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Seasonal Thermal Energy Storage Using Sand Batteries

Feasibility and Economic Analysis in Northern Norway

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Abstract

The global shift from fossil fuels to renewable energy sources necessitates effective energy storage solutions to address the intermittent nature of renewable power. This thesis investigates the feasibility and economic viability of using sand batteries for seasonal thermal energy storage in Northern Norway. Sand batteries leverage the high heat capacity of sand to store excess thermal energy during summer for use in winter, potentially providing a sustainable solution to meet heating demands in cold climates.

The research employs a computational model developed in COMSOL Multiphysics to simulate the heat transfer processes within a sand battery system. Key parameters, such as energy storage capacity, efficiency, and economic implications, are evaluated using data from the Tibber app, which monitors household energy consumption.

The simulation results indicate that sand batteries can effectively store substantial amounts of energy and provide significant cost savings during the winter months by meeting heating needs. However, the analysis reveals challenges in achieving economic viability over the system's lifecycle under current conditions, primarily due to high initial costs, inefficiencies in the charging process, and variable electricity prices.

Sensitivity analyses suggest that optimizing the charging and discharging cycles can significantly enhance the system's economic viability. Charging during periods of low electricity prices and discharging during high-demand periods, along with improving charging efficiency, can lead to much higher annual savings and a favourable economic outcome over the long term.

These findings highlight the potential of sand batteries as a viable thermal energy storage solution, with further research needed to optimize system efficiency and economic performance. The integration of smart grid technologies and real-world pilot projects are recommended to validate the model's predictions and explore the scalability of sand battery systems in diverse geographical settings.

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1 Introduction

1.1 Background

The global shift from fossil fuels to renewable energy sources is essential in combating climate change and fostering a sustainable future. Renewable energy technologies, such as solar and wind power, have become increasingly popular due to their declining costs and scalability. (Afif et al., 2022; Apostoleris et al., 2019; Apostoleris et al., 2021; DNV, n.d; Eikeland et al., 2020) Hydropower which has long been the biggest energy source, has been augmented by advancements in solar and wind technology, which has caused a change in the energy mix.

Despite these advancements, a major challenge remains: the intermittency of renewable energy sources. Solar power generation is dependent on sunlight, and wind power is contingent on wind conditions. This variability can lead to difficulties in consistently meeting energy demands. Therefore, effective energy storage solutions are necessary to store excess energy produced during peak times for use during periods of low production.

Thermal energy storage (TES) systems offer a promising solution to this problem by storing energy in the form of heat, which can be retained for long periods and utilized when needed. TES can be cost-effective, simple, and environmentally friendly. Among TES technologies, thermal batteries are emerging as a potential solution for long-term energy storage. (Eikeland et al., 2023) One thermal battery solution is the sand battery which leverages sand's high heat capacity and thermal energy density to store heat at temperatures up to 1000°C (Polar Night Energy, n.d).

1.2 Research Gap

While various TES methods have been explored, there is a noticeable gap in the research on sand batteries, particularly in the context of seasonal energy storage in colder climates like Northern Norway. Most existing studies focus on water-based or phase-change materials for TES. The potential of sand as an effective and scalable storage medium remains underexplored, especially considering its cost-effectiveness and environmental benefits. This thesis aims to address this gap by evaluating the feasibility and economic viability of sand batteries for seasonal thermal energy storage in Northern Norway.

1.3 Research Questions

To guide this research, the following questions have been formulated:

1. How much energy can sand batteries store during the summer, and how effectively can they retain this energy for use during the winter?

2. What are the economic implications of implementing sand batteries in Northern Norway, considering the variability in electricity prices?

1.4 Structure of the Thesis

The thesis is organized as follows:

1. Introduction: Establishes the context, motivation, and research objectives of the study. This is the last section of the introduction.
2. Theory: Reviews existing literature on thermal energy storage technologies, with a focus on different methods and their applications, including an in-depth analysis of sand battery technology.
3. Method: Describes the computational modelling approach using COMSOL Multiphysics, including setup, parameters, and simulation procedures.
4. Analysis: Presents data on the economic aspects of electricity use in Northern Norway and evaluates the annual electricity consumption used for heating.
5. Results: Presents the findings from the model simulations and assesses the economic viability of the sand battery system.
6. Discussion: Analyses the implications of the results, discusses potential improvements, and proposes directions for future research.
7. Conclusion: Summarizes the key insights and offers recommendations for the practical application of sand battery systems in Northern Norway.

By exploring the potential of sand batteries for thermal energy storage, this thesis aims to contribute to the broader goal of developing sustainable and reliable energy systems. The findings are intended to inform both academic research and practical applications, promoting the adoption of innovative energy storage solutions that support the global shift to renewable energy.

2 Theory

2.1 Thermodynamics

Thermodynamics is a core area of physics that examines the transformations and transfers of energy, particularly as heat and work, in various systems. It lays the foundational principles necessary to understand energy dynamics within any system, including sensible thermal energy storage systems, which play a key role in modern energy management and conservation strategies. (Drake, 2024)

Heat and Energy Transfer

Heat is a form of energy transfer associated with temperature differences. Understanding how heat transfers through conduction, convection, and radiation is crucial for the design of thermal energy storage systems, where energy is stored and retrieved by changing the temperature of a medium. (Drake, 2024)

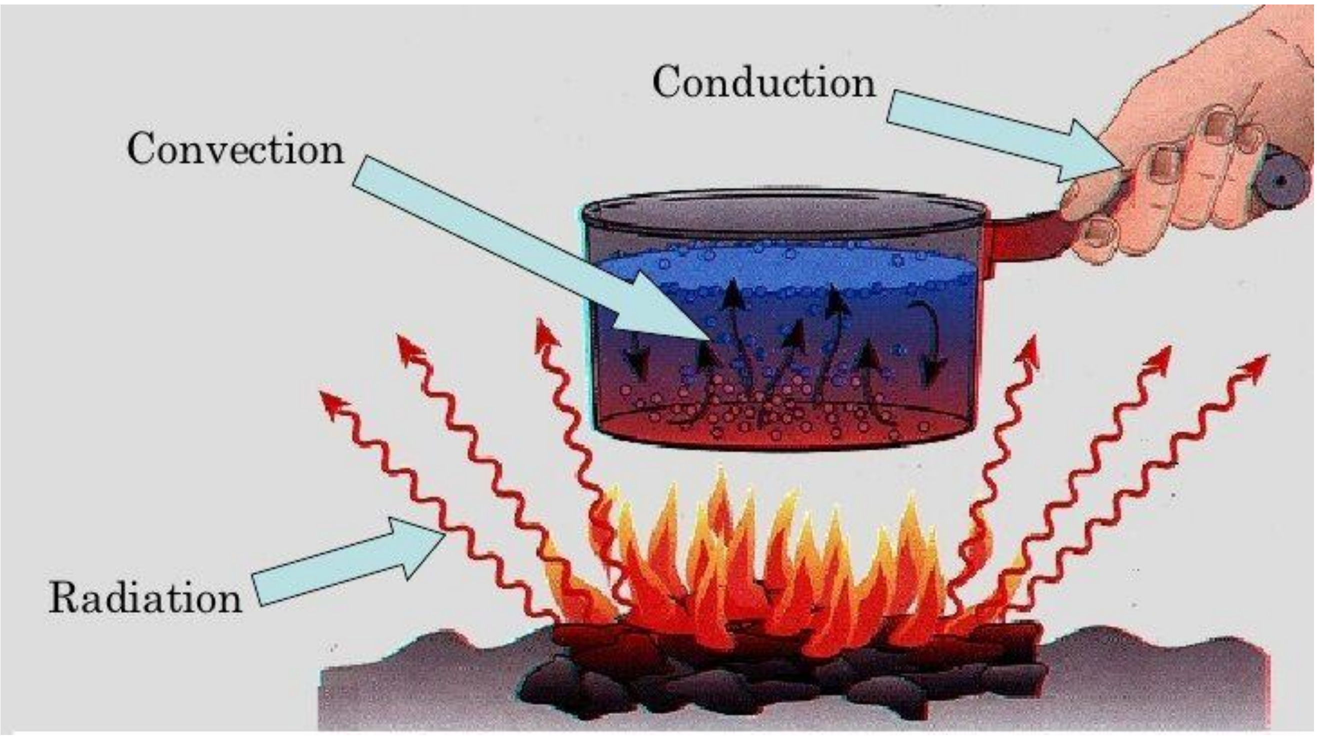


Figure 1 – The three types of heat transfer: Conduction, convection and radiation (Atico-Export, 2015)

The Laws of Thermodynamics

The Zeroth Law establishes the concept of thermal equilibrium and temperature, which is fundamental for the measurement and control of thermal energy in storage systems. (Stewart, 2022)

The First Law (Conservation of Energy) is essential for quantifying the energy stored in a thermal system, this law states that energy within a closed system is conserved. It translates to the principle that the change in internal energy of a system is equal to the heat added minus the work done by the system, expressed in the sensible TES formula $Q = m \times c_p \times \Delta T$ (Stewart, 2022)

The second law addresses the efficiency and entropy changes in thermal processes, indicating limits on energy conversions and emphasizing the importance of minimizing energy losses in storage systems. (Stewart, 2022)

The third law suggests the unattainability of absolute zero, setting theoretical limits on cooling processes within thermal energy storage applications. (Stewart, 2022)

Sensible TES systems utilize the heat capacity of materials (such as water, sand, or concrete) to store energy. The stored energy is proportional to the mass of the material, its specific heat capacity, and the change in temperature, which is directly based on the principles outlined in the first law of thermodynamics. (Koçak et al., 2020, p.138)

The materials chosen for such storage systems need to have high heat capacities to efficiently store thermal energy. The efficiency of these systems is significantly affected by the thermal properties of the storage medium, including thermal conductivity and density, which influence how heat is absorbed and released. (Koçak et al., 2020, p.143)

2.2 Sensible heat

Sensible thermal energy storage involves storing energy by changing the temperature of a storage medium such as water, air, oil, rock beds, bricks, concrete, or sand. The stored energy is directly proportional to the temperature increase, the mass of the storage medium, and its heat capacity. The selection of the storage medium is typically based on factors such as heat capacity and available space. The physics of sensible heat can be described by the formula:

$$Equation\ 1. \qquad Q = m \times c_p \times \Delta T$$

where Q is the heat stored in the material, m is the mass of the material, c_p is the specific heat capacity of the material and ΔT is the change in temperature. (Cabeza, 2022)

Common materials used in sensible TES systems include those with good thermal capacity and affordability. Properties like density, specific heat, operational temperatures, thermal conductivity, and compatibility among materials are crucial for effective TES. (Li, 2016) Sensible TES systems typically comprise a storage medium, a container (often a tank), and inlet-outlet devices. Tanks must retain the storage material and minimize thermal energy losses. A thermal gradient across the storage medium is advantageous.

Sensible TES can utilize solid or liquid media. Solid media are often used in packed beds, requiring a fluid for heat exchange. When a liquid fluid is employed, the heat capacity of the solid in the packed bed becomes significant, resulting in a dual storage system. (Cabeza, 2022)

For sensible TES systems, the most typical heat transfer fluids (HTFs) are air and water. Air is typically used with a packed bed system. Hot air is inserted into one end of the container/tank and passes through the medium and dumping the heat. The air will cool down through the process and exit at the other end of the container/tank. When heating is needed, the process will reverse, and cool air will draw heat from the medium and exit with a higher temperature. (Cabeza, 2022) Water serves as a versatile HTF in various storage systems, encompassing traditional water tanks used for heating and cooling as well as more recent applications in domestic solar systems. Effective water tank operation hinges on achieving thermal stratification, where layers of water with different temperatures naturally form within the tank. (Li, 2016) To optimize stratification, tall, thin tanks are preferred, with careful placement of inlet and outlet to promote uniform flow and minimize mixing. Solar ponds, another type of water storage system, leverage the natural stratification of saltwater, resulting in distinct layers due to differences in salinity. In such systems, solar energy absorbed by the water increases its temperature, causing thermal expansion and reduction in density, leading to stratification and trapping heat in the bottom layer for various applications like heating buildings or driving turbines for electricity generation. Water storage systems can be pressurized or unpressurized, with options for internal or external heat exchangers and single or multiple-tank configurations, offering flexibility to meet specific needs. While pressurized storage is favoured for smaller systems, unpressurized storage becomes more cost-effective for larger volumes, often integrated with pressurized systems for city water supply or domestic heating. Various configurations and heat exchanger arrangements are employed to enhance system performance and efficiency, catering to diverse applications and requirements. (Cabeza, 2022)

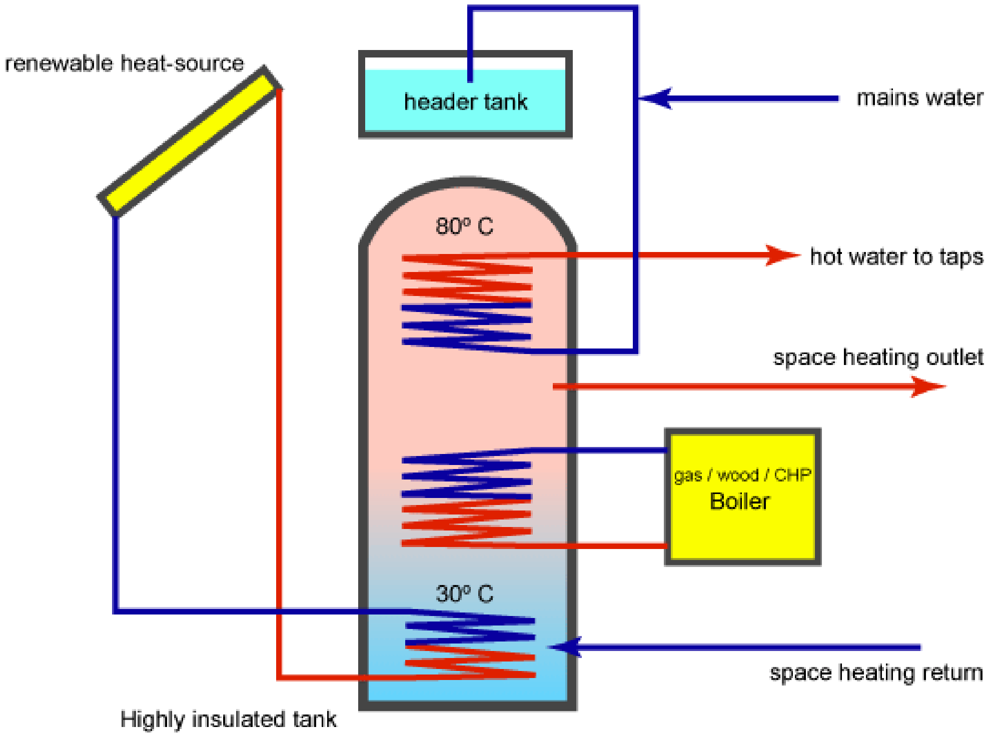


Figure 2 - Thermal energy stored in water tank (GreenSPEC, n.d)

2.2.1 Underground thermal energy storage

Underground thermal energy storage (UTES) is a strategic approach to managing energy in renewable systems or other industries, enabling the storage of heat or cold in natural underground formations to align energy availability with demand. This technology is pivotal in settings where significant, seasonal energy storage is needed. (Lim, 2013)

UTES is categorized into three main types: aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), and rock cavern thermal energy storage (CTES). Each system is tailored to fit specific geological and hydrogeological conditions. An aquifer, which is used in ATES systems, is a body of saturated rock through which water can easily move. ATES systems leverage the water and porous space in these aquifers to store or retrieve thermal energy by adjusting the flow and temperature of the groundwater. (Lim, 2013)

In Norway, the implementation of UTES showcases innovative adaptations to the nation's renewable energy initiatives. For instance, ATES is employed for both cooling and heating applications by exploiting the constant temperatures deep underground, which are largely unaffected by surface weather changes. During the summer months, this system extracts cool groundwater to help reduce building temperatures. Conversely, in the wintertime, the system is reversed to extract warmth from the water stored underground to heat the buildings. (Midttømme, Banks, Ramstad, Sæther, & Skarphagen, 2008)

Similarly, BTES uses the bedrock itself, rather than water-bearing aquifers, to store thermal energy. This involves installing borehole heat exchangers that enable the transfer of heat to or from the earth, depending on the season. This method is adaptable for both small-scale residential use and larger, seasonal energy storage needs, making it a flexible option for varying project scales. (Lim, 2013)

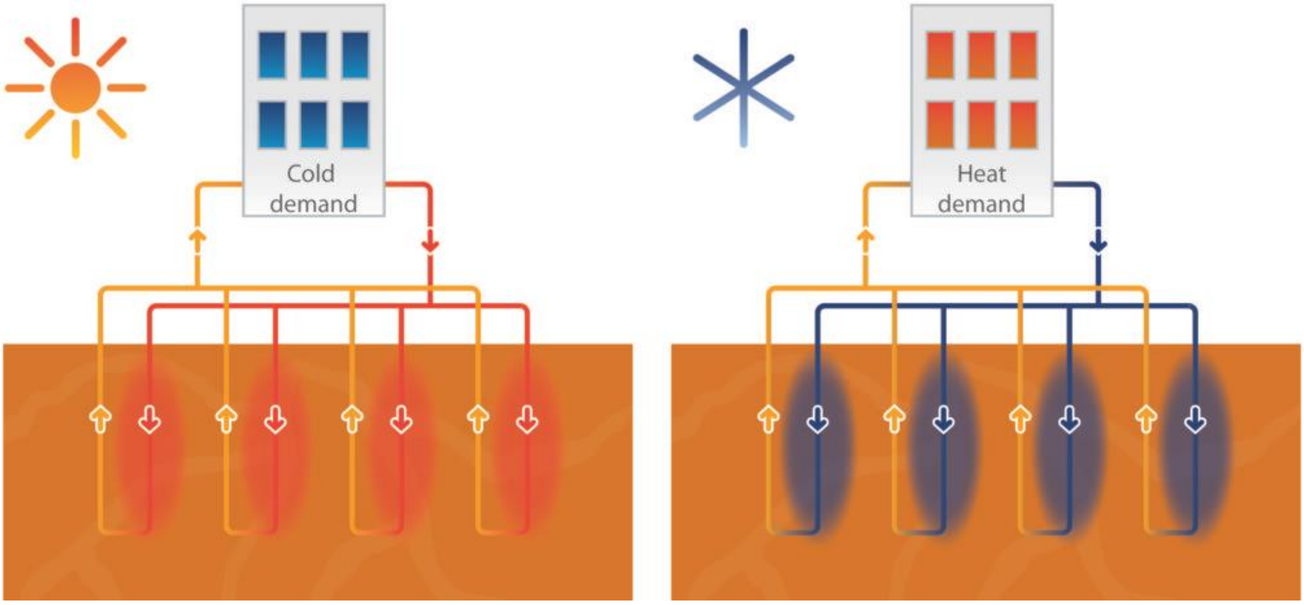


Figure 3 - Borehole TES system example. (IF Technology, n.d)

In Norway, technologies like ATES and BTES are critical for enhancing energy efficiency and supporting the shift away from fossil fuels. These underground energy storage methods not only help balance seasonal energy demands but also align with Norway's broader environmental and sustainability goals, promoting a more efficient use of renewable energy resources. (Midttømme, Banks, Ramstad, Sæther, & Skarphagen, 2008)

While sensible TES is great for storing heat by changing the temperature of materials like water, sand and bedrock, it has its limits. This method depends on how much the material can hold and how much it can heat up or cool down. To store more energy without needing more space, we look towards another method called latent thermal energy storage.

Latent TES works differently. Instead of just heating up or cooling down, it uses the heat from changes in the material’s state—like melting from solid to liquid or freezing back to solid. This change happens at a constant temperature, meaning the material doesn’t get hotter or colder even though it’s storing or releasing heat.

This method is especially useful where space is limited or where the temperature needs to stay the same. By shifting our focus from the common sensible storage to the unique properties of latent storage, we can explore new possibilities in how we manage and use stored energy.

Now, let’s take a closer look at how latent TES works, starting with what happens when materials change from one state to another, and why this is important for storing energy.

2.3 Latent heat

2.3.1 Phase changes and enthalpy

To understand latent TES, it is necessary to have a basic understanding of phase changes and enthalpy. Phase changes refer to the transformation of a substance from one state of matter to another, driven by changes in temperature or pressure. The most commonly observed phase changes include melting (solid to liquid), freezing (liquid to solid), vaporization (liquid to gas), condensation (gas to liquid), sublimation (solid to gas), and deposition (gas to solid). There is also ionization and recombination, which is the change from gas phase to plasma and vice versa. These transformations occur at specific temperatures and pressures unique to each material, known as the melting point, boiling point, and sublimation point. (Conecpt Group LLC, n.d)

Enthalpy is a fundamental concept in thermodynamics that represents the total energy of a system. It is defined as the sum of the internal energy of the system plus the product of the system's pressure and volume. Mathematically, enthalpy H is expressed as $H = E + PV$, where E stands for internal energy, P for pressure, and V for volume. Enthalpy is a state function, meaning its value depends only on the current state of the system—specifically its temperature, pressure, and composition—and not on how it reached that state. This property makes enthalpy particularly useful in scenarios involving heat transfer at constant pressure, such as phase changes. For example, the enthalpy of vaporization is the amount of energy required to convert a liquid into a gas at constant pressure, and this energy change is crucial for understanding processes like boiling. Similarly, the enthalpy of fusion describes the energy needed to melt a solid into a liquid. These values are typically measured in joules per mole, providing a quantifiable way of assessing the energy transformations during phase transitions. (Britannica, 2024) Processes where the change in enthalpy is positive (the reaction takes energy from the surroundings) are called endothermic processes while processes where the enthalpy change is negative (the reaction releases energy) are called exothermic processes. Figure 4 shows what type of reaction some of the phase changes are.

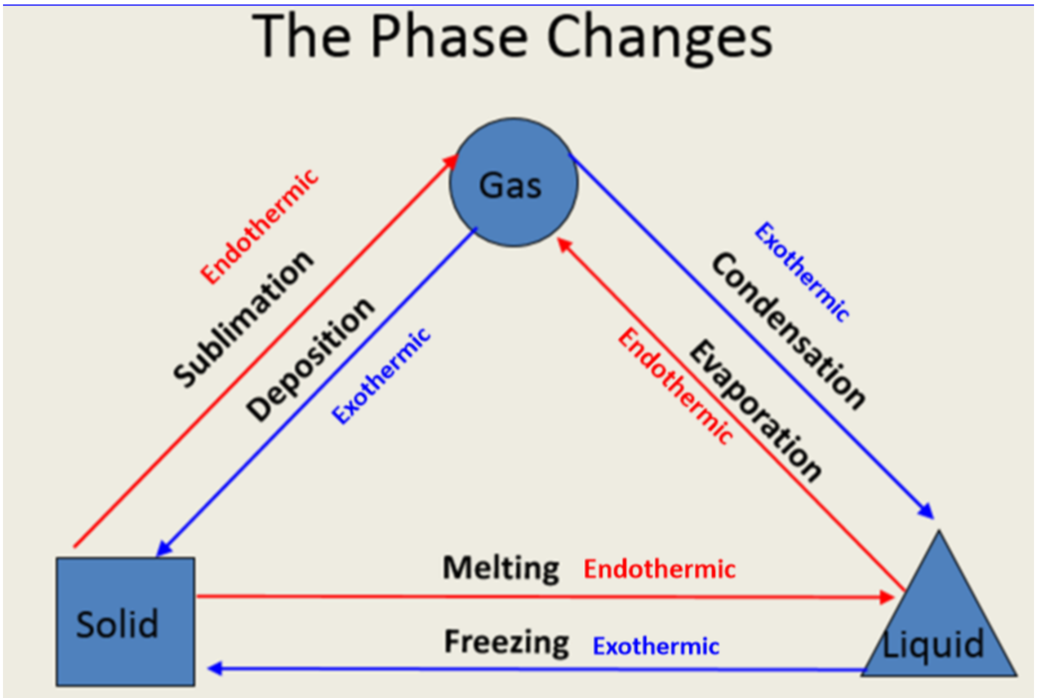


Figure 4 – Examples of phase change reactions. (Lovin, n.d)

2.3.2 Storage applications

Latent TES is a method where heat is absorbed or released during a material's phase transition, such as from solid to liquid during melting or vice versa. This approach can efficiently store substantial amounts of heat or cold, provided the appropriate material is selected. Unlike sensible TES, which correlates temperature changes directly with stored energy, latent TES maintains a constant temperature during the phase change process. We can describe the heat stored in the system as:

$$Equation\ 2. \qquad Q = m \times \Delta h$$

were Δh is the phase change enthalpy which describes the amount of energy needed to change the substance from one phase to another for example from solid to liquid. (Cabeza, 2022)

Water stands out as the most widely used phase change material (PCM), particularly for temperatures below 0°C. Alternately, paraffins, salt hydrates, fatty acids, and sugar alcohols find application in the temperature range between 0 and 130°C, while salts and inorganic materials become viable choices for temperatures exceeding 150°C. (Cabeza, 2022)

When evaluating the suitability of PCMs there are certain aspects of interest. These are split up into three groups, thermo-physical, kinetic and chemical properties. The thermo-physical properties consist of aspects such as melting temperature, a high heat of fusion per unit volume which tells us something about the necessary storage space, the capacity for sensible TES (high specific heat capacity), and a high thermal conductivity which is an indicator of how well the materials can charge and discharge energy. In addition, it is of value for the materials to have small volume changes while they change phases and that they melt congruently (they keep the same composition) to keep constant storage capacity. (Sharma & Sagara, 2005) For the kinetic properties, the two important ones are high nucleation rate and high rate of crystal growth. High nucleation rate is advantageous for ensuring that a material can quickly convert from a liquid to a solid. Regarding the high rate of crystal growth, it necessary to ensure quick response for extraction of energy as it improves the speed of the freezing phase change. The important chemical properties regarding PCMs include stability, the reversibility and degradation regarding phase change cycles, non-corrosive to the materials used in construction of the TES system, and for safety reasons it is important that the materials are non-toxic, non-flammable and no-explosive. (Sharma & Sagara, 2005)

Despite extensive research exploring various potential PCMs, only a handful have successfully transitioned into commercial viability, primarily due to factors such as availability and cost. Persistent challenges include issues like phase separation, subcooling, corrosion, long-term stability, and low heat conductivity, which continue to be subjects of ongoing research. (Cabeza, 2022)

Storage systems are broadly classified as either active or passive. Active systems involve forced convection heat transfer into the storage material and typically utilize one or two tanks. They are further categorized into direct and indirect systems based on the use of HTFs. In direct systems, the HTF also serves as the storage medium, whereas in indirect systems, a separate medium is employed for storing the heat. Passive systems, on the other hand, typically implement a dual-medium storage approach, where the HTF only interacts with the storage material during the charging and discharging processes. (Cabeza, 2022)

While latent thermal energy storage is great for keeping temperatures stable, it has its limits because it depends on the materials used and the temperatures at which they change state. To overcome these limitations and handle higher temperatures, we look towards another method called thermochemical energy storage (TCES). TCES is exciting because it can store more energy and work at much higher temperatures than latent or sensible energy storage. Instead of just relying on materials changing from solid to liquid or back, TCES uses chemical reactions to store and release heat. This method could change the way we store energy, making it possible to use it in more demanding situations like industrial settings.

2.4 Thermochemical storage

TCES holds significant promise, particularly for applications requiring high temperatures above 700°C. This innovative technology enables the storage of heat through chemical reactions, such as the breaking and reforming of chemical bonds. By harnessing these reactions, TCES allows for efficient storage and retrieval of thermal energy. At the heart of TCES lies the thermochemical storage reaction, where reactants undergo dissociation into separate products upon heating, and subsequently recombine to release stored energy when needed. This process offers distinct advantages over traditional thermal storage methods, including the potential for higher energy densities and compatibility with demanding high-temperature power cycles like supercritical carbon dioxide (sCO2) or air Brayton cycles. (Ho & Ambrosini, 2020)

However, realizing the full potential of TCES requires overcoming various technical challenges. These include ensuring materials possess suitable properties such as high reaction enthalpy, fast kinetics, thermal conductivity, cyclic stability, and cost-effectiveness. Additionally, issues like reversibility and material costs must be addressed to make TCES economically viable. (Ho & Ambrosini, 2020)

The processes of TCES can be separated into three stages. Charging, storing and discharging. For the charging process, we can describe it as endothermic reactions. This means that a reaction can be written as $C + heat = A + B$ where a substance C has heat added to it and reacts into two substances A and B. The heat in the reaction can for example come from renewable sources. For the storing process, the two substances A and B are stored separately at ambient temperatures to ensure almost no energy losses. The final process, the discharging process, requires an exothermic process. A and B are combined, and the resulting process releases the heat put in in the endothermic charging process and we end up with the original substance C. (Ali & Marc, 2011)

Implementing TCES involves a range of processes tailored to specific temperature ranges and operating conditions. While several TCES processes have been explored, none have yet been scaled up for industrial use. Nonetheless, there have been promising developments, with bench-scale and pilot-scale demonstrations showcasing the potential of TCES across various material systems. For example, ammonia based TCES systems have undergone extensive research, with notable demonstrations conducted at institutions like the Australian National University (ANU). Similarly, metal oxide TCES systems have attracted interest due to their high-temperature capabilities and energy density. Pilot-scale systems utilizing materials such as cobalt oxide have shown encouraging results. (Ho & Ambrosini, 2020)

Despite these advancements, ongoing research efforts continue to improve TCES technologies and address remaining challenges. By optimizing material properties, enhancing system efficiency, and reducing costs, TCES holds the promise of revolutionizing energy storage and utilization across a wide range of applications. (Ho & Ambrosini, 2020)

We have seen how sensible, latent, and thermochemical energy storage systems each harness unique methods to manage heat and energy. Sensible TES is straightforward and cost-effective, utilizing common materials to adjust temperatures based on the heat capacity. Latent TES, by contrast, captures energy during material phase changes, maintaining stable temperatures ideal for precise thermal management. Thermochemical TES offers advanced solutions, operating at higher efficiencies through chemical reactions that store and release heat, suitable for high-temperature applications.

Moving forward, we will go into a detailed comparison of these technologies, examining their advantages and drawbacks. This analysis will help us assess the practicality of each method across different scenarios, considering factors such as energy efficiency, cost implications, and operational requirements. By evaluating these aspects, we aim to provide insights into which TES technology might best align with specific energy needs, exploring their potential to innovate and enhance our energy storage capabilities.

2.5 Strengths and weaknesses

Sensible TES is characterized by its straightforward mechanism: storing thermal energy by increasing the temperature of a solid or liquid medium without a phase change. Commonly used materials include water, sand, and molten salts, which are noted for their high heat capacities and thermal conductivity. These systems are particularly advantageous because of their simplicity and cost-effectiveness. For instance, materials like water and sand are inexpensive and widely available, making sensible TES economically viable for large-scale applications, capable of storing up to several gigawatt-hours of energy. (Ho & Ambrosini, 2020)

One of the primary strengths of sensible TES is its scalability and relatively low capital cost, typically ranging from $0.1 to $10 per MJ. This makes it an attractive option for grid-scale energy storage, essential for balancing variable renewable energy sources. (Ho & Ambrosini, 2020) Furthermore, if the storage medium is a solid, it can withstand high temperatures without phase change risks such as freezing, which is particularly advantageous in colder climates where other materials might fail.

However, the main limitation of sensible TES lies in its thermal efficiency. The energy density of sensible materials is lower compared to phase change or chemical-based systems. This means that, although cost-effective, they require significantly larger storage volumes to hold the same amount of energy, which can be a spatial challenge. Additionally, maintaining the stored heat requires extensive insulation to minimize energy loss to the environment, especially when storing heat at very high or low temperatures. This necessity can drive up initial investment costs and complicate system design. (Ho & Ambrosini, 2020)

Latent TES utilizes phase change materials (PCMs) like paraffin or salt hydrates, which absorb and release heat at constant temperatures. This property makes latent TES particularly valuable in applications requiring precise temperature control, such as in building heating and cooling systems. Latent TES can offer higher energy densities per unit volume compared to sensible TES, enabling more compact storage solutions. (Eseslab, n.d)

The major advantage of using PCMs is their ability to store large amounts of heat with minimal temperature fluctuation during the phase change process. This results in a stable discharge of energy, which is crucial for maintaining the desired environmental conditions without the need for frequent cycling of heating or cooling equipment.

Despite these benefits, latent TES systems have notable drawbacks. Issues such as supercooling, phase separation, and inherently low thermal conductivity can significantly affect the practical deployment and operational reliability of these systems. These materials often require encapsulation to handle cycling stability and integration within larger systems, which increases the complexity and cost. Moreover, the higher cost of PCMs compared to traditional sensible storage materials can be a barrier to widespread adoption. (Yan et al, 2021)

Thermochemical Energy Storage (TCES) represents the most advanced form of TES, offering the highest energy density and the capability to store thermal energy indefinitely without significant losses. TCES systems utilize reversible chemical reactions to store and release heat, which can be particularly advantageous in industrial applications where high temperatures are required.

The primary strength of TCES lies in its efficiency and energy density. These systems can operate at very high temperatures, often exceeding 1000°C, making them suitable for high-temperature industrial processes and power generation applications using advanced thermodynamic cycles like the supercritical CO2 or air Brayton cycles. (Ho & Ambrosini, 2020)

However, the implementation of TCES technology faces significant challenges. The complexity of the chemical processes involved, the need for special materials that can withstand harsh conditions, and the high initial costs associated with setting up such systems are major hurdles. The technology is still largely in the development phase, with many aspects requiring further research and testing to enhance reliability, reduce costs, and facilitate integration into existing energy systems. (Yan et al, 2021)

After examining the strengths and weaknesses of sensible, latent, and thermochemical energy storage methods, it's clear that each technology offers unique benefits for particular situations. Yet the search for even more effective, economical, and adaptable energy storage solutions continues to be a critical focus within renewable energy management. This ongoing search introduces us to an innovative approach in thermal energy storage: sand battery technology. Spearheaded by Polar Night Energy, this emerging technology utilizes sand as a storage medium to retain heat at high temperatures, offering a promising new direction for energy storage. The sand battery not only complements existing TES systems with its potential for scalability and environmental sustainability but also aligns with the need for durable and efficient energy solutions. In the following discussion, we will explore the operational mechanisms, key components, and pioneering features of the sand battery, assessing its capacity to meet our evolving energy requirements effectively.

2.6 Existing sand battery technology

We have discussed the basics behind the three different types of TES. Now we will go deeper into how a storage system may be designed to operate in the real world. Polar night energy is a company that is trying to make TES available for the industry. The storage system uses sand as a medium and is heated up to 600-1000℃. The battery is said to have a nominal power of 100MW and a total capacity of 20GWh. (Polar Night Energy, n.d) To see how the battery functions we can take a look at the patent of the sand battery. We can split the patent into three main subjects. The components, the operational mechanism and, innovative features and advantages.

The following sub sections are based on the patent (Finland Patentnr. FI20195181A, 2019) by Markku Ylönen and Tommi Eronen and showcases their technological solutions.

2.6.1 System components

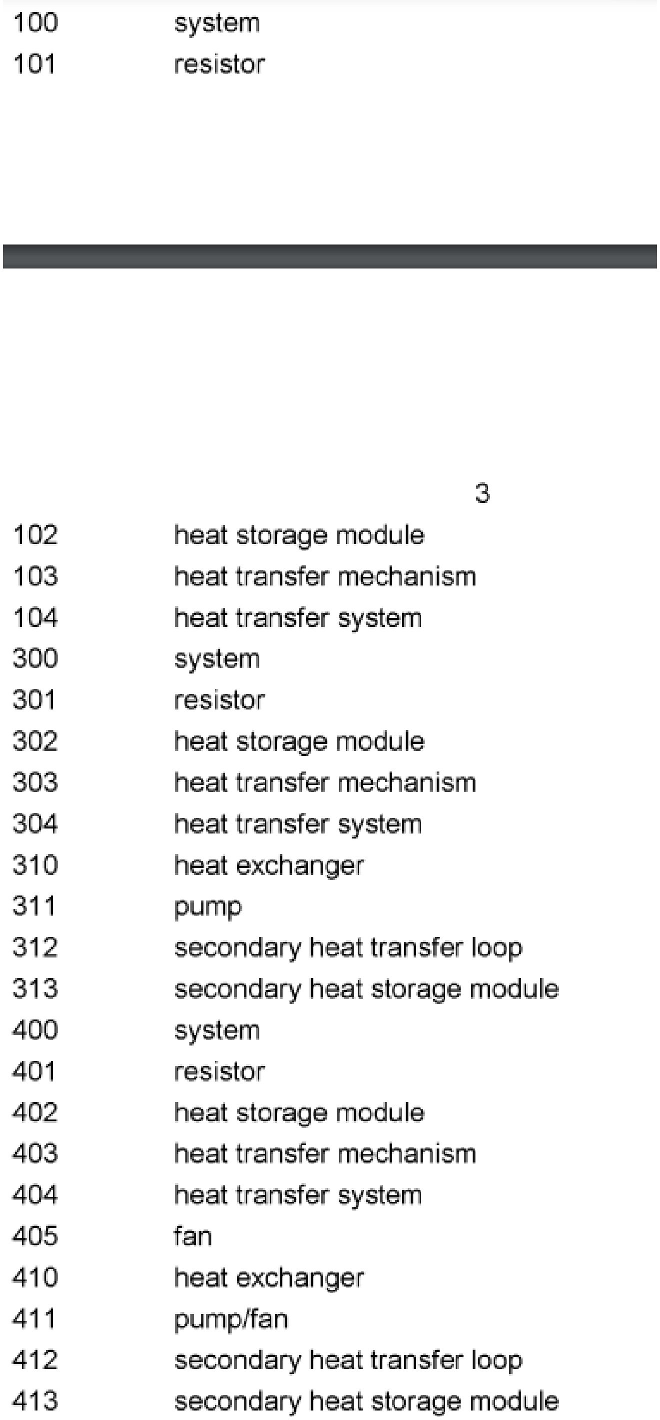
The sand battery system comprises three main components. These are the resistor, the heat storage module, and the heat transfer mechanism. The initial component in the system is the resistor, which converts electrical energy into heat. (Ylönen & Eronen, 2019) This process is crucial for the efficiency of the sand battery. The resistor generates heat as electrical current passes through it, based on the principle of electrical resistance, following Joule's Law, which states that the heat produced is proportional to the power consumed. (Britannica, 2022)

The central part of the sand battery is its heat storage module, which is made up of solid materials that can store large amounts of heat energy. Common materials used in this module are sand, gravel, and bedrock. These materials are selected for their high thermal capacity and stability at temperatures up to 1200°C (Ylönen & Eronen, 2019). They are also non-flammable and chemically inert, which reduces the risk of fire and chemical degradation. The heat storage module is designed to collect and retain heat during times of surplus electricity generation, such as during peak solar production (Ylönen & Eronen, 2019).

To utilize the stored energy, the system employs a heat transfer mechanism to move the heat from the storage module to where it is needed. This mechanism can either be a closed gas loop or a thermosiphon system (Ylönen & Eronen, 2019). For the close gas loop, a heat-transfer gas, typically an inert gas like nitrogen, is circulated through pipes embedded within the heat storage module. The gas absorbs heat from the storage medium and transports it to a heat exchanger, where it can be used directly or converted into another form of energy (Ylönen & Eronen, 2019) The thermosiphon system uses natural convection to circulate a fluid without mechanical pumps. It is particularly effective in passive energy systems, where minimal moving parts are preferred. The thermosiphon pipes are strategically placed to maximize heat absorption and transfer efficiency (Ylönen & Eronen, 2019).

The integration of these components allows the sand battery to function seamlessly. Electrical energy, potentially from renewable sources such as solar panels or wind turbines, is converted into heat and stored in the heat storage module. When energy is needed, the heat transfer mechanism activates to deliver this energy in a controlled manner, meeting the demands of households, industrial processes, or energy grids (Ylönen & Eronen, 2019).

Table 1 - List of all sand battery system components that are used in the patent by Ylönen & Eronen. (Ylönen & Eronen, 2019)



100	system
101	resistor
102	heat storage module
103	heat transfer mechanism
104	heat transfer system
300	system
301	resistor
302	heat storage module
303	heat transfer mechanism
304	heat transfer system
310	heat exchanger
311	pump
312	secondary heat transfer loop
313	secondary heat storage module
400	system
401	resistor
402	heat storage module
403	heat transfer mechanism
404	heat transfer system
405	fan
410	heat exchanger
411	pump/fan
412	secondary heat transfer loop
413	secondary heat storage module

2.6.2 Operational mechanism

The operational mechanism of the sand battery system involves several key processes: generating heat energy from electrical energy, storing this heat efficiently, and transferring the stored heat for use. Each step is crucial for the overall efficiency and effectiveness of the sand battery as an innovative energy storage solution (Ylönen & Eronen, 2019).

2.6.2.1 Heat Production

The process begins with the production of heat energy from electrical energy, primarily facilitated by the resistor. This component converts electrical energy into heat through resistive heating. When electric current passes through the resistor, it encounters resistance, converting electrical energy into thermal energy. This process is governed by Joule's Law, which states that the heat produced is proportional to the square of the current multiplied by the resistance and the duration of current flow (Ylönen & Eronen, 2019). This step is particularly important during periods of excess renewable energy generation, such as peak solar insolation or high wind speeds.

2.6.2.2 Energy Storage

Once the heat is generated, it is transferred to the heat storage module, where it is stored in materials like sand, gravel, or bedrock. These materials are selected for their high heat capacity and durability at elevated temperatures. The storage module is designed to minimize heat loss, ensuring that the stored energy remains available for extended periods, making it particularly useful for seasonal energy storage. The heat can be transferred to the storage medium either directly through conduction if the resistor is embedded within it, or via a heat transfer fluid (HTF) or gas that transports the heat from the resistor to the storage module (Ylönen & Eronen, 2019).

2.6.2.3 Heat Transfer

The final step is transferring the stored heat from the sand battery to its point of use. This is achieved through one of two mechanisms. The first is a closed gas loop. In this setup, an inert gas circulates through the system, absorbing heat from the heat storage module. The heated gas then passes through a heat exchanger, where the thermal energy is transferred to a secondary medium, such as water or air, that carries the heat to its end use, such as residential heating or industrial processes (Ylönen & Eronen, 2019). The second mechanism is a thermosiphon system. Utilizing the principles of natural convection, this passive system circulates a fluid without the need for mechanical pumps. The fluid in the thermosiphon pipes heats up, becomes lighter, and rises, transferring heat as it moves through the system. As it cools, it descends, creating a natural circulation loop that effectively transfers heat from the storage module (Ylönen & Eronen, 2019).

Both heat transfer mechanisms are designed to operate efficiently under varying thermal loads and can be integrated into different types of heating systems, depending on application requirements. The choice of mechanism can be influenced by factors such as desired energy output, system efficiency, cost considerations, and installation environment (Ylönen & Eronen, 2019).

Examples of how the mechanisms of the sand battery can be chained together to form a system is visualized in Figures 5, 6 and 7.

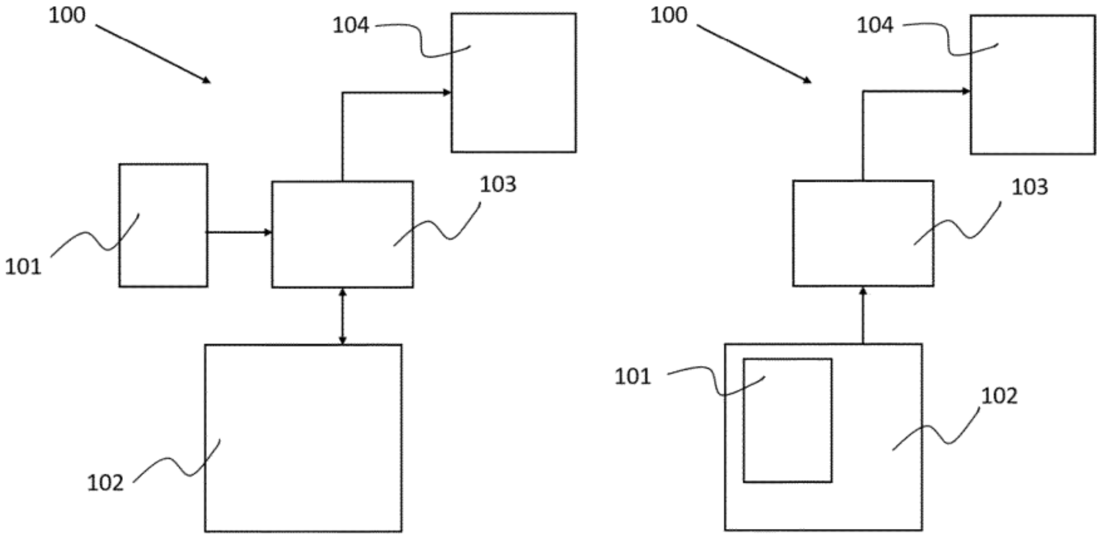


Fig. 1a

Fig. 1b

Figure 5 - Proposed system setup of mechanisms of the sand battery patent using the components detailed in Table 1. (Ylönen & Eronen, 2019)

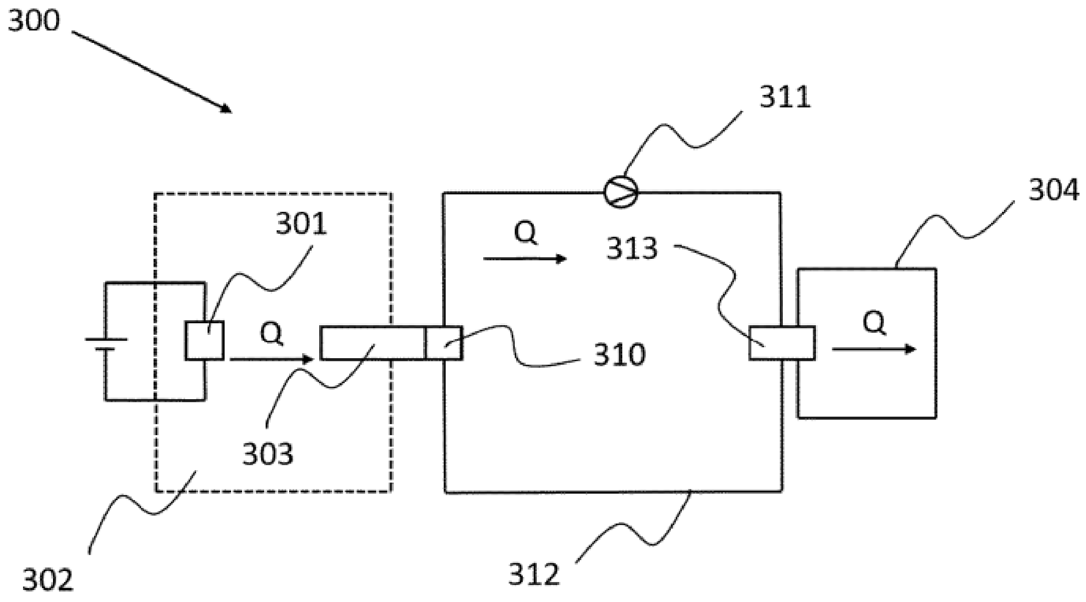


Fig. 3

Figure 6 – Example from the patent of a sand battery system process 300. (Ylönen & Eronen, 2019)

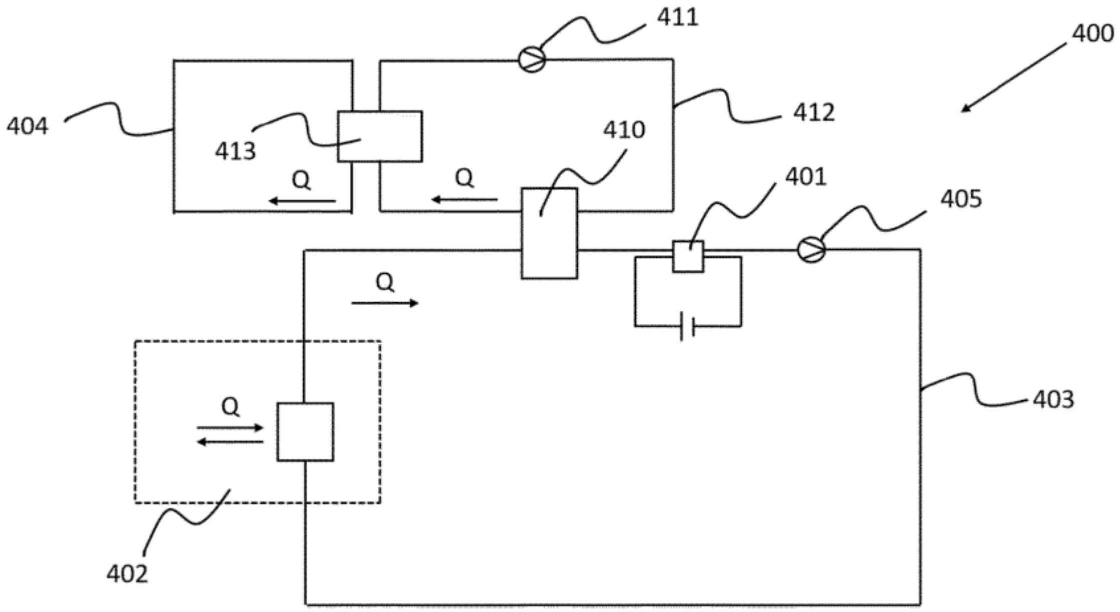


Fig. 4

Figure 7 – Example from the patent of a sand battery system process 400. (Ylönen & Eronen, 2019)

2.6.3 Innovative features and advantages

The sand battery system introduces several innovative features that distinguish it from conventional energy storage technologies. These innovations not only improve the system's operational efficiency but also offer substantial environmental, safety, and economic benefits (Ylönen & Eronen, 2019).

2.6.3.1 Enhanced High-Temperature Storage

A key innovation of the sand battery is its capability to store thermal energy at extremely high temperatures, reaching up to 1200°C. This high-temperature storage is enabled by the use of robust materials such as sand, gravel, and bedrock within the heat storage module. These materials are specifically selected for their thermal resilience and stability, allowing them to store significant amounts of heat without structural degradation. Operating at high temperatures increases the energy density and efficiency of the system, opening up new applications in industries requiring high-temperature processes (Ylönen & Eronen, 2019).

2.6.3.2 Safety and Environmental Sustainability

The materials used in the sand battery are inert and non-flammable, contributing to the system's safety and environmental sustainability. These properties significantly reduce the risk of chemical reactions and fires during operation. Additionally, the environmental impact of the sand battery is minimal, as the primary materials are abundant and can often be sourced locally, reducing the environmental costs associated with mining and transportation. Using non-toxic materials also means the system does not emit harmful pollutants or produce hazardous waste, aligning with global efforts to reduce environmental footprints (Ylönen & Eronen, 2019).

2.6.3.3 Cost Efficiency

The sand battery offers a cost-effective solution compared to other energy storage technologies. Utilizing inexpensive and widely available materials like sand reduces the initial investment and maintenance costs associated with the system. The simplicity of the design and the durability of the materials used ensure low operational costs and an extended operational lifespan, thereby decreasing the lifetime cost per unit of stored energy (Ylönen & Eronen, 2019).

2.6.3.4 Scalability and Versatility

The modular nature of the sand battery allows for significant scalability and adaptability. The system can be tailored to meet diverse energy storage requirements, from small-scale residential setups to large-scale industrial applications. This scalability is achieved by adjusting the size and number of heat storage modules used, offering versatility in application and integration into various energy systems (Ylönen & Eronen, 2019).

2.6.3.5 Optimized Energy Utilization

The sand battery effectively addresses the challenge of intermittency commonly associated with renewable energy sources like solar and wind. By storing excess energy produced during peak periods and releasing it on demand, the sand battery enhances the integration and utilization of renewable energy. The system's design ensures high thermal efficiency, minimizing energy losses during storage and retrieval, thus maximizing the availability and utility of the stored energy (Ylönen & Eronen, 2019).

This strategy underscores the importance of advanced storage solutions like the sand battery, which can take advantage of economic fluctuations. By efficiently storing energy when there's plenty and prices are low, and releasing it during high-demand periods, energy storage technologies can help stabilize and reduce energy costs for consumers. As we explore the details of sand battery technology, we must consider not just its technical benefits but also how it can help make energy more affordable, especially given the unpredictable nature of electricity prices. This connection between innovative energy solutions and market dynamics is crucial for modern energy management, linking new technologies with economic strategies.

As we move from discussing the strengths and weaknesses of different thermal energy storage (TES) systems and having taken a deeper dive into sand battery technologies, it's important to see how these technologies fit into the larger picture of energy market trends. The costs involved in producing and storing energy using methods like sensible, latent, and thermochemical storage affect their practical use and how well they can be integrated into our energy systems. Notably, during periods when electricity prices are low, such as in warmer months, these technologies can provide significant cost benefits. This highlights the strategic value of storing excess energy when it's cheaper and using it when prices are high during peak demand in colder seasons.

2.7 Price of electricity

Today there is a large emphasis on the continuous changing electricity prices in Norway. It has gotten even more attention over the last couple of years due to recent developments in the rest of the world such as war and a global pandemic. The prices have always had a seasonal difference. This difference is due to multiple variables. One of these variables is the fact that during the winter there is a larger demand for electricity due to heating. A colder season such as winter, late autumn and early spring will result in colder houses and to keep the buildings at a comfortable temperature, more heat is needed. In older times, the heating was primarily produced by firewood ovens, but in recent years it has become more and more common to install electric heating in floors or heat pumps with water or air. These developments means that the homes and buildings of today are more reliant on electricity, and the demand grows rapidly at colder temperatures. It is estimate in Norway that heating is the largest part of the total electricity consumption of homes with a total of up to 70-80% of the total electricity consumption. (Norgesenergi, 2022) Other factors such as irregularity of wind production, less sun during the day, and lower filling rate of water magazines can lead to lower electricity production which paired with a higher demand will cause the prices of electricity to rise and fluctuate.

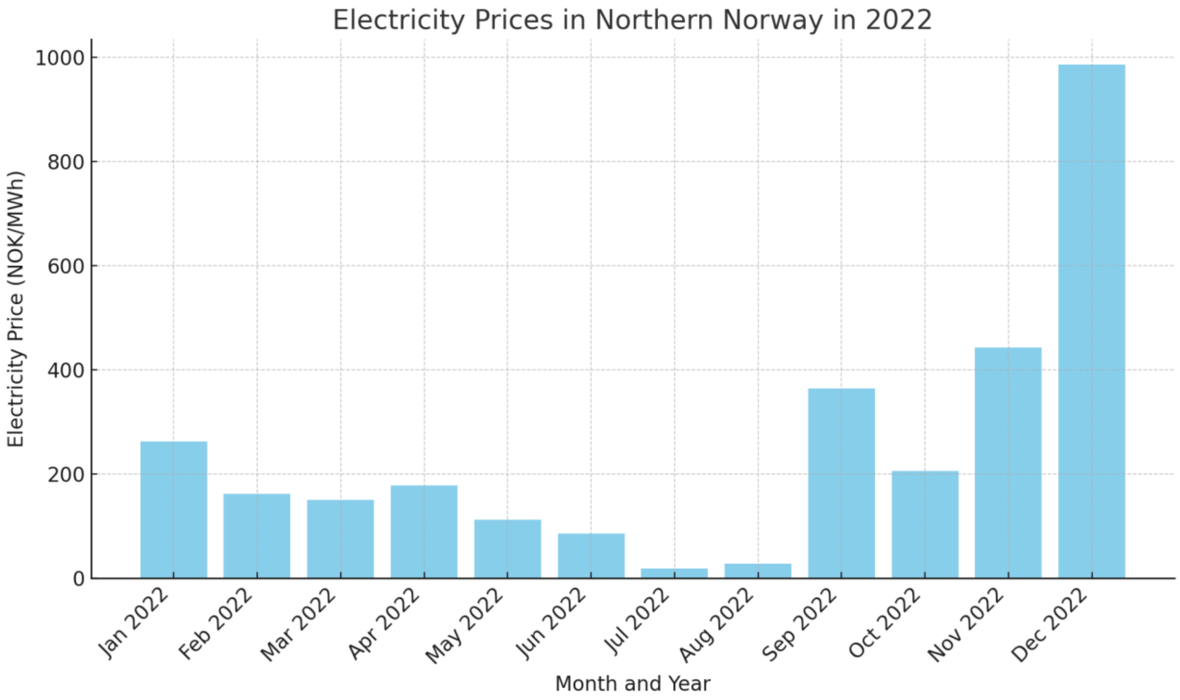


Figure 8 - The monthly average price of electricity in NOK/kWh for northern Norway in 2022. Data from (Nordpool, 2024)

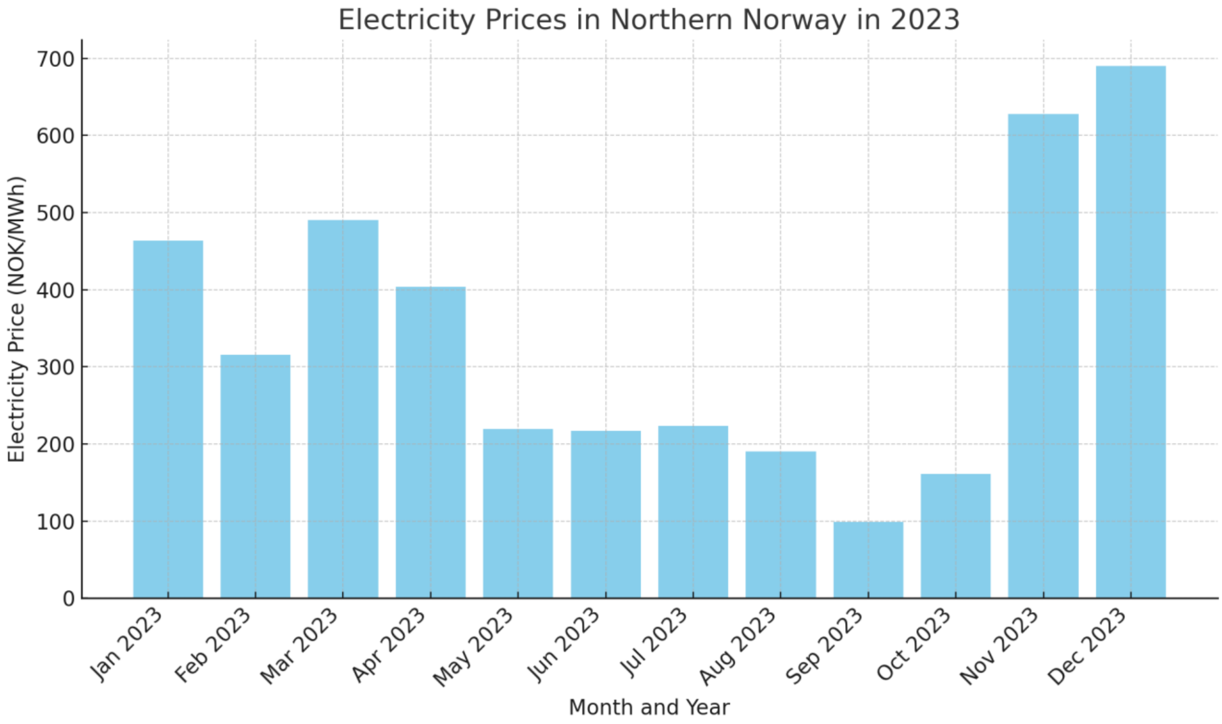


Figure 9 - The monthly average price of electricity in NOK/kWh for northern Norway in 2023 (Nordpool, 2024)

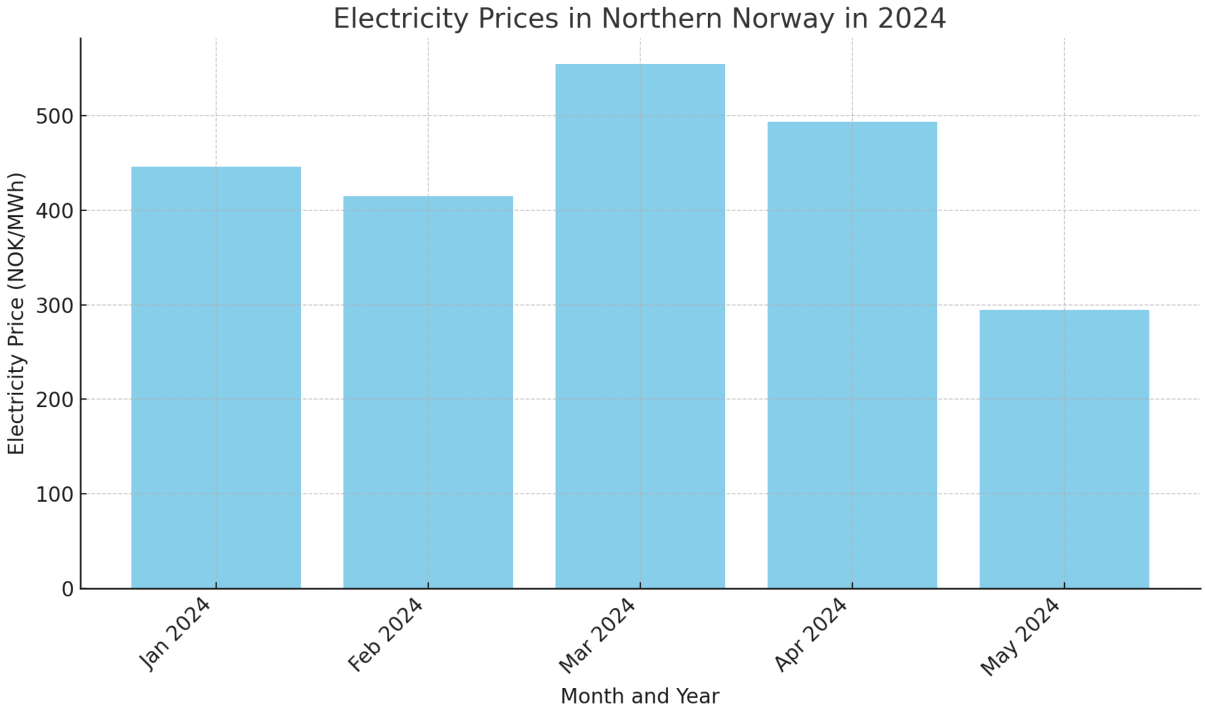


Figure 10 - The monthly average price of electricity in NOK/kWh for northern Norway as of May 2024 (Nordpool, 2024)

Figures 8, 9, and 10 represents the varying electricity prices of Northern Norway in the period January 2022 to April 2024. We can see that there is a drop in prices during the warmer summer months for the period which is expected. If we decide to focus on the three summer months of June, Juli and August, we can compare the average price with that of the remaining months to see what type of difference there is. For 2022 the three summer months has an average price of 44,31 NOK/MWh while the remaining months yield an average price of 318,22 NOK/MWh. This means that the summer months in 2022 had an average price of electricity that was more than 7 times less than the remaining year. In 2023 the averages were 210,083 NOK/MWh for the summer months and 385,51 NOK/MWh for the remaining months, which meant a 1,83 reduction in price during the summer months. Unfortunately, at the time of writing this thesis, the electricity prices of 2024 are incomplete. However, if we evaluate the trajectory of the prices for January, February, March and April we can see that the prices are similar to the ones of the corresponding months of 2023, and we can make an assumption that the rest of the year will look similar to the rest of 2023.

2.8 Research and applications in Norway

In Norway, the ground is used not just as a source of heat but also as a place to store excess heat, which can be particularly useful for balancing heating and cooling demands throughout the year. This is increasingly important as larger buildings in colder Nordic climates need systems that can both cool and heat. During summer, heat pumps move chilled water around buildings to pull heat out, which is then stored underground or in groundwater. In winter, this process is reversed—the stored heat is drawn from the ground to warm up the buildings.

The idea of using the earth for thermal storage goes back a long time. For example, in the late 1800s and early 1900s, Norwegian entrepreneurs exported ice to London, where it was kept underground in ice wells to be used later. This practice shows how natural resources have been used historically and continue to inspire modern storage solutions. (Midttømme, Banks, Ramstad, Sæther, & Skarphagen, 2008)

Today, Norway has developed several innovative underground thermal energy storage systems. Borehole Thermal Energy Storage (BTES) is a system that stores heat directly in the rock underground without exchanging any fluid with the ground. An example is the system at Falstadsenteret, a historical museum in Levanger, which includes a heat pump and nine deep boreholes. The system's efficiency is proven by its payback period of 12 years when compared to traditional heating and cooling systems. (Midttømme, Banks, Ramstad, Sæther, & Skarphagen, 2008)

Aquifer Thermal Energy Storage (ATES) is a system that uses groundwater to store heat. A significant example is at Oslo’s Gardermoen airport, operational since 1998. It uses a large heat pump and several wells to manage the airport's heating and cooling needs efficiently. (Midttømme, Banks, Ramstad, Sæther, & Skarphagen, 2008)

These examples highlight Norway's commitment to sustainable energy solutions. Research, like the studies by Kauko et al. (2022), continues to explore how district heating and waste heat from industrial processes can be stored and used seasonally. These studies mainly focus on well-known technologies like water-based or salt-based storage systems and show progress in thermal energy storage.

However, there is a noticeable lack of research on alternative materials like sand, which could be cheaper, more scalable, and less harmful to the environment. This gap emphasizes the need for further exploration of less common materials and technologies. This thesis expands on this by looking into using sand as a storage medium in Northern Norway's harsh climate. We are exploring whether sand can store enough energy during Norway's short summers to provide heat throughout the long winters. This research not only adds to academic knowledge but could also influence local energy strategies, offering a sustainable and cost-effective solution for energy storage challenges.

3 Method

3.1 Energy consumption approximation

When making calculations regarding the energy consumption, energy used for heating, and cost surrounding these aspects, it is necessary to gather the data required for making the calculations. The most common way to collect such data is via energy monitors. For this thesis a households energy consumption was observed via a monitor and an app called Tibber.

3.1.1 Tibber

Tibber is an electricity company that aims to help people get a better overview of their electricity usage and help optimize their consumption. The company have an app that is the centre of their service. When using the app, you can get an overview of how much electricity the household has used daily, monthly and yearly. They also offer an option that shows the consumption of electricity in real time, meaning that it is possible to see how much electricity is used at any time during the day. In addition, the current price of electricity is shown for the same day and the next which gives a forecast of what to expect and a warning on how to manage the consumption of electricity such as when to charge a car or take a shower. (Tibber, 2024)

In addition to the services regarding manual overview of electricity consumption and prices, Tibber offer some automated services. One is that of smart charging. In todays society, it is more and more common for households to own an electrical vehicle, especially cars. Such vehicles have the option of charging at home to ensure a full battery. However, this means that the household must account for the electricity. The electric cars of today can have batteries with a capacity of between 40 and 100kWh. (Eonenergy, 2024) With varying electricity prices, to fully charge the car batteries might vary buy ten folds. Because of this, Tibber offer the service to automate the charging of the car to when the prices are low or to not overload the capacity. (Tibber, 2024) This means that if the price forecast shows that the price is 0,9NOK/kWh between 16.00 and 24.00, while only 0,3NOK/kWh between 01.00 and 06.00, the car would be charged between 01.00 and 06.00 with the lower cost.

As mentioned, for this thesis it is also necessary to gather data regarding how much electricity is used for heating. The electricity company has implemented algorithms to analyse the electricity consumption to make calculations of how much electricity is used for different areas of consumption in the household. These areas are divided into heating, behaviour (things that are used daily such as lights and cooking appliances), and things that are always on such as fridges, freezers and wifi. With this, it is possible to get an overview of how much electricity is used for heating every month and year.

Because of these services, the Tibber app is a great tool to help get an overview the energy consumption of a household and get the required data needed for making calculations regarding energy storage and how much it is possible to save by using a sand battery.

3.2 COMSOL Multiphysics

The basis of this thesis is as stated to explore the potential use of thermal energy storage in Northern Norway by storing energy in the summer months and using it throughout the rest of the year. To make calculations and evaluate scenarios for necessary and potential capacity for the sand battery, a simulation model was necessary. The model was created in COMSOL Multiphysics.

COMSOL Multiphysics is a sophisticated simulation software environment designed to handle a wide range of applications across multiple scientific and engineering fields. It excels in providing a structured yet user-friendly interface that serves to both seasoned researchers and newcomers. What sets COMSOL apart is its comprehensive approach to multi physics simulations, a crucial feature for research involving thermal energy storage systems.

At its core, COMSOL Multiphysics is a simulation platform that mirrors real-world events as accurately as possible. It can combine multiple scientific models—such as acoustics, electromagnetics, chemical reactions, mechanics, fluid flow, and heat transfer—into a single environment. This integration is essential because real-world scenarios often involve interactions between different physical processes. By allowing these interactions to be modelled simultaneously, COMSOL provides a more realistic representation of how these events occur and influence each other in real time. (COMSOL Multiphysics, n.d)

COMSOL empowers users to go beyond traditional simulation limitations through its flexible environment. Users can freely combine any number of physical effects to mimic the complex interplay observed in their specific applications. This capability is particularly beneficial for thermal energy storage research, where heat transfer must often be analysed in conjunction with structural changes, fluid dynamics, or chemical transformations.

The software includes all steps of the modelling workflow—from defining geometries and setting material properties to specifying physics and running simulations. Users can adjust and control every aspect of their model, which opens up possibilities for innovative solutions and detailed exploration of thermal energy storage systems. (COMSOL Multiphysics, n.d)

3.2.1 COMSOL for thermal energy storage

For thermal energy storage, the ability to accurately model heat transfer alongside other physical phenomena (like phase changes or material deformation) is crucial. COMSOL's Multiphysics approach allows for detailed simulations that reflect the distinctive performance of energy storage systems under different conditions.

Researchers can input user-defined physics and expressions, which is essential when dealing with unique materials or storage conditions that are typical in thermal energy storage systems. This flexibility ensures that models can be finely tuned to reflect the specific parameters of a research project. (COMSOL Multiphysics, n.d)

COMSOL also provides advanced visualization tools that help researchers analyse the temperature distribution and effectiveness of heat storage and retrieval. This feature is great for optimizing the design and operation of energy storage units to improve their efficiency and reliability. (COMSOL Multiphysics, n.d)

Once a model is developed, it can be converted into a custom application using COMSOL's Application Builder. This feature is particularly useful for researchers who wish to make their simulations accessible to other stakeholders, such as industrial partners or educational collaborators, who may not be experts in simulation software. (COMSOL Multiphysics, n.d)

In conclusion, COMSOL Multiphysics is not just a simulation tool but a comprehensive environment that supports the complex needs of thermal energy storage research. Its ability to model realistic scenarios with high accuracy and flexibility makes it a valuable tool for researchers aiming to push the boundaries of what's possible in energy storage technology.

Now we will take a look at how the simulation model is built and explain the physics used for the simulation. Also we will explain why the different materials were used.

3.3 Sand battery model.

3.3.1 Objective of model

The objective of this model is to evaluate the energy storage capacity and efficiency of a sand battery during summer and its ability to retain that energy over a seasonal storage period. The model will simulate the heat transfer processes between the sand and the surrounding air, providing a detailed analysis of how much thermal energy can realistically be stored and maintained. This study aims to offer insights into the feasibility of using sand batteries for long-term energy storage and to identify potential improvements for optimizing their performance in real-world applications.

3.3.2 Geometry and domain

The simulation I created is a three-dimensional model featuring a box with dimensions of 4x4x4 meters filled with sand. This box is surrounded by a 1-meter layer of concrete, which serves as insulation to minimize heat loss to the environment. The concrete insulation is crucial for enhancing the thermal efficiency of the system. The box is partially embedded in the ground, with only the upper part exposed to air. Heat is introduced into the sand through nine steel rods, which are heated and subsequently distribute the heat throughout the sand. Figure 11 illustrates the geometry and construction of the model, although the concrete insulation is not visible in the figure.

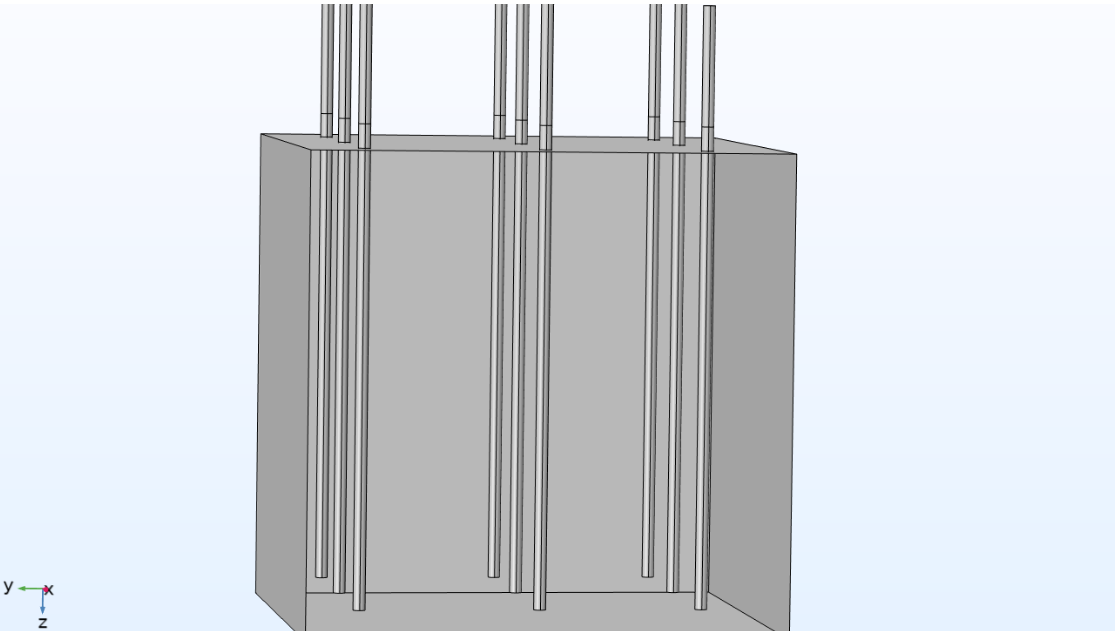


Figure 11 - Geometry and build of the sand battery model. Empty space in the box is filled with sand.

3.3.3 Physics and equations

The main equations that are used for the model is regarding heat flux and convection. As the only the top is exposed to air, it is the only side with free ambient convection. The calculations of loss by free ambient convection are done with:

$$\text{Equation 3:} \qquad Q_{loss} = H \times A \times \Delta T$$

Where Q_{loss} is the power in W lost due to convection, H is the heat transfer coefficient which says something about how easy the model transfers heat, A is the area of the surface exposed, and ΔT is the temperature change between the surface of the box and the air.

3.3.4 Material properties

As mentioned above, the materials used in the model are sand, concrete, steel, and wool. Sand is chosen as the storage medium due to its relatively high heat capacity, which allows it to store a significant amount of energy in the form of heat. The specific heat capacity of the sand is 850 J/(kg·K), and it has a density of 1620 kg/m³.

Concrete is used for insulation, despite its relatively high thermal conductivity compared to other insulating materials. The specific heat capacity of concrete is 880 J/(kg·K), and its thermal conductivity, while not ideal for insulation, makes it a widely available and practical choice.

Steel is utilized as the heat transfer material due to its good thermal conductivity of 44.5 W/(m·K) and its strong structural properties, although it is not as thermally conductive as materials like aluminium. Steel provides a balance of thermal performance and mechanical strength.

Additionally, there is a layer of wool surrounding the steel rods in the sections above the sand to further reduce heat loss to the environment. Wool acts as an effective insulator in these areas, complementing the concrete insulation and enhancing the overall thermal efficiency of the system.

3.3.5 Boundary and initial conditions

One of the outer walls of the concrete insulation is subject to free convection with the ambient air. This means that the heat transfer through these walls is modelled by considering the convective heat transfer coefficient, which depends on the ambient air conditions and the surface properties of the concrete. In the model the coefficient has been set at $3{,}7\frac{W}{kg*K}$. The remaining walls are subject to fixed temperature convection with the ground, where the energy loss comes from the temperature gradient moving from the core towards the outer walls.

The inner walls of the concrete, which are in direct contact with the heated sand, are assumed to be at a quasi-steady state with the sand’s temperature. This assumption simplifies the model by ensuring that heat primarily moves from the steel rods through the sand, and the concrete mainly acts to reduce any radial heat loss.

The total energy input is controlled by the power setting on the rods, specified at 10 kW in the scenario. This setup ensures that a continuous flow of 10 kWh of energy per hour is delivered into the system, leading to a significant accumulation of energy over the three-month period intended for summer storage. The potential energy delivered accumulates to approximately

21600 kWh over 90 days. The simulations will show how much of this theoretical energy is actually stored after the 90 days.

The model also utilizes a couple of initial values for temperature of different areas. For the sand in the box, the initial value is set to 293,15°K or 20℃. The external temperature of the air is set to 278.15°K or 5℃ for the charging period and for the simulation of energy loss over time.

3.3.6 Meshing

The model uses free tetrahedral meshing. This means that the COMSOL automatically creates geometries for the meshing which makes it more adaptable to changes and more complex modelling. Since the generation is automated and the quality of the tetrahedral can vary, some inaccuracies might occur. Figure 12 and 13 showcases the meshing on the outer wall of the box and for the cross section. We can observe that the individual meshes are larger for the walls than the steel rods and area of wall next to the rods. This is because the steel rods are a point of interest where most of the changes take place, and it is important to get accurate data from these areas.

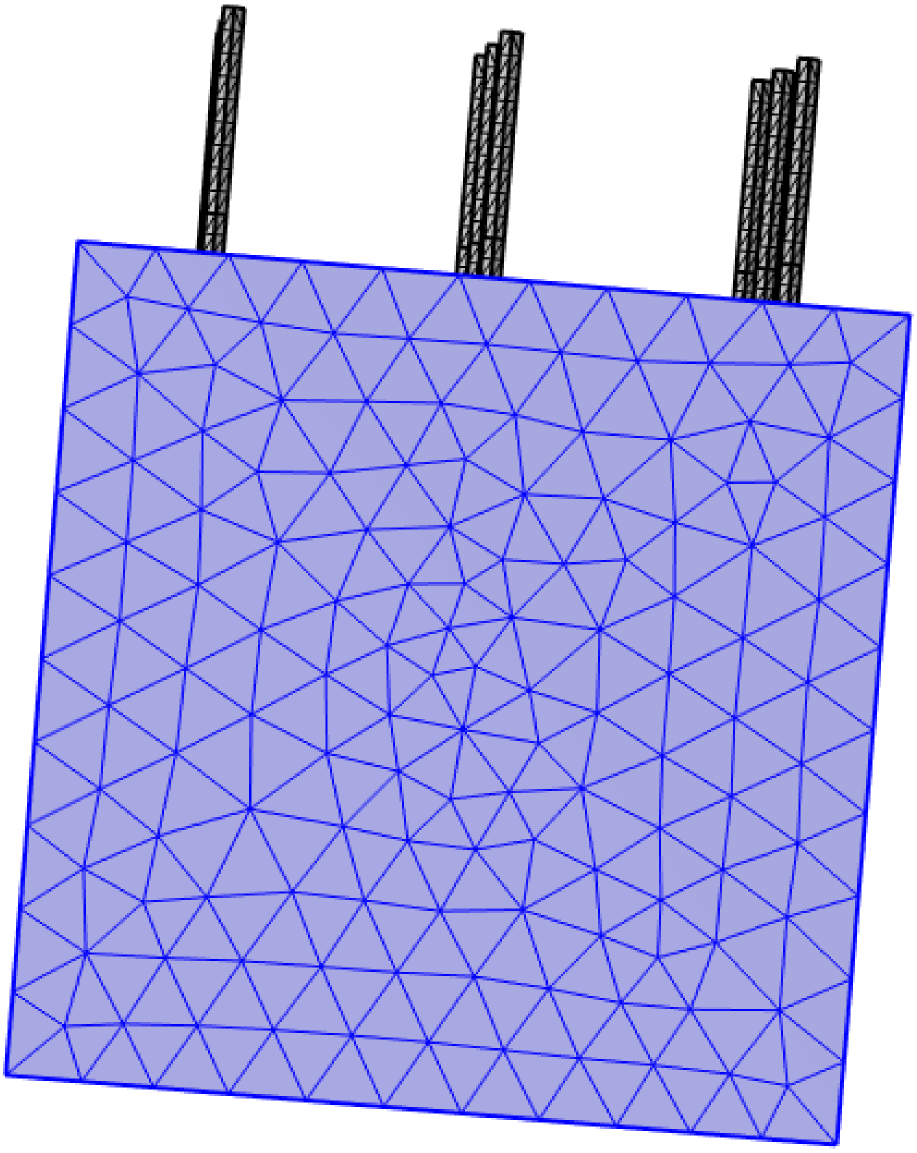


Figure 12 - Side view of the meshing of the sand battery model.

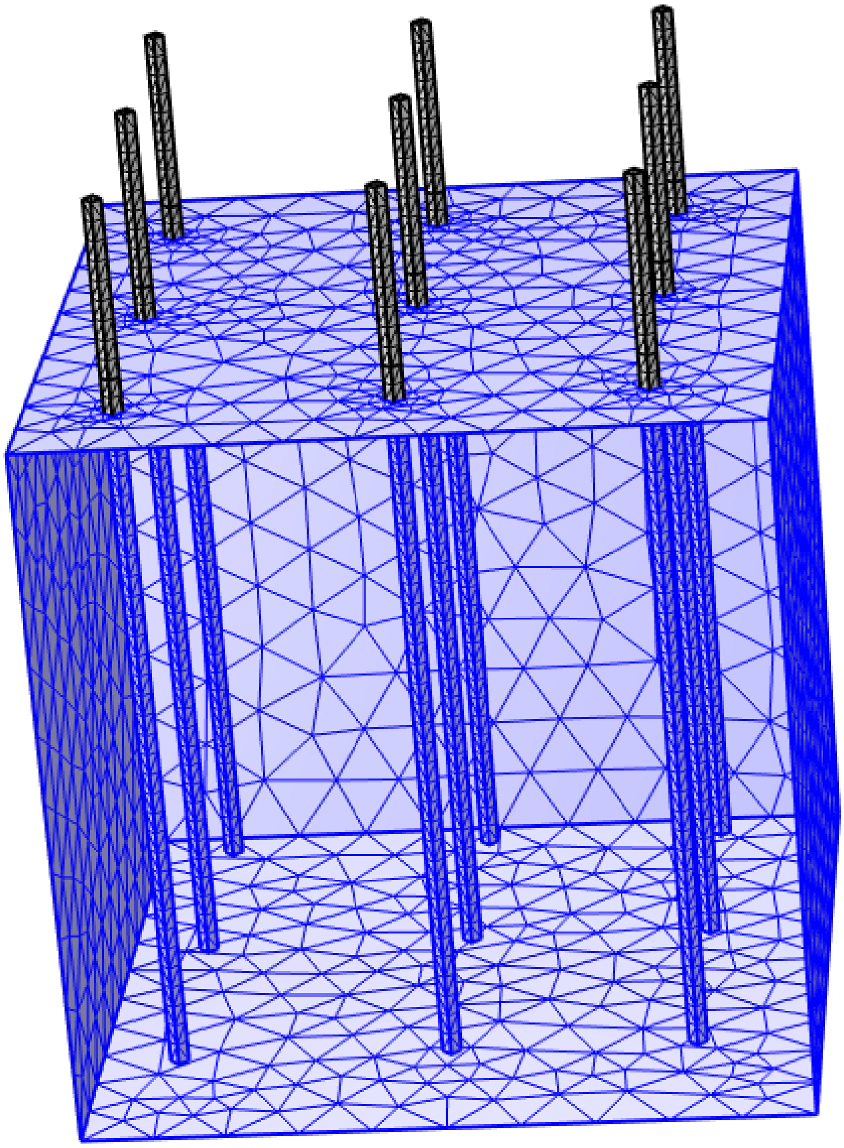


Figure 13 - Cross section of the meshing of the sand battery model.

3.3.7 Model limitations

The model has several limitations. Firstly, it does not explore the optimal methods for charging and discharging energy. Instead, nine steel rods are symmetrically arranged within the box to achieve a uniform energy distribution in a straightforward manner. While this setup is not optimized, it provides a simplified yet reasonably accurate overview of the storage potential.

Additionally, the temperatures in the model are set at initial values, with the external temperature remaining constant throughout the simulations. This constant external temperature is intended to represent an average rather than real-time temperature fluctuations. As a result, the model does not account for the dynamic variations in external conditions that would occur in a real-world scenario.

4 Analysis

Before diving into the deeper analysis of sand battery simulations, energy consumption, and economics, we will restate the main objective. Our goal is to determine if energy stored during the summer months, when electricity prices are lower, can be used during the winter months, when electricity prices and heating demands are higher. Additionally, we aim to assess if this can be accomplished profitably. The following chapters will present data from gathered from the Tibber app. This analysis will provide a foundation for calculating how much of the winter's energy demand can be met by the sand battery, the potential cost savings from this method, and whether it can be achieved with a financial profit.

4.1 Energy consumption of house in Northern Norway

To do calculations regarding electricity consumption, electricity consumption used for heating, and if thermal energy storage can be an effective way of saving, we need a benchmark for how much a household actually consumes. The energy consumption will vary from household to household and depending on what type of household it is. Consumption is also varied by what type of energy source is used as many households uses wood and other resources for heating instead of only being dependent on electric heating. We can see an overview of the average total energy consumption of different types of households in 2012 in Figure 14. The reason that the data is from 2012 is that there has not been made many substantial data collections regarding the electricity use and consumption for heating purposes in recent years.

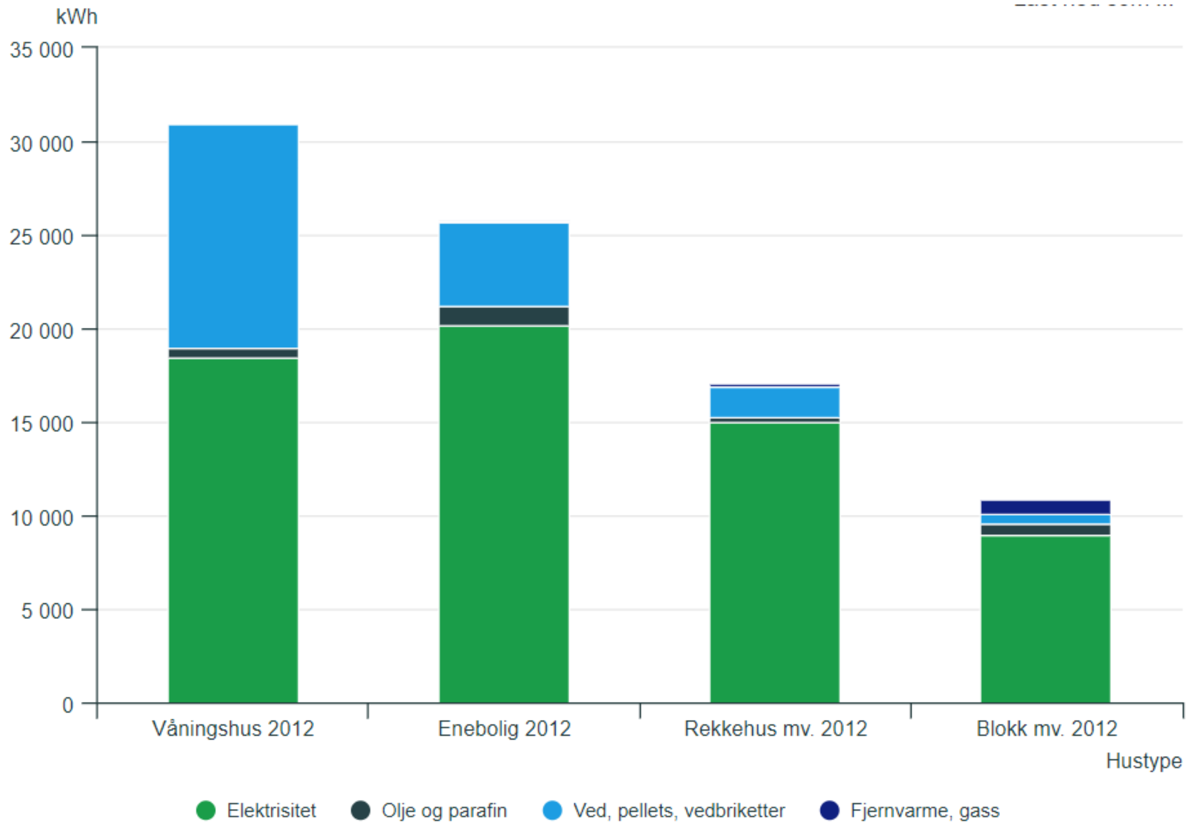


Figure 14 - Average energy consumption of households in Norway 2012 (Bøeng, 2023)

Figure 14 shows a comparison of annual energy consumption across different housing types in Norway for the year 2012. It categorizes energy usage into four main sources: electricity, oil and paraffin, wood-based fuels (such as wood, pellets, and wood briquettes), and district heating or gas. This breakdown offers insights into the common energy consumption habits based on the type of household.

Farmhouses, typically located in the countryside, show a substantial use of wood-based fuels, amounting to nearly 12000 kWh annually, which highlights a reliance on locally available resources for heating. These homes also consume a significant amount of electricity, around 18500 kWh, which might indicate the combined needs for electric appliances and possibly electric heating systems. On the other hand, detached houses, although similar in consumption of electricity at about 20,200 kWh, rely less on wood for heating and more on oil and paraffin, possibly due to slightly better access to these fuels compared to farmhouses.

Row houses and apartment blocks show markedly lower energy consumption figures across all categories. Row houses consume about 15000 kWh of electricity and less than 2000 kWh from wood-based fuels, reflecting their more compact size and possibly better insulation and energy efficiency than larger, standalone homes. Apartment blocks use the least amount of wood-based fuels and have significant consumption from district heating and gas (833 kWh), underscoring their urban setting where such infrastructure is more prevalent and efficient for centralized heating solutions.

It is important to mention that this is an average of such houses in Norway, and the fact that we are evaluating the northern parts of Norway may indicate that the consumption of energy is higher than these averages due to colder weather. To make sure we get accurate numbers for the area of interest, we need to gather data from a household in the area.

The household we are using for calculations in this thesis is a farmhouse in the inner parts of Troms in Northern Norway. It is located in the municipality of Bardu. The farmhouse is not an active farm and therefore does not use any extra electricity and energy on things that would normally be necessary at a farm. Heating of the main house and a small outhouse are the only areas consuming energy for heating and the main house has regular appliances as expected to find in a modern household in 2024. The following data was acquired through the Tibber app, designed to give an overview over electricity consumption and an overview over how much each part of the household uses. Figure 15 shows the electricity consumption in each month in 2023 alongside the corresponding price in Norwegian øre/kWh. Figure 16 shows the total cost of electricity for each month throughout 2023.

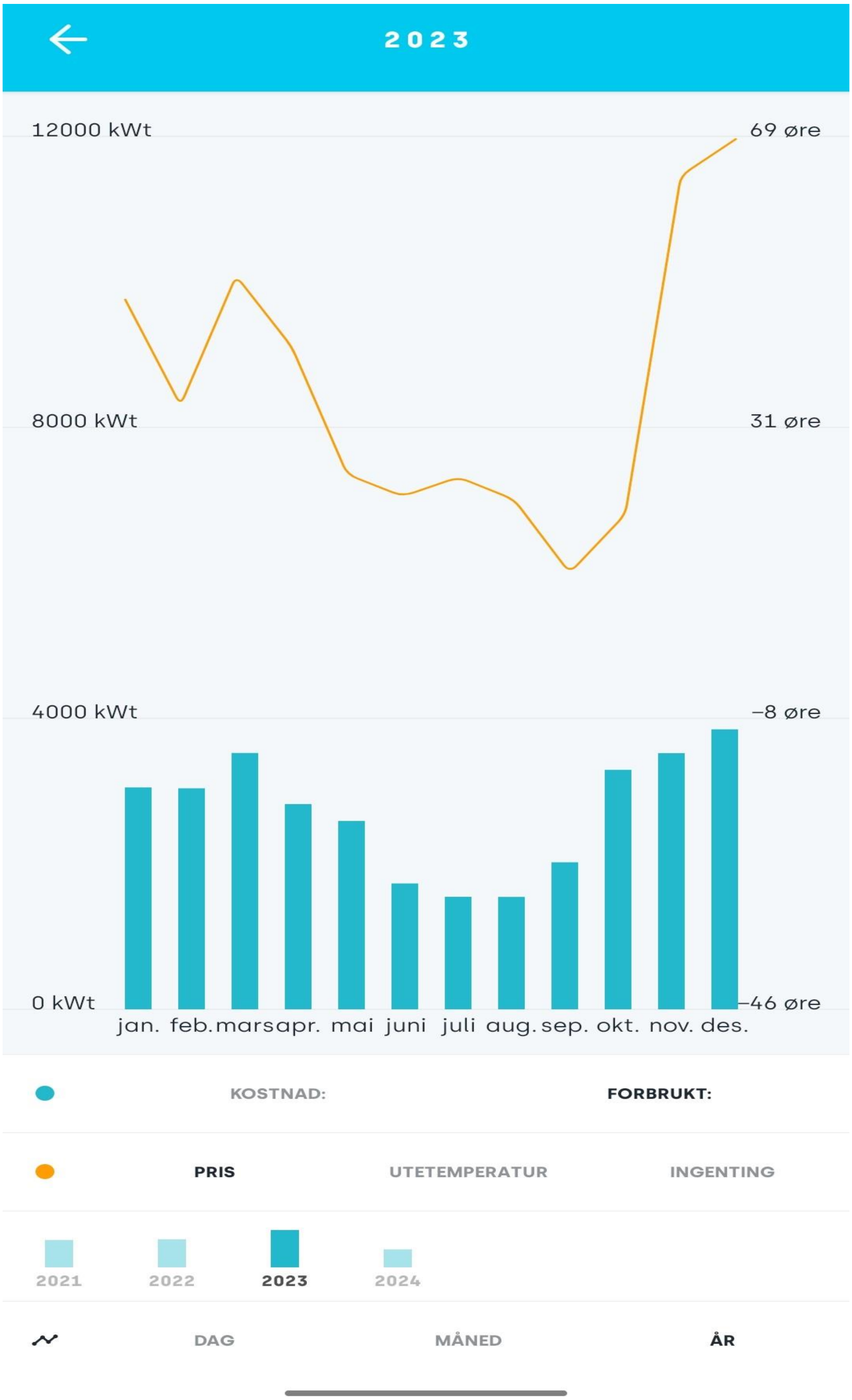


Figure 15 - Electricity consumption of house in Bardu alongside the average cost per kWh for the year 2023. (Data from the Tibber app)

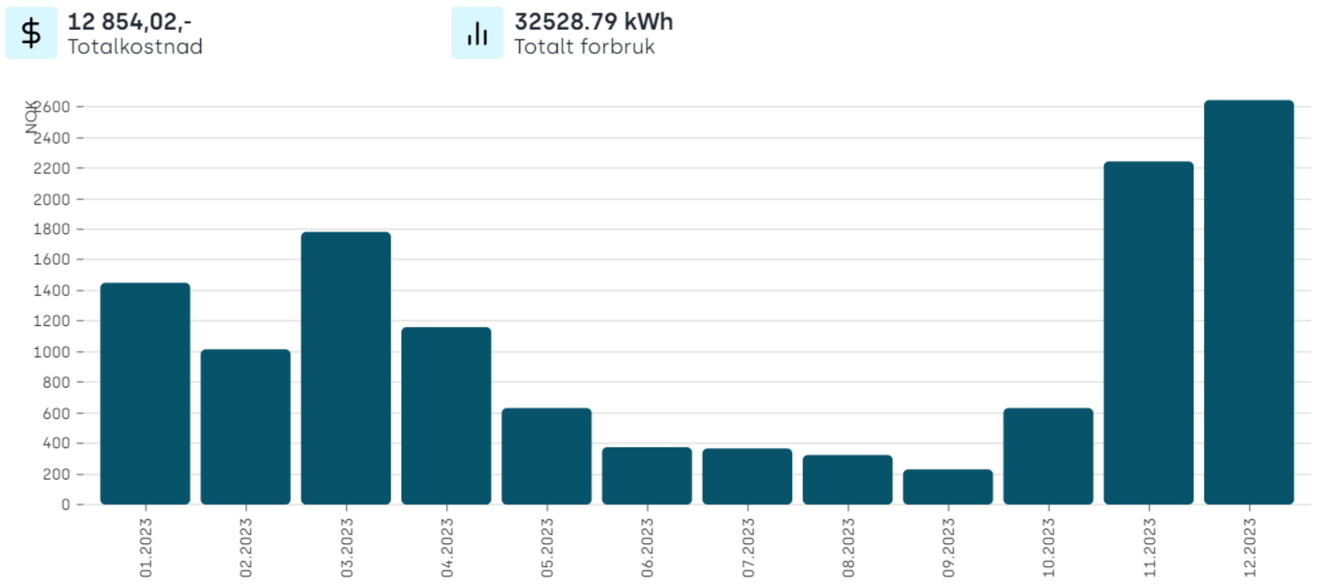


Figure 16 - Electricity costs per month in 2023 for the farmhouse in Bardu. (Data from the Tibber app)

Oppvarming 9 654 kr

73% gikk til å varme hjemmet (23 765 kWt).

Adferd 2 483 kr

20% gikk til lys, komfyr og annet som du bruker daglig (6 383 kWt).

Alltid på 717 kr

7% gikk til kjøleskap, wifi eller lignende ting som alltid er på (2 379 kWt).

Figure 17 - Electricity usage for the household in Bardu divided into total consumption, consumption used for heating, consumption due to behaviours and consumption on utilities that are constantly on. (Data from the Tibber app)

In Figure 17 we can see an overview of which sections of electricity consumption had the biggest impact. Earlier we mentioned that heating could be responsible for as much as 70-80% of the total electricity consumption, and in this case, it seems to be accurate as in 2023 the household used 23765kWh, a total of 73%, on heating alone.

Table 2 - Electricity consumption, cost and % of electricity used for heating during months of 2023 based on numbers from the Tibber app.

Month	kWh consumed	Price(NOK)	% of electricity used for heating
January	3050,45	1449,63	75
February	3038,15	1016,95	76
March	3523,57	1781,29	78
April	2820,93	1162,51	75
May	2589,14	629,91	74
June	1730,35	371,05	61
July	1547,15	370,92	52
August	1545,48	324,69	53
September	2021,08	229,15	62
October	3292,45	627,23	78
November	3521,57	2246,71	78
December	3848,47	2643,98	79

If we take a closer look at the monthly distribution of energy consumption, particularly the three summer months of June, July and August compared to the rest of the year, we see a clear discrepancy. In Table 2 we can see how much electricity and Norwegian kroner (NOK) the household used per month in 2023. The percentage of which was used for heating is also included and we can see that the summer months had a percentage of closer to 50% while the rest of the year was over 70% for all except one month. In Table 3 we can see how much of the electricity each month was used for heating and the corresponding cost.

Table 3 - Electricity used for heating and price of electricity used for heating per month in 2023 based on numbers from Tibber app.

Month	kWh used for heating	NOK used for heating
January	2318	1087,22
February	2338	772,88
March	2773	1389,41
April	2125	871,88
May	1864	466,13
June	1070	226,34
July	804	192,88
August	809	172,09
September	1309	142,07
October	2537	489,24
November	2779	1752,43
December	3040	2088,74

4.2 Cost of electricity

When we analyse the economics surrounding energy storage and heating, the main variables to consider are the price per kWh, the amount of electricity used for heating, and the cost of the TES system. To establish benchmarks for these key aspects, we again use the same house in Bardu, Northern Norway. From Figure 17 we can observe that the total cost of electricity in 2023 for the household was 12854 NOK. What is more interesting is the distribution of the cost per month. Calculating the average cost per month, we find that it was approximately

1071.17 NOK (12,854 ÷ 12). Now let’s separate the summer months from the rest. For June, July, and August, the average cost per month was 355.55 NOK (1,066.66 ÷ 3). For the remainder of the year, the average becomes 1,309.71 NOK (11,787.36 ÷ 9). This shows a difference of over three and a half times more for the rest of the year.

To calculate the average costs for heating, we will use Table 3. Analysing the average cost for the entire year, we find that it was 804.28 NOK (9,651.31 ÷ 12). Taking the average for June, July, and August, we find that it was 197.1 NOK (591.31 ÷ 3). For the remainder of the year, it was 1006.67 NOK (9060 ÷ 9). This amounts to more than a fivefold difference between the summer months and the rest. Table 4 showcases the values of cost for all electricity consumption and specifically for heating.

Table 4 - Average cost of electricity based on data from the Tibber app.

Description	Cost (NOK)
Average Monthly Cost	1071.17
Summer Average Monthly Cost (Jun-Aug)	355.55
Rest of the Year Average Monthly Cost	1309.71
Average Monthly Heating Cost	804.28
Summer Average Monthly Heating Cost (Jun-Aug)	197.10
Rest of the Year Average Monthly Heating Cost	1006.67

Another aspect we need to look at is the price per kWh. We will use the data from Figure 9 to calculate the average price per kWh hour and then compare it to the numbers in Table 2. For the months June, July and August, the corresponding numbers are approximately 0,22, 0,24 and 0,21 NOK/kWh. These numbers vary very slightly from those in Table 2, were by taking the price of electricity divided by the total consumed kWh we get 0,21, 0,24, and 0,21, but not enough to warrant any investigation into the difference. Table 5 gives a full overview of the price per kWh for all months of 2023 according to the data gathered from the Tibber app. Taking the average of the three months, we end up with a price of approximately 0,22 NOK/kWh for the three summer months. If we do the same for the remaining months, we find that the average is 0,40 NOK/kWh, almost double of the summer months. It is important to note that these numbers are based on approximation of values with two significant numbers making the values slightly different from those calculated from Table 2, but we will use them all the same for convenience's sake.

Table 5 - Price in NOK per kWh for months of 2023 using data from Tibber.

Month	NOK/kWh
January	0,47
February	0,34
March	0,51
April	0,41
May	0,24
June	0,21
July	0,24
August	0,21
September	0,11
October	0,19
November	0,64
December	0,69

Now as the objective of this thesis is to assess the possibility to cover the energy demand for heating during the remaining year with the stored energy from the summer, we must accept that the sand battery might not be able to cover all of it. Therefore, the most important and profitable months to cover will be the months with the highest NOK/kWh. We see in Table 5 that these months are the colder winter months of November, December and January with March also breaking the 0,5 NOK/kWh mark. This is advantageous for us as we can observe from Table 3 that these are some of the months with the highest consumption of electricity due to heating, meaning they are the months we can save the most amount of money by utilizing the stored heat.

As we now have analysed the economic aspects of energy consumption surrounding northern Norway and what amount is utilized for heating, we will look at the results of the sand battery simulations and evaluate what they mean practically when we use the numbers we derived. Specifically, we will see if the battery can be an economically viable storage solution in northern Norway.

5 Results

This section presents the simulation data and analyses what they represent and their practical implications. The primary goal is to evaluate whether the sand battery system can be a profitable solution for thermal energy storage in Northern Norway, specifically its ability to sustain heat throughout the winter and cover the energy needs for heating.

We will start by examining the temperature distribution within the sand battery during both the charging phase and the idle phase between the end of the charging phase and the beginning of the discharging phase. Understanding how heat is distributed and retained within the system is crucial for assessing its efficiency and capacity.

Next, we will evaluate the energy storage efficiency of the sand battery. This involves comparing the total energy input during the charging period with the actual stored energy after the charging period. The efficiency analysis will help identify any significant energy losses and their potential causes.

Following the efficiency assessment, we will conduct an economic evaluation. This analysis will compare the costs associated with charging the sand battery with the savings achieved by utilizing the stored energy during periods of high electricity prices. The economic viability of the sand battery system will be a key focus, determining if it can provide a cost-effective solution for heating in Northern Norway.

Additionally, we will perform a sensitivity analysis to explore how variations in key parameters, such as charging efficiency and electricity prices, impact the system's performance and economic outcomes. This will help identify potential areas for optimization and further research.

5.1 Sand battery simulations

5.1.1 Temperature

When the simulations were run at the initial conditions we mentioned in the method chapter, where the sand starts at $20°C$, the external temperature is at $5°C$, and the power input is

10kW, we found that the temperature had an almost linear increase throughout the charging period. Figure 18 shows the change in temperature of the sand in °C.

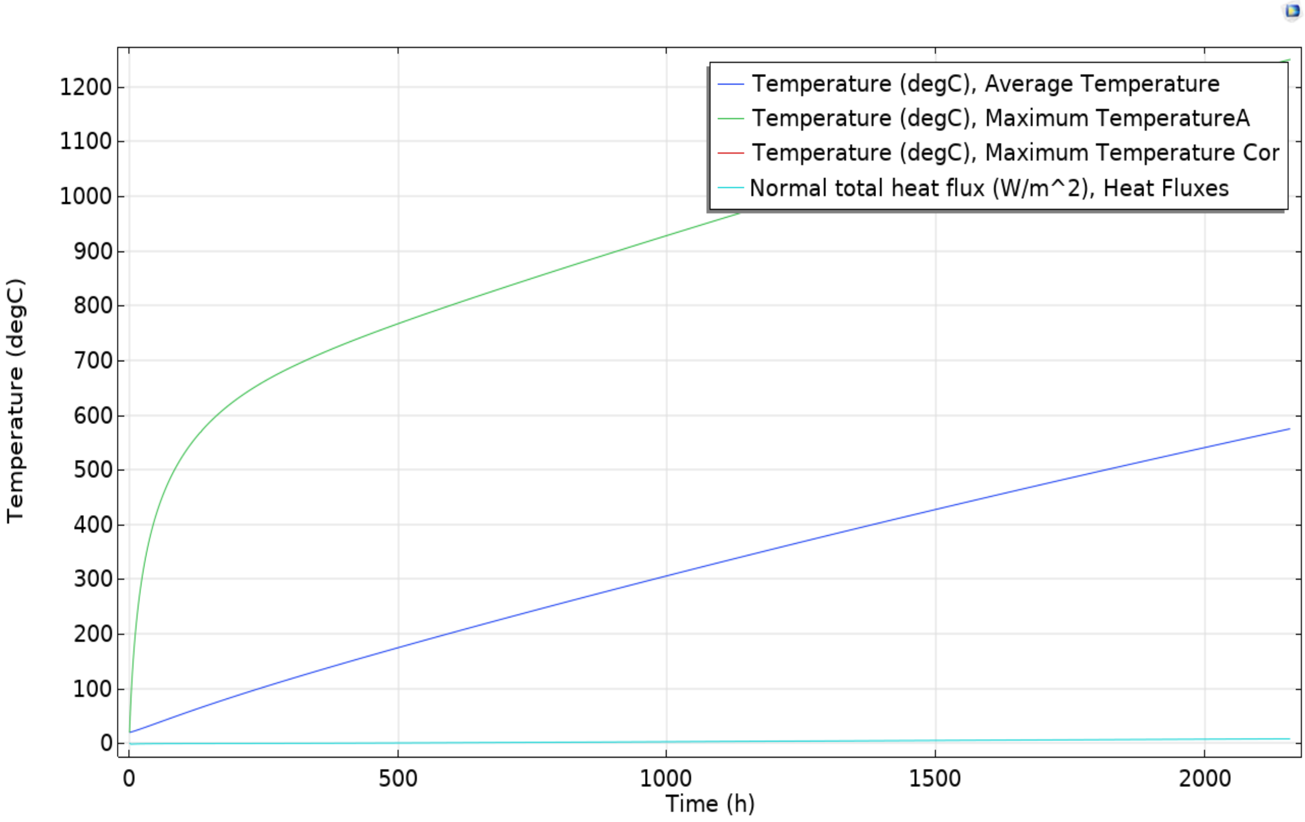


Figure 18 - Temperature change of the sand in the sand battery model with 10kW input power over 90 days.

5.1.2 Stored energy

We can observe from Figure 18 that the final average temperature reading after 90 days was at approximately 575°C. To calculate how much energy is stored in the battery at the final temperature, we can use Equation 1, where we use the fact that mass is the same as volume times density: $m = V * \rho$. This means that we get the equation: $Q = V \times \rho \times C_p \times \Delta T$.

We use the specific heat capacity of the sand from the model which was 850 $\frac{J}{kg*C}$ and the density of the sand at 1620 $\frac{kg}{m^3}$. With the change in temperature at 555°C, due to initial value of 20°C, we get the following calculations:

$$Q = 64m^3 \times 1620\frac{kg}{m^3} \times 850\frac{J}{kg*C} \times 555°C \approx 4{,}891 \times 10^{10}J.$$

We can calculate the kWh stored by using the fact that 1 kWh = $3{,}6 \times 10^{6}$J, which means the battery has stored a total of approximately 13600kWh throughout the 90 days. With a storage capacity of 13600kWh, we can observe from Figure 17 that the system won’t be able to cover the energy needed for heating throughout the entire year.

5.1.3 Loss of energy

5.1.3.1 Initial loss

It is clear that there are some energy losses during the charging period. If the charging process had been 100% efficient, with a power input of 10kW, the total energy stored in the battery after 90 days would be 21,600 kWh. This means we have an energy loss of 8,000 kWh, which is about 37%. In other words, of the 10kW power input, 3,7kW are lost and only 6.3 kW are stored in the battery.

The losses we are experiencing come from the free convection of the outer walls with the surroundings. As mentioned in the description of the model, the top side of the battery is exposed to the air and therefore has free ambient convection. Figure 19 shows the surface temperature of the sand battery after 90 days. The final temperature of the top surface exposed to the air was 303,15K or $30°C$ meaning there was a 25℃ difference between the surface of the battery and the surroundings.

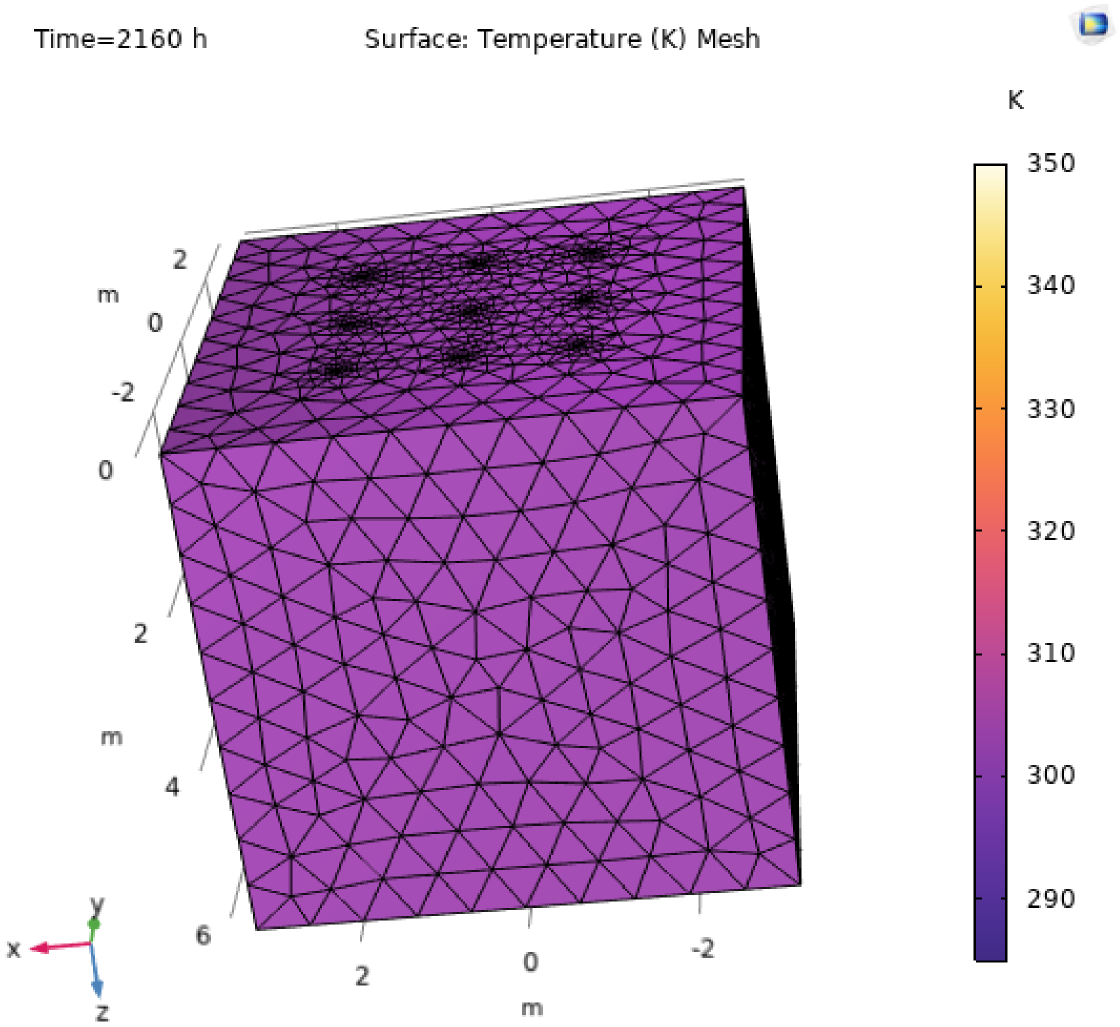


Figure 19 - Surface temperature of sand battery after 90 days with input power of 10kW.

We can estimate the charging power loss of the battery from this convection with Equation 3:

$$Q_{loss} = \frac{3{,}7W}{kg * K} \times 25m^2 \times 25K = 2312{,}5W$$

This accounts for about 62.5% of the total loss. The remaining 1,3875 kW of loss comes from the other walls that have convection at fixed temperatures. For these walls, the convection occurs at a fixed temperature where the heat loss is due to the temperature gradient moving from the core of the battery towards the outer walls.

5.1.3.2 Loss over time

As the battery is subject to convection, there will also be an energy loss over time. As we want to store the heat for multiple months, we need to assess how substantial this loss is. Since we want to use the heat during months with higher cost of electricity, we can assume that we need to store all the energy until at least November. This means a two-month storage period where the heat needs to stay idle. A simulation was run to simulate the period between the end of August until beginning of November by setting an initial average temperature of $575°C$, external temperature of surroundings at $5°C$, no input power and a running time of 1440 hours. Figure 20 shows the temperature change of the battery throughout the two months.

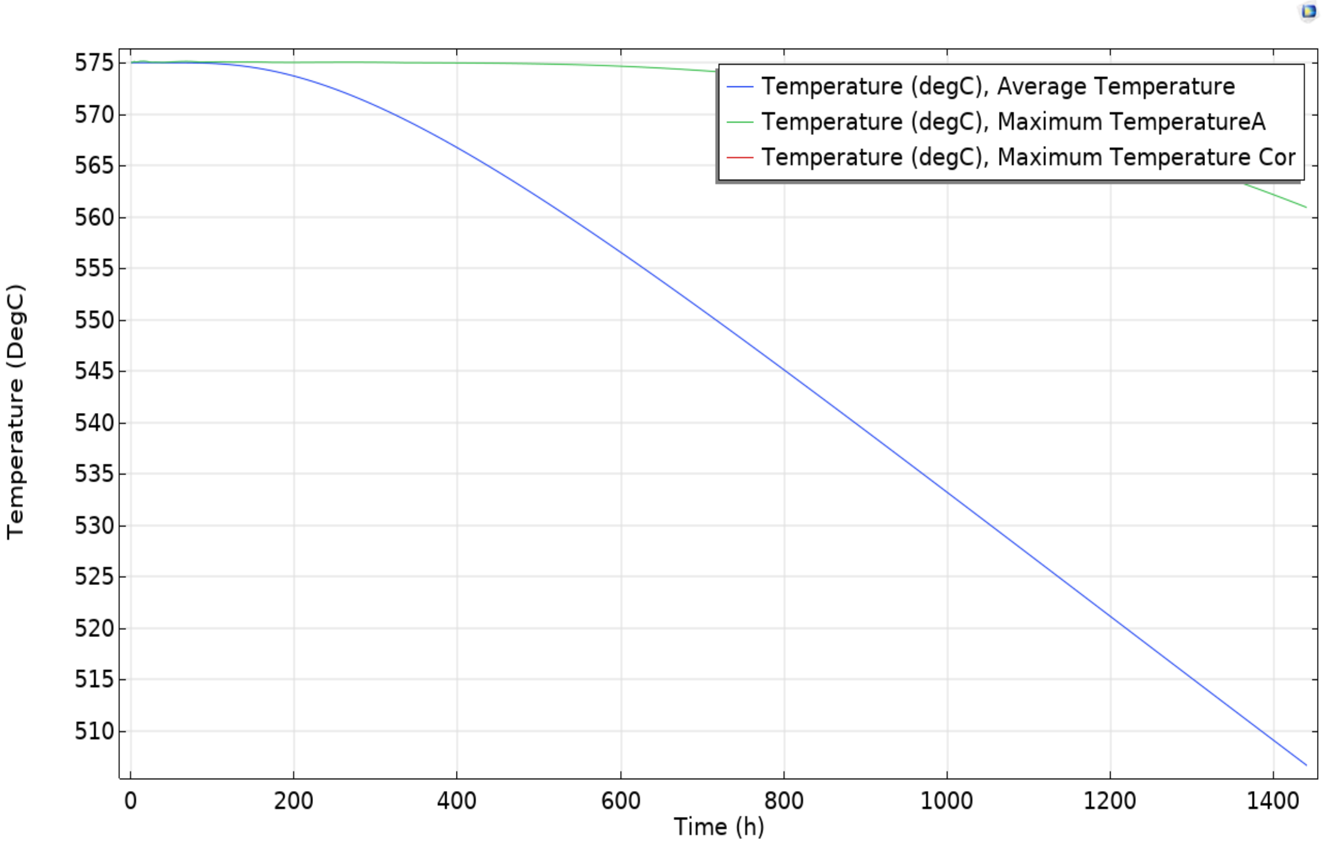


Figure 20 - Temperature loss of the sand battery model over 60 days at initial temperature 575C and external temperature 5C.

The final temperature reading at 1440 hours was $507°C$. Using Equation 1 we get that the battery contains $Q = 64m^3 \times 1620\frac{kg}{m^3} \times 850\frac{J}{kg*C} \times 487°C \approx 4{,}292 \times 10^{10}J$ corresponding with approximately 11900kWh. Compared with the original energy of 13600kWh, this is a decrease of 13,5% over the two months making the monthly loss of energy at 6,75%. However, we can observe from Figure 20 that there might have been some irregularities at the beginning of period making the loss a bit less for the first month than what we would expect throughout the following months. Therefore, we will set the average monthly loss of energy of the battery to 7%. We can see the evolution of the energy contained in the sand battery in Figure 21.

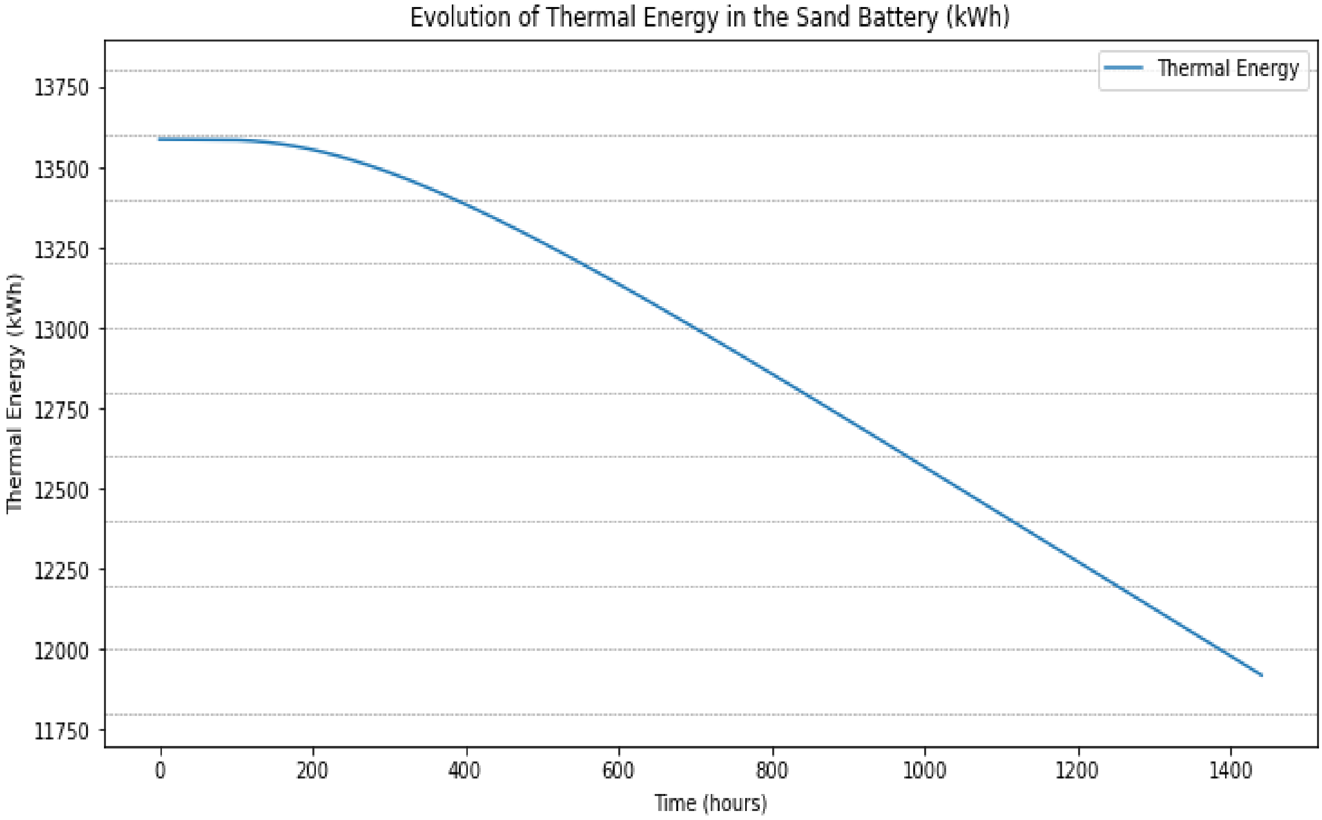


Figure 21 - Evolution of stored energy in the sand battery during two-month idle stage.

5.2 Savings and price of battery

Now that we have evaluated how much energy is stored in the battery, it is time to calculate how much we can utilize throughout the winter and how much money we can save. We will use the data from 2023 showcased in Table 3. From Table 3, we observe that the best months economically to use the heat in the battery are November, December, January, and March. In total, these months used 10910 kWh for heating purposes, costing a total of 6317 NOK. We know that at the beginning of November, the battery contains 11900 kWh. Since we utilize much of the energy throughout the following months, we know that the monthly 7% loss of energy will account for less and less energy. Therefore, we will assume that all the energy used for heating for the four months can be covered by the 11900 kWh, and that the loss of energy is 990 kWh. Following this assumption, we know that we are able to save 6317 NOK during the winter by utilizing the stored heat.

The original amount of energy we used during the charging of the battery was 21600 kWh. In section 4.2, we found that the average cost of electricity for the summer months of 2023 was 0.22 NOK/kWh. Using this average, we can find the total cost of charging the battery:

$$0.22 \text{ NOK/kWh} \times 21600 \text{ kWh} = 4{,}752 \text{ NOK}$$

Now we can calculate the net gain in cost for the year 2023:

$$6317 \text{ NOK} - 4752 \text{ NOK} = 1{,}565 \text{ NOK}$$

So, during the year 2023, the battery has helped us save 1,565 NOK in pure electricity costs.

If we set an expected price of the sand battery system to be 200,000 NOK and assume it has a lifecycle of 30 years, we can calculate the economics over the lifecycle of the battery. If we assume that the yearly savings from the implementation of the sand battery remain relatively similar to that of 2023 (we set the yearly savings at 1,500 NOK), then over 30 years we will save a total of 45,000 NOK. This means that during the lifecycle of the system, there will be a loss of 155,000 NOK under these conditions.

5.3 Sensitivity

When we discuss such concepts as energy consumption, generation and economics, we must consider the many variables used in the calculations and discussions. Variables can change and with changes in variables, changes in results might follow. It is therefore important that we perform a sensitivity analysis to evaluate potential changes. Variables such as NOK/kWh, storage capacity and power input for the sand battery model are key parameters to evaluate.

5.3.1 Optimizing economic upside

One thing we need to consider is that we are using a very simple and straightforward method of utilizing the heat stored in the sand battery. We used the heat throughout all the winter months when the price per kWh was relatively high on average. This means that although we might have used the heat at times when the price was beneficial for us, at 1 NOK/kWh or higher, we probably also used it at times when the price was less than the average price for which we charged the battery. The same can be said about the charging of the sand battery. In our calculations, we only used the average cost of the three summer months, which, although still lower than the winter months, means that at times the battery might have been charged at prices higher than the average of the winter months. This indicates that we have not optimized the potential of the storage solution.

If we were to implement an automated system that only charged the battery when the price of electricity was 0.1 NOK/kWh or less and discharged the battery at times when the price of electricity was 1 NOK/kWh, we would see a substantial increase in savings. Assuming we stored the same amount of energy as earlier, 13600 kWh, and used 21600kWh to fully charge it, the total charging cost (assuming a price of 0.1 NOK/kWh) would be 2160 NOK. Assuming we are then able to utilize all of this energy at times when the electricity price is 1 NOK/kWh, we would then, assuming that we have the same 10910kWh that we use for heating, we would save 10910 NOK and have a net gain of 8750 NOK. If this was the case for every year of the 30-year lifecycle of the system, then we would save a total of 262500 NOK, with a net profit of 62500 NOK with the system cost of 200000 NOK.

Practically, this might be a bit challenging if we look at the numbers from 2023. However, the Norwegian Water Resources and Energy Directorate (NVE) has predicted in a market analysis that the electricity prices in Norway might increase towards 2030, reaching an average electricity cost of 0.8 NOK/kWh. This prediction is for the whole of Norway, but they also state that the differences between the northern and southern parts of Norway will decrease. (NVE, 2023) Assuming this will come to fruition in the next couple of years, the scenario of charging at below 0.1 NOK/kWh and discharging only at above 1 NOK/kWh seems more probable.

5.3.2 Efficiency of charging

As we saw earlier, there was a substantial loss in efficiency during the charging of the system, with a total loss of 37% over the 90-day charging period. If we could somehow reduce this loss, it would potentially have a large impact on the overall savings for the system. With a 90% conversion rate from electrical energy to heat stored in the battery, it would mean that if our aim was to store the same amount of energy as in the original simulation (13,600 kWh before losses), we would only need a power input of about 7kW for the 90-day charging period. For our original calculations with 0.22 NOK/kWh for charging, the total cost of charging would decrease from 4752 NOK to 3326 NOK, making the net profit for the year 2991 NOK. Over the 30-year lifecycle, this would result in total cost savings of 89730 NOK. Although this still doesn’t make the system profitable at a price of 200,000 NOK, it is almost twice the amount of the original estimation and makes it an interesting subject for future research.

The economic viability of the sand battery for the three different scenarios above can be observed in Figure 22. We can observe that the original scenario with no optimization of the charging and discharging cost or the efficiency of the sand battery, has the worst economic viability with the only profitable life cycle cost being the scenario with optimized cost per kWh.

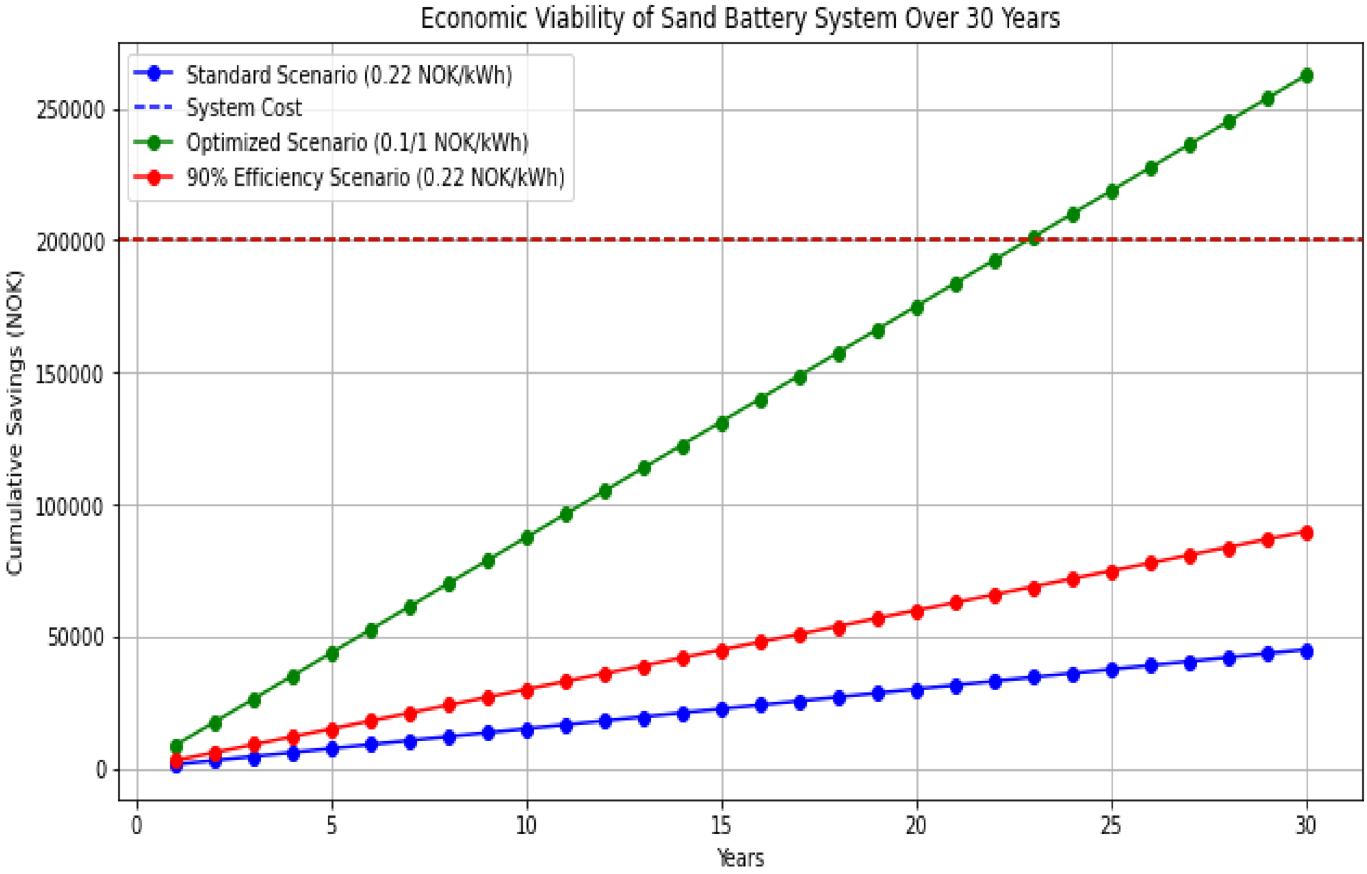


Figure 22 - The cumulative savings of the sand battery system for the three scenarios of cost per kWh and efficiency of the battery.

The analysis of the simulation data and economic evaluation of the sand battery system highlights both its potential and challenges as a viable thermal energy storage solution in Northern Norway. While the system shows promise in terms of energy storage capacity and potential cost savings, significant energy losses and economic constraints remain under current conditions. These findings underscore the importance of further optimization and real-world testing to fully harness the benefits of sand battery technology. In the following discussion chapter, we will explore these results in greater depth, considering their practical implications, addressing the study's limitations, and proposing directions for future research to improve the system and make it mor viable.

6 Discussion

In this chapter, we will look at the implications of the results presented in the previous section, assessing the practical, and economic aspects of the sand battery system for thermal energy storage in Northern Norway. The primary aim of this study was to evaluate the feasibility and profitability of using sand batteries to sustain heat throughout the winter and meet the energy needs for heating in a cost-effective manner.

We will start by summarizing the key findings from our simulations and economic analysis, highlighting the system's energy storage efficiency and economic viability. Following this summary, we will interpret these results.

Next, we will address the limitations of our study, acknowledging any constraints and assumptions that may have influenced the outcomes. This section will also identify potential areas for improvement and optimization.

Finally, we will propose recommendations for future research, suggesting ways to enhance the efficiency and economic feasibility of sand battery systems. By exploring these directions, we aim to contribute to the broader field of renewable energy storage and support the development of sustainable energy solutions.

6.1 Summary of findings

In this section we will go over the key findings from the analysis and results chapter and discuss what they might imply practically for the potential of implementing sand batteries in northern Norway.

6.1.1 Energy storage efficiency

In the simulation scenario, the sand battery stored 13600 kWh out of the original 21600 kWh inserted over 90 days. This indicates that the sand battery was able to store approximately 63% of the energy used to charge it. The energy loss was primarily due to free ambient convection at the top surface, with the remaining loss resulting from fixed temperature convection at the other surfaces. Additionally, we observed a monthly energy loss of about 7% due to convection.

6.1.2 Economic viability

Using the simulation scenario and the 2023 electricity costs for a household in Northern Norway, we calculated yearly savings and savings over a system lifetime of 30 years. The yearly savings based on the 2023 numbers showed a net saving of around 1500 NOK. Assuming this would be the average savings throughout the 30-year lifecycle, the total lifecycle savings would be 45000 NOK. With the system cost set at 200000 NOK, the net cost over the lifecycle would result in a loss of 155000 NOK, indicating that the system under these conditions would not be profitable.

However, changes in the NOK/kWh during the charging and discharging phases had a significant impact on the system's profitability. Under a scenario where the charging phase had an average cost of 0.1 NOK/kWh and the discharging phase had an average cost of 1 NOK/kWh with the same amount of stored energy, the lifecycle savings would jump to 262500 NOK, making the net cost of the system's lifecycle 62500 NOK.

Additionally, by reducing the energy loss of the battery to 10%, the savings would significantly increase compared to the original scenario. Although this would not make the net cost of the system profitable, the 30-year savings would increase from 45000 NOK to 89730 NOK.

6.1.3 Practical implications

When examining the numbers regarding energy storage in the summer and its usage during the winter months, the sand battery shows promise as it was able to cover most of the heating needs for the winter, with the exception of February. Despite the energy losses, the system was still profitable based on the net expenses and savings from the year's electricity cost for heating. However, factors such as variations in the cost per kWh and the cost of system implementation significantly impact the system's profitability from year to year and over its lifecycle. Given the unpredictable and variable electricity prices in Northern Norway, the system might be profitable one year but not the next.

6.2 Interpretation of results

6.2.1 Offload excess production

From the results, we can draw several key conclusions. Firstly, the sand battery demonstrates the ability to store a substantial amount of energy throughout the year, making it a viable option for seasonal storage. Although the system is not fully optimized and still experiences significant initial energy losses, the overall energy storage capacity remains large. This suggests that if the primary goal is to offload excess energy produced during periods of high renewable energy generation, the sand battery can effectively fulfil this role to a certain extent. Consequently, it has the potential to aid in stabilizing the energy grid and supporting the transition to more renewable energy sources.

6.2.2 Variability and risk

However, based on the economic evaluation of the yearly and lifetime savings, we can conclude that the variations in electricity prices and the high cost of the system make it challenging for the sand battery to be a viable and profitable alternative in Northern Norway. Significant optimizations are required to achieve profitability, particularly in terms of charging and discharging the battery during periods of lower and higher electricity prices, respectively. This optimization is heavily dependent on the future evolution of the electricity market, which is expected to undergo changes. (DNV, n.d) Implementing automated systems to optimize the charging and discharging processes could mitigate some of the risks associated with electricity price fluctuations.

6.3 Limitations of study and technology

6.3.1 Simulation model

As mentioned in the description of the model, there are several limitations. The model focuses solely on the storage of energy and the retention capabilities of the sand battery. It does not include a mechanism for discharging the stored heat, meaning it cannot reverse the circulation to withdraw heat when needed. Additionally, the charging system using steel rods, while a simple and effective way to demonstrate heat charging, is not optimized for even and consistent heat storage.

Moreover, sand has a property that could make it unstable when temperatures exceed 600°C. In our model, the steel rods reach much higher temperatures, which could lead to significant issues in real-world applications at areas where the steel rods contact the sand. Furthermore, the model assumes constant surrounding temperatures, which would vary significantly in real-world conditions, at least for the side that has free ambient convection with air. These variations could contribute to discrepancies between the simulation results and actual performance.

6.3.2 Data

In our analysis and results, we used the energy consumption of a single household as an example. This household was among the higher echelon of energy consumption in Norway, representing an extreme on the spectrum. This fact may have impacted the calculations regarding how much of the energy consumption the sand battery was able to cover. For households with lower electricity consumption for heating, the sand battery might have been able to cover a larger portion of the heating needs throughout the year. Conversely, for some households with even higher consumption, the opposite might have been true. Therefore, it would have been advantageous to evaluate the results for multiple households to provide a more comprehensive analysis. The results might not vary to much profit wise as we have established that price per kWh is the most important factor, however, the percentage of heating needs that the sand battery can cover might.

Additionally, the data collected from the Tibber app on electricity used for heating purposes might not be entirely accurate, as Tibber explained that this function is based on algorithms that approximate the data. This approximation means that the numbers may not be completely accurate, potentially affecting the real-world capacity coverage of the sand battery and the yearly savings.

Furthermore, the price of electricity is a significant factor in the economic viability of the sand battery. As we established, electricity prices are highly variable and uncertain, fluctuating from month to month and year to year. In our calculations, we only used the electricity cost data from 2023, which means our analysis is somewhat narrow and specific to that year. To gain a better understanding of how costs and savings might vary with different electricity prices, we should have evaluated data from multiple years.

Lastly, it is important to mention a factor not included in this study that could affect the economic aspects of the sand battery: the power grid fee. The power grid fee is paid to the electricity companies that own the power grid for transporting electricity to households. The price varies by company, but the main variable determining the cost is the maximum kW usage by the household at any given time during the month. This means that a household with a peak usage of 5 kW would pay less than a household with a peak usage of 15 kW.

This fee could significantly impact the costs associated with the sand battery system. During the charging phase, the additional kW added to the household's usage could increase the power grid fee. Conversely, during the discharge phase, the sand battery system could reduce the peak usage by covering the amount of electricity typically used for heating purposes, potentially lowering the power grid fee.

Another factor influencing the power grid fee is the time of day when electricity is used. Electricity used during the day costs more than that used at night. Therefore, if we only charged the battery during the night, the power grid fee would theoretically be lower than if we charged it during the day. Incorporating the power grid fee into our economic analysis would provide a more comprehensive understanding of the sand battery's financial viability.

6.3.3 Technology limitations

Although thermal energy storage solutions have been used in Norway before such as underground thermal energy storage, sand battery technology is a relatively new technology. Not many real-world products have been made. We mentioned Polar nights sand battery technology which do exist; however, it is fairly new and in addition it is mostly aimed at larger industries with its larger capacity. So, the fact is that the maturity of sand battery technology for the masses is in the early stages. Factors such as effective heat transfer, insulation and cost of production are reasons as to why it might be challenging to produce sand battery solutions that are widely available at a reasonable price.

6.4 Future research

We have found that sand batteries can have a potential to store substantial amounts of energy in Northern Norway, however, there are several drawbacks and limitations that leaves room for improvement. Future research is necessary in the quest to make sand batteries a part of the energy sector of the future. This section will outline some key improvement areas that can help the development of the technology.

6.4.1 Sand battery technology

For sand batteries to become a viable storage option, the technology must operate at a high level of efficiency. Therefore, it is crucial to conduct further research to optimize processes such as the charging and discharging phases. Developing effective methods for extracting stored heat with quick response times will be essential for making sand batteries practical and usable. Additionally, optimizing insulation is important to minimize energy loss during the charging phase and throughout the storage period. Testing various materials as insulation media and discovering new insulation techniques will be key to achieving these improvements.

6.4.2 Renewable energy integration

Future research should focus on integrating sand batteries with various renewable energy sources, such as solar and wind power. This includes developing strategies to utilize excess renewable energy for charging the batteries and optimizing the storage and discharge cycles to align with energy supply and demand. Additionally, the potential of smart grid technologies to dynamically balance energy supply and demand using sand battery systems should be thoroughly explored.

6.4.3 Pilot projects

As the technology matures and model simulations yield promising results, it will be crucial to implement pilot projects to test the real-world viability of sand battery systems. These pilot projects should be conducted in diverse geographical locations to assess how varying climates impact performance. Collaborating with industry partners will be essential to gain valuable insights into the functionality and adaptability of the technology under different conditions.

6.4.4 Economic and environmental impact analysis

Thorough economic analyses over extended periods are needed to understand the long-term financial benefits and costs of sand battery systems. This includes studying the impact of varying electricity prices and potential incentives. Moreover, environmental impact assessments, including lifecycle analyses of materials used in sand batteries, should be conducted to evaluate their sustainability and ecological footprint.

6.4.5 Innovations and future trends

Emerging technologies and trends in thermal energy storage and energy management should be continuously monitored. Future research should explore potential synergies with other innovative energy storage solutions and smart home technologies. Staying abreast of technological advancements will help in incorporating the latest innovations into sand battery systems, ensuring their competitiveness and efficiency.

By addressing these areas, researchers can contribute to the development of more efficient, cost-effective, and sustainable thermal energy storage solutions. The continued exploration and optimization of sand battery systems hold great promise for supporting the global transition to renewable energy sources and enhancing energy security.

7 Conclusion

We have explored the potential of sand batteries as a thermal energy storage solution in Northern Norway, focusing on their ability to store heat during the summer and retain it for winter use. Through a combination of theoretical analysis, computer simulations using COMSOL Multiphysics, and economic evaluation, we have assessed the feasibility and profitability of implementing sand batteries in this region.

Our findings indicate that sand batteries have significant potential for storing large amounts of energy, which could be crucial in balancing the seasonal variability in renewable energy production and heating demands. The simulations showed that the sand battery could store about 63% of the energy input during the charging phase. This efficiency highlights the need for further optimization to reduce energy losses primarily caused by convection.

Economically, the analysis revealed that under current conditions, the sand battery system is not yet profitable. The yearly savings based on 2023 electricity costs and simulation numbers, amounted to approximately 1,500 NOK, leading to a total lifecycle savings of 45,000 NOK over 30 years. However, with a system cost of 200,000 NOK, the net result is a loss of 155,000 NOK. Nevertheless, scenarios with optimized charging and discharging strategies show promise. For instance, charging at 0.1 NOK/kWh and discharging at 1 NOK/kWh could result in significant savings, potentially making the system economically viable.

The practical implications of these findings suggest that while sand batteries can cover substantial heating needs, variations in electricity prices and high implementation costs remain critical barriers. The technology shows promise, but achieving profitability will require significant advancements in efficiency and cost reduction.

Future research should focus on optimizing the charging and discharging processes, enhancing insulation methods, and integrating sand batteries with renewable energy sources. Pilot projects in diverse geographical locations will be essential to test the real-world applicability of the technology and gain insights into its functionality under various conditions.

In conclusion, sand batteries present a promising solution for thermal energy storage, offering potential benefits for renewable energy integration and energy security, but the technology is not yet mature enough to be a viable storage option. Continued research and development are crucial to overcoming current limitations and realizing the full potential of this innovative technology.

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