Energy storage for peak shaving:

*Case study for the distribution grid in Björnarbo*

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Abstract

Sala-Heby Energi Elnät is a supplier of electrical power for the communities of Sala, Heby, Morgongåva and Björnarbo in Uppland, Sweden. The electrical power grid in this area is currently facing several challenges. Bottlenecks and power shortages are some of them. As an expansion of the Swedish power grid lies many years in the future, there is a need for other solutions to these problems. Because of this, Sala-Heby Energi Elnät is looking at the prospect of installing an energy storage system in the small community of Björnarbo.

This report investigates a number of the most commonly used energy storage options available today and concludes that the most suitable choice for Sala-Heby Energi Elnät would be lithium-ion batteries implemented in a battery energy storage system, a BESS. This report also focuses on how a BESS can reduce power peaks by using a method called peak shaving. The financial implications of implementing a BESS of this kind for this purpose are taken into account as well.

The study shows that by utilising a BESS with an energy capacity of 500kWh, the power peaks can be reduced by peak shaving. This not only provides a solution to the capacity problem in Sala-Heby Energi Elnät’s power grid, but a BESS could also allow for them to reduce their power subscription to Vattenfall, Sweden’s electricity provider. This would allow Sala-Heby Energi Elnät to make some financial savings. However, a BESS of this type would be very expensive. The conclusion is that a BESS could manage the energy consumption by using peak shaving but will only be financially profitable in the long run for Sala-Heby Energi Elnät.
Preface

This project was performed as part of the course Independent Project in Sociotechnical Systems Engineering - Energy Systems at Uppsala University, 2022. The project was done on behalf of Sala-Heby Energi Elnät in collaboration with STUNS Energy Stories. We would like to thank Oscar Forsman at Sala-Heby Energi Elnät for his time and guidance, and Therese Fernlund at STUNS Energy Stories for all the support and advice. We would also like to express our gratitude to our supervisor at Uppsala University, Reza Fachrizal, for his technical expertise and assistance.
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1. Introduction

At any moment, the generation of electrical power must match the consumption. This balance is important in any type of electrical grid in order to provide a safe and stable supply of power. If the constant flow of energy through the grid does not reach the demand an additional source of energy is needed. That source must be able to deliver its stored up energy to the grid in order for the demand to be met. Today, when the world is moving towards electrification as a way to become less dependent on fossil fuels, devices that can effectively store energy are becoming important components in the effort to become a low-carbon society. This means that in the modern energy supply chain, the ability to effectively store energy is considered a key component. Energy storage can provide many essential benefits such as improved efficiency in energy systems, the conservation of fossil fuels and increased grid stability (Aneke and Wang, 2016). Stability in the grid means that there is a balance between consumption and production within the electrical grid. Simply, the amount of energy consumed has to be equal to the amount of energy generated. When that equality is not fulfilled, there needs to be adjustments made in the grid in order to maintain stability (Hivepower, 2021). One method that can be used to increase stability is peak shaving. Peak shaving is implemented in order to eliminate peaks in power consumption and level out the load on the electrical grid. (Next Kraftwerke, 2022).

Many of the green energy sources available today, such as sun and wind, are intermittent. This means that they experience imbalances. For example; During the summer, the demand for electricity for heating purposes goes down. But it is during the summer that solar panels produce the most energy. This is true for many intermittent energy sources: When the electricity demand is at its lowest, they are at peak production. That leads to a surplus of energy that is left unused (Sean, 2019). The same goes for areas where the demand for electrical energy is at times below what the energy provider supplies. If the demand is low yet there is a constant flow provided, energy goes to waste so to speak. Energy storages can accumulate this surplus energy and distribute it into the grid when the demand increases again. This is an especially important feature when the demand exceeds the supply. For example, lithium-ion batteries can charge up with energy and then discharge and send this energy back into the grid. In comparison to other batteries, lithium-ion batteries offer high operating voltages and are compact in size making them a popular way to store energy (Komarnicki, Lombardi and Styczynski, 2017).

Batteries are not the only option. There are many different types of technology used as energy storage today, although they differ in technological advancement, accessibility and capacity. The optimal modern energy storage has a high energy density, a minimal environmental impact and can offer a long, as well as reliable, life cycle (Aneke and Wang, 2016).
1.1 Aim
There are several bottlenecks in the electrical grid in the Mälardal area. This leads to a power shortage during part of the year. Since an expansion of the Swedish electrical grid is several years in the future, there is a need for another solution. This solution can come in the shape of new energy storages. Sala-Heby Energi Elnät is looking to install a new energy storage system in the small community of Björnarbo, to prevent these power shortages in the grid on a local level. The aim of this project is to research different possible solutions and investigate whether the chosen energy storage solution is effective and economically viable.

1.2 Research questions
- What is the optimal storage type and size to solve the capacity problem by using peak shaving in Björnarbo?
- Is this storage solution economically profitable why/ why not?

1.3 Limitations
Sala-Heby Energi Elnät supplies services for Sala, Heby and nearby communities. With that said, this report will only treat the community of Björnarbo as our system. Regarding the data provided by Sala-Heby Energi Elnät we are limited as we only have average hourly consumption from January 2014 to December 2021.

1.4 Delimitations
In order to answer the report's research questions the report will limit itself to only examine the more popular and commercially viable options within today's standard. Upon deciding what kind of storage to use, we will only take technical and economical factors into consideration.

2. Background

2.1 Preview of background
In this chapter, we review the different types of energy storage systems we have chosen to focus on. We will also give some background information on Björnarbo as well as the financial aspect of Sala-Heby Energi Elnät’s subscription to Vattenfall AB.

2.2 Björnarbo
As mentioned in the limitations section, this report will limit its examination to the community of Björnarbo. Compared to Sala and Heby, Björnarbo is large when it comes to its area but a lot smaller when it comes to its energy consumption. As a whole, Björnarbo is sparsely inhabited with many summer cottages and with an electricity subscription of 3.5
MW. This makes Björnarbo a great option in the form of a case study as Sala-Heby Energi Elnät is looking into the possibility of implementing a similar solution to the bigger communities of Sala and Heby.\footnote{Oscar Forsman electrical engineer Sala Heby Energi Elnät AB, digital meeting the 28th of march 2022.}

![Figure 1. Map of the electrical grid around Björnarbo and surrounding communities.](image)

### 2.3 Pumped hydro

Pumped hydro storage is one of the most popular energy storage alternatives. In 2017 pumped energy storage accounted for 95 percent of the utility-scale energy storage in the United States (EESI, 2022). Pumped hydro storage is also used all over the world and the first example of its usage can be found in Italy and Switzerland in the 1890s (Pumped Storage Hydropower, 2022).

Just as a hydropower plant, pumped hydro storage is dependent on an elevation between an upper reservoir and a lower reservoir where the electricity is generated as the water from the upper reservoir passes through a turbine to the lower reservoir. Pumped hydro storage can be seen as a giant battery as it stores energy that can be released when necessary, usually during periods of high electricity demands (Pumped Storage Hydropower, 2022). During periods of lower demand the upper reservoir is recharged by pumping up water from the lower reservoir. This usually takes place during nights or weekends when the demand and cost of electricity is lower (Pumped Hydropower, 2022).

Pumped hydro storage can be very useful as it provides stability, storage capacity and energy-balancing to the grid. Historically, pumped hydro storage has been used to respond to large changes in the electrical load very quickly. Pumped hydro storage is also useful in its
ability to provide capacity firming and grid stability in the case of wind and solar intermittency. Another advantage of pumped hydro storage is its efficiency. In most cases reaching over 80 percent it exceeds the likes of hydrogen storage and rivals the other common energy storage options (Pumped Hydropower, 2022)

2.4 Hydrogen

One way to store energy is by using hydrogen. This type of storage involves a process in which the excess energy created by renewables, or fossil fuels, is used to power electrolysis during periods of low demand (Östberg, 2017). During electrolysis an electric current is passed through water in order to separate hydrogen from oxygen. The hydrogen can then be combusted in order to create electricity. It can also be used in fuel cells and hydrogen powered vehicles.

Hydrogen can be stored both as gas and as a liquid. Usually, the storage of hydrogen in its gaseous form requires tanks with an internal pressure of 350-700 bar. When storing hydrogen in its liquid form it needs to be kept at a very low temperature to prevent it from boiling away. The storage of hydrogen has proved a challenge for stationary implementations as well as transportational ones since it demands relatively large storage facilities, especially in its gaseous form (Energy.gov, 2022).

One of the biggest advantages of hydrogen is that when combusted by using oxygen the only byproduct created is water vapour. Another, and important, property of hydrogen is that it has a high energy density (Östberg, 2017). Its energy density is about 120 MJ/kg which equals 33.6kWh of accessible electrical energy per kilogram of hydrogen (Molloy, 2019).

However, since hydrogen is the smallest atom in the periodic table, it is difficult to isolate and conserve. Along with this comes the fact that when hydrogen comes in contact with oxygen it creates an explosive reaction (Östberg, 2017). For this to happen, the concentration of hydrogen gas in air has to be somewhere between 18,2- 58,9% (Dorotheev et al,1994). A relatively high concentration, but enough to raise concern about the possibility of an explosion at the facilities where the hydrogen is stored.

2.5 Flywheels

The flywheel (also called a mechanical battery) is a type of rotating mechanical apparatus. A flywheel is made up of a rotating mass situated in its centre that is driven by a motor. Usually the mass in the centre is shaped like a disc that is connected to the shaft of an electric machine (Mousavi et.al., 2017). The rotational force of the mass drives the electric machine, similar to a turbine. This, in turn, creates electricity which can be delivered to the electric grid when necessary. Simultaneously, the rotation of the rotating mass slows down. By using the motor the rotation of the mass can be increased again, regenerating the kinetic energy of the flywheel.
Flywheels can acquire energy from intermittent energy sources and then deliver that energy back into the electrical grid when needed. They can also respond to changes in the grid instantly (Mechanical Energy Storage, 2022). However, this instant output is not great in magnitude (Mousavi et.al., 2017). Traditional flywheels were made with steel and had a relatively simple design but today more advanced flywheels are made with materials like carbon fibre and are stored in vacuum to prevent drag and maximise capacity. This enables them to rotate at a rate of up to 60 000 RPM (Mechanical Energy Storage, 2022).

Because of their efficiency, easy maintenance and low environmental pollution, flywheels have been used as technological solutions in vehicles, aerospace engineering and power stations. But flywheels are limited by their size. In order to consistently supply electricity, the flywheel must be able to store so much kinetic energy that the system keeps rotating for an extended amount of time. In order to achieve this, the rotating mass must be substantial in size. If the rotating mass of the flywheel is too large the system will transfer great forces onto its bearings, causing them to fail. How one designs a large enough flywheel that can reliably produce electricity over a prolonged time period and hold up over time without failing is therefore a dilemma for modern flywheels (Mousavi et.al., 2017).

2.6 Battery

Energy storage in the form of batteries is not a new concept as it has been used since the early 1800s, the first ones being lead-acid batteries. However, due to their low energy density and short life cycle they are not very popular for grid storage. Since then, the technical development of batteries has grown tremendously and today there are plenty of different options on the market (EESI, 2022).

Energy storage in the form of batteries are mostly used for short-term energy storage and the most common one is lithium-ion (Li-ion) batteries, controlling more than 90 percent of the global grid energy storage market. In recent years Li-ion batteries have also become a more competitive option for long term storage as well from new innovations like replacing graphite with silicon to increase its power capacity. (EESI, 2022).

Li-ion batteries have plenty of advantages compared to other rechargeable battery technologies. The energy density of the Li-ion battery (100-265 Wh/kg or 250-670 Wh/L) is one of the highest among different kinds of today's battery technology. Furthermore, Li-ion battery cells have the ability to deliver 3.6 Volts which is higher than other technologies such as nickel-cadmium (Ni-Cd) and nickel-metal-hydride (Ni-MH) batteries. This leads to Li-ion batteries being able to deliver high-power applications with a large amount of current. Li-ion batteries also have low maintenance compared to other technologies and do not require a scheduled cycling to maintain its battery life. Another advantage of the Li-ion battery is that it does not suffer from something called memory effect (reduction in the longevity of a rechargeable battery's charge, due to incomplete discharge in previous uses), something both Ni-Cd and Ni-MH batteries can develop (Lithium-Ion Battery - Clean Energy Institute, 2022).
Despite all the advantages of Li-ion batteries mentioned above, they are not problem free. Safety is one problem as the Li-ion batteries at high voltages have a tendency to overheat and be damaged. Another problem is the cost, which is around 40 percent more than Ni-Cd (Ibid). However, new innovations and a larger production of Li-ion batteries have made the price go down over the years (EESI, 2022).

When a battery is integrated into a storage system, it is sometimes called BESS. BESS stands for battery energy storage system. This is the term that will be used when referring to a battery as part of an energy storage.

The key characteristics for a BESS are related to the amount of energy that it itself can accumulate and later deliver. One of these characteristics is rated power. Rated power is the maximum amount of power that the BESS can provide. This is measured in MW and kW. The energy capacity of a certain kind of battery, that is implemented in a BESS, is important as well. Energy capacity is measured in MWh or kWh. The energy capacity dictates the amount of energy that the BESS can store. Another important aspect of a BESS is its state of charge. The state of charge is, simply put, the amount of energy the BESS has at its service at a certain point in time. The state of charge is usually measured in percentages. A battery, and as a result, a BESS does have an expected life cycle. What constitutes the life cycle of a battery is the amount of times it can be charged and discharged before needing to be replaced. The efficiency of a battery and, in turn, a BESS is also limited to its own capability to charge or discharge. When determining the efficiency of a BESS, its own capability to charge or discharge is examined. The aspect of discharge takes into account electrical losses as well as losses due to self-discharge (Solartechadvisor, 2021).

2.7 Peak Shaving

Peak shaving refers to a method of levelling out peaks, or spikes, in electricity consumption. Peak shaving can be achieved by either using a power generation system, briefly scaling down production or relying on a battery. The goal by doing this is to reduce power consumption for a short period of time in order to avoid peaks in the amount of energy consumed (Next Kraftwerke, 2022).

2.8 Economical factors

Sala-Heby Energi Elnät pays Vattenfall Eldistribution AB a flat fee for their electricity subscription. In addition to the flat fee, they also pay an annual power fee depending on how large said subscription is, in this case being 3.5 MW. On top of the flat fee and annual power fee, Sala-Heby Energi Elnät pays for something called a transmission fee. The transmission fee is equivalent to the cost of transferring the electricity. This cost varies between two different prices. The first and higher price is during high load, occurring on weekdays 06-22 from the months of November to March. During the remaining hours of the year, the lower price is used (Vattenfall Eldistribution AB, 2022).
Besides contributing with grid stability and other advantages, an energy storage system can aid with some economical aspects. In the case of Björnarbo, if the electricity demand in Björnarbo exceeds Sala-Heby Energi Elnät’s subscription they need to pay a penalty fee. Calculating this fee is done by looking at the two months with the highest maximum consumption during one hour and taking the mean value of those two (this value will later in the report be referred to as the Max mean value). If that value exceeds their subscription they are obligated to pay double for that exceeding amount. Therefore, with the use of an energy storage system Sala-Heby Energi Elnät can shave down those peaks and avoid paying that penalty fee. When it comes to the best way to optimise the usage, it's preferable to charge the system during a time with a lower load as the cost of electricity is cheaper\(^2\).

*Table 1. Electricity cost for Björnarbo.*

<table>
<thead>
<tr>
<th>Flat fee</th>
<th>400 tkr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual power fee</td>
<td>265 kr/kW</td>
</tr>
<tr>
<td>Transmission fee (high load)</td>
<td>11.0 öre/kWh</td>
</tr>
<tr>
<td>Transmission fee (other time)</td>
<td>3.9 öre/kWh</td>
</tr>
</tbody>
</table>

2.9 Lowering the power subscription

As mentioned prior, Sala-Heby Energi Elnät has a subscription of 3.5 MW for Björnarbo. One possibility of implementing a battery storage unit besides peak shaving is the opportunity of cutting down their power subscription to Vattenfall and utilising the battery to support the grid. This would bring down the annual power fee and save Sala-Heby Energi Elnät money. But before taking such a decision it must first be determined if there has been any growth on the load, meaning an increase in power consumption, over the years. Otherwise reducing the subscription could lead to a higher penalty fee if there's any signs that Björnarbo in fact has had an increase on the load and the reduced subscription isn't enough in the future.

3. Methodology

3.1 Preview of methodology

This report was primarily based on the results produced by our MatLab model along with literature studies. In this section we will go through the choice and motivation for our energy storage system as well as the design and function of our MatLab model. Included in this section is also an analysis of our data, a flowchart for our BESS and the economical calculations we relied on.

\(^2\) Oscar Forsman electrical engineer Sala Heby Energi Elnät AB, digital meeting the 5th of april 2022.
3.2 Choice of storage system

First, given the information we collected surrounding the different types of energy storage options we determined what kind suited our system the best. This was done by comparing them against each other whilst taking our system's conditions into consideration. There are two important characteristics associated with each type of energy storage option that are to be taken into account when deciding which option to choose. The first one is storage capacity. This refers to the specific amount of energy that can be accommodated by the energy storage. The second one is weight specific energy which is energy per unit mass.

Batteries can discharge power over a longer time than flywheels. Because of their weight specific energy, flywheels are not used for providing energy for a longer duration of time (Hedlund et.al., 2015). This means that batteries are more suitable for a grid that needs a continuous and stable supply of power. Since lithium-ion batteries are an energy storage option that is already well established on the energy market it makes for a reliable choice since methods for installing, operating and maintaining them are already in place. Something that is worth considering when choosing batteries as an energy storage solution is that they don’t last forever. They do lose a small fraction of their efficiency for every cycle, which is something that needs to be taken into account. The battery or batteries that are installed must also have the energy capacity needed to successfully support the grid.

In comparison to some other storage options, the cost of Li-ion batteries are relatively high. But, the price of Li-ion batteries has decreased perpetually over the last thirty years, showing a clear trend of decline (Ziegler and Trancik, 2022). As of 2021 the price of Li-ion batteries is $132 per kWh (Firth, 2022). Converted into Swedish crowns this amounts to 1327kr.³

Worth mentioning is that financial gain isn’t always the main goal. Installing an energy storage system might come with technical benefits that out do the financial costs. These benefits could come in the shape of increased flexibility in the grid, increased stability in the grid as well as a possibility for future participation in the market of the frequency containment reserve.

In order for the Swedish power grid to function optimally, the frequency in the grid needs to be kept at 50.00 Hz. When the frequency fluctuates, power either needs to be added to the grid or removed from it. The market of the frequency containment reserve allows energy consumers to sell their excess energy to the grid operator in order for them to keep the frequency at 50.00 Hz (Energy Plaza.se, 2021).

3.3 MatLab model

We acquired our data from our contact at Sala-Heby Energi Elnät. That data being the hourly consumption over the last eight years, from the first of January 2014 to the last of December 2021. Using MatLab we analysed the data and constructed an algorithm on how to optimise

³ This number is based on the exchange rate between United States dollar (USD) to Swedish Krona (SEK) on the 16th of May 2022.
the use of a battery as an energy storage unit, a BESS. The algorithm determines whether and when the BESS should charge or discharge and its own state of charge. When the demand exceeds a certain threshold the BESS discharges its stored energy into the grid. When the demand is below that threshold the BESS charges up again. By optimising this process, the result would be a BESS that immediately starts charging when the demand is below the threshold. As soon as the demand reaches the threshold, the BESS supports the grid by shaving down the peaks or clipping them entirely. The model also took into account the efficiency of Li-ion batteries, which is estimated to be 80% - 95% (Johnsson and Wingren, 2018). The percentage used in this project is 95%.

The algorithm was constructed so that it was able to find an optimal size, or, energy capacity for the BESS. To find this optimal size the algorithm calculated the smallest energy capacity needed to support the peak shaving. This value was determined by iterating through all data and testing whether the BESS had enough energy capacity to shave off the peaks. For every iteration the energy capacity was increased until all full peak shaving was successful.

Below follows a flowchart of the algorithm. It iterates through the data over the average hourly consumption of energy for each year. The average consumption for each hour is the incoming data value, our Pload(i). The algorithm decides whether this value is above the set threshold, our Pthresh. If the value exceeds the threshold the algorithm checks if the BESS has enough energy capacity to support full peak shaving. If it does, the BESS discharges. The outgoing data value, Pgrid(i) is then set to be equal to Pthresh(i) meaning that when Pgrid is plotted, it can be seen that the peaks have been shaved off, see figure 4 and figure 5. If the BESS does not have enough energy capacity to shave off the peak, Pgrid(i) is set to Pload(i). This means that the peaks have not been shaved, which again can be visualised by plotting Pgrid. If the value of Pload(i) does not exceed the threshold the algorithm checks if the BESS is fully charged. If it is not, the BESS starts charging. If the BESS is already fully charged nothing has to be done. This process is repeated for every single hourly data, for every hour of each year.
Figure 2. Flowchart of MatLab model (for leap years the end value was set to 8784).
3.4 Trend and temperature correlation

To analyse if a potential trend can be determined from our data, the Max mean value was first calculated for each year. This can be seen below in table 2. The Max mean value was then plotted over the years 2014 to 2021 and a linear trend line was added with corresponding R-squared value, see figure 3. The R-squared value describes the trendlines' accuracy. A value closer to 1 is to be seen as more accurate and values below 0.5 should not be considered as significant (Pryor.com, 2022).

Björnarbo has not gone through any major expansion in regards to new industries or an increase in population over the years. Therefore, if a trend cannot be determined, is it reasonable to assume that any outlying Max mean values depend on something else than a trend of increased power consumption. These high Max mean values could instead be explained by extreme weather, as colder weather increases power consumption in households. When a trend can not be seen, the extreme cases will be further looked upon in order to investigate if the higher Max mean values in fact can be explained by colder temperatures. This will be done by comparing the hours for when the Max mean value peaked to data from the Swedish Meteorological and Hydrological Institute, SMHI. SMHI has a database of recorded temperatures for every day over the past several years. By comparing the temperature of two previous years, the increase in Max mean value could be attested to a significant difference in average temperature rather than a trend of increasing power consumption.

3.5 Economical calculations

The financial factors surrounding the BESS that were taken into account in this report were; cost of the BESS, the cost of penalty fees resulting from exceeding the annual energy subscription as well as the amount saved by lowering the annual subscription to Vattenfall.

Since the cost of Li-ion batteries is $132 or 1327kr per kWh, $C_{batt}$ is

$$C_{batt} = B_{cap} kWh \cdot 1327kr/kWh$$  \hspace{1cm} (1)

where $B_{cap}$ is the BESS's energy capacity measured in kWh. $C_{batt}$ is calculated in Swedish crowns. The annual fee Sala-Heby Energi Elnät pays to Vattenfall is 265kr/kW as mentioned in chapter 2.8 on economical factors. Because their current subscription is 3.5MW, which is equal to 3500kW, the current annual subscription fee can be defined as

$$F_{current\ annual\ sub} = 3500 kW \cdot 265 kr/kW = 927500 kr$$  \hspace{1cm} (2)

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4 Oscar Forsman electrical engineer Sala Heby Energi Elnät AB, digital meeting the 11th of may 2022.
The lowered subscription fee is defined as

$$F_{\text{new annual sub}} = x \cdot kW \cdot 265\,kr/kW$$

(3)

where $x$ is the new subscription measured in kW. This means that the annual amount saved by lowering the subscription, $C_{\text{sub}}$, is therefore

$$C_{\text{sub}} = F_{\text{current annual sub}} - F_{\text{new annual sub}}$$

(4)

The accumulated amount saved during our 8 year period is

$$C_{\text{total sub}} = C_{\text{sub}} \cdot 8$$

(5)

since $C_{\text{sub}}$ remains the same value over all 8 years.

On top of the annual fee, Sala-Heby Energi Elnät pays a penalty fee if the energy consumption exceeds their annual subscription to Vattenfall. The annual penalty fee is determined by taking the amount of kWh the Max mean value exceeds the annual subscription with, times twice the cost of the annual power fee. This penalty fee is what we call our $C_{\text{penalty}}$ and is calculated as

$$C_{\text{penalty}} = \text{Max}\text{M exceed}\,kW \cdot 2 \cdot 265\,kr/kW$$

(6)

Where $\text{MaxM exceed}$ is the difference between the annual Max mean value and the annual subscription. The total sum of penalty fees will be called $C_{\text{total penalty}}$. This is the accumulated cost of penalty fees over our 8 year period.

The total cost, $C_{\text{cost}}$, is calculated as follows

$$C_{\text{cost}} = C_{\text{batt}} + C_{\text{total penalty}}$$

(7)

The subsequent economic impact of the implementation of a battery, $C_{\text{tot}}$, was calculated as the difference between the total amount saved and the total cost.

$$C_{\text{tot}} = C_{\text{total sub}} - C_{\text{cost}}$$

(8)
4. Results

This section includes our results. The most suitable energy storage option was determined to be a BESS composed of Li-ion batteries. No trend in energy consumption could be found, meaning that Sala-Heby Energi Elnät could lower their power subscription to Vattenfall from 3.5MW to 3.3MW. The optimal size for the BESS was determined to be 500kWh. Technical as well as financial consequences of implementing this type of BESS whilst lowering the power subscription follow below.

4.1 Data analysis for deciding on a new power subscription

4.1.1 Trend

As seen in figure 3, the R-squared value reads 0.007081 and should therefore not be seen as a significant trend. As a significant trend could not be seen it is important to see if the varying Max mean value could be explained in some other way. One explanation for the higher Max mean value could be attributed to colder temperatures during the time of the highest recorded energy consumption as more electricity would be required for heating.

What we found was that for the years when the Max mean value was high, at least one of the calendar months was extremely cold. The Max mean value peaked in 2021 and 2016. During 2021 the two months that produced the Max mean value were February and December. The peaks in electricity use occurred on February 10th and December 7th. The mean temperature recorded at the nearest weather station during these two days was -9.5 °C and -15.3 °C respectively. These temperatures are below average (SMHI, 2022). During 2016, the values that produced the Max mean value occurred on January 15th and February 16th. These two days also had temperatures below average. Thus, the peaks in the Max mean value are likely to be the result of an unusually cold winter, rather than an increasing trend in electricity usage.

<table>
<thead>
<tr>
<th>Max mean value (kW)</th>
<th>3829.5</th>
<th>2783.5</th>
<th>3427.5</th>
<th>3419.5</th>
<th>3171.5</th>
<th>3483.5</th>
<th>2949.5</th>
<th>3295.5</th>
</tr>
</thead>
</table>

*Table 2. Max mean value 2014-2021.*
4.1.2 Deciding on a new power subscription

No trend could be found when analysing the Max mean values and the peaks in the Max mean values could be explained as having been caused by factors relating to weather. This means that there is an option for Sala-Heby Energi Elnät to lower their energy subscription to Vattenfall. Instead of a subscription of 3.5MW, a lower subscription could be proposed.

By calculating the average of the Max mean values we acquired an idea of how large the Max mean value is expected to be as long as there isn’t a trend. Thus, this average of the Max mean value provides a relevant starting point of what the new power subscription to Vattenfall should be. This number turned out to be 3.295MWh. To be on the safe side, it was rounded up to 3.3MWh. Implementing this new threshold in our MatLab model meant that the peak shaving would now be at 3.3MWh instead of 3.5MWh. To find an optimal energy capacity for the BESS, all data for each respective year was iterated through in the same way as before until the smallest amount of energy capacity needed to support full peak shaving for each respective year was found. Since our data spanned 8 years this process yielded 8 different suggestions on energy capacity. After evaluating these 8 suggestions with respect to economical and technical factors, the most suitable option was chosen. It became obvious that a BESS with an energy capacity large enough to support full peak shaving for all years would simply be oversized and too expensive. Instead, the BESS’s energy capacity was set to a
value such that, while not being able to fully shave the peaks off, the financial savings made by lowering the energy subscription 3.3 MW were greater than the losses caused by the penalty fees.

4.2 Economical analysis and technical analysis

After reviewing the different energy storage systems we chose to include in this report, our conclusion was that a BESS would be the best option.

Running our MatLab model with a threshold at 3.3MW yielded the results seen in table 3. Each year gave a different result since each year had different data peaks. The null values are caused by the energy demand simply not reaching the threshold that year. During 2021 and 2016, when the demand was unusually high, the BESS would have required a very high energy capacity.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy capacity (kWh)</td>
<td>15 817</td>
<td>0</td>
<td>420</td>
<td>374</td>
<td>174</td>
<td>13 042</td>
<td>0</td>
<td>181</td>
</tr>
</tbody>
</table>

Table 3. The minimum energy capacity required to support full peak shaving for every year

![Figure 4. Consumption in Björnarbo during 2019 before peak shaving.](image)
As mentioned before, the assumed cost of a BESS is $132 per kWh, or about 1327 kr per kWh. A BESS that could support full peak shaving during 2021 and 2016 would therefore be unproportionally costly. Instead, a BESS with lower energy capacity was chosen. The capacity that was settled for was 500kWh which was our $B_{\text{cap}}$ value. The reasoning behind setting the $B_{\text{cap}}$ to 500 kWh was that while the BESS would not be able to shave off all peaks, it would shave most of them whilst not being too expensive.

The cost, $C_{\text{batt}}$, of a BESS this size would be 663 500kr, since

$$C_{\text{batt}} = 500 \text{ kWh} \cdot 1327 \text{ kr/kWh} = 663500 \text{ kr}$$

(9)

The penalty fee is zero for all years where the consumption is below 3.3MW, because the BESS can achieve full peak shaving during those years. The BESS did not have enough energy capacity to shave the peaks during 2021 and 2016. This would have resulted in penalty fees for Sala-Heby Energi Elnät. The penalty fee for the year 2021 was calculated to have been
while the penalty fee for 2016 would have been

\[ C_{\text{penalty}} = 183.5 \text{ kW} \cdot 2 \cdot 265 \text{ kr/kW} = 97,255 \text{ kr} \]  

(11)

This means that the total amount that would have been paid in penalty fees during this 8 year period amounts to

\[ C_{\text{total penalty}} = 280,635 \text{ kr} + 97,255 \text{ kr} = 377,890 \text{ kr} \]  

(12)

If the annual subscription is lowered from 3.5MW to 3.3MW this gives us the equation

\[ C_{\text{sub}} = F_{\text{current annual sub}} - F_{\text{new annual sub}} = \]

\[ = 3,500 \text{ kW} \cdot 265 \text{ kr/kW} - 3,300 \text{ kW} \cdot 265 \text{ kr/kW} = \]

\[ = 927,500 \text{ kr} - 874,500 \text{ kr} = 53,000 \text{ kr} \]  

(13)

Meaning that a subscription of 3.3MW instead of 3.5MW would cost 53,000 kr less per year. Over our time period of 8 years, from 2014 to 2021, this would have amounted to a total of 424,000 kr saved since

\[ C_{\text{total sub}} = 53,000 \text{ kr} \cdot 8 = 424,000 \text{ kr} \]  

(14)

The total cost of implementing a BESS would be comprised of the cost of the BESS itself and the penalty fees that would come as a result of lowering the annual power subscription.

\[ C_{\text{cost}} = C_{\text{batt}} + C_{\text{total penalty}} = 663,500 \text{ kr} + 377,890 \text{ kr} = 1,041,390 \text{ kr} \]  

(15)

The difference between total amount saved and the total cost over this 8 year period would have been

\[ C_{\text{tot}} = C_{\text{total sub}} - C_{\text{cost}} = 424,000 \text{ kr} - 1,041,390 \text{ kr} = -617,390 \text{ kr} \]  

(16)

All in all, had Sala-Heby Energi Elnät invested in a BESS with an energy capacity of 500 kWh and implemented it for peak shaving over the years 2014 to 2021, they would have made a total loss of 617,390 kr. Assuming our analysis of there being no significant trend of
decrease or increase in energy consumption is correct, the repayment time for this type of BESS would be another 12 years.

4.3 Sensitivity analysis

There are many factors that contribute to the overall cost of implementing a battery energy storage system. One of them is the sizing of their power subscription as it affects the amount saved and also how much Sala-Heby Energi Elnät would have to pay in the event of a penalty fee. A sensitivity analysis was done with a BESS with an energy capacity of 500kWh and varying subscription sizes from their existing one of 3.5 MW down to one at 3.0MW (see table 4). The cost for the resulting penalty fees was calculated using equation (6). In table 5 below, the amount of money Sala-Heby Energi Elnät could save on varying reductions of their subscription is displayed. This was calculated to determine the total amount saved or lost using equation (4) and subtracting the total from Table 4.

<table>
<thead>
<tr>
<th>Subscription (MW)</th>
<th>3.5</th>
<th>3.4</th>
<th>3.3</th>
<th>3.2</th>
<th>3.1</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>174 635</td>
<td>227 635</td>
<td>280 635</td>
<td>333 635</td>
<td>386 635</td>
<td>429 635</td>
</tr>
<tr>
<td>2020</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2019</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>73 405</td>
<td>148 135</td>
<td>226 575</td>
</tr>
<tr>
<td>2018</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>67 840</td>
<td>94 340</td>
<td>129 585</td>
</tr>
<tr>
<td>2017</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>37 895</td>
<td>90 895</td>
</tr>
<tr>
<td>2016</td>
<td>0</td>
<td>44 255</td>
<td>97 255</td>
<td>150 255</td>
<td>202 195</td>
<td>228 659</td>
</tr>
<tr>
<td>2015</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2014</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>33 655</td>
<td>74 955</td>
<td>13 303</td>
</tr>
<tr>
<td>Total 2014-2021 (SEK)</td>
<td>174 635</td>
<td>271 890</td>
<td>377 890</td>
<td>658 790</td>
<td>944 155</td>
<td>1 118 652</td>
</tr>
</tbody>
</table>

Table 4. Penalty fee each year with a BESS (500 kWh)
Table 5. Total amount saved over the period 2014-2021

<table>
<thead>
<tr>
<th>Saved on subscription</th>
<th>3.5</th>
<th>3.4</th>
<th>3.3</th>
<th>3.2</th>
<th>3.1</th>
<th>3.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annually (SEK)</td>
<td>0</td>
<td>26 500</td>
<td>53 000</td>
<td>79 500</td>
<td>106 000</td>
<td>132 500</td>
</tr>
<tr>
<td>Total saved 2014-2021</td>
<td>0</td>
<td>212 000</td>
<td>424 000</td>
<td>636 000</td>
<td>848 000</td>
<td>1 060 000</td>
</tr>
<tr>
<td>Total ± 2014-2021</td>
<td>-174 635</td>
<td>-59 890</td>
<td>46 110</td>
<td>-22 790</td>
<td>-96 155</td>
<td>-188 685</td>
</tr>
</tbody>
</table>

As seen from the tables above, a subscription of 3.3 MW is the only option resulting in a positive net gain given a BESS with an energy capacity of 500 kWh.

5. Discussion

After reviewing some of the most commonly used energy storage options available today it was determined that the type that suits this project the best is the lithium-ion battery implemented in a BESS. Lithium-ion batteries take up little space while still being very effective. Unlike hydrogen, batteries can be stored above ground under normal pressure and temperature. They can be stored in containers, for example, and can be moved to different locations. Neither does the implementation of batteries call for landscaping projects or the construction of dams which would have been the case if pumped hydro had been chosen instead.

Since a construction of a pumped hydro-plant is not possible at the moment in Björnarbo, this option is not suitable. Hydrogen energy storage systems demand a large storage facility, making their total storage capacity unsuitable for this project. Our results show that by installing a lithium-ion BESS with an energy capacity of 500kWh, that is used for peak shaving only, Sala-Heby Energi Elnät would be able to lower their annual power subscription to Vattenfall by 0.2MW. The sensitivity analysis shows that this decrease in power subscription, from 3.5MW to 3.3MW is the only option that has a positive net gain. This equates to a power subscription that costs them 53 000kr less, annually. When the BESS is used for peak shaving, Sala-Heby Energi Elnät could avoid paying penalty fees and thereby make some further savings. However, the BESS can only shave the peaks if it has enough capacity. If the peaks are too large, and the battery doesn’t have the capacity to shave them completely, it won’t shave them at all. When this happens, Sala-Heby Energi Elnät will have to pay a penalty fee. But, in this case, the total savings made over the 8 year period would have been greater than the total amount of the penalty fees. Perhaps, if our algorithm had allowed for partial shaving of the peaks, the savings could have been even greater.
This report relied on data which consisted of the average hourly energy consumption from January 1st 2014- December 31st 2021, which is a rather long period. But since we couldn’t detect any trend of either increase or decrease in energy consumption over these years, it is reasonable to assume the consumption will remain unchanged in the future. This implies that our calculations of the amount of possible savings are reliable when making predictions about the years to come.

The main drawback of using a BESS with lithium-ion batteries is that lithium-ion batteries are very expensive. Even though some savings relating to Sala-Heby Energi Elnät’s power subscription can be made from installing one, the total cost of a BESS with a 500kWh energy capacity will be far greater than those savings. A BESS is not economically profitable in the short-term. After our time period of 8 years (2014 to 2021) the BESS’s cost is greater than the savings it provides. When this type of BESS is used for peak shaving only, our calculations show that the BESS would be repaid after an additional 12 years. If there are no significant changes in the power demand, which our trend analysis suggests there won’t be, the BESS would not start to make revenue until after this amount of time. Even though the financial pros are not obvious the first couple of years, this type of BESS could be profitable in the long run. Furthermore, a BESS of this kind will have a long life-span since it is quite rarely used, thus preserving its cycles. This also speaks to the idea that a BESS is more of a long-term solution in this case. However, as mentioned previously, it is important to note that a BESS loses some of its efficiency for every cycle. If this had been taken into account in our model, the repayment time might have turned out to be longer.

In order to shorten the repayment period, the BESS could be used in order to participate in the market of the frequency containment reserve, which would serve as a source of profit. As seen in table 3 in section 4, during the years 2020 and 2015, the BESS was not “necessary” in regards to peak shaving. This opens up further possibilities for other ways to increase revenue, participation on the frequency containment market being only one of them. Something else that could produce savings, that might in time add up to the total cost of the BESS, is optimising the BESS with respect to low-load hours and high-load hours. By optimising the BESS in this way, it would charge during low-load hours when the transmission fees are 3.9 öre/kWh. It would then be able to discharge this energy back into the during high-load hours when the transmission fees are 11.0 öre/kWh, thus saving money and shortening the repayment time. Another thing that a BESS can be optimised for is the hourly spot price for electricity. The hourly spot price for electricity fluctuates depending on the state of the energy market. By optimising the BESS in this manner, it would charge when the price of energy is low and then discharge when the price rises again, thus increasing its financial utility.

A BESS that is optimised with respect to low-load hour and high-load hours, whilst still being able to shave peaks and contribute to the frequency containment reserve is an interesting subject for future research.
6. Conclusions

With the help of a BESS, there are indications that Sala-Heby Energi Elnät can save money by reducing their power subscription to Vattenfall from 3.5MW to 3.3MW and allowing the BESS to shave down potential peaks above the new subscription limit. The optimal size, or energy capacity, of this BESS was determined to be 500kWh.

However the cost of BESS:s today, even though the cost has been declining over the last couple of years, is still very high. This makes for a long repayment time. Our data spanned over 8 years, from 2014 to 2021. Had the power subscription been lowered to 3.3MW and our BESS implemented at the beginning of that time span, Sala-Heby Energi Elnät would still have to wait many years before the BESS would provide revenue. In fact, had a BESS with an energy capacity of 500 kWh been installed at the beginning of 2014, the difference between the losses and profits would still make up a total loss of 617 390 kr by the end of 2021. A BESS is therefore to be considered a long-term solution, not a short-term one. Especially in this case, when the BESS is used for peak shaving only. If the BESS’s life cycle is long enough, the expense will eventually be repaid. But, if the goal of installing an energy storage system is to make immediate profit, a BESS is not the way to go. There is, however, the possibility to make profit in the long run.

A BESS allows for opportunities in frequency market participation as well as optimisation of low-load hours and high-load hours. This would provide a source of profit and a BESS which would be able to minimise transfer fees. We found no trend in our data that would indicate an increase in energy consumption, which further promotes a BESS as a long-term solution for Sala-Heby Energi Elnät.

A BESS is still the best option for an energy storage in Björnarbo. The other options lacked either the capacity, flexibility or sophistication needed for this system.

For future studies it would be interesting to look into how the addition of frequency market participation would impact the cost and viability of a battery energy storage system. This would allow Sala-Heby Energi Elnät to gain some revenue and help shorten the repayment time. It would also be relevant to investigate the financial savings made by optimising the battery to high-load hours and low-load hours.
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Books, articles and reports


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