later to calculate the estimated pay back times and to discuss the economic viability of BTES systems.

4 Analytic Method for Energy System Models

The aim of this thesis is to highlight the possibility to close the mismatch between solar power production and heating demand, consequently cutting electricity costs and releasing capacity on the grid. This will be done by modeling two different energy systems utilizing seasonal geothermal energy storage.

Part 1 will explore the possibility of improving single homes with already installed energy well infrastructure and PV panels by incorporating seasonal storage. Typically, private PV installations produce excess energy in the summer which equals to approximately 20-30% of the annual energy consumption. This energy surplus limits how much energy that can be stored in the energy well. The study in part 1 therefore investigates the effects of energy storage on the well fluid temperature and how seasonal storage can improve self-sufficiency and lower energy costs in winter. The sum of these individual contributions could result in release in grid capacity. A key advantage of this system is its minimal requirement for additional investment or effort, enhancing accessibility for consumers which is an essential factor for widespread adoption in the private consumer market.

Part 2 examines a larger scale BTES system designed to meet increased energy demands using a greater amount of locally generated solar power. This model considers a BTES system comprising of multiple energy wells, resulting in a larger storage capacity. Such systems are scalable and adaptable for various applications. Enhancing the self-sufficiency of residential and commercial buildings will alleviate pressure on the grid.

In both parts the fluid temperature is considered the result, with a higher internal temperature being favorable. The average temperature is then being used to determine the GSHP efficiency through the COP function presented in section 3.3. From there, the electricity consumption and the potential cuts in electricity import is calculated.

To produce demand profiles, simulate the geothermal storage systems and to determine energy flows three software tools have been used. Due to accessibility and familiarity PROFet, GAMS and EED was determined to be most suitable. The following section describes these tools in detail. Additionally, Python was used for data analysis and plotting.

4.1 Demand Estimator - PROFet

To determine the energy demand, PROFet was used. PROFet is an energy load profile estimator in buildings developed by SINTEF and used for FME ZEN (the research center of sustainable

energy, Zero emission neighborhoods)⁴. PROFet splits the energy demand into two components, electric demand and heating demand as shown in equation 4.2. The electric demand consists of some space heating demand (SHD), electric specific demand and cooling. The heating demand consists of the majority of the space heating and domestic hot water (DHW). The demand profiles is outputted on an hourly resolution and is based on real world measurements.

$$\text{Electric} = \text{SHD}_{el} + \text{electricity} + \text{Cooling}_{el} \quad (4.1)$$

$$\text{Heat} = \text{SHD} + \text{DHW} \quad (4.2)$$

4.2 Energy System Modeling - GAMS

GAMS (General Algebraic Modeling System) is a modeling environment designed to solve optimization and mathematical programming problems. The program was used to simulate and optimize operation of the energy system of a single house with PV panels and energy well. The model optimizes the costs given a set of constraints which is further described in section 5.

4.3 Earth Energy Designer - EED

EED is a digital tool to simulate vertical borehole heat exchangers. It allows for simulation of 1-1200 boreholes making it applicable for both part 1 and part 2 of the thesis. EED inputs a number of parameters, including; load profiles, thermal properties, configuration, and time resolution. In return EED outputs the average heat carrier fluid temperature for the given time resolution. EED also provides an optimization functionality, which optimize the borehole configuration within a set of constraints which were used for the reference setup in Part 2 of the thesis.

⁴Access to PROFet provided by Igor Sartori, senior researcher at Sintef

Part I

System with Single Borehole

Part 1 of the thesis presents an analysis of the single home energy system utilizing a single energy well for storage. It includes a detailed description of the system model, outlines the key assumptions and limitations underpinning the analysis, and specifies the input parameters used in the simulations. The section concludes with a presentation of the results, followed by a discussion of their implications and relevance.

5 Model of Single Home Energy System

As the starting point, the simulation of single home with existing PV and energy well infrastructure was conducted. The objective is to demonstrate the potential of transforming the existing energy system into a seasonal storage system with minimal modifications. To achieve the model's objectives, the previously discussed modeling tools are designed to interact, as illustrated in Figure 5.1.

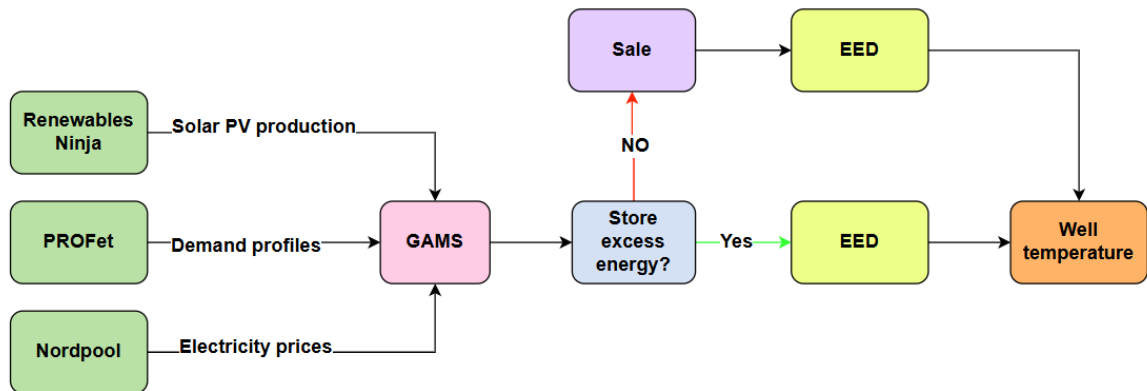


Figure 5.1: Schematic figure of model. Input parameters such as PV power production, demand profiles and electricity prices are fed into GAMS which allocates the energy flow depending on the decision to store or sell excess energy produced in the summer. This decisions affects the fluid temperatures.

Figure 5.1 shows a schematic drawing of the model. Irradiation data from renewable ninja, electricity prices from Nordpool and demand profiles from PROFet is fed into the GAMS model. GAMS then minimizes the total costs of electricity. To minimize the costs, GAMS allocates the energy flows to an optimum given certain constraints, which will be further described later in this section. As figure 5.1 shows, the excess energy produced in summer can either be sold to the grid or be stored in the geothermal storage system. This decision makes up the two scenarios,

later referred to as scenario "store" and scenario "sale". The energy balance in the well is then fed into EED to calculate the temperature of the heat carrier fluid. If the excess energy is stored instead of sold, the fluid temperature will increase, potentially making the GSHP more efficient. If the excess energy is sold, the fluid temperature will only be affected by the surface temperature and the geothermal heat flux. The fluid temperatures is then analyzed and visualized in python.

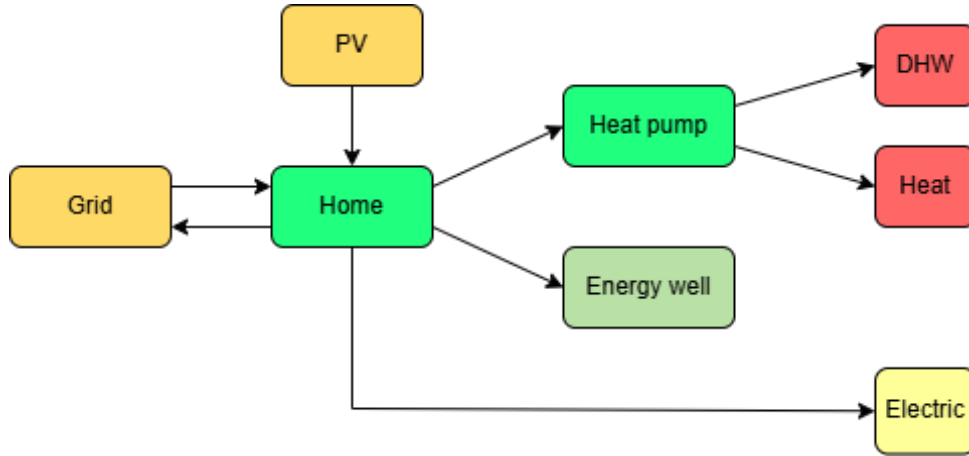


Figure 5.2: Flow chart representation of the single home energy system. Home serve as a hub receiving electricity from the grid and the PV system. Home then makes sure that the DHW and heating demand is covered at all times, the surplus is stored for later use

The overall energy system can be seen in figure 5.2. As shown in the figure, the home is bidirectional connected to the grid allowing for both import and export. The home also receives electricity from the installed PV system. In general the PV production covers the electric demand, however any surplus power is either exported to the grid (scenario sale) or stored in the energy well (scenario store). During winter, the GSHP extracts heat from the energy well and elevates the temperature with a constant COP factor of 4. Heating and DHW in the summer is solely covered by the GSHPs internal electrical coil ⁵.

The GAMS model outputs the total costs alongside the energy balance around the energy well in both scenarios. The optimal cost function is described by the following equation.

$$Min(Cost) = \sum_{h=1}^H (I_h * P_h * T) + T_e * 12 + \sum_{h=1}^H I_h * T_p - \sum_{h=1}^H S_h * I_h - \sum_{h=1}^H E_h * P_h + E_h * L \quad (5.1)$$

⁵Electric, DHW and heating demand are predetermined demands provided by PROFet in hourly resolution.

H = Number of hours in a year, 8760

h = Specific hour

I_h = Hourly grid import

P_h = Hourly spot price

T = Tax on import, 25%

T_e = Energy tariff

T_p = Power tariff

S_h = Hourly electricity support scheme compensation

E_h = Hourly grid export

L = Grid loss compensation, 0,05 kr/kWh

Equation 5 represents the minimization of energy costs for the home over a year. The first term sums the cost of imported electricity, considering spot prices and taxes. The second and third terms add fixed energy and power tariffs. The last two terms subtract compensation from electricity support schemes and revenue from exported electricity, including grid loss compensation.

To ensure that the model operates within physical limitations and possesses realistic behavior some constraints was defined. First, the demand must be met every hour through out the simulation period. Secondly, to ensure proper allocation of the energy flows, two energy balances were created for the main hubs of the system, the "home" and the "heat pump", represented by the green boxes in figure 5.2. The home represents the fuse box in the house.

$$I_h * E_h = 0 \tag{5.2}$$

$$I_h - excess_h + PV_h = Grid_{hp_h} + D_{el_h} \tag{5.3}$$

Equation 5.2 ensures that the model can not import and export simultaneously.

Equation 5.3 ensures energy balance at the fusebox. The home receives energy from its PV system. If the PV production is less than the overall electric demand, the shortfall is met by importing the remaining electricity from the grid. Conversely, if the PV production exceeds the combined demand, the surplus becomes excess. In the sale scenario the excess will be sold to

the grid at spot price. However, the two scenarios will be operated similarly between October - April. In the remaining months any excess power is directed to the heat pump, which then transfers the energy to the energy well. The GSHP has a maximum capacity dependent on the size of its electric heat coil. This capacity should cover both the DHW and heating demand alongside the excess energy which is stored, as described in equation 5.4.

$$Storage = HP_{max} - D_{DHW} - D_{Heat} \quad (5.4)$$

Any surplus beyond this constraint will be exported to the grid.

$$grid_{hp_h} * COP_h = D_{DHW_h} + D_{Heat_h} \quad (5.5)$$

Equation 5.5 calculates how much electricity the GSHP requires to ensure that the DHW and heating demand is met at all times.

After running the GAMS simulation, the balance over the energy well are used as an hourly input in EED. The EED model then simulates the fluid temperature evolution over a 25 year period for both scenarios. Further description on EED inputs will be presented in section 5.2.

5.1 Model limitations and assumptions

First and foremost, it is important to acknowledge that the demand profiles generated by PROFet are empirical estimations rather than precise measurements. These profiles are constructed using a combination of modeled data and statistical techniques. Moreover, the input parameters used in PROFet are primarily derived from literature reviews and reflect average values typical of Norwegian households.

A key assumption made in the model is that thermal demand is considered purely as thermal energy, without accounting for temperature levels. This means that both domestic hot water and space heating are treated uniformly as thermal energy demands, regardless of their differing temperature requirements. In this model the output temperature is assumed to be 45°Cf or both DHW and space heating.

The selection of input parameters in EED is based on values obtained from scientific literature and data from existing systems. However, it is important to recognize that several of these parameters, particularly those related to geothermal properties can vary depending on geographic location. In practice, site-specific factors such as soil composition, groundwater

presence, and thermal conductivity introduce considerable variability. The model is not considering the depth of the unconsolidated mass layer, the groundwater table, and potential groundwater flow, all of which will have an influence subsurface heat transfer dynamics. Additionally, the model assumes no thermal contact resistance between the borehole pipe and the surrounding grout material. This simplification implies perfect thermal contact, which does not fully reflect real world conditions.

The result in EED is the temperature of the heat carrier fluid. EED does not describe the how the temperature behaves in the different layers of the BTES system.

GAMS receives hourly input profiles, meaning the model theoretically has foresight into future events. However, its main limitation is that it does not truly value of stored energy. Instead of storing energy when beneficial, the model opts to sell the surplus to minimize costs. As previously mentioned, this behavior will persist unless explicitly modified via strict constraints. In practice these limitations and the lack of decision variables means that the GAMS model functions more as a simulation of the system as compared to an optimization model.

In GAMS, the energy well functions purely as an energy flow measured in kWh, with unlimited storage capacity. The output is determined solely by heating demand and the COP factor, While injected energy depends entirely on excess energy. Regardless of fluctuations in the energy balance, the COP factor remains constant. In reality, energy extraction and injection would cause temperature variations, which in turn would impact the COP factor.

The COP of the GSHP during heat injection into the energy well was omitted in the model. This simplification is justified by the exclusion of cooling demand in the energy system. Incorporating a COP during heat injection would imply the presence of additional heat pump infrastructure capable of extracting heat from an external source, such as the ambient air, and transferring it into the borehole. Since such a system configuration falls outside the scope of this study, and no cooling demand is considered, the injection process is treated without accounting for a COP factor.

As a simplification, it is assumed that energy extraction from the well is completely shut down from April to September. During this period, heating demand is solely met by electrical heating. In reality, especially in Norway, some heating demand persists during the summer months, making a more dynamic operation of the energy well system a more realistic approach.

Additionally, the system does not include an accumulator tank. As a result, the GSHP must deliver the exact amount of thermal energy required for each hour throughout the year. The

model lacks the ability to store excess heat or shift thermal loads using a thermal storage tank.

The freezing potential of groundwater is neglected. This means that although the fluid temperature in some cases drops below zero it is assumed that the groundwater will not freeze.

Finally, the energy consumption of circulation pumps and other minor components in the system is not taken into consideration.

5.2 Model inputs and constraints

To accurately simulate the performance of the single home energy system, input data was collected and structured according to the specific needs of each modeling tool. PROFet, EED, and GAMS. These tools cover different aspects of the system, including energy demand estimation, ground system behavior, and overall energy flow optimization. Each model relies on a unique set of input parameters, drawn from empirical data, literature, and representative assumptions, every key parameter has been presented earlier in the thesis.

5.2.1 PROFet inputs

To ensure realistic and representative demand profiles, key assumptions were made regarding building characteristics and climatic conditions. These assumptions aim to reflect the typical Norwegian single home and are aligned with average national values and climate data. The input parameters to the demand estimator is summed up in table 5.1.

Table 5.1: PROFet inputs based on average Norwegian single home and typical meteorological year in Oslo.

PROFet	
Housing size	168 m^2
Housing efficiency	Regular
Outside temperature	TMY - Oslo

The average single home in Norway is 168 m^2 and was used as the area input [25]. PROFet also differentiates between housing standards, and split them into three categories, regular, efficient and very efficient. Regular housing is considered the average of the Norwegian housing stock. Efficient is considered TEK10 energy standards while, very efficient housing is considered to be at passive house standards. In this model the efficiency is set to regular, for closer representation of the average Norwegian home.

The most important parameter affecting the heating demand profile is the outside temperature profile. In this model, the hourly temperatures for a typical meteorological year in Oslo served as input. Ev cars per household was not included in the model, but would in practice increase the electricity demand substantially.

5.2.2 EED inputs

The EED model requires detailed input data to simulate the thermal performance of the borehole heat exchanger system. These inputs are divided into three main categories: ground thermal

properties, borehole and heat exchanger geometry, and heat carrier fluid characteristics. The values used in the model are either provided by EED as representative for Norwegian conditions or derived from literature and typical installations in the region as presented in 2 and 3. The inputs are summarized in tables 5.2, 5.3, and 5.4.

Table 5.2: EED ground properties based on typical values in Oslo region.

Ground properties	
Thermal conductivity	3 W/m*K
Volumetric heat capacity	2,4 MJ/m ³ *K
Annual average ground surface temperature	6,2 °C
Geothermal heat flux	0,06W/m ²

Table 5.3: EED borehole and heat exchanger inputs based typical borehole values in the Oslo region.

Borehole and heat exchanger	
Type	Single-U
Configuration	0
Depth	200 m
Spacing	0
Diameter	115 mm
Filling thermal conductivity	0,6 W/m*K
Flow rate	0,6 L/s
U-pipe	
Outer diameter	40 mm
Wall thickness	3 mm
Thermal conductivity	2,4 W/m*K

Table 5.4: EED HX35 heat carrier fluid inputs.

Heat carrier fluid (HX35	
Thermal conductivity	0,4 W/m*K
Specific heat capacity	4000 J/Kg*K
Density	1100 kg/m ³
Viscosity	0,0052 Kg/m*s
Freezing point	-18 °C

5.2.3 GAMS inputs

The GAMS model requires a range of technical and economic input parameters to simulate the energy system accurately. These include demand profiles, pricing structures, and system performance values. Since some of these inputs vary over time, such as electricity spot prices and tariffs, the retrieval date and data source are specified. An overview of the input values used in the model is presented in Table 5.5.

Table 5.5: GAMS model inputs. Power tariff, energy tariff and support scheme values were obtained from ELVIA in February and March.

Input	Value	Retrieved
Irradiance		Renewables Ninja, February 25
Electric demand		PROFet
DHW demand		PROFet
Heat demand		PROFet
Spot price	NO1 2023	NORDPOOL
Power tariff	215 kr/month	ELVIA , February 25
Energy tariff	0,425 kr/kWh and 0,325 kr/kWh	ELVIA, February 25
Support scheme	$(P-0,73)*0,9*1,25$	March 25
COP factor	4	Reference value
HP_{max}	4,5	NIBE-S1256[66]

5.3 Results for Single home energy system

This section presents the results from simulations and analyses conducted to evaluate the feasibility of enhancing heat pump performance through seasonal thermal energy storage in an energy well system. This is done by elevating the fluid temperatures to achieve higher GSHP efficiency. By doing this, excess energy in summer can be utilized for heating in winter months. The results are presented and compared for the both scenarios.

To highlight the mismatch between solar PV production and the heating demand profile figures 5.3 and figure 5.4 were created. The graphs shows the actual demand and PV production profile for the specific system, as derived from section 5.2.

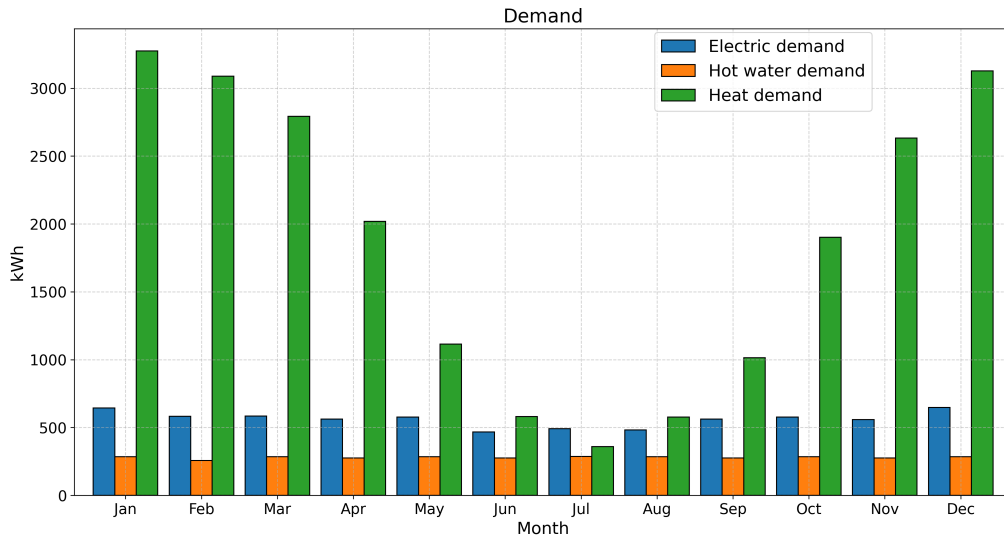


Figure 5.3: Monthly aggregated demand, showing that electric (blue) and hot water demand (orange) is not effected by seasonal variations. While heat demand (green) is clearly higher in winter.

The figure above shows the energy demand of the single house, as generated by PROFet. The data is aggregated monthly over the course of a year. The orange bars represent the domestic hot water demand, which remains relatively constant throughout the year. The blue bars indicate the electricity demand, which varies from approximately 500 kWh during the summer months to just below 600 kWh in the winter. The green bars represent the space heating demand, which exhibits significant seasonal variation, ranging from around 300 kWh in the summer to approximately 3 300 kWh in the winter.

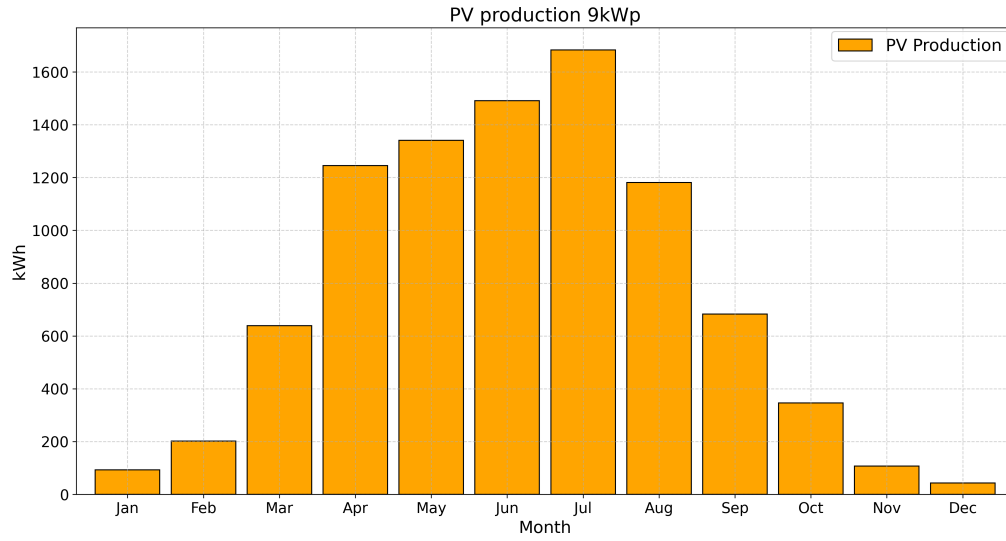


Figure 5.4: Monthly aggregated PV production. Production is clearly affected by seasonal variations.

Figure 5.4 illustrates the PV production over the course of a year. The graph presents the monthly energy output from the PV system. Production is relatively low in January, at approximately 100 kWh. By April, it increases significantly to over 1 200 kWh, peaking in July at around 1 700 kWh. After July, the production gradually decreases, reaching its lowest point in December with just 50 kWh.

In Scenario "sale" GAMS allocates the power production and energy demand as seen in figure 5.5. This diagram shows the annual flow of energy for the entire system when excess power production is being exported to the grid.

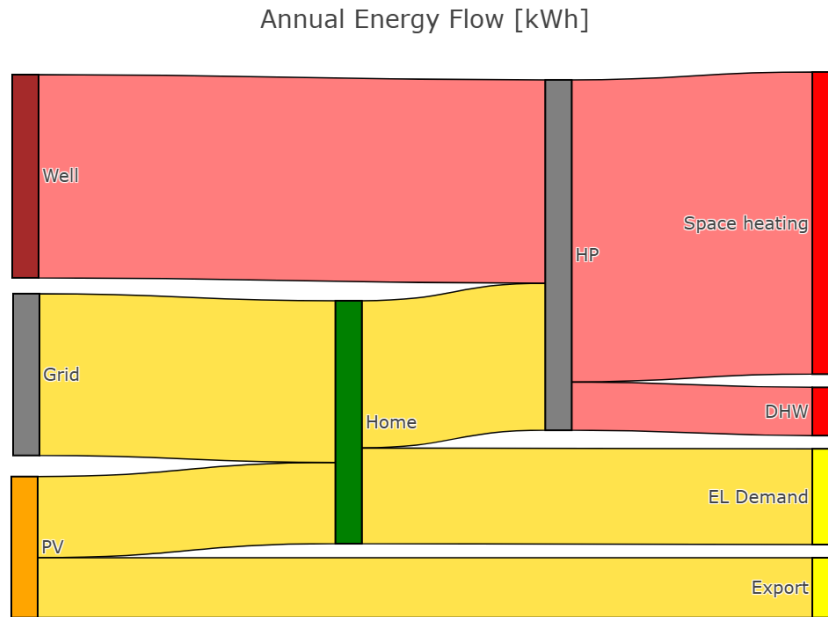


Figure 5.5: Sankey diagram of scenario sale visualizing how the energy is allocated in the model. Heat flow is represented by the red flows, while electricity is represented by yellow flows.

The sankey diagram illustrates the quantity of energy through the thickness of the flows. Thicker flows indicate higher energy volumes. This figure offers a clear overview of the relative sizes of energy demand and the sources from which that energy is obtained. Two colors are used to distinguish the types of energy: yellow represents electrical energy, while red indicates thermal energy. Keep in mind that "Home" is a node used as a central for the incoming energy. From there, the energy is distributed to electric demand and heat pump. Exact energy flow values are provided in table 5.6

Table 5.6: Break down of sankey diagram: Energy flow values in kWh for scenario sale.

Energy Flow Sale	
Flow	kWh
Well - HP	12 916
Grid - Home	10 282
PV - Home	5 159
PV - Export	3 803
Home - HP	9 351
Home - El Demand	6 089
HP - Space heating	19 204
HP - DHW	3 063

Table 5.6 presents the annual energy data in kWh. The combined electricity demand of the heat pump and the household totaling to 15 441 kWh. The PV system generates 8 962 kWh

annually. Despite the total electricity demand being approximately 1.7 times greater than the PV production, 42% of the PV output is exported to the grid, once again highlighting the seasonal mismatch between production and consumption.

The heat pump supplies 22 267 kWh of thermal energy to meet the heating and domestic hot water needs. During the winter months, 75% of this energy is extracted from the ground via the energy well. In contrast, the summer demand is entirely met by electricity, sourced either from the grid or the PV system. Over the course of the year, the energy well contributes 58% of the total energy required by the heat pump.

In the "store" scenario, the allocation of energy flow differs slightly. The sankey diagram for the "store" scenario is presented in figure 5.6.

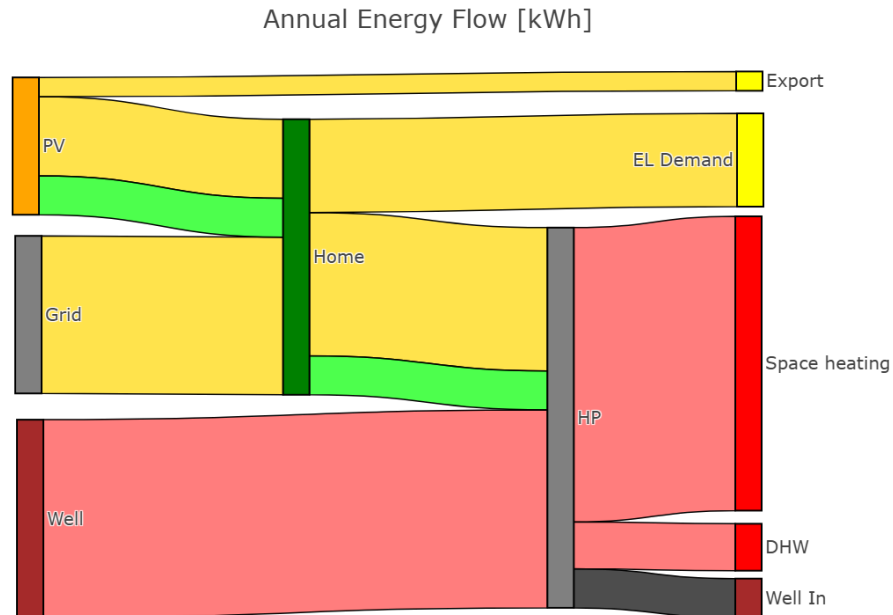


Figure 5.6: Sankey diagram of scenario store visualizing how the energy is allocated in the model. Heat flow is represented by the red flows, while electricity is represented by yellow flows. The green flow visualizes the amount of energy allocated to storage.

The green flow is energy produced by the PV system and directly allocated for storage in the energy well. Table 5.7 shows the energy flows in scenario "store" between the nodes in kWh.

Table 5.7: Break down of sankey diagram: Energy flow values in kWh for scenario store

Energy Flow Store	
Flow	kWh
PV - Export	1 260
PV - Home	7 702
Grid - Home	10 283
Home - El Demand	6 089
Home - HP	11 895
HP - Well	2 544
Well - HP	12 916
Hp - Space heating	19 204
HP - DHW	3 063

The total PV system generation remains the same as in the Sale scenario, at 8 962 kWh. However, only 16% of the PV production is exported, compared to 42% in the Sale scenario. The sankey diagram highlights the storage of excess energy in the energy well. However, further analysis is required to evaluate the recovery rate and the effectiveness of seasonal energy storage within the energy well, presented later in this section.

Given the initial results, further investigation on the cost saving potential of scenario "store" as compared to scenario "sale" is presented. Figure 5.7 shows the monthly cash flows for scenario "sale" and figure 5.8 shows the monthly cash flows for scenario "store" as calculated by GAMS.

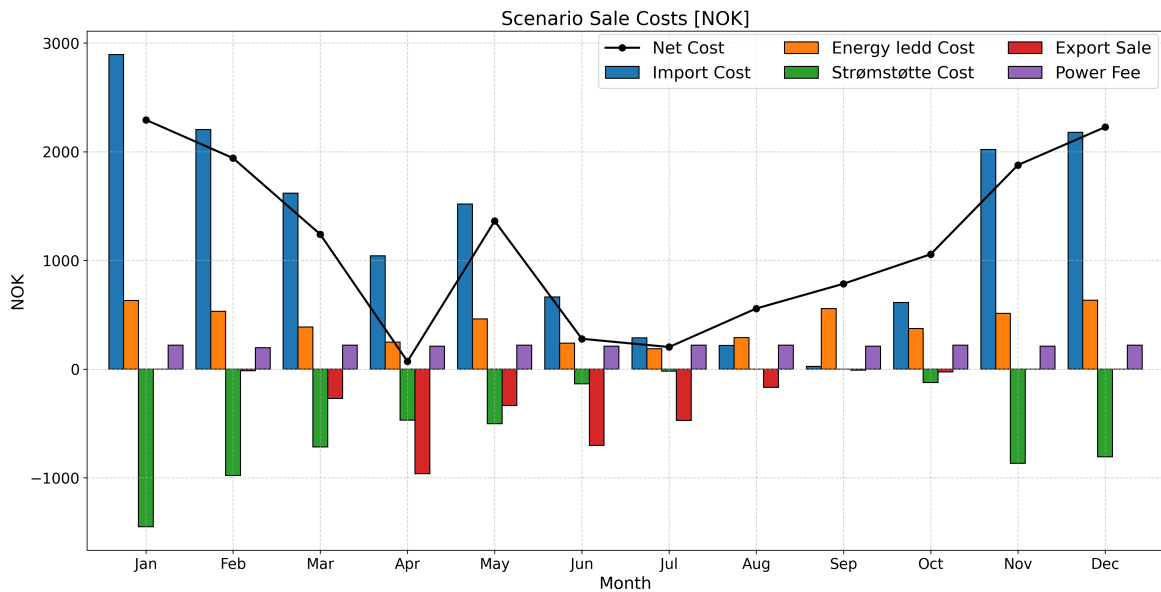


Figure 5.7: Cash flow each month throughout the year when exporting excess energy in summer. The black line represents the sum of the monthly cash flow (net cost).

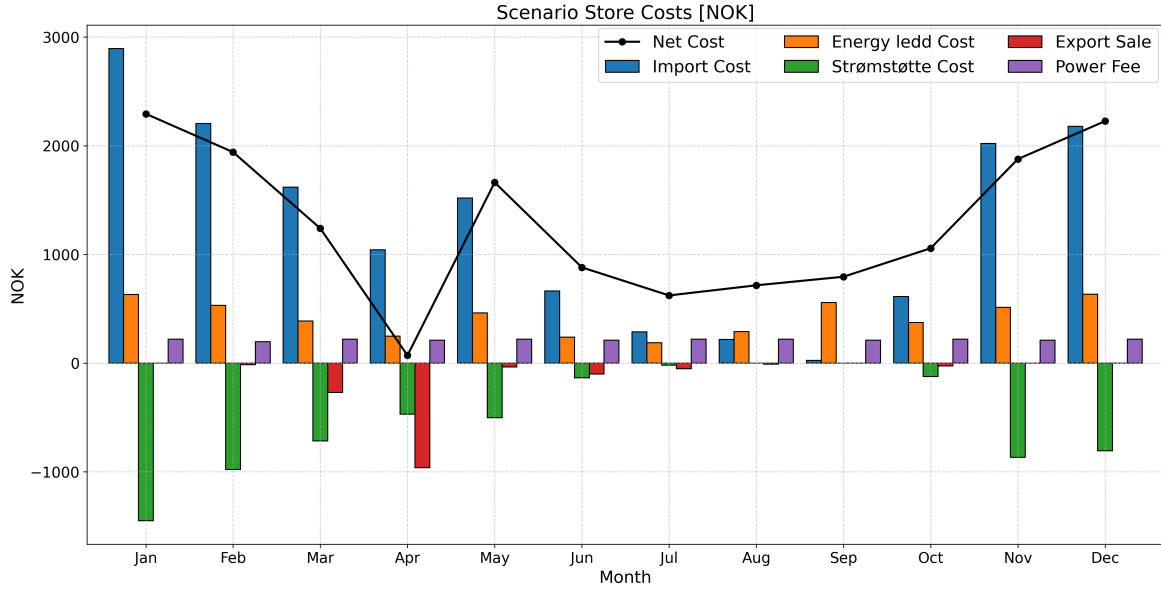


Figure 5.8: Cash flow each month throughout the year when storing excess energy in summer. The black line represents the sum of the monthly cash flow (net cost). In the summer the priority is to store excess energy, however, since the heat pump has a capacity limit some of the excess electricity is exported.

The costs apply to the first year of operation. Negative costs are savings by exporting electricity to the grid and power support scheme. As the graph shows, no cost reduction in winter is achieved when excess power is stored. The plot is intended to highlight the lost revenue potential when excess energy is stored rather than sold. The black lines shows the total costs each month, and are further compared for each scenario in table 5.8.

Table 5.8: Monthly costs in NOK. Showing the difference in cash flow for May-September, due to less export income in the store scenario.

Month	Store [NOK]	Sale [NOK]
January	2 293	2 293
February	1 941	1 941
March	1 240	1 240
April	71	71
May	1 662	1 363
June	881	279
July	623	203
August	716	558
September	795	785
October	1 057	1 057
November	1 877	1 877
December	2 226	2 226
Total	15 380	13 892

These results show that selling excess electricity instead of storing it provides savings of 1 488 NOK on the annual electricity bill. For seasonal storage to be a viable alternative, the resulting

increase in fluid temperature must improve the system's winter efficiency enough to compensate for the lost revenue from PV electricity sales.

To investigate the long term storage potential, the following approach has been taken. Firstly, EED calculates the average temperature of the heat carrier fluid for the two scenarios, presented in figure 5.9. The blue graph shows the fluid temperature trends in scenario "store" and the red graph shows the temperature trends in scenario "sale".

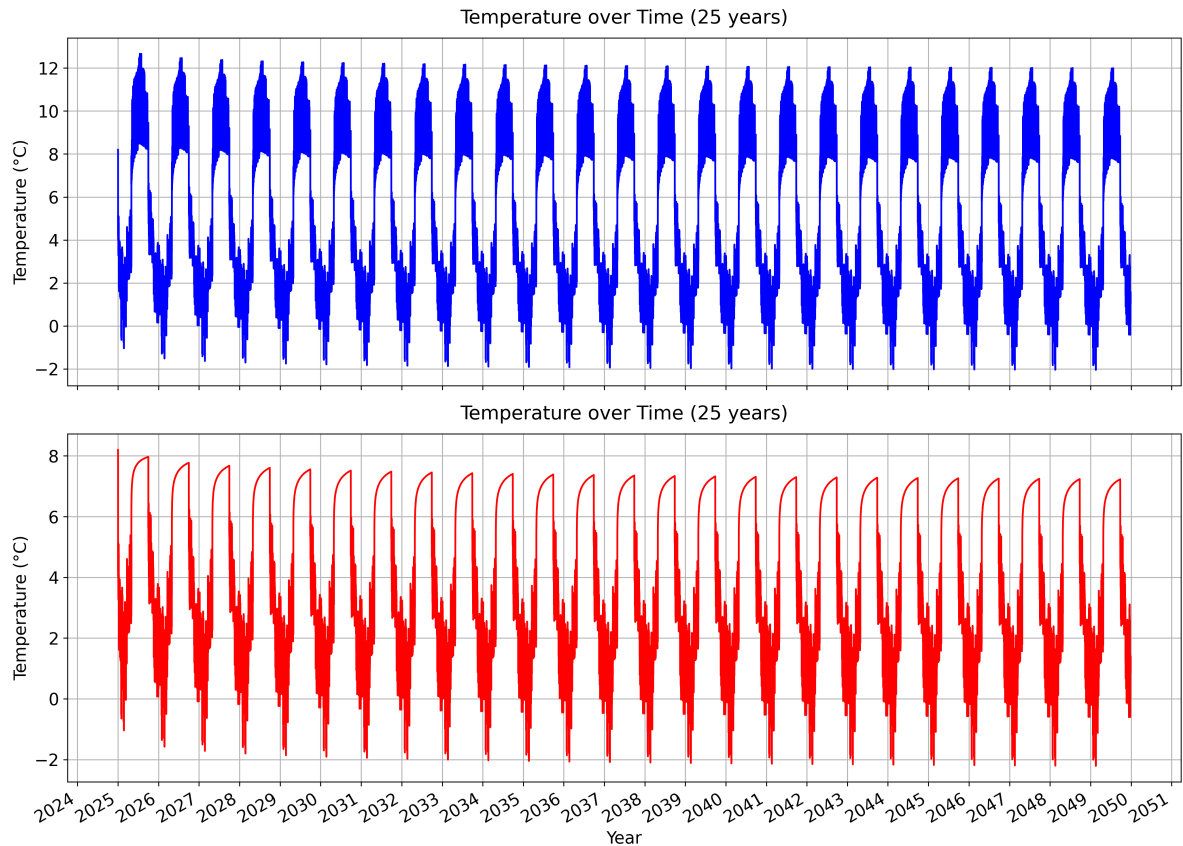


Figure 5.9: scenario "store" in blue and scenario "sale" in red: Heat carrier fluid temperature over 25 years simulation. The plots shows stable temperature across the 25 years. In scenario store the maximum temperature is approximately 12 °C and slightly less than 8 °C in scenario sale. The minimum temperatures are similar in both scenarios, indicating limited potential in energy storage.

The fluid temperature trends is plotted over 25 years of operation. In the scenario "store", the temperature ranges from -2°C to 12°C. Scenario "sale" shows a smaller temperature difference from -2°C to 8°C. Each cycle in the graph represent one year of operation. The temperatures are higher in the summer for two reasons. Firstly, the energy well is being charged with excess energy (store scenario) and secondly, energy is not being extracted since heating demand is neglected. This means that the geothermal heat flux heats up the well. The results shows that the temperature drops almost immediately when charging ceases and heat is being extracted to cover heating demand.

Both scenarios have a stable temperature range over the duration of the simulation. The temperature difference from the first year of operation to the last is less than half a degree in the store scenario and one degree in the sale scenario. Suggesting that the energy well is close to its equilibrium at the current load. Figure 5.10 expands on the temperature variations throughout one year.

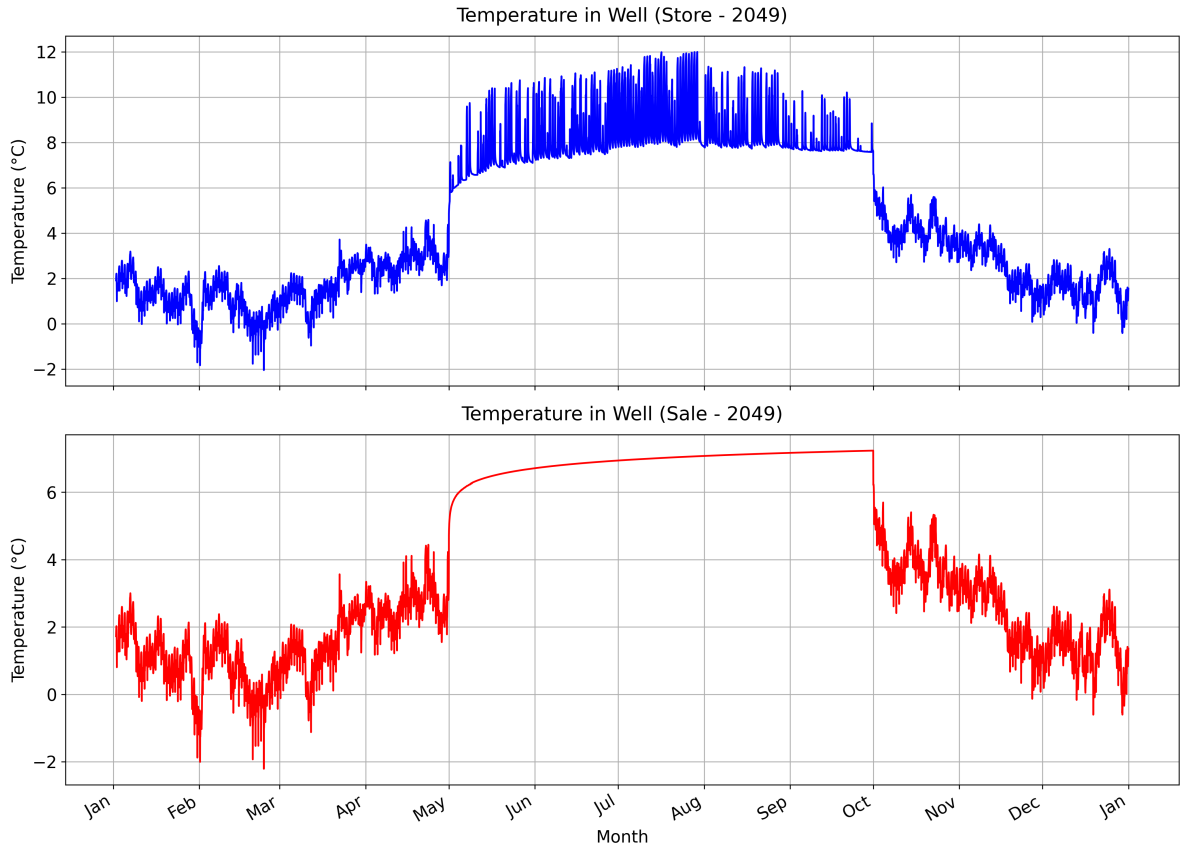


Figure 5.10: scenario "store" in blue and scenario "sale" in red: Heat carrier fluid temperature over the last year in the simulation. The plot shows that even though 2 544 kWh is injected into the energy well in summer (scenario store), the temperature drops immediately and ends up at almost the same level in both scenarios.

The graph illustrates fluid temperature fluctuations in the well during the final year of operation, at which point the system is considered to have reached thermal equilibrium. Both daily and longer term variations in the fluid temperature are evident. Naturally, the fluid temperature drops during periods when the heating demand exceeds the geothermal heat flux. Conversely, temperature increases can also be observed during winter periods when the heating load decreases. In these cases, the geothermal heat flux becomes sufficient to raise the overall temperature in the well. This effect is amplified when the well temperature is low, as the greater temperature difference enhances heat transfer from the surrounding ground.

To further elaborate on the seasonal storage capabilities of the proposed system, the fluid

temperature difference between the "store" and "sale" scenarios over a 25-year period was analyzed for two specific dates and is presented in Figure 5.11.

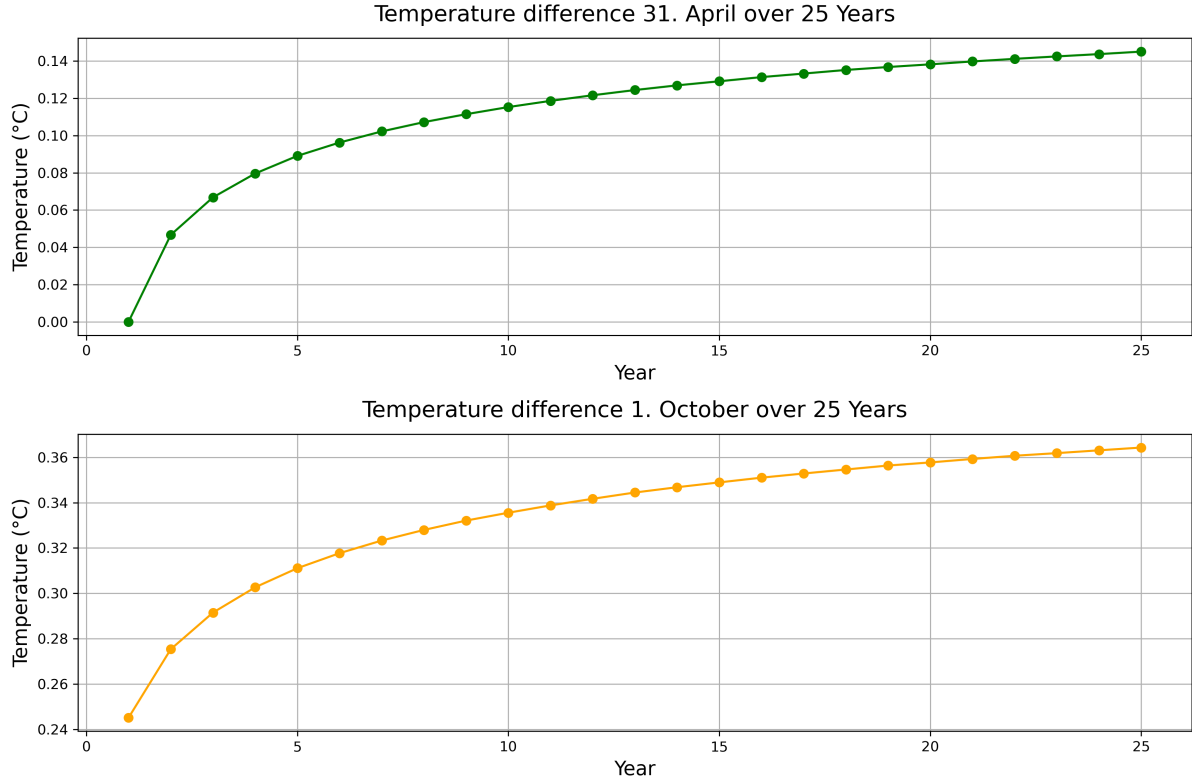


Figure 5.11: Temperature difference between scenarios at the start of the charging period, April 31st (green) and at the end of the charging period, October 1st (orange), highlighting the small temperature difference achieved in the two scenarios.

October 1st is chosen because it represents the day after the charging period the energy well. April 31st is chosen because it represents the last day of heating, before the charging starts. In the first year the green graph shows a temperature difference of 0, this is because the starting point of each scenario is the same. However, beyond this day the fluid temperature in the "store" scenario increases gradually. In the final year, the temperature difference reaches its peak at 0.14°C.

In the first year, the orange graph starts at a temperature difference of 0.24°C since the first charging season has been completed. In the remaining years the temperature difference exhibits almost the same rate of increase as the the green graph, reaching its peak at 0.36°C.

Comparing the two graphs, shows suboptimal storage potential. Right after the end of the first charging season the temperature has increased by 0.24°C, however after the subsequent heating season the temperature drops by 0.20°C. This means that after a full year, the temperature difference for the two scenarios is 0.04°C, even though the same amount of energy is being

extracted in both cases. The temperature increase will not provide any notable increase in GSHP efficiency as shown in figure 3.3. These results therefore show that the injected energy escapes and is no longer usable for heating purposes in winter time.

5.4 Discussion and evaluation of single well energy storage

As discussed in the previous section, the improvement in GSHP efficiency resulting from increased fluid temperatures would need to yield energy bill savings equivalent to the revenue generated from summer energy exports. Figure 5.12 shows the COP factors as a function of fluid temperatures, derived from the graph presented in figure 3.3. The COP factors are based on the temperature difference between the fluid temperature and the GSHP outlet temperature. The outlet temperature is set to 45 °C.

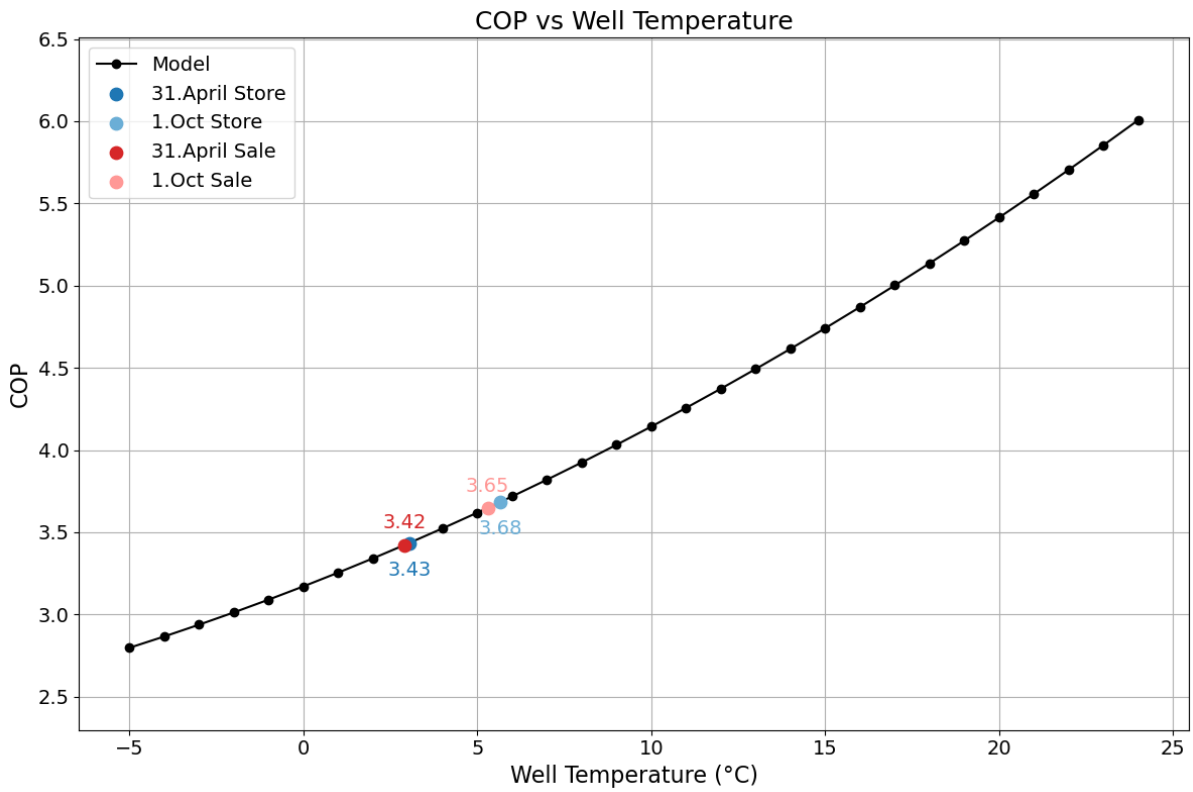


Figure 5.12: COP factor based on fluid temperature. The blue and red dots show the cop factor for the different scenarios before and after charging periods. Highlighting the small difference in GSHP efficiency. The graph is based on the function in figure 3.3 [52].

The colored markers on the graphs highlight the COP factors for each scenario during the final year of operation, as derived from figure 5.11. A comparison of the scenarios reveals a marginal COP increase of 0.01 at the end of the heating season, which would translate to a 15 kWh reduction in electricity consumption. Following the charging season, the figure shows a COP increase of 0.03, corresponding to a 39 kWh yearly reduction in electricity consumption.

In order to evaluate the required increase in the COP of the GSHP necessary to realize the savings detailed in table 5.8, figure 5.13 were generated.

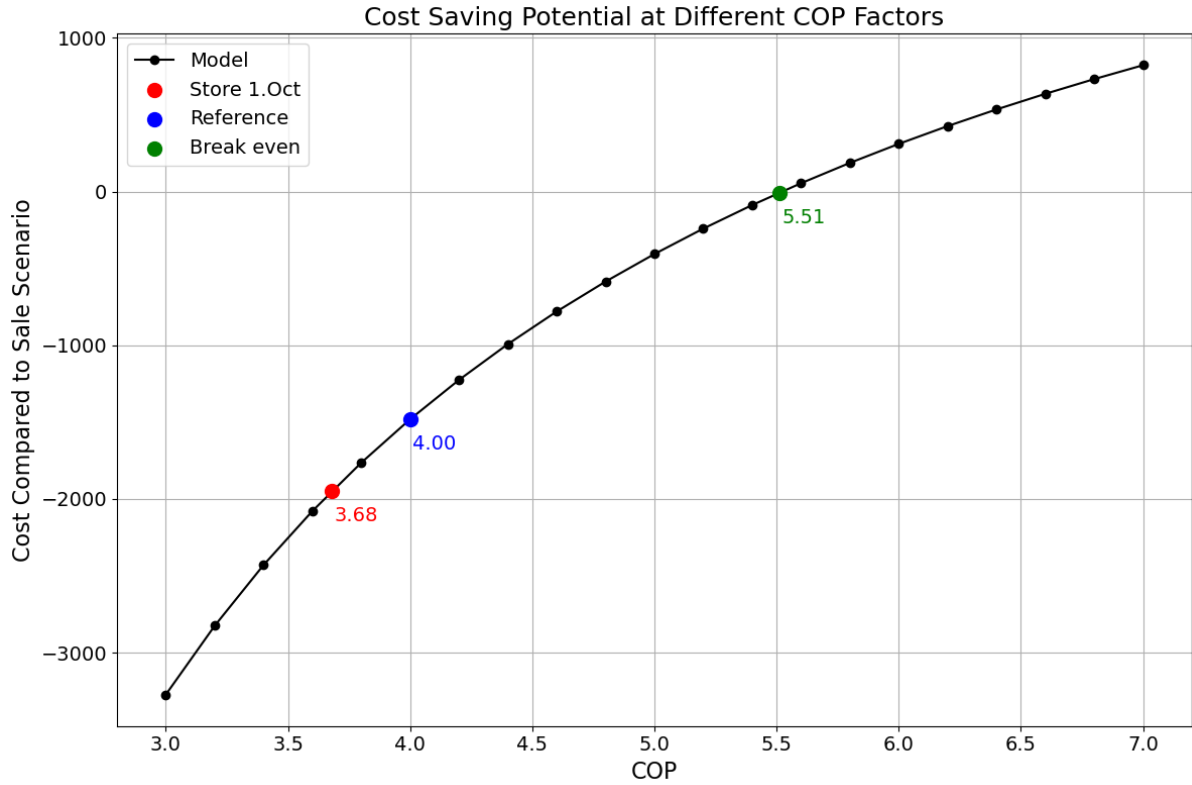


Figure 5.13: Cost saving potential at different COP factors. Based on an average spot price of 1.25 NOK/kWh in the heating period. The red dot represent the COP factor given the well temperatures at the end of the charging period in scenario store. The blue dot represent the reference COP factor of 4 used as input in the model. The green dot represent the COP factor where the consumer break even due to energy savings.

Figure 5.13 shows the COP factor along the x-axis and the associated costs relative to the sale scenario on the y-axis. The graph illustrates the yearly total net cost in store scenario at different COP factors compared to sale scenario. The cost are calculated with the assumption that the average spot price in the heating period is 1.25 NOK/kWh. Its important to note that for simplicity, the COP factor displayed is constant throughout the heating period. The blue marker represents the reference COP value used as input in the model, while the red marker indicates the cost outcome at a COP of 3.68, corresponding to the value achieved in the store scenario in October 1st. The green marker displays the COP threshold at which winter savings offset the profit lost during summer. At this COP factor the temperature in the well is approximately 21°C. The figure demonstrates that achieving the necessary improvement in GSHP efficiency would require fluid temperatures significantly higher than those observed in the results. Since the average electricity price of 1.25 NOK/kWh excludes power support, consumers would effectively pay less for their electricity. This reduction implies that the actual break-even

point would be even higher under realistic conditions.

A higher COP indicates reduced electrical energy consumption relative to the thermal energy delivered, meaning that a smaller share of the total energy output must be supplied by electricity. As a result, a greater proportion is drawn from the energy well. An increase in COP resulting from thermal energy storage leads to a more rapid decline in fluid temperature during operation, due to the enhanced heat extraction. However, the temperature will not drop below that of a system without storage, as the COP values will eventually converge.

As presented in Section 3.5, heat dissipates from the energy well into the surrounding ground through thermal conduction. This process is governed by the temperature gradient between the energy well and the surrounding rock mass, the thermal conductivity of the materials involved, and the size of the contact surface area between them. A larger contact area facilitates greater heat transfer, which, in the context of energy storage, can lead to increased thermal losses. Therefore, to minimize conductive losses, the total thermal storage volume must be sufficiently large relative to the surface area exposed to the surrounding ground.

Under standard operating conditions, the temperature within the borehole is typically lower than that of the surrounding rock. The thermal gradient facilitates conductive heat transfer from the warmer rock to the cooler borehole. The resulting heat flux is directly proportional to the temperature difference between the two materials, thereby gradually replenishing the thermal energy within the borehole. However, when external heat is injected into the borehole, its internal temperature increases. As this temperature approaches or exceeds that of the surrounding rock, the thermal gradient diminishes or reverses. Consequently, the natural conductive heat flux is reduced, and when the well temperature surpasses the surroundings, heat will be transferred from the borehole back into the surrounding rock, resulting in a net thermal loss.

In scenario "*sale*", all the heat supplied to the energy well is derived from the geothermal heat flux. In scenario "*store*", however, the injection of external heat displaces most of the geothermal contribution due to a reduced or reversed temperature gradient. In larger scale systems with multiple, closely spaced boreholes, the geothermal heat flux available per borehole decreases. Consequently, this deficit must be compensated by an increased input of externally injected energy. In a system with more boreholes the domain volume which heat can be extracted from is bigger.

5.5 Conclusion for Single Well System

Part 1 of the study investigates the potential cost savings for single-family homeowners by storing surplus PV energy generated during the summer to meet heating demand in the winter. The system modeled consists of average single-family dwelling equipped with PV panels, a GSHP, and a single energy well.

The findings from literature study indicate that for a single-family dwelling, the inclusion of an energy well will reduce the electricity consumption since GSHP are more efficient than ASHP. Such systems will therefore lower the costs related to heating in the winter time. However, based on the results, extending the system to include either seasonal or short-term storage is not a justifiable investment.

For the consumer to break-even, the average COP factor must be 5.51, at this point the fluid temperature is 21°C on average. However, higher COP factor results in more heat extraction, which means that in an real life applications the average temperature needs to be even higher. Higher well temperatures will also decrease the incoming geothermal heat flux. Additionally, the brake-even calculations does not consider economic aspects, such as the power support scheme, which would make the saving potential even lower.

In conclusion storing PV energy in single well is not economically viable. This shortfall is primarily attributed to radial thermal losses form the energy well into the surrounding ground, extending beyond the well's immediate domain. These thermal losses result in a substantial reduction of the energy retained within the well, making it difficult to achieve the desired storage efficiency. Additionally, the elevated well temperatures, as a result of heat injection, affects the capacity to effectively harness geothermal heat flux, further compromising its efficiency as an energy storage solution. The findings indicate that consumers would derive greater benefits by exporting excess energy rather than storing. However, consumers could potentially benefit from utilizing the energy well as an energy sink to meet cooling demands during the summer months. This approach offers a cost-effective method for cooling residents by dumping excess heat from the house into the borehole, taking advantage of the high SEER. However, it is essential to acknowledge that the inputted energy can not be retained in the winter time.

Examining alternative applications for the system such as short term storage. The results indicate that 80% of the temperature increase disappears within 3 hours after daily charging. Over 95% is gone after 12 hours. Using the single well storage system as short term storage will provide poor efficiency and easily be out competed by other technologies, such as batteries.

The results show that the storage potential of a single energy well is ineffective. This is due to limited thermal capacity and heat loss to the surrounding ground. The injected heat counteracts the geothermal heat flux that normally supply the energy well. One strategy to mitigate these limitations is to implement a network of multiple boreholes arranged in a compact configuration for larger systems. Larger BTES systems have the potential to enhance total stored energy as a result of increased storage volume. It also improves the surface area-to-volume ratio. This improvement reduces the relative impact of conductive losses and facilitates more efficient thermal storage.

Part II

System with multiple boreholes

In Part 2 of the thesis, the focus shifts from small-scale energy single well systems intended for individual homeowners to reduce heating costs. Instead, the discussion moves toward BTES systems with multiple boreholes to combat the inherent limitations discovered in part 1. In part 2 the emphasis will be switched to investigation of the load shifting potential in BTES systems, in order to release grid capacity in winter months.

To further investigate the potential of geothermal seasonal energy storage as a way of load shifting, simulations of a BTES systems have been conducted. A bigger BTES scale application is chosen because, as previously discussed in section 3.6, BTES systems have proven efficient for longer term energy storage through multiple realized projects, i.e Drammen skole, drakes landing, Tømtebanen and Ljan skole

The following section will describe how the simulation of the BTES systems were established. The section will also lay out the most important assumptions and limitations that affect the results. At the end, recommendations for future work will be discussed.

6 BTES Model description

The model uses the ITS Kjeller building as a reference building. ITS Kjeller is an university building located in Lillestrøm, Akershus. The total area is approximately 2500 m^2 with 5 floors of 500 m^2 each. Outside of the building there is a small square park, with dimensions of $30\text{ m} \cdot 30\text{ m}$. The well park must be contained within this park.

The goal is to explore how the fluid temperatures shifts in a BTES system as a results of different changes in parameter. The fluid temperatures will then be used to calculate the electricity demand as compared to conventional space heating and energy well without storage. In this model, the ratio between injection and extraction of heat, alongside the spacing and the configuration was changed to explore what combination of parameters that provide the best potential in seasonal energy storage.

Similarity as in part 1, the size and type of building was put into PROFet along with temperature data for a typical meteorological year in Oslo. PROFet then calculates the space heating demand on an hourly resolution. The hourly load profile is then aggregated by calender month to derive

monthly heat demand. The demand states how much energy is required to keep the building at a stable temperature throughout the year. The energy demand must be met by the energy well system in combination with a GSHP. The energy input into the system is determined using hourly solar irradiation data over the course of a year. From this data, the percentage contribution of each month to the total annual irradiation is calculated. This approach allows for easy scaling of the PV system's energy production.

The injection and extraction of energy from the boreholes requires a separate HP, and for both instances a COP factor is determined. In injection mode, the ASHP extract thermal energy from the ambient air and uses electricity from the PV to cover the required amount of injected energy. In heating mode, the thermal energy is extracted from the boreholes and the electricity is imported from the grid.

The predetermined parameter changes are based on earlier discussions in sections 3.7.2 and 3.6. In this model, spacings of 3, 3.75, and 5 meters have been selected, as boreholes should be spaced less than 7 meters apart due to thermal interference and better storage capabilities. Naturally, changes in spacing between boreholes within the defined area will change the configuration and numbers of boreholes accordingly.

In single well energy systems the majority of the heat comes from the geothermal heat flux. In a larger scale well parks with borehole closer together the amount of heat flux per borehole decreases. The heat flux will no longer be enough to supply the system, therefore more energy has to be injected to the system. Input ratios of 75, 100 and 150% have been chosen as examples. These were chosen because as previously mentioned in section 3.7.3 BTES systems needs to be charged with considerable amount of energy to avoid freezing due to thermal interference between boreholes. As a baseline comparison, an energy well system without energy storage capabilities is added to the simulations. Further descriptions of the setup follows in the next section.

6.1 Model inputs and constraints

Table 6.1 shows the heating demand aggregated over calendar months used as input in EED. The table also includes PV generation percentage of each month.

Table 6.1: Aggregated Heat demand and PV generation percentage for each month. Highlighting the seasonal variation in both heating demand and PV production

Month	Heat Demand [kWh]	PV production [%]
Jan	63 440	1,0
Feb	60 416	2,2
Mar	51 172	7,1
Apr	31 768	13,8
May	13 113	14,8
Jun	6 043	16,5
Jul	4 247	18,6
Aug	6 273	13,0
Sep	11 269	7,5
Oct	27 662	3,8
Nov	47 053	1,2
Dec	58 631	0,5
Total	381 086	100,0

For the simulation of the BTES systems in EED the same parameters as shown in tables 5.2, 5.3, 5.4 were used. However, changes in configuration, spacing and depth have been applied as seen in 6.2. There are 4 different configurations, and they are visualized in figure 6.1. The remaining inputs are shown in the tables below. From now on the different setups will be referred to with their spacing and input ratio as seen on the left hand side of the table.

Table 6.2: Inputs for BTES simulation. All setups are confined to a 30 m* 30 m area. Setups are named based on their spacing and input ratio, categorized as Low (L), Medium (M), or High (H). Values with * represents the input for the energy well system without energy storage, setup ref* is the optimization of a reference energy well system provided by EED

#	Spacing [m]	Depth [m]	Input[%]	Config.	Boreholes	Total length [m]
3-L	3	30	75	11 X 11	121	3 630
3-M	3	30	100	11 X 11	121	3 630
3-H	3	30	150	11 X 11	121	3 630
3.75-L	3.75	30	75	9 X 9	81	2 430
3.75-M	3.75	30	100	9 X 9	81	2 430
3.75-H	3.75	30	150	9 X 9	81	2 430
5-L	5	30	75	7 X 7	49	1 470
5-M	5	30	100	7 X 7	49	1 470
5-H	5	30	150	7 X 7	49	1 470
Ref*	10*	279.3*	0*	4 X 4 *	12*	3 351.6*

Alongside the input parameters, the number of boreholes and total borehole length is given. For simplicity, the simulations were constrained so that the maximum available area is 30 m · 30 m, which implies that the energy park cannot exceed this area limitation. In contrast to previous discussion in section 3.7.1, the form factor was set to be 1, which means that the depth of the boreholes are equal to the diameter of the confined area. This was done because the diameter

of the available area is relatively small, which means that a form factor of 2 would result in very shallow boreholes. Figure 3.4 shows that other BTES systems with a form factor of 1 achieves a recovery efficiency of 90%. Above this point the rate of improvement stagnates. Setup 10 is a reference energy well system provided by EEDs optimization tool. EED was given the energy demand, area limitation of 30*30 m, depth limitation of 300 m and minimum heat carrier fluid temperature at -3°C. The Figure 6.1 below illustrates the different configurations.

Borehole Layouts

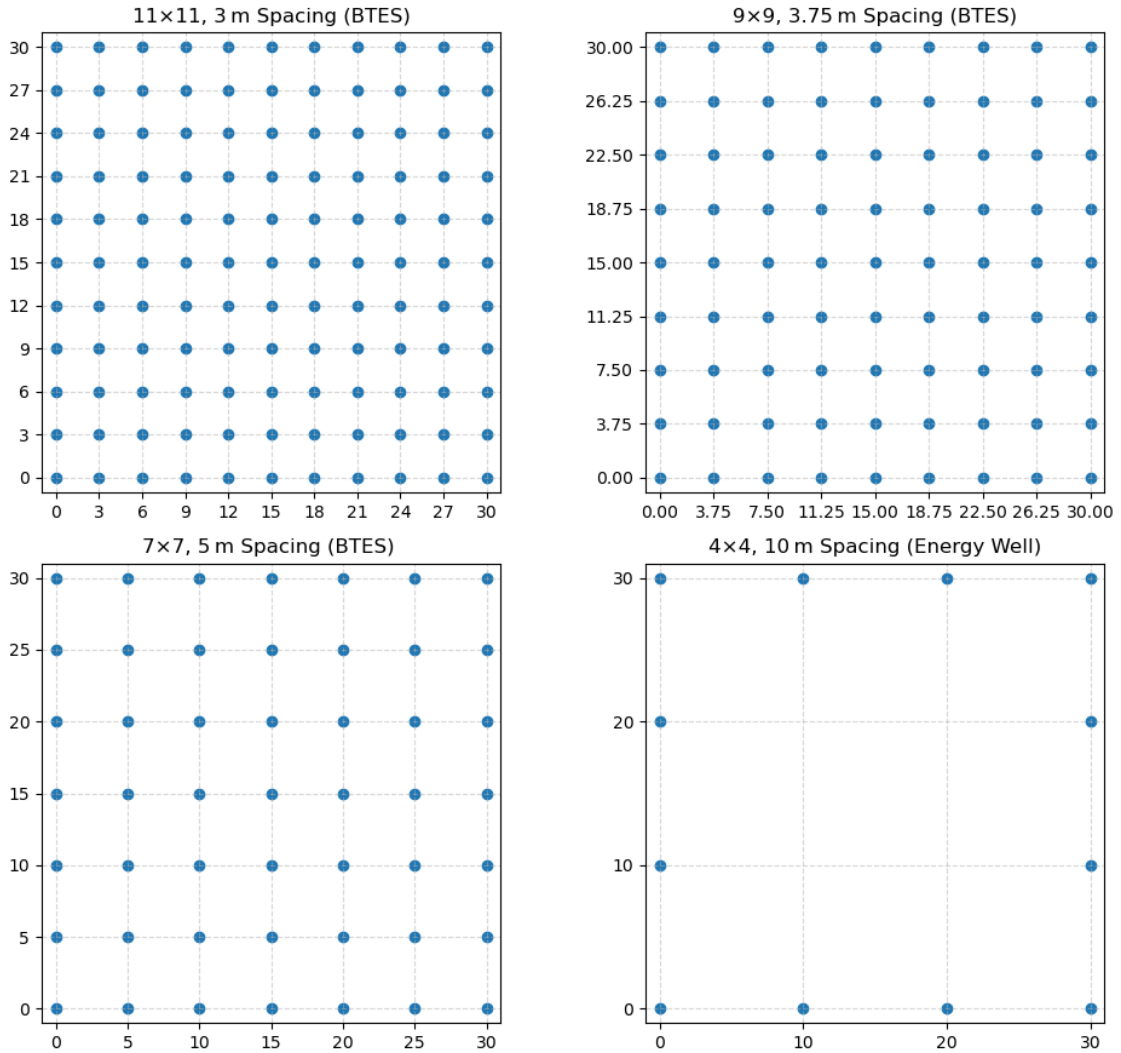


Figure 6.1: All the different configurations used, showing the placement and spacing for each setup. Note : The 4X4 in lower right is setup Ref, configuration open rectangle with 10 m spacing.

The necessary solar photovoltaic (PV) area required to meet the injection requirements is presented in table 6.3. To inject 75% of the space heating demand, 268 m^2 of PV panels are required. Injecting 100% and 150% of the demand would require 356 m^2 and 535 m^2 of

PV respectively. Note that the values presented in the tables account for a GSHP efficiency factor of 4, meaning that $\frac{3}{4}$ of the space heating demand is supplied by geothermal energy. This corresponds to 286 MWh, from which the necessary PV input for each setup is derived. The input assumes the use of a ASHP with a COP of 4.

Table 6.3: Required energy input for different input ratio and the corresponding PV area needed to supply the input, assuming the ASHP operates at a COP factor of 4

Input/Output [%]	Output [MWh]	Input [MWh]	PV area [m^2]
75	286	215	268
100	286	286	356
150	286	429	536

The required PV system size is calculated by assuming that 20% of the irradiation is converted to energy by the PV modules.

6.2 BTES model assumptions

In order to simulate and optimize the BTES system in EED, multiple assumptions were established. This provides the necessary simplifications to be able to extract usable results from EED.

Due to the shallow depth of the boreholes, it is assumed that the totality of the energy well is surrounded by solid rock and filled with ground water. If this was not the case the geothermal efficiency would be significantly decreased.

Additionally, the demand is limited to only account for space heating demand estimated by PROFet. This means that electric demand and domestic hot water demand is neglected. Furthermore, the space heating demand is 381 000 kWh annually, and is assumed unchanged and constant throughout the simulation period.

Moreover, the seasonal performance factors—HSPF for heating and SEER for cooling—were both set to 4. Although SEER is typically higher than HSPF in real-world applications, they were assumed to be equal in this case.

Another key limitation of the GSHP model is that as the COP increases, due to higher fluid temperatures, more energy must be extracted from the ground. This increased extraction would in reality lower the well temperature over time. Although this is a significant factor, it is neglected in the simulation for the sake of simplicity. Furthermore, the model does not account for the heat pump's size, assuming it can always meet any space heating demand or electrical input with a COP of 4, regardless of practical capacity constraints.

Further, it is assumed that the heat is extracted and injected evenly throughout the boreholes. This is default in EED, however, in real life applications this is often not the case. The operation of the BTES system at Fjell skole as previously discussed in section 3.6 serves as an example of this.

In EED it is not possible to define a circular configuration. The closest representation is therefore a rectangular shape. However, as previously explained in 3.5 a circular configuration is beneficial due to the uniform heat distribution and a better surface area-to-volume ratio. In practice this means that optimal configuration would be a cylinder where the diameter is equal to the width of the available area.

Depending on how the heat is distributed in the building the required fluid temperature changes. As mentioned in section 3.2.4 The efficiency of the GSHP is very sensitive to changes in the outlet temperature. A typical water borne floor heating system requires a temperature of 30-45 °C. In this simulation it is assumed that the required heat is 45°C.

6.3 Results for Multiple Boreholes

The following section presents the results given the inputs from the previous sections.

Table 6.4 shows the initial results of the model simulation, when changing spacing and energy ratio. All setups are confined within the the same area, which means that the number of boreholes is changed according to the spacing. The energy ratio percentage show how much energy is being injected into the well compared to the extraction (space heating demand). Min and max Tf are the minimum and maximum fluid temperature in the 25th year of operation. ΔT shows the temperature difference between Min Tf and Max Tf.

Table 6.4: BTES system initial results in a in 30 m · 30 m · 30 m configurations. The min and max temperature for the 25th year of operation. The setups with 150% input achieve positive minimum Tf in the last year of operation.

Multiple borehole initial results						
#	Spacing [m]	Number of wells	Energy ratio [%]	Min Tf [°C]	Max Tf [°C]	ΔT
3-L	3	121	75	-4.86	8.06	12.92
3-M	3	121	100	-1.04	14	15.04
3-H	3	121	150	6.61	26	19.39
3.75-L	3.75	81	75	-7.19	9.76	16.95
3.75-M	3.75	81	100	-3.05	16.7	19.75
3.75-H	3.75	81	150	5.25	30.5	25.25
5-L	5	49	75	-11.86	13.3	25.16
5-M	5	49	100	-7.21	21.8	29.01
5-H	5	49	150	1.88	39	37.12

Table 6.4 shows that the highest temperature is achieved in setup 9. Furthermore the results

clearly show sub optimal results when the energy balance into the well is negative. Comparing the setups with a 150% energy ratio, it becomes evident that less boreholes within the confined volume correlates with higher fluid temperatures. Conversely, the setups with less boreholes also have the lowest minimum temperatures. This suggests that systems with fewer boreholes per unit area, thereby greater spacing between boreholes, are more likely to experience localized heat and cold spots within the BTES. This is because the total heat injection and extraction is divided into fewer points.

To get an better overview of the performance of the presented setups, the average fluid temperatures in October-April across 25 years were simulated. The results are presented in figure 6.2.

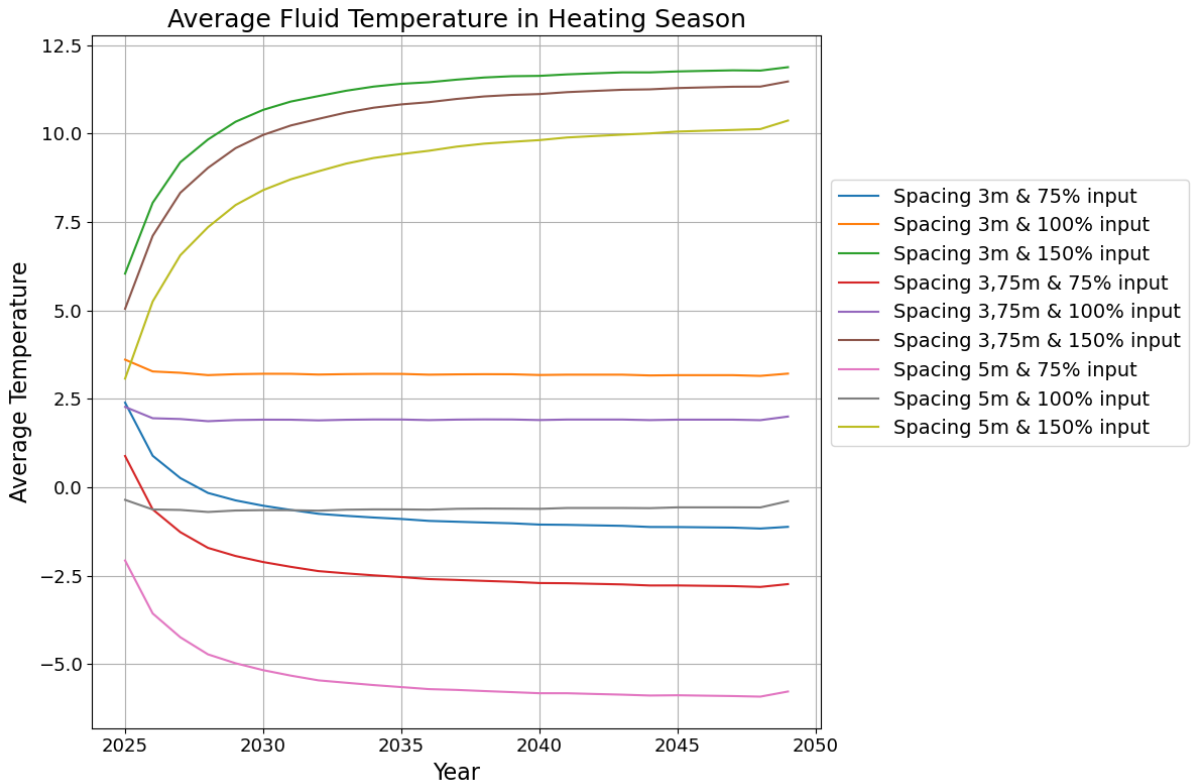


Figure 6.2: Yearly average fluid temperatures in October-April (heating season) across 25 years in operation. Setups with 75% input experience decreasing temperatures, 100% is stable, and 150% is increasing.

As the figure clearly shows and as previously stated in section 3.7.3 the temperature stabilizes after 10-15 years of operation for all setups. The highest average temperature is achieved with a spacing of 3 meters and an input of 150%, while the lowest average temperature is achieved with a spacing of 5 meters and an input of 75%.

In all setups with an input of 100%, the temperatures remain stable throughout the simulation

period. One possible explanation for this stability is that, although some heat is lost beyond the usable domain, these losses are compensated for by heat replenished from the geothermal heat flux.

To investigate the temperature profiles further, plots on the fluid temperature in the last year of operation was made and presented in figure 6.3. This plot shows how the temperature in the different setups is changing throughout the year.

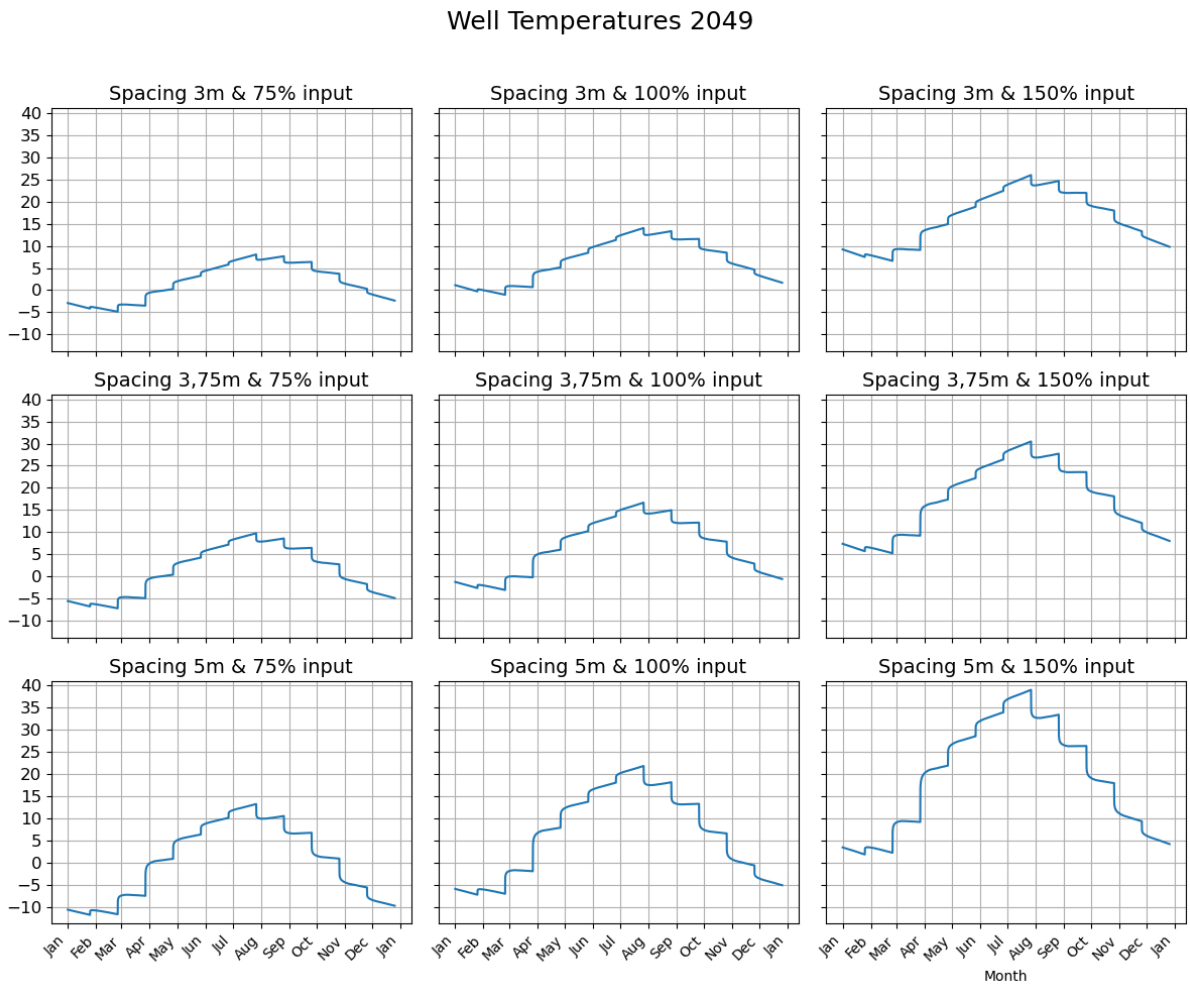


Figure 6.3: Fluid temperatures in the last year of operation for each setup. Low spacing corresponds to lower temperature difference throughout the year. Higher energy input values elevates the over all temperature.

Figure 6.3 illustrates the temperature profiles for each configuration during the 25th year of operation. Notably, the setups with a 3-meter spacing exhibits the most stable temperature over the course of the year. This stability is likely attributed to a higher density of boreholes per unit area, which facilitates a more uniform distribution of heat among the boreholes, resulting in a more consistent heating of the storage volume. Furthermore, the average temperature is lowest in the setups with the lowest input ratio. As the input ratio rises, both the average

temperature and the temperature difference increase, primarily because the input of thermal energy is concentrated during the summer months. To optimize energy storage and maximize the efficiency of the GSHP, it is essential to maintain the highest possible temperatures during the winter months. As illustrated in figures 6.2 and 6.3, the best setups for achieving this are 3-H and 3.75-H.

The following figure 6.4 is comparing the COP factors based on fluid temperatures for setup 3-H and 3.75-H with setup ref* without seasonal storage. The COP factors are based on the polynomial function as described in section 3.3 [52].

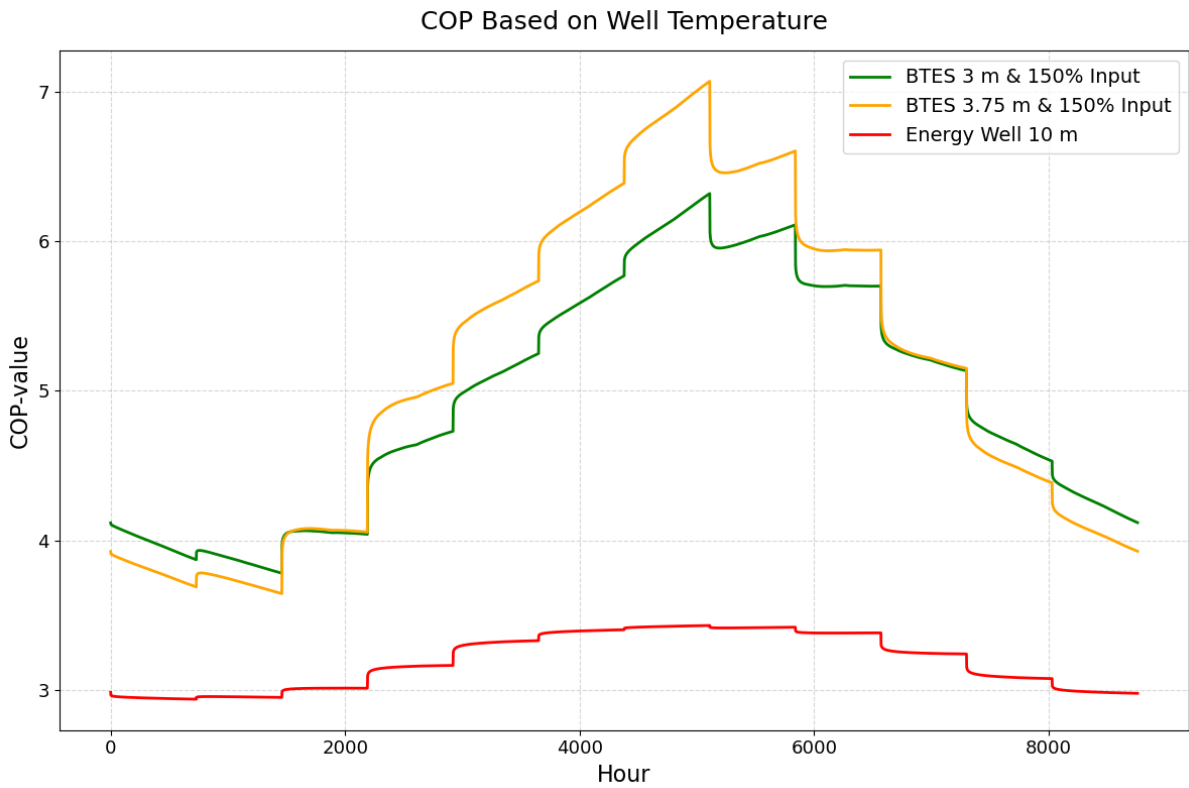


Figure 6.4: The COP factors, derived from the polynomial function described in 3.3, indicate that during the winter months, the 3-H setup exhibits an approximate increase in COP of 0.2 to 1 compared to setup 3.75-H and setup ref* respectively.

The figure shows that the highest COP is achieved for setup 3.75-H during summer time, however, setup 3-H shows better GSHP efficiency in the winter months. This figure serves as the basis to calculate the weekly and daily electricity consumption for each setup compared to conventional space heating and reference setup without energy storage. This comparison is shown in figure 6.5 and figure 6.6.

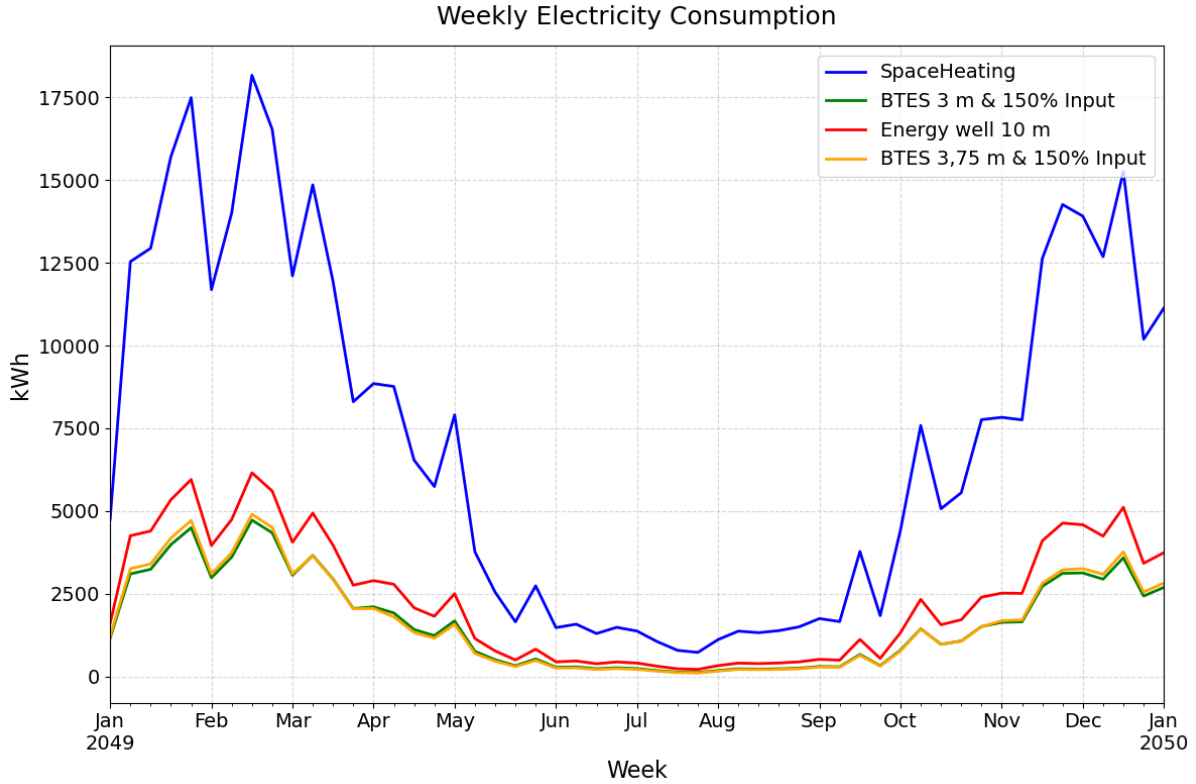


Figure 6.5: Aggregated weekly electricity consumption for setup 3-H (Green), 3.75-H(yellow), ref* (red) and electric heating (blue) as a result of their respective COP factor. The weekly fluctuating electricity demand is due to the temperature dependent behavior of the heating demand

The blue graphs shows the electricity consumption where the space heating demand is solely covered by electricity. The red graphs shows the electricity demand where the space heating demand is covered by thermal energy and a GSHP in setup ref*. The green and orange graphs shows the electricity consumption where the space heating demand is covered by a BTES system and a GSHP in setup 3-H and 3.75-H. The weekly plots shows a marginal difference between setup 3-H and 3.75-H, but it highlights the potential in reducing electricity consumption by storing excess energy as compared to setup ref*. Compared to conventional space heating, setup ref* consumes 67% less electricity. By storing excess energy in setup 3-H 76% electricity consumption can be cut compared to conventional heating. From an electricity consumption perspective setup 3-H and setup 3.75-H shows marginal differences.

To capture the daily differences and the peak power consumption, the highest consuming hour was plotted in figure 6.6.

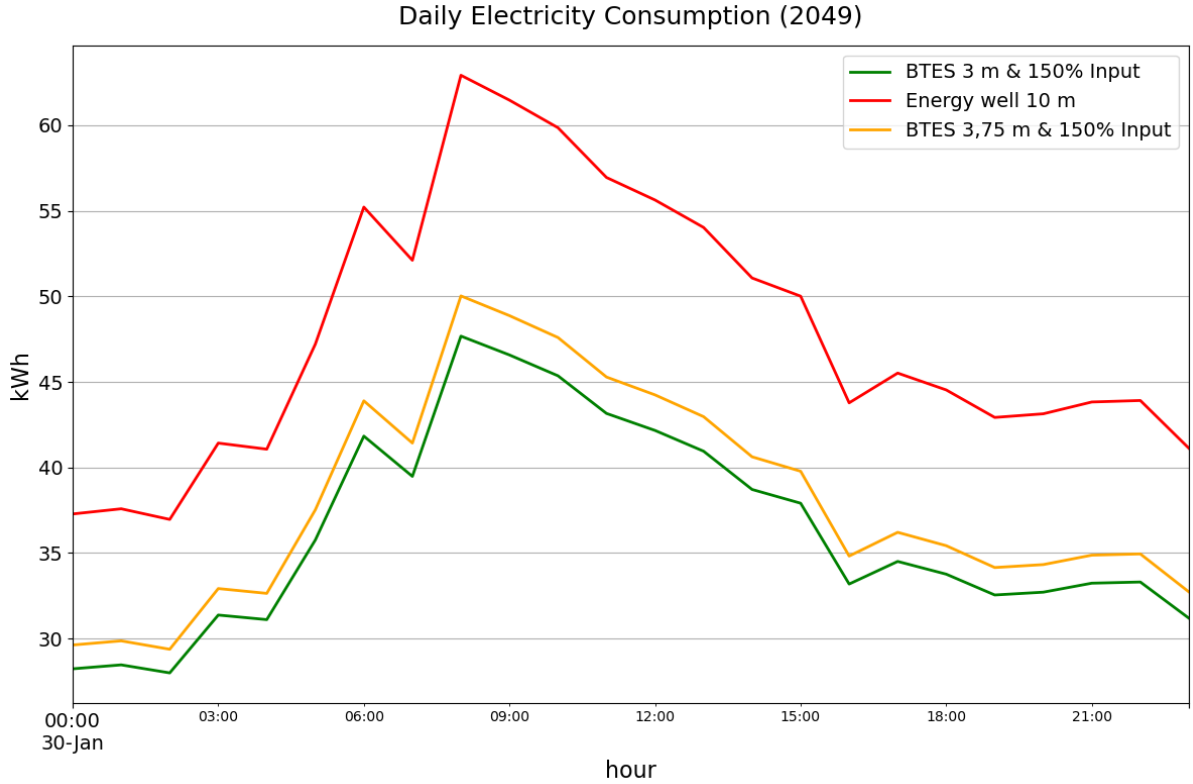


Figure 6.6: Electricity consumption for 30th of January. During the highest consuming hour (08:00) setup 3-H consumes 24.2% and 4.6% less electricity than ref* and 3.75-H respectively.

The highest consuming hour is at 08:00 the 30th of January. In this hour the peak heating demand is 184 kW. In setup ref* the peak demand could be cut by 66% to 62.9 kW. Setup 3.75-H shows a peak demand of 50.0 kW, which is a 20% reduction compared to setup ref*. Setup 3-H shows a peak demand of 47.7 kW, which is a 4.6% reduction compared to setup 3.75-H.

6.4 Discussion and Evaluation of BTES System

It is important to highlight that in order to determine the optimal dimensioning of a BTES system with greater accuracy, a comprehensive understanding of the thermophysical properties is essential. As discussed in Section 3, numerous factors influence the performance and efficiency of a BTES system, including borehole depth, spacing, geological properties, and the number of boreholes, among others not fully explored in this study. The design must be tailored to the specific site conditions and application requirements, taking into account a wide range of interdependent parameters. Hence why this thesis has isolated the spacing and input ratio to gain better understanding how they influence the costs and performance of BTES systems.

From the results it is evident that closer spaced boreholes exhibits more stable temperature throughout the year, with less difference between the minimum and maximum fluid temperature.

The total energy input and output is divided evenly between the boreholes. This means that systems with 5-meter spacing, comprising 49 boreholes, experience more than twice the energy input and output per borehole when compared to systems with 3-meter spacing, which include 121 boreholes. This disparity leads to a more homogeneous distribution of heat in closely spaced BTES systems. In contrast, systems with larger borehole spacing develops localized temperature variations. BTES systems with 5 meter spacing exhibits the highest fluid temperature in summer and the lowest in winter. Systems with closer spaced boreholes exhibits the highest average fluid temperatures in heating season.

Figure 6.2 illustrates that the BTES requires an energy input of at least 100% to achieve elevated temperatures, insufficient heat energy injection causes the BTES system to gradually cool down. Naturally the more energy that is injected the higher the fluid temperature gets. However, setups injected with 150% exhibits a bigger temperature difference between minimum and maximum fluid temperatures compared to setups with less energy injection, indicating bigger thermal losses.

It is important to note that results are based on a decrease in electrical consumption as a result of increased GSHP efficiency. As previously mentioned the amount of energy extracted from the BTES will increase in conjunction with the enhanced GSHP efficiency. Consequently leading to decreasing BTES fluid temperatures during operation. The model fails to capture the dynamic behavior of the GSHP COP factor, potentially resulting in a overly favorable assessment of the system.

Although Setups 3-H and 3.75-H demonstrate the best potential for seasonal energy storage, they are also associated with the highest investment costs. For developers, the biggest costs are related to borehole drilling and PV system capacity. Based on the cost estimations outlined in Section 3.8, the borehole drilling cost for Setup 3-H and 3.75-H is approximately 1.27 million NOK and 850 000 NOK respectively. Both setups require the installation of 535 m^2 of PV panels, representing an additional investment of approximately 1.7 million NOK. The total costs will be 2.98 million NOK for setup 3-H and 2.55 million NOK for setup 3.75-H. In comparison, setup ref* has the greatest total drilling depth, resulting in an estimated cost of around 1.56 million NOK. However this setup does not require any PV installation. Even though these costs estimations do not include, labor, engineering etc, they clearly shows that there are substantial cost differences between BTES systems.

A rough comparison of the cost saving potential between setup 3-H and a setup with conventional heating shows a payback time of 9.3 years. Comparing setup 3-H and setup ref* shows a

payback time of 43 years. However, comparing setup ref* with conventional electric heating shows a payback time of 5.5 years. These results are derived from multiplying the difference in electricity consumption in the winter months with the average winter electricity price. Keep in mind that the costs presented is rough estimates. In real life the pay back time would be considerably longer.

Since both the consumer and the DSO gains benefit from seasonal storage technology, an interesting question arises around who should be economically responsible for development of the technology. The relative costs of development may be too big for the consumer while the DSO is subject to strict requirements regarding cost and revenue frameworks. This issue creates a barrier to development, although the overall socioeconomic and environmental benefits may be substantial. One of the most relevant benefits today remains energy security. In times of increasing political tension and extreme weather events, seasonal energy storage could offer highly sought-after energy security. This raises the question of whether the development of seasonal storage technologies could be integrated into the societal preparedness budget, potentially reducing some of the costs for consumers or the DSO.

6.5 Conclusion on BTES System

Part 2 of the thesis simulates a multi-borehole BTES system with long-term storage. The system comprises of PV power generation, a GSHP, a ASHP and a BTES system. Changes in borehole spacing and energy input ratio was done to examine the effects on the BTES performance. The aim of the simulation was to explore the extent to which electricity consumption associated with heating can be reduced by storing PV energy. By doing so consumers can shift their consumption, potentially alleviating pressure on the power grid and reducing their individual heating costs.

The results indicates that to achieve a functional BTES system energy input should be above 100%. Additionally, BTES systems with closer spaced boreholes exhibits higher average fluid temperature in heating season. From all the tested setups it is evident that setup 3-H and 3.75-H exhibits the best seasonal storage potential. Setup 3-H reduces electric consumption by 76% compared to conventional space heating. The estimated investment costs of setup 3-H is 2.98 million NOK equivalent to a payback time of 9.3 years. However, the reference setup reduces electricity consumption by 67%, with 52% of the investment costs, resulting in a payback time of 5.5 years.

The analysis reveals reductions in electricity consumption when employing a BTES system.

However the difference in comparison to a traditional energy well system without seasonal storage is modest, particularly regarding economic viability. Without economic support or cost-sharing among different stakeholders the cost of implementing a BTES system is too high. Based on the analysis conducted in this thesis, we recommend a traditional energy well systems to reduce electricity demand for the system modeled in this thesis.

7 Thesis Conclusion

This thesis examines the mismatch between heating demand in households and the PV production in nordic conditions. The aim of the thesis to explore the potential of seasonal storage in BTES systems as a viable solution to the mismatch.

Through literature review, average values for existing Norwegian systems and geological conditions were identified. These values were used to simulate a single well BTES system to assess the seasonal storage potential through increased fluid temperatures.

For a single well system, the analysis indicates that it is challenging to raise the temperature to the necessary level for such a system to be economically viable. According to the results the temperature increase achieved by charging the system in summer will at best, yield a COP factor increase of 0.03, equivalent to 39 kWh reduction in electricity consumption during heating season. This ineffectiveness arises because the injected heat opposes the natural geothermal heat flux that normally provides energy to the borehole. Because of this, single wells are not a suitable option for energy storage.

Given the shortcomings observed in Part 1, an analysis of a multi-well BTES system was conducted. This analysis focused on how spacing and energy injection influence system performance. The results reveal that increased energy input raises the temperatures of the boreholes. However, it also leads to greater thermal losses to the surroundings. Additionally, spacing affects borehole performance, with closer spacing resulting in a more uniform temperature distribution. Furthermore, reduced spacing correlates with higher average winter temperatures. The findings indicate that systems with closer spacing and higher energy input yield the best storage potential.

Specifically, the setup with 3-meter spacing and 150% energy input reduces electricity consumption by 76%, while a reference well without thermal storage achieves a 67% reduction in electricity consumption, while exhibiting 50% lower investment costs. Based on this analysis, we conclude that, without further economic support or collaboration, the development of an

energy well system without thermal storage is recommended.

Ultimately, the conclusion is that seasonal storage will not be effective in a single borehole system. However, the results for a multi-well system are more promising and can improve the GSHP efficiency, but exhibits twice the costs than energy well systems without storage.

7.1 Recommendations on Future Work

To further develop the research presented in this thesis, future work is recommended.

Firstly, we recommend investigating the impact of a more dynamic control system, which would enable more efficient energy injection and extraction within the BTES systems. In EED equal amounts of energy is being injected and extracted from the boreholes, which is not a realistic approach. This research could lead to improved operational strategies, enhancing the overall performance and effectiveness of BTES systems in real-world applications. One example of a more dynamic control system is presented in section 3.7.3 regarding the BTES system at Fjell skole. We believe that this could have an effect on the storage efficiency.

In addition, we recommend looking into the effects of the change in COP factor. As previously discussed, a higher COP results in more energy being extracted from the BTES. Simulating this effect is crucial to properly determine the potential of BTES systems. We think that this will lower the overall performance of the system, while also capturing realistic behavior.

It would be beneficial for further research to create a model that can display temperature changes in the surrounding rock as well as in the heat carrier fluid. This type of model would help in understanding how different configurations and setups affect the efficiency of the system. By including temperature data from both the fluid and the surrounding ground, the model would offer important insights into how heat is transferred and how to design systems that perform better in geothermal storage applications.

Finally, it is recommended that future research explore the effects of reduced electricity consumption resulting from seasonal energy storage in BTES systems on the power grid, both from practical and economic perspectives. Future work could include an examination of existing rules and regulations that may limit the development of seasonal energy storage. Additionally, investigating the potential for valuing energy security and consumer flexibility, particularly through load shifting, could help to improve future development of seasonal energy storage systems. Future research should aim to address the question: To what degree will seasonal energy storage systems alleviate capacity issues on regional distribution lines?

8 Research question evaluation

The following section aims to evaluate the extent to which the research questions outlined in section 1.2 were addressed within the thesis. The evaluation is based on a personal assessment. Additionally the section aims to answer each research question concisely. The answers are based on results and discussion presented in the thesis.

Table 8.1: Table showing to what degree the research questions were answered through results and discussion in the thesis. The rating is given on a scale of 1-5, where 1 is low degree of satisfaction and 5 is high degree of satisfaction.

Research question	Score
RQ1	4
RQ2	5
RQ3	4
RQ4	3

Research question 1: “What are the potential synergy between solar photovoltaics power production and heating demand when utilizing seasonal energy storage?”, If successfully implemented, it can lead to significant benefits such as cost reduction, enhanced utilization of PV capacity, increased grid capacity, and improved energy security and self-sufficiency.

Research question 2: “To what extent can seasonal BTES systems be economically viable for single-family homes with a single energy well?” Results show that implementing a seasonal storage system for single well is not economically viable for single home or other applications.

Research question 3: “How do design parameters, such as borehole spacing and energy input ratio affect the energy storage performance of seasonal BTES systems?” Closer spaced boreholes result in higher average temperature in heating season. Higher input ratio results in higher fluid temperature and bigger heat losses.

Research question 4: “To what extent can thermal energy storage in multi-borehole systems help reduce electricity consumption in winter thereby alleviate pressure on the power grid?” The results show that by storing excess energy in BTES systems roughly 76% electricity consumption can be cut compared to conventional electric heating.

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