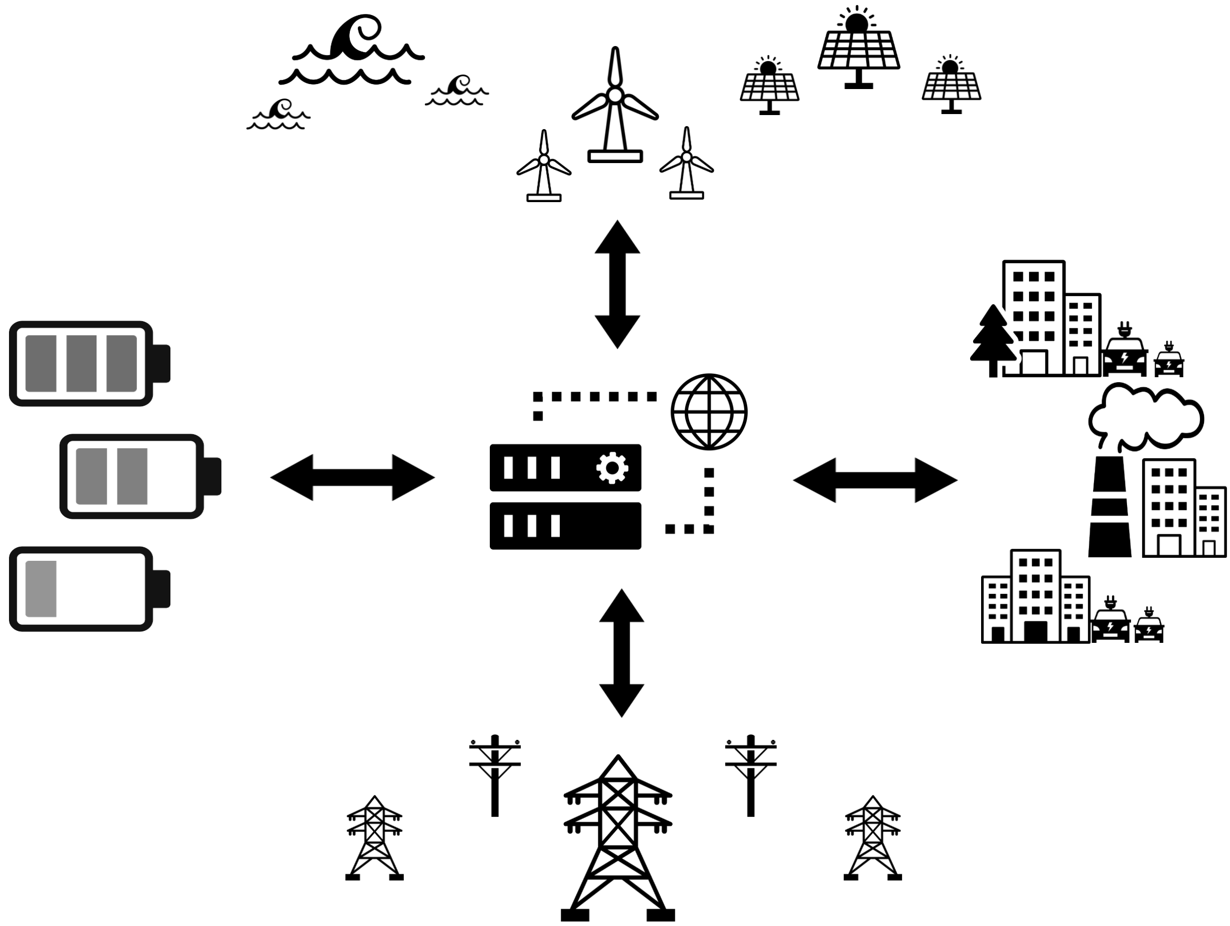

On drivers, barriers, and design parameters for implementation of microgrids in the Swedish power grid

Bachelor's thesis in Electrical Engineering

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Cover: A visualization of a microgrid.

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Abstract

Microgrids are emerging in the power grid due to the increasing local integration of renewable energy sources (RES) and electrification of the industries and other energy sectors [1]. This thesis aims to create a model for estimating the dimensions of an energy storage system (ESS). Extensive literature review and interviews have been carried out to identify drivers and barriers for microgrid implementation in Sweden. Furthermore, a local distribution grid has been adapted as a case study to conduct the analysis.

The thesis has found that the integration of RESs and the introduction of energy communities facilitate potential microgrid operation of the local distribution grids. However, the thesis has identified the main barriers which include current laws regarding ESSs and island mode operation. The case study has found that a diversified grid with multiple types of loads and power sources decreases the requirements of an energy storage system. Furthermore, the case study concludes that the implementation of microgrids, including ESSs,in the Swedish distribution grid are currently possible with today's technology standards, within certain limitations.

Sammanfattning

Mikronät växer fram i elnätet på grund av ökad lokal integration av förnyelsebara energikällor och elektrifiering av industrier och andra sektorer [1]. Detta arbete syftar till att skapa en model för att dimensionera ett energilagringssystem. Omfattande litteraturgranskning och intervjuer har utförts för att identifiera drivkrafter och hinder för implementeringen av ett mikronät i Sverige. Vidare har ett lokalt distributionsnät anpassats som en fallstudie för att utföra analysen.

Arbetet har visat att integrationen av förnyelsebara energikällor och introduktionen av energigemenskaper möjliggör potentiell mikronätsdrift av de lokala distributionsnäten. Däremot har arbetet visat att de primära hindrena, vilka inkluderar nuvarande lagar angående energilagrinssystem och ödriftsläge. Fallstudien har funnit att ett diversifierat nät med flera typer av laster och energikällor minskar kraven på energilagringssystem. Vidare har fallstudien funnit att implementering av mikronät, som innefattar energilagrinssystem, är möjligt med dagens teknik inom vissa gränser.

Keywords: microgrid, drivers, barriers, energy storage system, renewable energy sources, power grid

Acknowledgements

This thesis is our last stop on our journey towards a bachelor's degree, in other words, our bachelor's thesis. The thesis is written within the department of electrical engineering.

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Lastly, we would like to thank our near and dear ones for their support throughout this work. Without everyone mentioned above, this thesis would not have been possible to carry out.

Matilda Arvidsson, Max Hessman, Katriine Koit,
Tim Lindberg and Oskar Nordlander Hurtig

Gothenburg, May 2021

Contents

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Acronyms

AC alternating current. 42

BESS battery energy storage system. 3, 19, 43, 48
BNEF Bloomberg New Energy Finance. 2

CEC citizen energy community. 21–25, 47, 48
CEEP Clean Energy for all Europeans Package. 3, 21, 47

DC direct current. 42
DER distributed energy resources. 18, 19, 23, 25, 26
DF demand flexibility. 18, 23, 27, 28, 47
DoE Department of Energy. 8, 18, 52
DSO distribution system operator. 2, 11, 14, 22–26, 28, 30–34, 40, 42, 46

Ei The Swedish Energy Markets Inspectorate. 11, 12, 14, 15, 28, 33, 34, 39, 40, 48
ESS Energy Storage System. ix, x, xiii–xviii, 2, 3, 6, 8, 18, 19, 23, 25, 27, 28, 32, 33, 42, 43, 46, 49–87, 89–94
EU European Union. ix, 2, 3, 5, 21, 22, 39, 42, 44, 45, 48
EV electric vehicles. 32

GDPR General Data Protection Regulation. x, 44, 45

IRENA International Renewable Energy Agency. 2
IT information technology. 26
IVA Kungliga IngenjörsVetenskaps Akademin. 16, 27

li-ion lithium-ion. 2, 3, 19, 38, 42

PCC point of common coupling. 1, 18, 25
PV photovoltaic. xvii, 2, 14, 17, 27, 29, 32, 38, 92

REC renewable energy community. 21–25, 47
RES renewable energy systems. 1–3, 12, 16, 18, 19, 22, 42, 45

SAIDI System Average Interruption Duration Index. 29, 37
SAIFI System Average Interruption Frequency Index. 29, 37
SMHI Meteorological and Hydrological Institute of Sweden. 8, 55
SvK Svenska Kraftnät. 11, 19, 22, 24–26

TSO transmission system operator. 11, 14, 24, 32, 46

US United States. 8, 18, 52

Vattenfall Vattenfall Eldistrubition AB. 5, 26, 42, 46, 48, 91

1
Introduction

In this chapter, an introduction to the state of the Swedish power grid and its reliability issues is given. It also presents how smart grids and microgrids could be possible solutions to the problem. Furthermore, the aim, problem description, and limitations of this project are described.

1.1 Background and Motivation

In 2005,the southern parts of Sweden were significantly affected by the storm Gudrun. Directly after the storm had occurred, 730,000 customers had no power [2]. Many customers were without power for several days, or even weeks, following the storm [2]. As a result of this, in order to minimize future power outages, more than 50,000 km of overhead transmission lines have been replaced with underground ones. The Swedish government also responded by sharpening laws and regulations regarding electricity, stating that power outages should last no longer than 24 hours [3]. Despite this, large-scale power outages are still occurring. A recent example is the storm Alfrida which, in early 2019, prevented approximately 100,000 local grid users from having electricity the day after the storm. A week after the storm, 12,000 users still had no electricity [4].

One solution that is being implemented to improve the reliability and safety of power delivery is smart grids. Smart grids uses two-way flows of electricity to create a distributed energy system. They can respond to events that occur in the grid and change the power flow to continue delivering power [5]. A key part of the smart grid concept is the microgrid which can be implemented to improve reliability on a smaller scale than smart grids [6].

During grid failure, a microgrid is capable of isolating itself from the main grid and make use of its storage system and surplus energy from its renewable energy systems (RES) to keep operating in island mode [7]. Microgrids thus offer local reliability and flexibility. Due to the current global climate conditions, the demand for RES usage is increasing [8] and implementing microgrids could boost RES usage. A microgrid can utilize different energy sources connected to a point of common coupling (PCC), making them appear as one collective unit to the distribution grid. The usage of different types of energy sources leads to challenges when balancing power generation and load demand. Therefore, the system must be controlled and managed properly to ensure reliability for local users [9].

In the past, barriers of implementing microgrids have included high prices for energy sources and storage units, as well as limited energy storage capacity. International Renewable Energy Agency (IRENA)'s 2019 publication presents that costs of electricity produced by solar PVs fell 82 % between 2010 and 2019 [10]. Bloomberg New Energy Finance (BNEF) reported, in their 2019 Battery Price Survey, that prices of lithium-ion (li-ion) batteries fell 85 % from 2010 to 2018 [11]. Since costs of renewable energy production and battery energy storage units have decreased in the last years, implementing a microgrid in Sweden is more relevant from a cost perspective today than it previously has been.

The possible advantages of using microgrids in terms of reliability and environmental benefits, combined with price reductions in recent years, are some of the reasons why a microgrid is a viable alternative to other grid reinforcement solutions today.

1.2 Aim

This thesis aims to identify the different drivers and barriers of implementing microgrids in Sweden. Furthermore the thesis aims to identify key parameters when deciding on where a microgrid could be implemented as a solution to existing problems within the electric distribution system. The thesis also aims to develop a model for estimations of required ESS capacity in terms of power and energy and implement this on an existing load and generation profile.

1.3 Problem description

The electricity market in Sweden is undergoing considerable changes in different ways at the moment [12]. Some of the reasons for this include commitments to decrease carbon dioxide emissions in the Paris Agreements, shutdowns of nuclear plants, new directives from the EU, and increased profitability of intermittent RESs. [12][13]. At the same time, smart technology is developing fast, enabling distribution system operator (DSO)s, consumers, producers, and other actors in the grid to keep track of and control the power consumption in new ways [1]. The grid changes mentioned above, the management of it, in combination with the ongoing technical development, allows for new technical solutions when it comes to our daily power supply.

One of these possible solutions is the microgrid. To fulfill the aim of this report, two main questions regarding the implementation and design of a microgrid in Sweden will be investigated and discussed. These are:

- What drivers and barriers exist for implementing a microgrid in Sweden?
- How can the power and energy capacity of an energy storage system be dimensioned depending on different load and generation profiles?

1.4 Scope

When studying the drivers and barriers of implementing microgrids, the report will focus on legal, technical, time, economic, and environmental aspects. For the legal aspect, both regulations that are currently in effect in Sweden, as well as regulations that are planned for the future (such as the EU's Clean Energy for all Europeans Package (CEEP)), will be considered. However ,the report will not include laws and regulations outside of Sweden and the EU.

When investigating which RESs to include in the microgrid, only those with high availability in Sweden will be discussed. The report will therefore mainly consider solar, wind and, hydro generation. However, only wind power and hydropower generation data were processed in the case study due to limited access to real-time data for energy sources.

The report is only investigating microgrids capable of operating in both island mode and grid connected mode. Costs associated with the implementation of microgrids will not be investigated beyond cost of ESS. Microgrids in Sweden are in the research stadium and the costs associated are therefor not representative. Furthermore, power grids of voltages higher than 40 kV will not be discussed in the report as the microgrids studied are of a smaller scale.

The case study is solely focused on microgrid ESS dimensions for 1 and 24 hour island operation.

As for ESSs, this report will only focus on li-ion batteries and hydrogen storage. The reasoning behind this include that the li-ion battery is the most commonly used battery energy storage system (BESS), controlling more than 90% of the global BESS-market in 2019 [14] and hydrogen storage having many long term storage possibilities and already existing implementations of significant scale [15]. Studying further ESS technologies is not necessary to achieve the aims of the project.

When calculating the maximum ESS energy capacity, it is assumed that both the hydropower plant and the wind power plant is curtailing excess power production meaning that the ESS dimensions is only dependent on the net load.

2
Method

The method used in this report is divided into two parts; one literature study and one case study. They are presented below.

2.1 Literature study

In order to identify the drivers and barriers of microgrid implementation, information and data were gathered through researching scientific articles and studies, collecting data from Swedish grid companies, reading reports and studies performed by actors in the energy and electricity business, and studying Swedish laws. Interviews were also carried out with employees from Vattenfall Eldistrubition AB (Vattenfall) to gain a perspective from the industry. These interviews were mostly used to validate information gathered, thoughts, and assumptions for further discussion, rather than basing results upon it.

The first step was to gather an understanding of the power grid and electricity market, how the Swedish power distribution is evolving, and what defines a microgrid. Parameters associated with functions and components in microgrids were then researched. Each parameter was evaluated as either a driver or a barrier, and sorted into suitable categories. The regulatory and technical aspects, as well as the EU directive, were presented with extensive background information explaining the issue/idea, in some cases alternative solutions, and the impact they could have on microgrids. Other drivers and barriers directly addressed the impact on microgrids.

Dividing the parameters into drivers and barriers, at the same time as providing the background information already in the results, contributes to clarity and improves the reader experience. However, it could contribute to more bias when writing. Overall the combination of reports and articles written by authorities and, energy and electricity companies, in combination with scientific journals, contribute to a broad spectrum of opinions and facts.

2.2 Model case data analysis

In order to investigate how the power and energy capacity of an energy system could be dimensioned, a case study was conducted. The cases studied are modeled from hourly data from an area that includes hydropower, wind power, heavy load (pulp and paper industry), and a small village with a population of just below 10 000[16].

The data includes hourly data points from all four separate connection points. The exact location, and name of the area, are not disclosed in order to preserve the integrity of the population and companies situated in the area.

2.3 Case model calculations

The modeling methods and calculations used are presented in the following sections.

2.3.1 Wind penetration

The wind penetration, which is referred to in this report, is the annual wind penetration. Equation 2.1 below was used to calculate the percentage of the wind penetration for every step when scaling the installed wind capacity. The equation divides the sum of the installed wind power (ΣP_w) with the sum of the demand (ΣP_d) during one year.

$$100 \cdot \frac{\sum_{t=1}^{8760} P_w(t)}{\sum_{t=1}^{8760} P_d(t)} \tag{2.1}$$

2.3.2 ESS $\mathbf{P}_{\max}$ and $\mathbf{E}_{\max}$

This section presents how the maximum energy capacity ($E_{\max}$) and maximum power capacity ($P_{\max}$) of the energy storage system was obtained.

Net load per hour

Equation 2.2 describes how the net load was calculated for each hour. Every load data point is subtracted with the corresponding power generation data point. The 23 extra hours, (1 year = 8,760 hours), are obtained from the first 23 hours of the year 2019 to ensure that every 24 hour period received enough data points to be calculated successfully.

$$P_{nl_n}(t) = P_{l_n} - P_{pg_n}, \text{ for } n = 1, 2, ..., 8783 \tag{2.2}$$

l: load, pg: power generation

1 hour island operation

To calculate $E_{\max}$ and $P_{\max}$ during one hour island operation, the hour with the maximum load or net load during year 2018 was extracted from the time series. This represents both the $E_{\max}$ and the $P_{\max}$ because of the hourly resolution of the data points. This can be seen in the 1 hour island operation tables in section 5.2.

24 hour island operation

Equations 2.2, 2.3, and Algorithm 1, were used to calculate $P_{\max}$ and $E_{\max}$ for 24 hour island operation. The variable n is the hour when island operation starts.

Maximum power capacity

The first $P_{\max}$ was obtained by taking the maximum value of the 24 first net load values in the time series. The second $P_{\max}$ was obtained by taking the maximum value of the 24 next values, incremented by one step. This leaves the first data point out and adds the 25th in order to calculate the second $P_{\max}$. Since data from both of the years 2018 and 2019 was available during the case study, this iteration could continue for 8760 plus 23 extra steps to obtain a $P_{\max}$ for each 24 hour period. When all 8783 values of $P_{\max}$ had been calculated and put into an array, the different percentiles were obtained.

$$P_{max_n} = max(P_{nl_n}, P_{nl_{n+1}}, ..., P_{nl_{n+23}}), \text{ for } n = 1, 2, ..., 8760 \tag{2.3}$$

Maximum energy capacity

$E_{\max}$ for each 24 hour period was obtained by executing a cumulative sum over every net load value in its respective 24 hour period with if-statements. The cumulative sum continues as long as the next value is positive. If the following value becomes negative, it stores the cumulative sum temporarily into a variable and starts over on a new cumulative sum. This continues until it reaches the 24th value of the current period. Then the maximum cumulative sum obtained during the 24 hour period is extracted and put into an array. Every 24 hour period is calculated by taking one step at a time starting with the 1st to the 24th net load value and then the 2nd to the 25th and so on, until it reaches step 8760. Then the array is filled with a $E_{\max}$ corresponding to each 24 hour period. The calculations are made assuming curtailment for both the hydropower and the wind power is allowed and, therefore, all values equal to, or smaller than, zero are disregarded.

Algorithm 1 - 24 hour $E_{\max}$ algorithm

```
E_max[8760] // Create empty array
for n=1..8783 // To 8783 since including the first 23 data points from year 2019
    P_temp = 0 // Reset temporary P_max
    E_temp = 0 // Reset temporary E_max
    for i=1..24
        E_temp24[i] = 0 // Reset temporary energy sum array.
        for k=1..24
            P_temp = P^nl[n + k − 1] // Assigning next net load value
            if P_temp < 0 then
                E_temp24[i] = E_temp // Save the last energy sum and..
                E_temp = 0 // reset the sum
            elseif P_temp ≥ 0
                E_temp = E_temp + P_temp // Update the accumulative sum
            end if
        end for
    end for
    E_max[n] = max(E_temp24)
end for
```

Capacity decrease and ratios

The capacity decrease was calculated by taking the maximum value of the 100th percentile and dividing it by the maximum value of the n:th percentile to obtain the corresponding capacity decrease in either $P_{\max}$ or $E_{\max}$. The ratios are presented in every 24 hour ESS table. These represent the increase of $P_{\max}$ and $E_{\max}$ for a 24 hour ESS compared to a 1 hour ESS.

2.3.3 Percentiles

The percentiles used in different case study figures represent different standard deviations from the mean value, with percentile 68.5 corresponding to one standard deviation, 95 corresponding to two standard deviations, and 99.7 corresponding to three standard deviations. An additional 98th percentile is added due to it being used as a point of reference by the United States (US) Department of Energy (DoE) **98th_percentile**.

2.3.4 Time-series graphs

The one-hour time-series graphs show all cases' hourly net loads in chronological order with percentiles of different hourly maximum power demands shown as horizontal lines. To make the graphs easier to read, the lines of load and net load were plotted as trend lines with a centered moving average of 30 points. This means that for each data point, the average was calculated from the 30 points surrounding the current data point, making the graph less fluctuating. The 24-hour time series graphs show all cases hourly net loads in chronological order with percentiles of different maximum power demands during 24 hour periods shown as horizontal lines.

2.3.5 Duration curves

In the case study, all measurement points were sorted in descending order. Additionally, the measurement points were divided into groups of 24 where the peak value, and the maximum uninterrupted cumulative sum, were calculated for each group, according to the 24-hour $P_{\max}$ and $E_{\max}$ algorithms mentioned earlier in this chapter. A minor difference from the 24-hour $E_{\max}$ algorithm was made so that when a group of 24 values only contained negative values, the minimum cumulative sum was calculated instead. These methods were used to construct the duration curves for one hour and 24 hour periods duration curves of all cases of the case study.

2.3.6 Stormy seasons

To calculate the peak load during stormy periods, the highest measured load value was extracted from the day when the storm occurred. The dates when the storms occurred in Sweden were collected from Meteorological and Hydrological Institute of Sweden (SMHI) [17]. Since the data consists of hourly measurements from 2018 and 2019, $P_{\max}$, has the same value as the peak load and $E_{\max}$. To calculate the 24 hour island operation, $E_{\max}$, the hours during the day of each storm were summed up. These values were then presented in a table.

2.3.7 Scaled wind penetration and scaled load increase curves

In the case study, certain measurement series were scaled with the increase of different parameters. These series were then added to different measurement series. From the resulting series the 24 hour $P_{\max}$ and $E_{\max}$ were calculated using the above mentioned algorithms. The percentiles explained earlier in this chapter were then calculated for each of the resulting series. The percentiles were also calculated for the series of 24 hour $P_{\max}$ and $E_{\max}$ values. This method was used to plot the scaled curves of each c) case in the case study.

2.3.8 Power exchange

Firstly the net load of each microgrid was calculated with equation 2.2, and plotted as time series in a diagram. Secondly, the net load of the two microgrids was summed up per hour and plotted as a red column chart in the same plot. These three plots are then used to visualize the power exchange between the microgrids during island operation.

The energy extracted from the upper grid level was calculated for each microgrid by summing all the positive values, representing the net load not covered by the power generation. The total energy extracted was then obtained by summing the previous sums.

3

Overview of Electricity Grid and Evolution of Distribution Grid

In order to solve the cases presented in the problem description, a basic understanding of how the Swedish electricity grid functions must first be established. In this chapter, an introduction to the Swedish grid structure, the electricity market structure, the physical delivery process of electricity, and the evolution of the distribution grid is given. Moreover, a definition of a microgrid is presented with its most vital functions and requirements.

3.1 Overview of power grid and electricity market

In this section, the focus is to introduce the Swedish power grid and electricity market, describing how they operate.

3.1.1 Introduction to the Swedish grid

Today's electricity market is divided into the electricity and the distribution market. The Swedish electricity market is deregulated since 1996, meaning that the consumer can choose the electricity supplier in their favor. There are several parties involved in the structure of the Swedish power grid, these are [18] [19]:

- Electricity power producers
- The national grid company, the transmission system operator (TSO), Svenska Kraftnät (SvK)
- Electricity retailers
- Regional and local distribution grid companies, the DSO
- The electricity market, Nord Pool
- The electricity consumers
- The Swedish Energy Markets Inspectorate (Ei)

The electric power grid, which includes transmission and local distribution grids, is operated in monopoly, which leads to an obligation to pay tariffs to the DSO of the area. The TSO have the overall responsibility of reliable power transmission on a national level. It is the Ei that regulates the grid and electricity market[20].

3.1.2 Electricity market structure

The market is compromised of large-scale centralized power production, such as hydro- and nuclear power, where the electricity is transmitted from the producers to the consumers. The amount of RESs in the market has increased, which indicates a larger demand for decentralized and weather-dependent power production. These weather-based renewable power generators are intermittent in power production, imposing additional demands on flexibility and balance in the grid [21].

On the Nordic day-ahead electricity energy market, Nord Pool, the electricity retailers buy electricity from producers. Small end users can, on websites such as *elpriskollen.se* provided by Ei, sign agreements with retailers and compare energy prices on the market. In Figure 3.1 this model is shown. The end user's energy retail price is based on the wholesale area price [22].

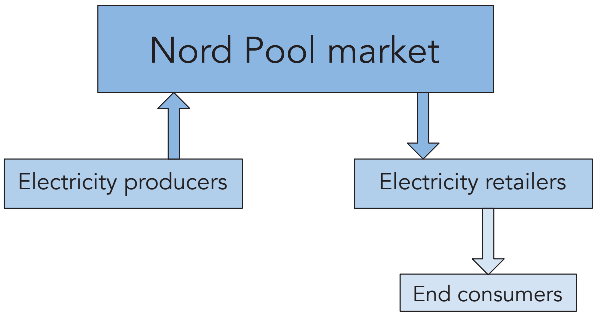

Figure 3.1: An overview of the Swedish electricity market structure.

The grid owner has to negotiate and create an agreement with the power producer, allowing it to connect to the transmission- or the distribution grid. A company cannot produce its own electricity, transfer the produced electricity into its own grid, nor engage actively in the electricity distribution of the grid. Exceptions may be made to these regulations if [23]:

- In the same corporate company, the energy supplier and the distribution company are associated. To achieve a fair market, the corporate group must take special steps to ensure that the affiliated companies cannot exchange information [23].
- The distribution company generates electricity only to make up for the losses of the grid [23].

As seen in Figure 3.2, Sweden is divided into four different price areas. The price of electricity depends on the region where it is consumed. The four different regions are Luleå (SE1), Sundsvall (SE2), Stockholm (SE3), and Malmö (SE4)[24]. In regions SE1 and SE2, there is a surplus of electricity due to high amounts of electricity production and low amounts of consumers. In regions SE3 and SE4, there is a lack of electricity. The reason behind the border placement is insufficiency in the transmission grid capacity. In order to transmit electricity, transmission lines are necessary[24]. However, in places where the main grid capacity is insufficient, natural limitations occur in the grid. The regions were created to shorten the distances between producers and consumers of electricity, making it beneficial to generate electricity where the population density is higher in order to reduce transmission needs [24].

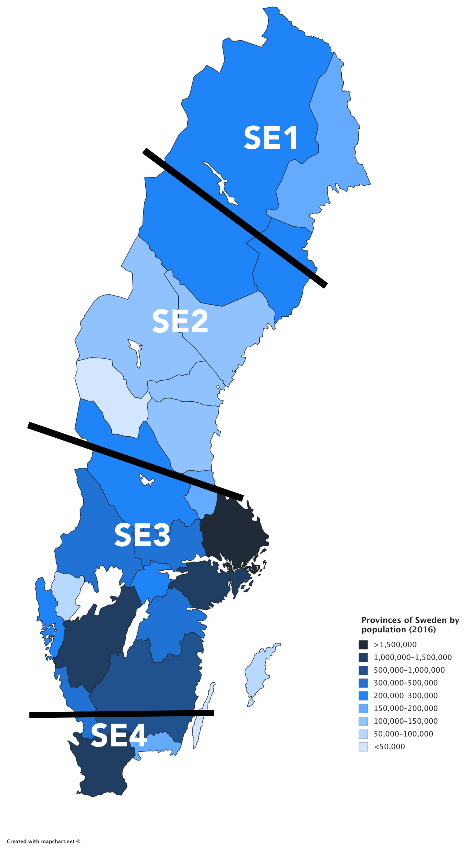

Figure 3.2: The four different energy regions, SE1, SE2, SE3 and SE4 in Sweden with a population density map in the background. The population density map in the background is created by *mapchart.net* [25]. Edits were made to the original image.

The prices vary from region to region. In Figure 3.3 the spot price in öre per kWh on the Nord pool market is visualized. It is clear that the prices are lowest in region SE1 and higher in more southern regions. Prices in the figure exclude value-added taxes and other tariffs for the regions. It is only a visualization of the spot prices per month [26].

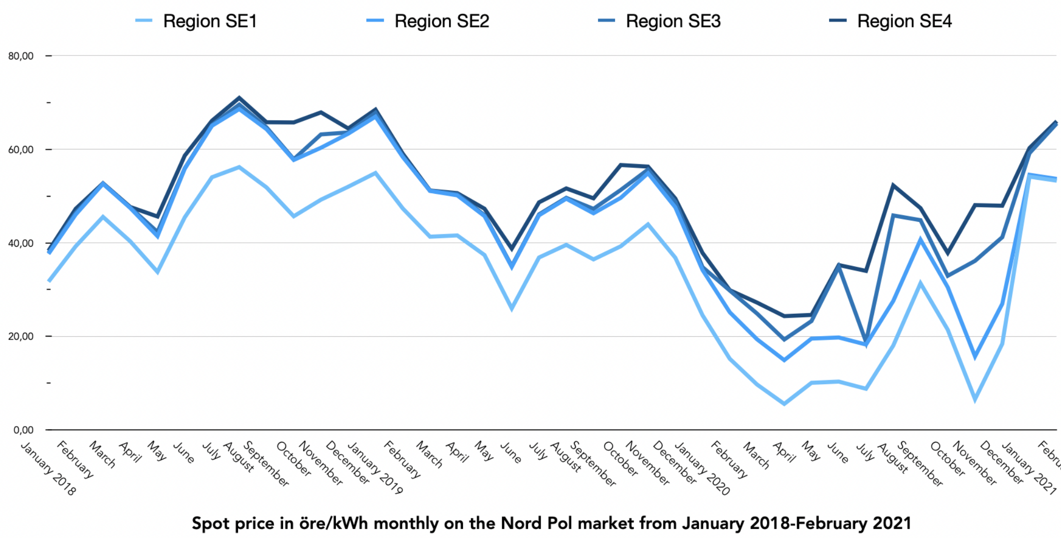

Figure 3.3: Spot price in öre/kWh monthly on the Nord pool market from January 2018 to February 2021.

Furthermore, the national grid consists of approximately 170 DSOs and one government-owned TSO. The TSO owns and operates all parts of the transmission system. The DSO controls the other entities in the system. Permits to operate power lines are issued by Ei and are called concessions [27][23]. More information about concessions is presented in section 4.4.1.

3.1.3 Physical delivery process

An overview of the physical delivery process can be seen in Figure 3.4. The Swedish transmission grid interconnects with the transmission grid in the neighboring countries and they share the same electricity market, Nord Pool. The grid in Sweden follows a hierarchy where the transmission grid is at the top. The transmission grid consists of 400 kV and 220 kV lines. Most of the largest power plants are connected to this grid, transmitting powers in the order of 1000 MW. The main purpose of the transmission grid is to transport power long distances while limiting the losses. When electricity leaves the transmission grid, it enters the regional or sub-transmission grid, where the voltage level is 70-130 kV. Larger industries are connected directly to the regional grid. The next level is the local distribution grid, where the voltage level is 10-69 kV. The purpose of the local voltage grid is to distribute energy within urban areas and industries. Most industries are directly connected to this part of the grid. Urban areas consists of local distribution grids with lower voltages. The lowest level connects to both the end consumers and industries via the low-voltage distribution grid, where the voltage is at 400 V. However, private consumers can also generate electricity, using for example solar PVs, and transfer it to the distribution grid, making them prosumers [28].

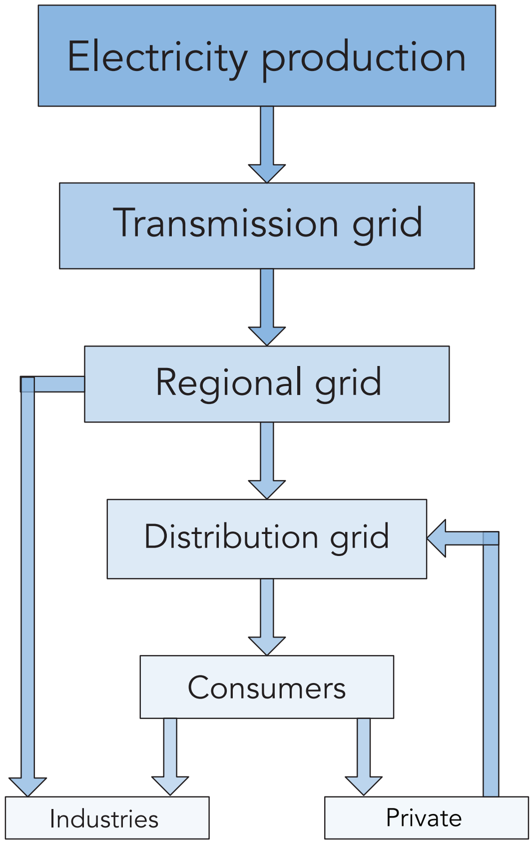

Figure 3.4: An overview of the Swedish power grid structure.

Since the distribution market is regulated, there is no competition between grid companies price-wise. It is Ei who makes sure that the grid companies are not overcharging their customers. Ei sets up a revenue framework that decides how much the grid companies can charge customers, regarding total revenue, in their area over a four year period (the current active period is between 2020-2023). This model will be further analyzed in Section 4.2.4. Furthermore, a tariff system decides how much individual customers are charged [22]. More information about tariffs is given in section 4.4.1.

3.2 The evolution of the distribution grid

As a consequence of new production options for electricity in the grid, mainly RESs, new production can be connected to different instances in the electrical grid. In Figure 3.5, the expected changes in electricity production can be seen. If Figure 3.4, in the previous section, was to be updated for upcoming changes larger connections between the private sector and the distribution grid would be needed due to the increasing amount of prosumers. Exactly where in the grid the new power generators would be connected depends on the capacity of the production unit. It would need to be adapted to the voltage levels of the connected grid. To simplify, it is important to take into account that the small-scale production is connected to the local grid, medium-scale production is connected to the regional grid and large-scale production is connected to the national grid [22].

Not only will the structure of the grid be affected by future changes, but also the electricity market prices. The prices are based on coverage of the cost of operation, cost of maintaining the capacity in the grid, and cost of capital. Factors such as reliability, technology development, and investment climate are taken into account for the revenue model [22]. All tariffs in the system must be objective and non-discriminatory and it is the electrical grid companies who set the prices in each area based on the local conditions and settings [22]. Because of, for example, the electrification, the implementation of smart grids, and the urbanization, prices may change in the future. Introduction of additional tariffs during peak hours can become more common, rewarding customers can who chose to plan their power consumption. Consequences of urbanization, such as rural areas being drained of citizens, are problematic. Since the grid has to be non-discriminatory and always available, the same cost as today will be carried by fewer customers in the future in rural areas. Therefore, Kungliga IngenjörsVetenskaps Akademin (IVA) suggests introducing a *Sweden price* which could be less discriminating [22]. Another solution could be to simplify evening the costs for low-populated areas with high-populated areas [22].

As *Energimarknadsbyrån* states on their website, the future grid is a smart grid [29]. The definition of a smart grid varies and it is often described as a grid that is beneficial for electricity producers, grid owners and consumers as it enables safer connections and more effective deliveries, as well as provides relevant information about how the grid operates. As the grid becomes more dependent on renewable energy resources, smart grids can add crucial information about the usage, distribution and management of necessary loads, energy storage and generation. Smart grids can also reduce environmental impact and lower grid losses [30].

As the IVA sees it, there are multiple scenarios for electricity production in the future. The four main scenarios predicted are:

- Scenario one: more solar and wind power
- Scenario two: more bioenergy
- Scenario three: more hydropower
- Scenario four: new nuclear power

Scenario one and two are mostly built upon the theory of increased levels of integration of renewable energy sources, leading to production at new locations and small-scale electricity generation combined with large-scale wind parks. This will result in new requirements on the grid, such as new power lines or reinforcing existing ones. In Figure 3.5 the developments of the electricity production from all four scenarios are put together to get an overview in which regions changes and developments are supposed to be implemented. As seen in Figure 3.5, new hydropower plants and many large-scale wind power parks will be placed in region SE1 and SE2, increasing the need for transmission capacity further from those regions. In addition to this, the loss of nuclear power in region SE3 will further increase the need for power transmission from region SE1 and SE2. The local grids in region SE3 and SE4 are mostly affected by the implementation of solar PVs. Implementing bioenergy will affect region SE3 in the regional grid [22].

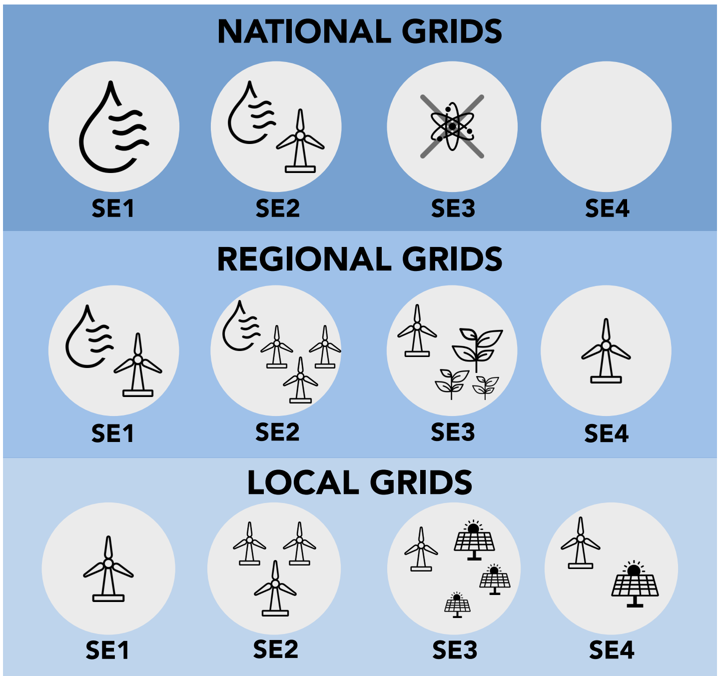

Figure 3.5: Overview of in what level, in which regions, and which energy sources are predicted to be incorporated in the Swedish grid. In figure 3.6 the explanations of the symbols are made.

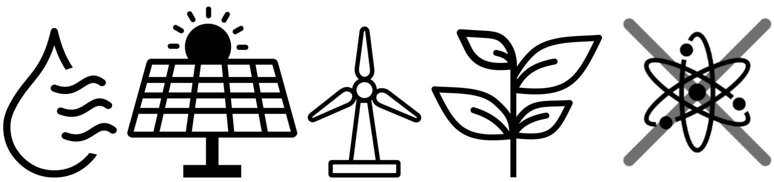

Figure 3.6: From left to right: symbol for (a) hydropower (b) solar power (c) wind power (d) bioenergy (e) loss of nuclear power

3.3 Microgrids - function and requirements

The US. DoE defines a microgrid as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid connected or island mode" [31]. This means that in order for a distribution grid to be defined and work as a microgrid, certain components must be included in it, as illustrated in Figure 3.7.

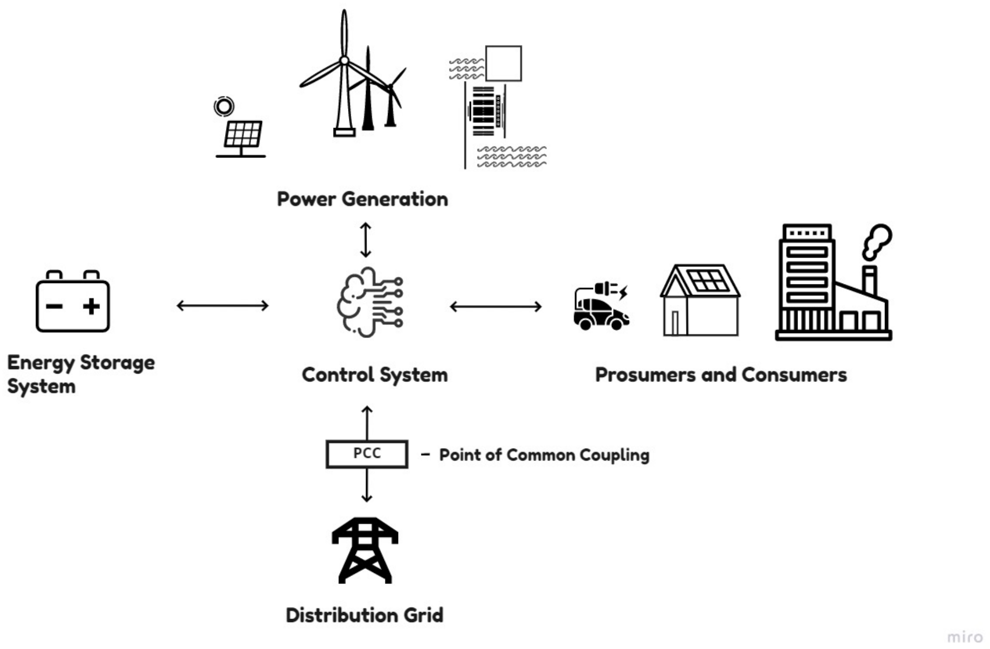

Figure 3.7: Illustration of a microgrid.

In the definition stated above, loads and distributed energy resources (DER), including distributed generators and distributed energy storage [32], are the components mentioned. For a microgrid to be able to operate in both island mode and grid connected mode, certain components are required. These are DER (can be a generator, an ESS or a combination of both), loads, a control system (preferably including forecasting of loads, electricity price and generation), and a connection point to the main grid, PCC [6][33]. Regardless of whether the microgrid is operating in grid connected or island mode, the requirements on the power quality are the same [33].

There are different ways in which implementing microgrids could be beneficial. Typical requirements for microgrids can be a minimum time of island operation, usage of RES, lower costs, and/or to offer grid services when connected [34]. Services that could be offered to the main grid include peak shaving, demand flexibility (DF), black start, and increased reliability [34][33]. Black start means that, in case of a larger power shortage, the microgrid could make use of its ESS to start other generators to restart all loads affected by the shortage [33].

Challenges of operating a microgrid in island mode compared to traditional operation include increased sensitivity to intermittent production and uneven loads [35]. The production plants' capacity would need to be adapted to the voltage levels of the connected grid [35]. In the main grid, this is the responsibility of SvK, who can buy flexibility and make sure there is inertia in the grid [36]. If a microgrid is operating in island mode, assurance of high power quality has to be done differently, utilizing the components within the grid, the control system, the loads, and the DERs [35].

3.3.1 ESS technologies

In order to integrate high levels of RES, and to be able to operate microgrids in island mode, energy storage is crucial. RES are intermittent and unreliable, and can create grid quality issues if not handled [1]. Two available storage techniques that are being extensively researched today are li-ion batteries and hydrogen fuel tanks. As both technologies have different features, the usage of one is not necessarily exclusive, and again it depends on what is necessary to achieve high power quality and meet the requirements of the microgrid.

The largest installation of a BESS in Sweden today is a 5 MW, 20 MWh large installation located in Uppsala. It is the first of its kind in Sweden and it is installed both as a solution to mitigate grid capacity shortage in the region, as well as an innovation project with the purpose of investigating the potential of large batteries in the distribution grid [37].

Li-ion batteries

Li-ion batteries are one of the most commonly used energy storage technologies today, with implementations ranging from smartphones and electric vehicles to grid-scale storage systems. Li-ion batteries' round-trip efficiency decreases with time and has a higher round-trip efficiency for shorter periods. Therefore they are more suitable for time frames ranging from fractions of a second to weeks [15][38].

Hydrogen fuel tanks

When solely considering storage, the hydrogen fuel tank is the most cost-efficient storage method utilized on an industrial scale today. The round-trip efficiency drastically drops when considering conversion losses. Since the loss over time can be very small, hydrogen storage tanks are ideal for longer storage time frames ranging from days and weeks to months and even years, enabling seasonal storage [15].

4

Drivers and Barriers of Microgrid Implementation

In Chapter 4 the literature study regarding the drivers and barriers of implementing a microgrid are presented. In the last section the results are discussed and evaluated.

4.1 Drivers - EU Directive on Clean Energy

Sweden has been a member of the European Union (EU) since 1995. Being a member of the EU means abiding by their laws and regulation. If Swedish and EU laws contradict each other, the EU laws take precedence [39]. In addition to this, there are directives (goals) set by the EU and it is the responsibility of each participating country to implement suitable laws and regulations in order to achieve these [40]. The CEEP is a new policy document launched by the European Energy Union in 2019, affecting many different directives [41]. The main purposes of the package includes improving the inner European energy market, easing the transition from fossil to renewable energy and strengthening the consumers' position in the market [42]. At the time of writing this thesis, these directives are in the process of being implemented in Swedish law. A constitution draft (*författningsförslag*)[43] has been presented, but has not yet entered into force.

Adapting trade rules and reinforcing interconnections to prepare for future needs, utilizing less reliable and more intermittent renewable energy, are essential steps in improving the market. It is predicted that by 2050, 50 % of the European households will produce energy on their own [42]. As a result of this, the CEEP predicts a more decentralized energy market in the future, where renewable energy community (REC) (*gemenskaper för förnybar energi*) and citizen energy community (CEC) (*medborgarenergigenemnskaper*), will have a strengthened position on the market [42]. By making it easier for consumers to organize in groups, the EU believes the transition from fossil energy to small-scale renewable energy will go faster. A reason for this is that the incentive for private investments increases. Furthermore, it is believed that by involving the consumer more, the energy can be used more efficiently, and the cost of energy can decrease [44].

4.1.1 Renewable energy communities

In the constitution draft, members of RESs can be physical people, local authorities, including municipalities, and small companies, as long as their main business is something other than participation in the REC or the energy sector [43]. Members must be physically close to the renewable energy projects the communities are developing or utilizing, meaning RECs are restricted to smaller areas. However, membership within these areas must be optional. Furthermore, RECs have the right to produce, consume, store, and sell energy in all available markets, provided that the energy production is renewable. RECs can operate within the whole energy sector, meaning they are not limited to electricity [43].

As for the responsibility of RECs, they can take over the balance responsibility in connection points from the DSO in that area [43]. Being responsible for the balance means making sure that the amounts of electricity delivered and consumed, in the connection points one has undertook responsibility for, are always balanced [43]. Predictions of consumption and production are made by the balance responsible and are agreed upon with SvK. If deviations occur, the balance responsible is economically liable for the unbalances they cause [45]. DSOs should cooperate with RECs to ease the energy transitions within the RECs [43].

4.1.2 Citizen energy communities

CECs, as described by the EU, are communities where the end users act as both producer and consumer, i.e. prosumers [44]. The purpose of introducing this is similar to that of RECs; to strengthen the consumers' position in the market and ease the transition to renewable energy.

In the constitution draft, it is stated that CECs can operate as actors as long as they prioritize providing their members with environmental, financial, or social benefits, over making an economical profit. CECs can produce, use and deliver electricity to their members. Furthermore, CECs can also provide their members with charging stations for electric vehicles, energy efficiency services or other energy services. If CECs operate as electrical distributors, just like RECs, they have balance responsibility for that connection point.

Compared to RECs, CECs do not need to limit membership to a geographical area, but can be connected virtually [43]. In a CEC, there are no constraints requiring the electricity produced to be renewable [43]. However, if it comes from prosumers it will most likely be solar based [42]. Furthermore, members of CECs can also be members of RECs, with the exception that companies' only business could be participation in the CEC. Neither RECs nor CECs are allowed to transfer electricity on behalf of others using a power line outside of a building [43].

Membership in RECs and CECs is open to all who participate in some way, such as by consuming, generating, or performing administrative work [43]. This means that no technical requirements are placed on the members. Instead, the technical requirements depend on what the REC or CEC want to be able to do. In order to be able to store, sell, consume, and produce power, as well as participate in all available markets, some technical requirements will be introduced. These include ESSs for storage, loads for consumption, controllable loads for participation on flexibility markets, DERs for generation of power and the possibility of participating in electricity retail, and a control system to optimize the production and consumption of the REC or CEC and its members.

4.1.3 Aggregators and demand flexibility

Aggregators are actors on the market that combine customers to sell and buy electricity from the market in larger volumes. Both RECs and CECs can operate as aggregators since both physical and juridical persons can be aggregators [43]. It works by aggregators selling power not used by its customers to either the electricity market, balance market, or to the local grid operator. It is suggested that aggregators should be responsible for the imbalances they cause [43]. Aggregation is a way to reduce the need for additional production. Instead, the already existing power is rerouted, hence aggregators provide DF [43]. DF have four significant positive effects on the Swedish grid; it can help maintain the right frequency, reduce the risk of power shortages, ensure more stable prices and more effective production, and contribute to more effective use of local and distribution grids, decreasing the need for additional grid capacity [46].

4.1.4 Rights and responsibilities of actors in the distribution grid

Traditional actors in the local distribution grid include the retailers, distributors, producers, consumers, and prosumers. New actors include REC operators, CEC operators, and service aggregators. The new actors may provide grid services to the grid operators that were not done before. In Table 4.1 below, the rights and responsibilities of different actors are presented to visualize what they can and cannot do. Based on this, it is clear that the rights and responsibilities of electricity retailers, electricity producers, RECs, and CECs are very similar, while the rights and responsibilities of DSOs differ from these. Aggregators typically handle the trading of energy and grid ancillary services using their customers resources. There are no legal obstacles for aggregators owning energy storage or energy production, though it is not the typical practice of aggregators. Further explanations can be found in the footnotes belonging to the table.

Table 4.1: Rights and responsibilities of different actors in the local grid

	Electricity retailer	DSO	Electricity producer	REC	CEC	Aggreg.	End customer[1]
Rights							
Own grid		X					
Own energy storage	X	X[2]	X	X	X	X[3]	X
Own energy production	X		X	X	X	X[3]	X[4]
Buy electricity	X	X[5]	X	X	X	X	X
Participation on the day-ahead market[6,7]	X		X	X	X	X	
Participation on the intra day market[6,7]	X		X	X	X	X	
Participation on the balance market[7,8]	X		X	X	X	X	
Responsibilities							
Power quality management		X					
Balance responsibility[9]	X		X	X	X	X	
Reliability		X					

[1] Include consumers and prosumers
[2] Only to make up for grid losses
[3] It is more common for someone else to own the grid components used by aggregators
[4] Separate taxes for micro producers
[5] Can buy electricity to make up for losses
[6] Minimum requirement to participate is 0.1 MW
[7] Requirement: balance responsibility or being a supplier of balance services
[8] Minimum requirement to participate is 5 MW in SE4 and 10 MW in SE1-3
[9] Balance responsibility is negotiated with SvK, indicated actors can take this responsibility

The rights of RECs and CECs are more extensive than for regular end customers. Aggregators combine existing loads, production, and storage, and sell ancillary services to the DSOs and the TSO. What limits the participation in the different markets is the minimum power limit of at least 0.1 MW to bid on the market. Currently, the day-ahead, intra day, and balance markets are limited to balance responsibility actors. This is scheduled to change during 2021, as the balance market will be opened up to all providers of balance services [45]. Since REC and CEC operators can act as service aggregators, they can provide balance services and are allowed to bid, as long as they can combine enough power to surpass the 0.1 MW limit. Most end customers do not reach these levels of consumption nor production and are therefore unable to participate in the balance market without the help of an aggregator.

4.1.5 The impact on microgrids

RECs and CECs are introduced to speed up the integration of renewable energy and combine customers in order to strengthen their position on the market and lower their electricity costs. Thus, it is predicted that many of the energy consumers today will become energy prosumers in the future. In section 4.1.2 it is stated that possible requirements for RECs and CECs include ESSs, loads, controllable loads, DERs, and a control system. Compared to the requirements for operating a microgrid, as mentioned in section 3.3 (loads, DERs, ESSs, a control system, and PCC), the potential components of RECs or CECs do not differ much. Now, in section 4.1.2 it is clearly stated that these components are not all required for a REC nor CEC to function, and they have not been dimensioned for island operation, but the already existing components of either a REC or a CEC could be utilized in a potential transition into a microgrid.

Microgrids are geographically limited, thus virtually connected CECs are unsuitable for island operation, but RECs and local CECs are better candidates. Since grid concessions are limited to DSOs, it is not an option for RECs nor CECs to operate in island mode without collaboration with the local DSO. Neither RECs, nor CECs, can decide to disconnect from the main grid on their own. As previously mentioned, RECs and CECs can contribute by letting the DSO utilize their components and steer their loads in accordance with the available power.

4.2 Drivers - Regulatory and Technical Aspects

This chapter will describe how microgrids can be an asset in future grids in Sweden in terms of technical and regulatory requirements.

4.2.1 Grid capacity shortage

Grid capacity shortage occurs when the power demand is higher than what the grid is dimensioned for. It can occur at all levels of the grid, from transmission to local levels [47]. Electrification of industries and the transport sector, urbanization, and the establishment of server halls in Sweden are only a few of the reasons why power consumption is increasing in Sweden. This has led, or is threatening to lead to, a grid capacity shortage in Sweden on a national, regional, and local level [48]. Grid capacity shortage does not imply, or deny, that there is a power or energy shortage. SvK is planning major investments in the transmission grid to ensure delivery to all parts of Sweden. However, predicting power demand is harder than ever and issues with grid capacity will still exist locally [49].

Causes and locations of grid capacity shortage

Some of the main factors causing capacity shortage are population growth, automation and electrification of factories and industries, old grid infrastructure, construction of new residential buildings, offices and factories, and electrification of the transport sector [50][51]. The transmission capacity in the area around Stockholm, including Uppsala and Västerås, and in Malmö, in southern Sweden, are particularly strained and will continue being so in the coming five to ten years [51].

In an interview with a technical expert at Vattenfall, he empathized the issues of the capacity shortage in smaller areas, especially in areas serving as popular vacation spots. The reason why vacation spots are mentioned is due to the electrification of both cars and boats. This far out in the grid, systems are rarely dimensioned for the kind of peak loads that charging of electrical vehicles could induce. Moreover, he warned that these kinds of issues will occur more frequently all over Sweden at roughly the same time, challenging the DSOs in the affected areas. This is why Vattenfall chose the island Arholma to investigate how small microgrids far out in the grid can delay, or even eliminate, the need for local grid reinforcements.

As mentioned in Section 3.2, the grid capacity shortage in sparsely populated areas can become a problem as the grids get older and urbanization make people leave rural areas. When fewer people pay the grid fee, cost per customer in the area increases to ensure good quality delivery [48]. Since rural areas, by definition, are located far away, the need for reinforcements can become very expensive. In the local grids, increased investment needs are primarily for information technology (IT) and measuring equipment, as well as new cables. The estimated yearly cost of grid stations, transformers, and other equipment is roughly the same as in previous years [52]. IT and measurement equipment have not been very common in the local grid before, but as grids get smarter, more installations of this kind are necessary. These are also the components with the shortest estimated life time [53].

Traditionally, as mentioned in Section 3.1.3, power has traveled from high voltage levels to low, from the producer, through the main grid, and then ended up at the customer. This will probably change with the introduction of DER, such as consumer owned solar power which will be directly connected to the local grids. Reverse flow of power will present new challenges, mainly affecting the local grids which will need to be able to handle these fluctuations[54].

When is the grid capacity insufficient?

Over the year, the power demand in Sweden varies, both seasonally and during the day. Typically, the power demand is the highest during the coldest periods of the year, mainly due to households using electric-based heating [55]. The peak load hour (*topplasttimmen*) is the one hour of the year when most power is used and normally occur in, or around, January [56]. It is the responsibility of SvK to make sure the grid capacity is large enough to provide each region with the demanded power during this hour.

As mentioned in the previous section, the need for investments in the local grid is very unpredictable. There is also a great uncertainty regarding how the local grid would be affected if large levels of renewable energy production and ESS would be connected to it [54]. In a scenario in IVA's report involving more wind and solar power, it is predicted that during some periods the available power in the grid will exceed five times the demanded power [54]. This poses new challenges for the grid, and implies that the required grid capacity in the future will not be determined by the consumption, but rather by the production.

Table 4.2 presents the months of the year when the problems regarding grid capacity shortage, high loads and high production occur. The table clearly shows that these problems do not occur simultaneously. Furthermore, solar PVs on the scale they are installed today are not causing capacity shortage, but if the capacity of PVs is increased this could change [54].

Table 4.2: When during the year the power consumption [48] and the PV production [57] is the largest

	J	F	M	A	M	J	J	A	S	O	N	D
High loads	X	X									X	X
Large production from PV				X	X	X	X	X				

Solutions to mitigate grid capacity shortage

The most common solution to grid capacity shortage is to reinforce the grid and, by doing so, enhance the capacity. However, there are also other measures that can be done in order to use the existing capacity more efficiently; these include:

- **Demand flexibility** - DF can help improve the overall need of grid capacity by dividing the power demand equally over the day. This is done by shifting loads from peak hours to hours when the power demand is lower. DF is the most beneficial when it can be used to solve problems in the local grids and other issues involving inefficient grid use [46].
- **Energy storage systems** - Installing batteries, or other kinds of ESSs, in the grid is a way to reduce the strain on the grid during peak hours. Batteries can be used for peak shaving. By charging during low demand hours and discharge when demand is high, grid capacity, primarily in low voltage grids, can be reduced [58]. Long term energy storage could be water ponds connected to hydro power plants, pumped storage, or hydrogen storage [59]. One of the benefit of batteries compared to grid reinforcements is that the lead time is much shorter [58].
- **Relocating loads** - If the grid capacity in an area where a load is located, or planned to be located, is limited, a solution could be to relocate the load.

> Long term this is not a preferable solution, as the region has to deny the connection, which prohibits the societal development. A DSO is only allowed to deny connections of new or extended loads if there is a lack of capacity in the grid [52]. For example a battery factory was planned to be established in Västerås, but since the grid there is already strained, it was established in Skellefteå, in the north of Sweden, instead [60].

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Two out of the three examples above can be connected to microgrids; DF and ESSs. Energy storage units and the control system used within the microgrid can be used by the main grid when not operating in island mode [58]. For example, the microgrid could be seen as an aggregator selling flexibility services, using its loads and batteries [58]. These components are also requirements for the microgrid to be able to operate in island mode, hence they can be utilized both by the main grid and in island mode.

4.2.2 Reliability

A reliable grid has been, and will continue to be, crucial for the development of, and opportunities for, establishing industries for companies, and for people [48]. This section presents the reliability of the Swedish power distribution grid and what measures DSOs are taking to improve the reliability today. It also implicates how a microgrid could improve the reliability in the distribution grid.

Grid code requirement

The grid code is written and upheld by Ei, regulating requirements on the delivery quality. According to the grid code, the reliability is good when the amount of unannounced power outages longer than 3 minutes are less than 3 per connection point per year in the low voltage grid, and considered bad when they exceed 11. In addition, outages cannot go on for longer than 24 hours; if they do, the reliability is also considered poor [61].

Overview of reliability situations in the Swedish power grids

In 2019, 53,333 different stations suffered from power outages longer than 24 hours. In 2018, only 3,488 stations experienced interruptions that long. This is due to the storm Alfrida taking place at the beginning of 2019 [4]. The power interruptions caused by Alfrida were mainly due to trees or branches falling onto overhead power lines located in remote areas [62]. In the past ten years, 16 storms similar to Alfrida have occurred [17]. Due to these interruption problems, it is concluded that the electrical grid in Sweden requires further improvements of the supply quality [63].

Despite the remaining issues with reliability during storms, Sweden's electricity system is evaluated as sturdy [48]. Because of the reoccurring storms a lot of improvements have been made, such as widening the tree corridors around overhead power lines and replacing critical overhead lines with underground cables [63]. In the future, one of the most prominent reliability issues in Sweden is the aging grid, which requires large investments on a national, regional, and local level [48].

Reliability issues

A great expansion of the grid took place in the 1970s, during which many of the nuclear plants in Sweden were built. Grids built during this time are now in need of restoration and large investments [54]. There is also an ongoing reformation in the Swedish power production as nuclear plants are shut down and more solar PV arrays and wind power plants are built. This decreases the resiliency for disruptions in the system which could disconnect customers involuntarily from the grid [64]. The lead times for building new power lines is longer compared to building wind power and solar PV-plants. This is occurring at the same time as there are uncertainties regarding where new power generation will be installed [48]. Urbanization increases the power demand locally and in some areas there could be lack of space for installation of new net stations and cables. This also affects people living in sparsely populated areas since maintenance of those remote parts of the grid will not be prioritized [48].

Areas suffering from low reliability are mostly remote areas with low population and low voltage overhead lines, making them more sensitive to bad weather. Rural grids are also built with less redundancy than grids in densely populated areas [65]. An example of this is the island of Gotland which is largely affected by both numerous and long power shortages. This is to such an extent that Gotland is among the places with the worst reliability in Sweden. The average outage time System Average Interruption Duration Index (SAIDI) and average number of unannounced outage System Average Interruption Frequency Index (SAIFI) on Gotland are almost the highest in Sweden, 501 minutes and 7.88 outages, respectively [65].

Causes of power interruption

Tables 4.3 and 4.4 present the causes of outages in areas with low reliability. As mentioned in the grid code requirement section above, areas are considered low reliability areas if there have been more than 11 outages in one year or there have been outages lasting for longer than 24 hours. These tables also show which months of the year these outages usually occur. Storms primarily occur during late autumn months and during the winter months [17] and, along with snow fall, are the primary reasons for trees falling. In this table, weather refers to hard winds that make conductors gain contact and heavy snow that cause stations to collapse [66].

Based on the table, roughly 75 % of the outages can be seasonally predicted, with the majority of the outages occurring during winter. 64 547 outages of this kind are due to defects in materials or cables, making up half of the non season related outages. As mentioned in section 4.2.2, this number is predicted to increase due to aging equipment.

Table 4.3: Reasons for outages in areas with more than 11 outages during 2019 [66] and when they typically occur [17]

	Number of outages	J	F	M	A	M	J	J	A	S	O	N	D
Falling trees	158,694	X	X									X	X
Thunder	114,019						X	X	X				
Weather	76,747	X	X									X	X
Non weather/season related	128,699												

The same reasoning has been used in table 4.4. In this table, the causes of outages lasting for more than 24 hours are presented. The table shows that more than 80 % of the outages occur during the late autumn and winter months and only a few, due to thunder, can be anticipated to occur during summer. Less than 20 % of the outages are not bound to any time of the year. 98 % of the outages that were not weather related or seasonal were caused by errors in the upstream power grid [63]. The remaining non weather related outages were due to faulty technical equipment, problems during reconstruction of power lines or flocks of birds flying into the power lines [63].

Table 4.4: Reasons for outages lasting longer than 24 hours in 2019 [66] and when they typically occur [17]

	Number of outages	J	F	M	A	M	J	J	A	S	O	N	D
Falling trees	42,487	X	X									X	X
Thunder	7,731						X	X	X				
Weather	1,977	X	X									X	X
Non weather/season related	9,156												

Solutions to improve reliability

Today, there are a some measures DSOs can take in order to improve the reliability of the power distribution in the regional and local grids. In the list below are the most common ones [66].

- **Deforestation** - as mentioned in the section before, falling trees is the most common reason for outages. Because of this, cutting down trees around overhead power lines is an effective way of preventing this.
- **Burying cables** - this is another way of preventing trees from destroying power lines. This demands less free space around the cable, but burying cables is more expensive than overhead lines. As a consequence of the high price of digging, old cables risk being left in the ground when depleted [67].

- **Insulation** - changing to, or increasing, the insulation of the cables. Insulation is needed to protect the overhead lines from humidity and wind.
- **Grid planning, rebuilding, and process improvement** - includes all measures taken to either improve existing components and processes, or the process of installing new components
- **Reparation and continued maintenance**

Microgrids are suitable in areas with low reliability since these can disconnect from the main grid if an interruption occurs. During the interview with the technical expert at Vattenfall, he mentioned that one of the main factors motivating Vattenfall's research on the subject was the ability of running the grid in island mode during the time it takes to repair damages caused by an outage. That way the customers would experience better reliability and Vattenfall could decrease their outage costs.

From tables 4.3 and 4.4 it is clear that many of the outages occurring today are weather and season related. These kind of outages could therefore be forecasted and, if that is the case, the microgrid could be prepared when, for example, a storm is coming [68].

4.2.3 Supply voltage quality

It is of importance that the voltage quality in the grid is kept within certain sets of values. Components and loads connected to the grid can be sensitive to voltage fluctuations that are too large or goes on for too long, but it is important that the connected components are resilient toward the fluctuations that are deemed acceptable[69]. The requirements of the supply voltage quality is regulated in EIFS 2013:1 [61].

Grid code requirement

DSOs have the responsibility to provide the customers with voltage of good quality. The voltage quality is determined by six different factors presented below. All values are measured over a one-week period in ten minute intervals [61].

- **Slow voltage variations** - the effective value of the voltage may not exceed the interval of 90 - 110 % of the reference voltage.
- **Voltage harmonics** - the occurrence of voltage harmonics must be limited in accordance with values regulated in the grid code [61].
- **Voltage asymmetry** - can not exceed 2 %.
- **Short voltage dips or swells** - the acceptance of short voltage dips/swells is regulated according to values in the grid code [61].
- **Fast voltage change** - the amount of fast voltage changes added with the amount of short voltage dips may not exceed values regulated in the grid code [61].

The grid code of the voltage quality is currently being reevaluated and might be updated in the coming years. The reason for this is the vast changes in the grid, both regarding production and loads [69]. What is suggested is that some of the accepted values are increased, due to increased difficulty to maintain the values set today [69]. Above all, it is an increased amount of inverters that contribute to the need for this reevaluation [69].

Causes of decreased supply voltage quality

What the grid code regulates can be divided into three parts: voltage levels, harmonics, and symmetry. These are all affected by the predicted future usage of the grid in different ways. Three of them are described in the following section [69].

Firstly, harmonics may increase and behave differently due to a largely increased level of inverters [69]. Harmonics are the occurrence of voltages and currents with a frequency deviating from the normal 50 Hz in the grid. The inverters are necessary, especially in renewable energy generators such as wind and solar power, but also in components like industrial drives and heat pumps [69]. The inverters change the level of emission in the grid, leading to increased and slightly changed harmonics. Today the solutions to increase energy efficiency often involve inverters and fast changes of load and production, thus increased energy efficiency can become a part of this problem [69].

Secondly, asymmetry becomes an issue when heavy loads are connected only to one phase. An example of this can be charging electric vehicles (EV) at home, using a one-phase outlet. Asymmetry can be prevented if the charging is coordinated with the charging of other nearby vehicles [69]. Problems associated with asymmetric voltage is damage to induction machines, increased heating, and uneven currents [70].

Thirdly, voltage dips and swells are dependent on the load and the generation. One one hand, electric vehicles charging and/or households using electric heating during cold winter days might cause the load to be too high and lead to voltage dips during peak hours [71]. On the other hand, large scale installations of solar PV panels can contribute to voltage swells during windy, sunny summer days when the load is low [72]. Another problem that can arise during the low load summer days is excessive reactive power, especially in the low and medium voltage grids, creating a problem for both the DSO and TSO.

Solutions to increase supply voltage quality

In order to decrease the abundance of harmonics in the grid, harmonics of different degrees needs to be eliminated. Power electronic converters can help mitigate harmonics, either by filtering the voltage [73] or by producing a current which cancels out the harmonics [70]. Furthermore, symmetry in the grid is achieved by balancing the load, and making sure the network configuration is even [70]. A control system can also detect uneven phase voltages and use ESSs to compensate for them [74].

ESS can be used to improve voltage fluctuations in the distribution grid through reactive power compensation. Furthermore, due to the relatively high ratio between resistance and reactance (R/X) in the rural cable network, voltage fluctuations can also be reduced through active power regulation by ESSs [75]. Smart ESSs can sense the voltage and reduce the fluctuation by charging or discharging accordingly. Other solutions include curtailment, load shifting, installation of inverters, and reactive compensation by shunt reactors or capacitors [76]. All of these solutions requires a control system which can dictate how and when to use these measures [76].
Smart control systems, ESSs, and flexible loads are components that are usually included in microgrids. While the microgrids are connected to the grid, the components of the microgrids could be utilized by the main grid to manage and ensure high voltage quality. Maintaining a high voltage quality when operating in island mode is important since the same electrical components are connected regardless if the microgrid is operating in island mode or not.

4.2.4 Grid losses and efficiency

Grid losses are defined by the difference between the input and the output power from a grid. There are not only technical grid losses, such as electricity dependent-, non-electricity dependent- and corona losses, but also non-technical losses. The non-technical losses are the power which is used to heat up grid facilities, measurement errors, and power taken illegally from connections in the grid. These types of factors account for 3-6 % grid losses according to Ei [77].

Incitement for minimizing the grid losses

A revenue cap is set by Ei for each DSO in Sweden; four years at the time. When setting the cap Ei considers the reliability of the supply and the extent of effective utilization of the power of the grid. The revenue cap decides the total amount that the DSO can charge its customers. To calculate the revenue cap, controllable, non-controllable, and asset-based costs are included, see Figure 4.1 for an overview of the system [23].

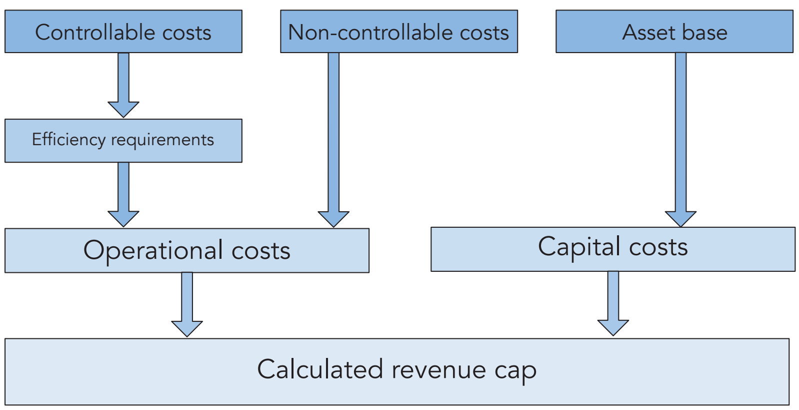

Figure 4.1: Overview of the revenue cap system.

The operational costs are divided into controllable and non-controllable costs. The DSOs can manage the controllable costs by themselves, however Ei have added an efficiency requirement to simulate a non-monopoly market. The DSOs have more difficulties affecting the non-controllable costs. The capital costs also include asset-based costs, which are the sum of all present purchase values [23]. If the DSO can reduce the grid losses and streamline the grid usage, the costs are reduced, creating a larger profit margin to the revenue cap. Thereby the DSOs can make a larger profit if their systems are effective with low losses [23].

Loss factors

As mentioned above, losses in the grid are either due to technical or non-technical factors. Furthermore, the technical losses can be divided into two categories; the load losses and the no-load losses. The load losses follow the equation presented in 4.1 where R is the resistance, I is the current, and P_{loss} is the power loss. These occur due to heat that is generated whilst transmitting energy in the grid, both in the cables and in the transformers.

$$P_{\text{loss}} = I^2 \cdot R \tag{4.1}$$

Additionally, I^2 can be expressed in active and reactive lead power, P and Q, supply voltage, V, and susceptance, B, as seen in equation 4.2.

$$I^2 = \frac{P_{\text{loss}}^2 + (Q- \mid V \mid^2 \cdot \frac{B}{2})^2}{\mid V \mid^2} \cdot R \tag{4.2}$$

It is evident that the physical factors affecting the grid losses are active power, reactive power, supply voltage, and cable length. Thereby it is clear that the impedance increases with increasing cable length [78]. Local production can sometimes lead to increased grid losses but it depends on the type of grid, load-profiles, type of production, etc. [77].

The no-load losses occur due to the iron core in the transformers. 25 % of the losses are load losses and 75 % are no-load losses [78]. Beyond the no-load losses, the non-technical losses occur due to:

- Maintenance energy
- Electricity theft
- Energy output without billing
- Billing errors

The maintenance energy is lost to, for example, cooling transformers or heating substations. The other factors, such as electricity theft, energy output without billing and billing errors are all connected to the customer not paying for their electricity service. This means stealing electricity illegally or simply by mistake. But it can also include errors in the billing process due to for example measurement faults or the energy output not being billed [78].

Solutions

There are multiple solutions to minimize the grid losses and increase grid efficiency. The most common measures are listed below.

- **Grid updates** - Replacing existing cables with new ones, having lower impedance, or incorporating more energy-efficient transformers, minimizes the grid losses [77].
- **Grid structure** - By interpreting long-term rationalizations of the grid structure and more efficient grid operations the grid structure can be improved greatly [77].
- **Integrated solutions** - Smart integrated solutions with control systems are an example of an integrated solution that optimizes the voltage level and can be incorporated in all levels of the grid to minimize losses [77].
- **Demand response** - A demand response model for the operators creating simulations for the consumers to evenly load the grid can also minimize the losses through demand response and demand side management [78].
- **Local production and consumption** - Losses in the grid due to transmission of electricity, can be reduced by reducing the distance which the electricity has to travel.

The Swedish power grid is facing multiple challenges and will need both component-wise updates as well as structural updates. Minimizing the grid losses and making the grid more efficient are thereby necessary acts to reduce the stress on the grid. As a result of this, new integrated technologies will need to be connected into the existing grid. Microgrids could be one way to update the grid in suitable areas. Furthermore, the demand response model is suitable for the incorporation of microgrids since it involves smart solutions and also is built upon the idea of the demand response model. A coordinated control among different assets in a microgrid can make the grid more effective and reduce the grid losses. Lastly, in Sweden the energy often has to travel long distances from production to the end consumers, leading to power line losses. This results in the need of additional power generation. Microgrids however, can lower these losses since the electricity is generated very close to where it will be used.

4.3 Drivers - Economical & others

In this section, some final drivers of implementing a microgrid will be presented.

4.3.1 Lead time

An important aspect to consider is the lead time of implementing a microgrid solution compared to other solutions. The lead time of a microgrid depends on what is already available in the area. Here, two scenarios are considered; one where existing energy sources are sufficient for the microgrid and one where new energy sources need to be constructed. In Table 4.5, the estimated lead time of microgrid solutions is compared to a conventional solution to increase distribution capacity; adding a new power line.

Table 4.5: Estimated lead time of different operations and components, where X marks that the operation is not needed for the specified solution

Operation	Construct new line	Implement microgrid with new power sources	Implement microgrid without new power sources
Preparatory work before concession request[1]	3 - 5 years[79]	X	X
Processing concession request	9 - 18 months[79]	X	X
Implementing new line[2]	3 - 5 years[79]	X	X
Acquiring asset and interconnection permissions[3]	X	1 - 2 years[80]	1 - 2 years[80]
Li-ion battery	X	0.2 years[15]	0.2 years[15]
Hydrogen storage	X	0.5 years[15]	0.5 years[15]
Wind turbine	X	2 years[81]	X
Total	7-12 years	3 - 5 years	1 -3 years

[1] Pilot studies, consultations, environment stock takings, etc[79]
[2] Final permissions, detail projection, construction, etc[79]
[3] There are requirements concerning design, installation, testing, equipment etc that must be full-filled to be granted a permission[80]

Note that the estimated total lead time for the microgrid solutions is not the cumulative sum of the lead time of the operations listed in Table 4.5. This is due to the fact that these operations can occur simultaneously, while the operations needed to implement a new power line cannot. The table offers some time aspects of implementing a microgrid, but the lead time can vary depending on what is already available. If a lot of new units are produced, the amount of permissions required will increase as well. In a business case conducted by ABB the lead time of their microgrid suggestion was estimated to be approximately 1 year[82] as well.

Even if the lead times in Table 4.5 are approximate, it is clear that there is a significant difference between the lead time of constructing a new line and implementing a microgrid. The construction of a new line would take at least 3 - 5 years even if the grid owner has an area concession and does not need a new concession. If a new concession is required, the lead time for a new line would be approximately ten years, which is a long time compared to a microgrid that could be up and running within one year, depending on available resources. Thus, lead time serves as a driver for implementing a microgrid solution.

4.3.2 Economical aspects regarding reliability

High reliability is worth a lot for the economy. In Table 4.6, the costs associated with long, unannounced power outages for different kinds of customers are presented as SEK/kW and SEK/kWh. From this table it is clear that power outages impact different areas of business differently. For a household, a power outages is not very economically damaging, but for a retailer low reliability can amount to large economical losses .

Table 4.6: Costs inflicted upon different customers of unannounced long (>3 min) power outages, Non Delivered Power (NDP), Non Delivered Energy (NDE) [65]

Load category	NDP [SEK/kW]	NDE [SEK/kWh]
Agriculture	9.78	34.35
Industry	70.75	159.96
Retail and services	17.78	175.06
Government controlled business	7.65	96.97
Household	1.95	5.84

Following is a price example of what the bad reliability on Gotland costs a store located there, using on average 15.8[1] kWh/h. In Section 4.2.2 it is stated that the SAIDI and SAIFI is 501 minutes respectively 7.88 outages. This information can be used to estimate the cost per year for this store due to bad reliability.

$$17.78 \cdot P_{out} \cdot \text{SAIFI} = \text{estimated cost for NDP/year [SEK]} \tag{4.3}$$

$$175.06 \cdot E_{out} = \text{estimated cost for NDE/year [SEK]} \tag{4.4}$$

Where E_{out} is

$$15.8 \cdot \frac{501}{60} = \text{estimated non delivered energy [kWh]} \tag{4.5}$$

Using 4.3, 4.4 and 4.5 the estimated cost of outages for a store located at Gotland, using SAIDI and SAIFI from 2019, is 25,310 SEK/year.

4.3.3 Environmental aspects

Environmental benefits are often measured in terms of avoided emissions which is the outcome of fossil-based generation. Common emissions that are measured are SO_X, NO_X, particulates and CO_2 [83].

In terms of environmental benefits, the opportunities for the incorporation of renewable and clean energy sources, such as wind and solar power, increases with the implementation of microgrids. Furthermore, the decrease in grid losses, which is a consequence of local power production, will contribute to lowering the global greenhouse gas emissions [84]. As mentioned in section 4.2.4, the demand for electricity varies during short and long time frames, creating fluctuations in the grid leading to instabilities. Beyond this, the weather-based renewable generation also varies. This is where demand-side management plays an important role. The term includes

[1] Average hourly consumption in small sized grocery store, measured over a year. Electrical bill attached in Appendix A

control and modification of power usage and the behaviors around it, to handle local net load variations and to achieve a more sustainable power consumption [85].

Not only are pollutants affecting the environment negatively, but it also costly seen from a financial perspective. In table 4.7 the cost of pollutants per ton is presented. When studying the tabular it is obvious that to cut costs, cutting the amount of pollutants is an effective way to go [83].

Table 4.7: Price per ton pollutants [83].

Pollutant	$US per ton
Particulates	9,500
NO_X	2,400
SO_X	3,190
CO_2	7

However, there is one aspect of implementing microgrids that can be considered adverse from an environmental perspective. It is the usage of li-ion batteries and the manufacturing of solar PV as well as wind turbines. As for battery production, it exploits the finite resources on Earth, lithium in this case. Moreover, the batteries also contain toxic substances, which can result in hazardous waste products that can cause harmful consequences if not handled with care [84].

If studying the manufacturing process of solar PVs, it is evident that this could harm the environment in two different ways. Solar PVs consist of a large amount of silicon, one of the most common elements in Earth's crust [86]. However, the production of the PVs needs pure silicon, which is difficult to find naturally. The manufacturing of pure silicon needs about 120 kWh of electricity per kg. So in total, the production of pure silicon makes up for half of the energy for the manufacturing process of solar PVs. The next step in the process is turning the silicon into wafers. This step includes toxic and corrosive materials, resulting in waste products, such as hydrochloric acid and trichlorosilane. It is possible to recycle those waste products. Despite this, it is both expensive and demanding, leading up to not many manufacturers doing it[86].

When shifting the focus to wind turbines, it is evident that the manufacturing process is relatively benign. Multiple components used are already used in the traditional turbine generators. However, there is one rare earth element used in the process, neodymium. But the wind turbine manufacturing stands for a rather small component of the worldwide demand for this element [86].

Moreover, when studying the manufacturing process, it is evident that the largest environmental effect that wind turbines have on the environment is greenhouse gas emissions. The substantial carbon footprint occurs during the transportation phase and the second largest carbon footprint occurs in the construction and erection phase due to the emissions of greenhouse gasses from the production of the cement foundation. However, the carbon footprint can be reduced by 12 % for an onshore turbine and up to 19 % for an offshore turbine if the input materials are recycled [87].

Even though there are negative aspects, it is also important to mention that the recycling process in the EU has become better and regulations regarding the topic are quite clear and constantly in a developing state, due to the increase of usage [88].

4.4 Barriers

Barriers identified will be presented in this section.

4.4.1 Swedish law of electricity

The Swedish law of electricity was established in 1997 with the purpose of regulating electric facilities and electricity trade in Sweden [89].

Grid Concessions

In *2 Ch, 1 §* of the Swedish electricity law it is stated that in order to construct or use a high voltage line, a grid concession must be granted prior to the construction [89]. A concession is a permit for a power line (line concession), or several power lines within an area (area concession), granted by Ei [89]. This means that only the concession owner is allowed to transfer electricity over the concession bound grid. In some exceptional circumstances you can be permitted to construct and use power lines without a concession. This applies for internal grids within a building and can also apply for some restricted areas [89]. These exceptions are not relevant in this report however. In order to build a power line to transfer electricity between at least two buildings in a non restricted area, such as a residential area, a concession is required however.

Once a concession has been granted, there are several regulations that the concession owner must abide by. In *3 Ch, 6-7 §* of the electricity law it is stated that the concession owner is legally obliged to connect the transmission line or area to an electrical facility, unless there are specific reasons not to [89]. This means that a distribution grid would not be permitted to operate in island mode unless Ei deems its' reasons for not being connected to the main grid as viable. A scenario where a microgrid might be exempted from this rule is if the microgrid is implemented on a remote island where there are difficulties establishing a stable connection to the main grid [89].

The law regarding concessions is a potential barrier when implementing a microgrid in a residential area. A central aspect of the microgrid is the potential of running in island mode, which may become problematic due to the obligation of connecting to an electrical facility.

Energy Storage

In *1 Ch 4 §* of the Swedish electricity law, a grid operation's purpose is defined as to use available electrical power lines for transferring electricity [89]. Furthermore, the law also states that a grid operation includes design, construction, and maintenance of lines, switchgear and transformer stations, the connection of electrical facilities, measuring and calculating transferred power and energy, as well as other operations needed in order to transfer electricity on the electrical grid [89]. This indicates that energy storage can be a part of a grid operation, since energy storage could be included in "other operations" if it is needed to transfer electricity over the grid, meaning that a grid owner can own energy storage legally [90]. A grid owner owning energy storage would, however, face the limitation of not being allowed to produce or trade with electricity as stated in the *3 Ch, 1 §* of the electricity law. The grid owner is only allowed to produce electricity in specific circumstances, such as for purposes of covering for grid losses or compensating for electricity shortage during a power outage [89].

The specific circumstances for when a grid operator is allowed to use energy storage are actually sufficient for running a microgrid if the purpose of the energy storage is to supply the microgrid with backup power when the main grid is down. However, the restrictions of energy storage usage would still, most likely, have a negative impact on incentives for grid owners to own energy storage. A possible solution would be to let a third-party service provider own the energy storage, although incentives for the service provider to own energy storage could also be low due to network tariffs [90].

Network Tariffs

Since the grids in Sweden are operated without competition, there are laws concerning how network tariffs should be established [91]. A network tariff determines how customers in an area are charged for the electricity they consume. In *4 Ch 1 §* of the Swedish electricity law, it is stated that network tariffs should be designed to be objective and nondiscriminatory [89]. Since the network tariffs are designed to be nondiscriminatory, this means that all customers in an area are charged in the same way for the electricity they consume. If a third-party service provider was to own energy storage in a microgrid they would be charged in the same manner as all other customers in the area [90]. Thus, owning energy storage as a third party could limit the profitability. A possible solution to this is for the service provider to charge the DSO for the extra costs, meaning that the DSO would need to pay more for the service.

In a report from 2012, Ei analyzed whether or not more regulations were needed when establishing network tariffs to increase renewable production and increase energy efficiency for end customers [91]. The possibility of introducing subsidized network tariffs in favor of renewable production was brought up and dismissed, due to the discriminating effect it would have [91]. Investments for renewable production are instead handled through electricity certificates [91].

The non discriminatory requirement of the Swedish tariff structure does not favor energy storage. It harms financial incentives of owning energy storage or renewable production units. Furthermore, electricity producers within the microgrid will likely be favored for the microgrid to be self sufficient. This means that electricity producers outside the microgrid could be discriminated, which violates the electricity law.

Swedish law of electricity's implications for microgrid

While the Swedish law of electricity does not directly forbid the implementation and running of a microgrid, it creates several barriers as discussed previously. The main barriers include:

- Running in island mode might not be allowed
- Grid companies owning energy storage are limited in their usage of it
- Lack of financial incentives for third parties to own energy storage
- Electricity producers outside the microgrid might be discriminated

Finding a way to operate a microgrid in accordance with the law and, at the same time, maintain incentives for all parties involved will be difficult with the current electricity law.

4.4.2 Swedish law of energy taxation

In *11 Ch 1-2 §* of the Swedish law of taxation it is stated that electricity consumption in Sweden is taxed unless it is produced or consumed in specific circumstances [92]. It can be produced within a facility without taxation as long as the total installed power capacity within the facility is no higher than 50 kW [92]. For solar energy, the energy production is not taxed as long as the installed capacity is no higher than 225 kW [92]. However, the law also states that in order to avoid taxation the electricity must not be transferred over the concession bound grid [92]. This means that as soon as the electricity is transferred from one building to another it is taxed even if it is not sold. The power used to charge battery storage would therefore be taxed twice; once when transferred from the concession bound grid to the energy storage and once when transferred from the energy storage back to the concession bound grid. Since 2019 new taxation regulations have come into effect in Sweden, including *11 Ch 13 §* which states that taxes for energy storage can be repaid as long as electricity is transferred back to the same concession bound grid as it was transferred from [92][93].

Double taxation of energy used to charge battery storage would be a barrier for implementing a microgrid since incitements to own energy storage would be low from an economic perspective. Due to the law change in 2019, though, owning energy storage is not as economically unfavorable as it has been, even if the energy storage owned would have to wait until the tax refund to get their money back.

Thus, the Swedish law of energy taxation is not as much of a barrier as it previously has been.

4.4.3 Lack of existing experience and knowledge

Microgrids are a new concept in Sweden, as the microgrid built by E.ON in Simris was the first of its kind in Sweden [94]. The purpose of the project was to conduct research on how this kind of solution could be integrated into the grid, and help with the integration of RES and prosumers. The Simris project is part of an EU innovation initiative [94]. The microgrid on Arholma is also a research project, designed by Vattenfall, for them to learn how a microgrid works in grid connected and island mode [95]. DSOs in Sweden need to gain this knowledge before microgrids can become commercially implemented as an efficient and competitive alternative to conventional distribution grids.

4.4.4 Energy storage

For most grids, being able to operate in island mode would require an ESS. ESSs are associated with a number of downsides compared to traditional grid solutions ranging from costs and lifetimes to conversion losses.

Life time of ESSs

Most ESSs have significantly shorter life times compared to overhead lines and buried cables, which can be operational for 35 to 60 years and 50 to 80 years, respectively [53].

When correctly operated, li-ion battery systems have a life span of 15 to 20 years while hydrogen storage tanks have a life span of up to 25 years before reactions between the hydrogen and the metal tank (hydrogen embrittlement) makes them unsafe to use. As long term solutions, the ESS costs accumulate and makes them less competitive against traditional solutions that can have higher initial costs but longer lifetimes [15].

Conversion losses

For li-ion batteries, the losses can be split into operational losses and standby losses where the operational losses mainly consist of conversions between alternating current (AC) and direct current (DC) as the battery both charges and discharges in DC. The standby losses occur due to powering components that regulate and maintain the battery cells as well as a gradual self discharge occurring due to internal power leakage. The self discharge at room temperature is approximately 0.1 % per day and increases at higher temperatures [15].

For hydrogen fuel tanks, the operational storage losses mainly consist of loss of pressure when the gas is compressed into the storage tanks. This loss is <1 % and generally negligible. The standby losses vary depending on what type of storage tanks are used. The main cause for this is hydrogen permeation in which the small hydrogen atoms escape through the tank material and this results in a pressure loss over time. The level of hydrogen permeation varies with different materials and with the cheapest and most commonly used tank types, which are made of steel and aluminum, the permeation is negligible [15].

Hydrogen is produced by electrolysis of water and an electric current separates the hydrogen and oxygen atoms. When converted back to electricity, hydrogen reunites with oxygen to form water and electricity. These two conversions lower the round-trip efficiency to between, approximately, 30 % and 47 % [96].

Costs of ESSs

In table 4.8 below, estimations of ESSs costs based on various catalogs deriving data from real companies and applications are presented. The listed prices for order and maintenance (O&M) are reoccurring annual costs and the hydrogen tank system cost excludes converters. The prices are adjusted for inflation and predicted prices for 2021, they are also exchanged from original currencies to Swedish Kronor (SEK). The estimations are rough approximations, real prices may vary.

Table 4.8: Estimated costs of ESSs

Storage method	SEK/kWh 2021	SEK/kW 2021	O&M SEK/kW	O&M SEK/kWh
Li-Ion battery system	3560 [15][97]	14 230 [15][97]	77 [15][97]	-
Hydrogen storage system	680 [15][97]	6 300 - 9 900 [38]	-	6 100 [15][97]

The costs of BESS technologies have decreased by more than 80 % in the last decade [11] and cost projections indicate that the costs will be between 144$/kWh and 293$/kWh by the year 2030 [98] showing that the costs for BESSs, most likely, will continue to decrease.

If the cost of ESSs is considered a barrier, it is becoming less so as prices continue to decrease. The cost of implementing a new power line is higher for longer lines and construction costs are higher for underground lines than overhead lines [67]. In a remote area with low reliability and long distance to the closest net station, ESS costs become less of a barrier.

4.4.5 GDPR and data collection

In the GDPR from the EU, it is stated that every citizen has the right to protection of its own personal data [99]. Collecting data on the consumer's behaviors is necessary for the microgrid to operate smoothly, especially from the viewpoint of demand management [100]. In a microgrid, sensitive information is accessible from transmission nodes if not correct safety precautions are taken. Information that could be sensitive from a privacy perspective is the time series data from power consumption and energy consumption patterns. This data could include information about the residents' private activities and behaviors [101].

For data collection to work together with privacy issues, certain requirements must be met. Firstly, sensitive information should only be accessible by authorized personas. Secondly, the data should be accessible when the authorized personnel needs it. Thirdly, the persons who have access to the data should not have the ability to extinguish or infer with the collected personal data [101].

To summarize, on one hand, this could imply an invasion of privacy through data collection. On the other hand, the users have better opportunities to adapt their consumption to the current power price and availability, resulting in lowered cost and more efficient use of resources [100]. Thereby it is crucial to take the safety and privacy issues into account when designing the systems [101].

4.5 Summary and discussion of drivers and barriers

4.5.1 Summary

In Sections 4.1 - 4.4 different drivers and barriers have been presented and analyzed. In Table 4.9 these are presented and categorized to show in which aspect they drive or prohibit microgrid implementation. What can be gathered from the table is that in grid connected mode, only drivers have been identified. Meanwhile, all aspects concerning the Swedish law serve as barriers for microgrid implementation. Regarding island mode operation, the possibility of improved reliability and reduction of grid losses are primary drivers, as well as utilization of energy storage. However, the lack of knowledge and the cost of implementing microgrids today are barriers.

Table 4.9: List of factors as drivers (Ds) and barriers (Bs) in microgrid implementation

	Operation in island mode	Operation in grid connected mode	Profitability	Social and ethical factors
EU-directive		D	D	D
Grid capacity shortage		D	D	
Reliability	D		D	
Supply voltage quality		D		
Grid losses & efficiency	D	D		
Lead time				D
Environmental impact				D
Electricity law	B		B	
Energy taxes			B	
Lack of knowledge	B	B	B	
Cost of implementation	B		B	
Energy storage	D	D	B	
GDPR				B

Beyond what has been presented in the table above, integration of RES could be considered a driver as well. Since high levels of RES often require batteries to manage the power quality and even out the load, components needed in microgrids will already be in the grid. The RES are included in the EU directive and the environmental factors. Many of the services provided by the microgrid to the main grid are needed because of the increased integration of intermittent RES. Furthermore, the reduction target of greenhouse gas emission is the main reason behind the Clean Energy initiative.

4.5.2 Discussion

Microgrids are special cases of smart grids, with the unique ability to connect to, and disconnect from the main grid. From the results gathered in this report, some drivers and barriers can be clearly categorized, and the primary barriers are connected to profitability and usage of energy storage in island mode operation.

To begin with, it is uncertain whether island mode operation would even be allowed due to the requirements of concessions. Furthermore, microgrids are miniature main grids, combining the different roles of actors in the main grid on a small scale. The monopoly of the DSOs prohibits them from participating in the electricity market and owning energy storage, complicating the development of microgrids due to less incentive of investments. For example, one of the main drivers identified for microgrids operating in island mode is the increased reliability it brings. It is the grid concession owner, the DSO, who is liable for the costs associated with bad reliability. However, DSOs cannot invest in ESSs if the ESSs are used to sell services to the main grid. Many of the drivers identified rely on the microgrid providing ancillary services the main grid when connected, which is not possible if the DSO owns the storage unit. In the cases of the microgrids in Simris and Arholma, it is the DSOs (E.ON and Vattenfall, respectively) that initiate the projects, which implies that they are the actors most likely to invest in microgrids. The DSOs are also the ones who benefit from not having to reinforce grids.

A possible solution to this is for DSOs to rent the ESS from a third party when they expect power outages to occur. Based on Tables 4.3 and 4.4, the majority of the outages are weather related and could be seasonally predicted. If DSOs and owners of the ESSs could cooperate, and keep the ESS charged in standby mode when the risk of power outages is the highest, the ESSs could be utilized in a microgrid running in island mode to improve the reliability. When the risk of outages is small, the owner of the ESS could instead sell ancillary services to the DSOs or TSO, and earn profits that way. This could be further improved with precise weather predictions, maximizing the use of the ESS and minimizing the time spent in standby.

An aspect to emphasize when comparing microgrids to regular measures of improving the grid is the flexibility of location. Uncertainties in levels of power consumption, whereabouts of power consumption and also how the power will be generated makes grid planning hard. In addition to this, the climate in Sweden might change in unforeseen ways in the coming years as well, making production planning even harder. Microgrid and ESS solutions have a shorter lead time, and can be moved where needed, which could be a good complement to traditional grid reinforcements.

Furthermore, the drivers and barriers indicate that a microgrid implementation is more beneficial in remote areas, far away from the center of the main grid. These areas tend to have lower reliability and the distance to the closest net station is higher. Longer high voltage power lines are required, which means higher costs and lead time. In these scenarios, a microgrid implementation is quicker and possibly more cost efficient in comparison to reinforcing the grid. Building microgrids in urban areas however, is less motivated. The cost of grid reinforcements is not as high, and the reliability is typically higher. Services provided by microgrids to the main grid could be organized by either a CEC, REC or an aggregator without having to solve the technical issues of going into island mode.

Another aspect to consider, and that could be viewed in two ways is reliability. In one way, bad reliability is a driver for implementing microgrids, but it could also be looked at the opposite way. Good reliability is a barrier. If the high reliability can be maintained in Sweden, it is likely that the incentive for microgrids will be low. And on the contrary if the main grid experiences regulatory problems and causes black outs because of it, or if the weather in Sweden gets more extreme, the incentive will most likely rise.

Social and ethical aspects

The implementation of a microgrid can also be seen from the user's perspective. Something that could have significant impact on the consumer within a microgrid is DF, depending on the requirements set. Today very little adaptations in the daily life are made with consideration to power consumption, DF could change this. If demands on DF in homes are set to high, consumers might be opposed to the adaptions they have to make.

There is also a socio-economic aspect of the implementation and operation of a microgrid. Even though a microgrid can provide cost-efficient electricity, the implementation costs of a microgrid can be quite high. Not all communities have the financial strength to make such investments, thereby the question of if the implementation of microgrids can lead to an economic divide, arises. However, in Sweden, the grid is supposed to be non-discriminatory, and the CEEP also emphasize equality for all members as very important, solving the issue before it even arose.

From an environmental aspect, there are multiple advantages of implementing microgrids in Sweden. Since microgrids mainly make use of local renewable resources, fossil fuel dependency would decrease. With proper management, energy resources can be stored and utilized effectively. By using more zero-emission electricity resources, greenhouse gas emissions will decrease, lowering climate changes. However, the mining of materials, and the manufacturing processes, for a microgrid's components, could have negative effects on the environment. Considerations thereby have to be made to the whole life cycle of the components, via for example life cycle analysis.

What needs to change in the future in order to implement a microgrid?

In order to be able to implement microgrids in the Swedish distribution grid, the Swedish law of electricity needs to change. The law does not favor energy storage, island operation or CEC. EU regulations differ from the Swedish regulations, but, while EU regulations take precedence over Swedish regulations, incitements for implementing a microgrid will continue to be low as long as the Swedish electricity law remains in its current state. An employee at Vattenfall stated, in an interview, that the electricity law is too vague and contains too many gray zones for there to be a real change in the Swedish distribution grid. Clearer directives, in which components such as BESSs are specified, are needed in the electricity law for microgrids to be implemented effectively in the Swedish distribution grid.

Uncertainties in results

For some of the results, approximations had to be made. For example, costs and lead time of a microgrid can vary a lot depending on size, location, available resources, etc of the microgrid. As for lead time of a new power line, the numbers used in the report are gathered from Ei and are approximated for power lines of all lengths. According to a source at Vattenfall, the lead time of a 10 km power line ranges from 4 to 8.5 years depending on complexity of the line, and the lead time of a 50 km power line ranges from 6.5 to 9.5 years depending on complexity. While these numbers indicate a shorter lead time than what is presented in Section 4.3.1, the lead time of implementing a new power line would still be longer than implementing a microgrid, if these numbers were used.

The choice of method and, especially, structure of the sections also lead to some potential uncertainties. By splitting the section into drivers and barriers, the report risks being biased in the different subsections. However, even if, for example, an area is primarily considered a driver for microgrid implementation and has been categorized as a driver, potential negative impacts on microgrid implementation within that area have not been disregarded in this thesis. This thesis has presented a broad variety of information and has touched upon many different aspects. However, this also means that the thesis has not immersed itself in one particular aspect and, therefore, does not offer a detailed analysis of specific aspects.

5
Case study

In this chapter results and discussions of the case study are presented.

5.1 Distribution grid case study

The distribution grid selected for the microgrid design in this report is a medium-sized community in southern Sweden. The community has a population of just below 10,000 citizens [16] and a large paper mill is located there. There are two types of electricity production installed, a medium-sized hydro power plant and a limited number of wind turbines. The local power grid has two substations. The first substation connects the paper mill and the hydropower plant to the grid. The second connects the community and the wind turbines to the grid. The ESS dimensioning for the microgrids is based on two years of hourly measurement data from the two loads and the two power generators. The data have been used to construct three different cases.

Table 5.1 summarizes the annual energy and peak power from two types of consumers and producers.

Table 5.1: Annual 'P'=production and 'C'=consumption, year 2018.

Load/Source	P/C	Annual Energy [GWh]	Peak power [MWh/h]
Village	C	43.6	11.0
Wind power	P	32.0	11.9
Paper mill	C	154.0	35.6
Hydro power	P	159.8	35.1

Case study structure description

The following list describes the structure of the case study. In every (a) and (b) scenario for each case, there are 1 hour ESS dimensions, 24 hour ESS dimensions, and stormy period analysis. Every (c) scenario is unique for each case with ESS dimensions based on different parameters.

List over case study structure:

1. Case 1: ESS dimensions for a microgrid consisting of a village and wind power
   (a) Without wind power generation
   (b) With wind power generation
   (c) Net load at different installed wind power capacity
2. Case 2: ESS dimensions for a microgrid consisting of a paper mill and a hydropower plant
   (a) Without hydropower generation
   (b) With hydropower generation
   (c) Net load with paper mill load increase
3. Case 3: ESS dimensions for a microgrid consisting of a village, wind power, a paper mill and a hydropower plant
   (a) Net load without power generation
   (b) Net load with power generation
   (c) Net load with increased paper mill load and increasing wind power penetration
   (d) Power exchange

5.2 Case 1: ESS dimensions for a microgrid consisting of a village and wind turbines

The dimensioning of an ESS for a microgrid consisting of a village and wind power is presented below.

5.2.1 a) Without wind power generation

This scenario presents a microgrid consisting of a village without wind power generation. The dimension of the ESS is based on the requirements for two different durations of island operation: a 1 hour and a 24 hour case based on hourly data from 2018.

1 hour island operation

Figure 5.1 shows the time series of the power demand of the village. Different percentiles of the load are also represented in Figure 5.1. The seasonal variation of the load is clearly observed and implies that the heating of the households may be electricity-based and is a significant part of the load during the winter. Another implication of the seasonal behavior is that the risk of an ESS not being able to cover a 1 hour operation is greater in the period between October and April.

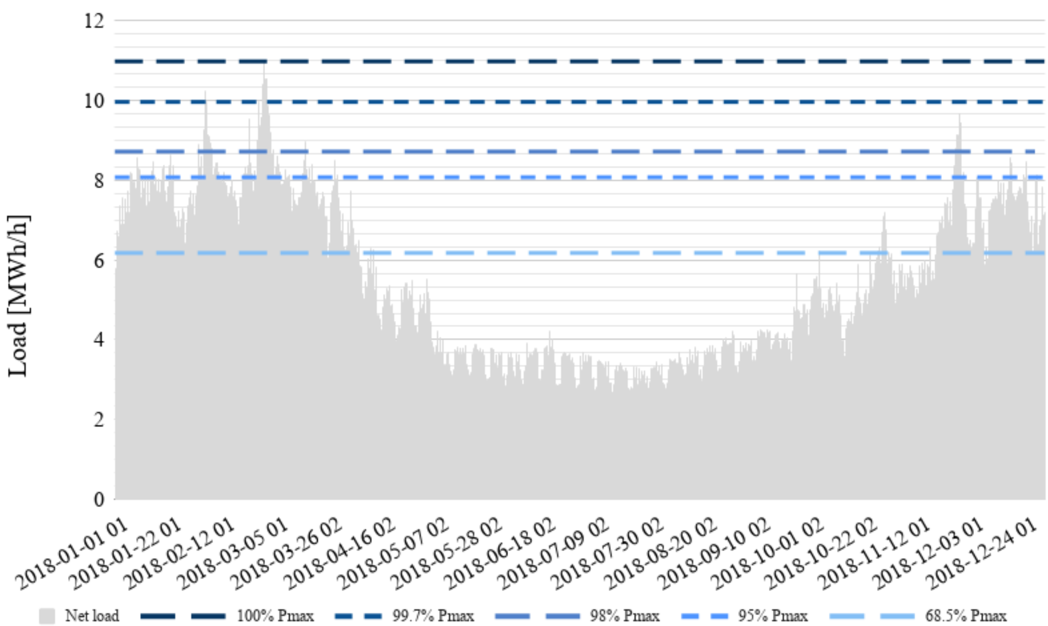

Figure 5.1: Village load without power generation during 2018 presented with dashed horizontal lines showing the different power load percentiles during 1 hour of island operation.

The left part of Figure 5.2 shows the corresponding duration curve of the load in Figure 5.1. The figure also indicates the power capacity of an ESS, $P_{\max}$, required to cover different percentiles of the load during 1 hour of island operation. The right part of Figure 5.2 shows the duration curve of the corresponding energy consumed by the load for one hour of island operation. The corresponding energy capacity of an ESS, $E_{\max}$, is also indicated.

There is a drastic change in the curve derivative around 8.2 MWh/h. This shows that the number of hours where the load is above 8.2 MW are few, which implies that an ESS dimensioned for this transition point would still be sufficient to cover a 1 hour island operation for the vast majority of the year. According to the US. DoE [31], the microgrid should be able to reduce outage time of required loads by 98%. To fulfill this requirement, the required power capacity of the energy storage in this case is 8.71 MW. Table 5.2 summarizes the $P_{\max}$ and $E_{\max}$ of the energy storage needed to cover different percentiles of the load.

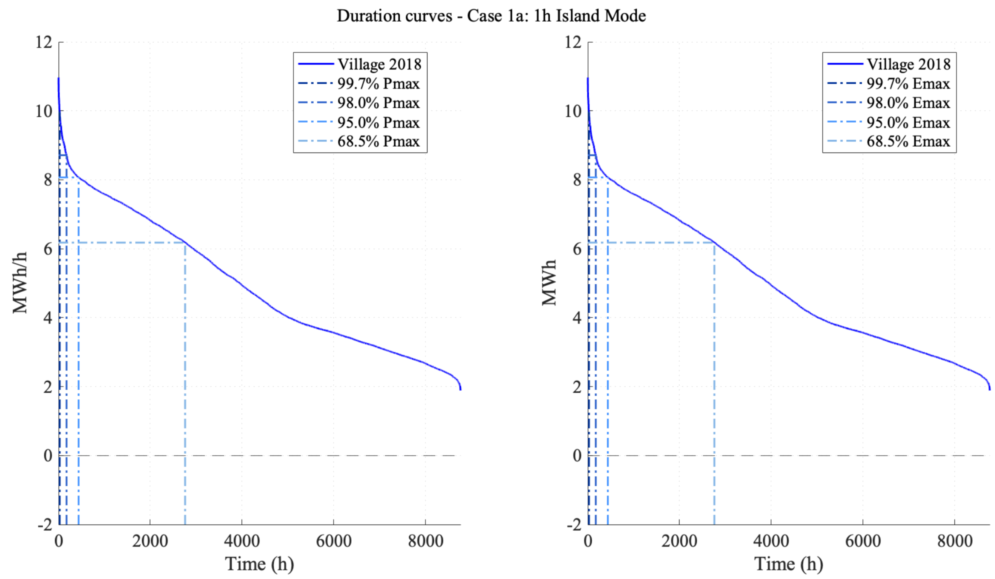

Figure 5.2: Duration curves of the power (left) and energy (right) demand during a 1 hour island operation without wind power over year 2018. The dashed lines shows different percentiles of the load in terms of power and energy.

As shown in Table 5.2, by lowering the energy and power capacity of the ESS by 20.6 percent, the system is still able to cover 98 percent of the 1 hour island operation cases. When examining Figure 5.1 and, in particular, Figure 5.2 it is apparent that there are few hours during the year when the peak demand reaches values higher than 8.71 MW. This implies that by dimensioning an ESS to cover the 98th percentile of load values during a year would contribute to significant cost and material savings, compared to the 100th percentile of load.

Table 5.2: The the power capacity and energy capacity needed for an ESS to meet the load at the different percentiles, during 1 hour of island operation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak load [MWh/h]	10.97	9.95	8.71	8.07	6.18
$P_{\max}$ [MW]	10.97	9.95	8.71	8.07	6.18
$E_{\max}$ [MWh]	10.97	9.95	8.71	8.07	6.18
Capacity reduction [%]	0.00 %	-9.30 %	-20.60 %	-26.44 %	-43.66 %

24 hour island operation

Figure 5.3 shows the time series of the maximum power demand of the village during 24 hour periods starting at every hour of the year. The different percentiles of load are also represented in the figure. Similarly to the 1 hour time series, Figure 5.3 shows a clear seasonal difference. This implies that the heating of the electric-based warming of households constitute a significant part of the load during winter time. Another implication of the seasonal behavior is that the risk of an ESS not being able to cover a 24 hour island operation is greater in the period between the period between October and April. In this case an ESS dimensioned for the 98th percentile would result in a 1.3 MW difference in what is demanded at the peak load and what the ESS would be able to provide.

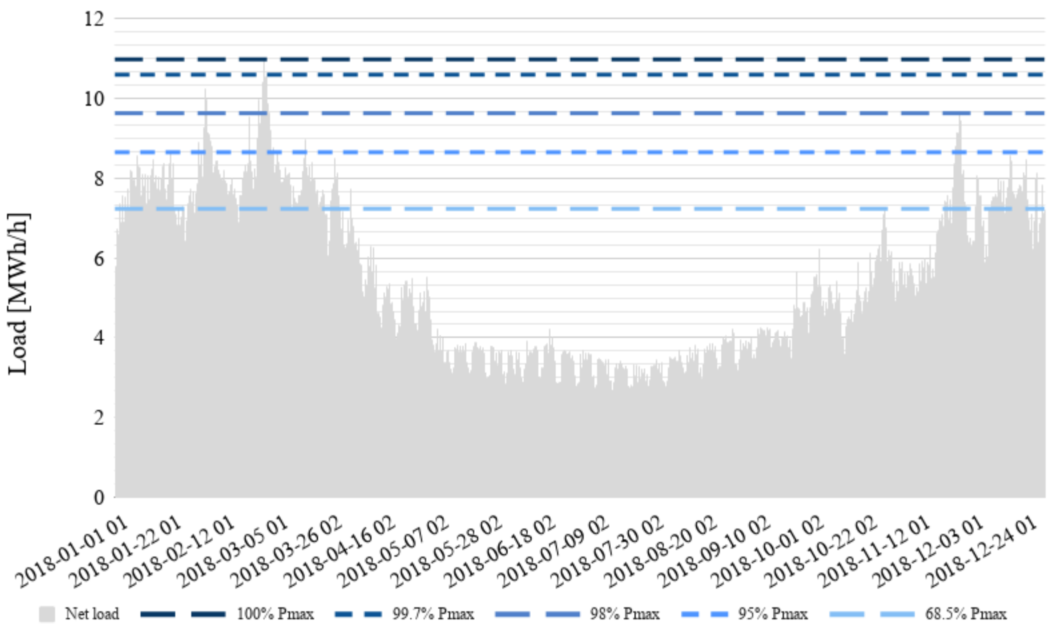

Figure 5.3: Village load without wind power over year 2018 presented with dashed horizontal lines showing the different load percentiles during 24 hour of island operation. The horizontal axis shows the starting point of a 24 hour period for every hour of the year.

The duration curve to the left in Figure 5.4 shows how many 24 hour periods an ESS dimensioned for a certain percentile of load will not be able to cover over a year when in island operation. The higher curve amplitude compared to the 1 hour case is due to several 24 hour periods sharing the same peaks. This implies that an ESS dimensioned for 24 hour island operations would require a higher power capacity than an ESS dimensioned for 1 hour of island operation. The drastic change of derivative at 8.65 MWh/h shows that the number of 24 hour periods that would not be covered by an ESS dimensioned for this value, is low over a year. To the right, the corresponding duration curve for the maximum cumulative energy sum consumed by the load shows a similar pattern for the energy capacity dimensioning at 185 MWh. Both these behaviors imply that these points could be interesting to look at in a cost vs. benefit analysis.

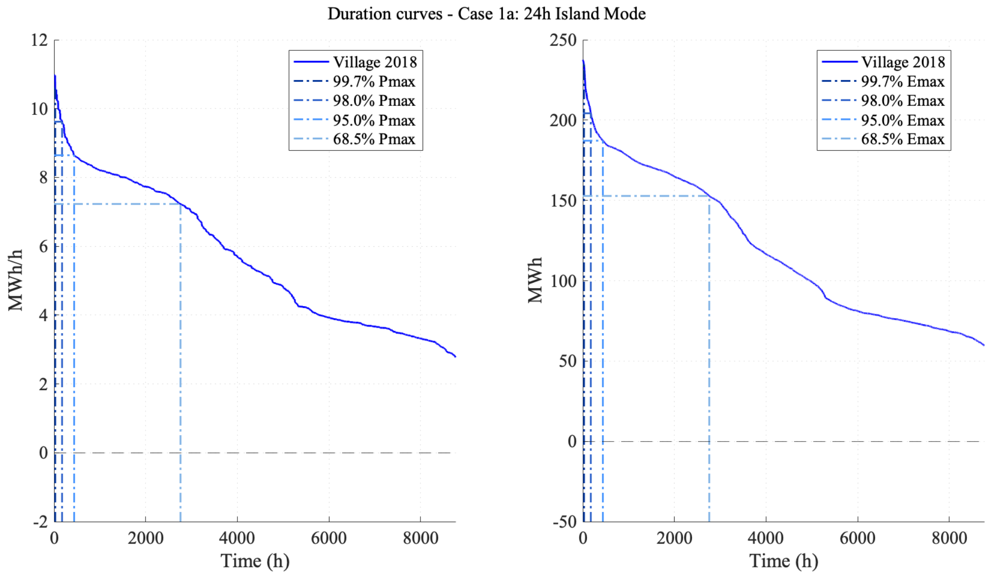

Figure 5.4: Duration curves of the power (left) and energy (right) demand during a 24 hour island operation without wind power over year 2018. The horizontal axis shows the starting point of a 24 hour period for every hour of the year. The dashed lines shows different percentiles of the load in terms of power and energy.

The $E_{\max}$ and $P_{\max}$ reductions presented in Figure 5.3 show that ESS dimensions for 24 hour island operations do not decrease at the same rate as the 1 hour ESS dimensions, for the different percentiles. That is the reason for the $E_{\max}$ and $P_{\max}$ ratios increasing in comparison to the corresponding percentile of the 1 hour ESS dimensions. By examining the ratios further, it can be observed that they are mostly below 24, but at the 68.5th percentile the ratio for $E_{\max}$ is 24.73. The fluctuations of the $P_{\max}$ and $E_{\max}$ ratios is caused by basing them on certain 24 hour period. Every percentile is corresponding to different 24 hour periods, making the 100th percentile the 24 hour period where the maximum energy capacity and power capacity is calculated. This causes the power capacity of the ESS for 24 hour island operation to differ from the 1 hour case.

The $E_{\max}$ ratios are also affected by the $E_{\max}$ being calculated over 24 hour periods instead of 1 hour periods which is shown in Algorithm 1 in the method section. The algorithm does a cumulative sum of every net load value as long as the next value is positive or equal to zero. When the next value turns negative it stores the accumulated E_{max} as a temporary E_{max} and then continues to sum the next values during the 24 hour period. This changes the outcome significantly since E_{max} is not only based on one data point as in the 1 hour calculations.

Table 5.3: ESS dimensions for different percentiles of the net load. Capacity reduction for different percentiles of ESS dimensions compared to the 100th percentile, and the ratios for 24 hours compared to 1 hour, of island operation during no power generation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak load [MWh/h]	10.97	9.95	8.71	8.07	6.18
P_{max} [MW]	10.97	10.59	9.62	8.65	7.23
E_{max} [MWh]	237.50	234.53	204.21	187.17	152.77
P_{max} reduction [%]	0.00 %	-3.51 %	-12.31 %	-21.19 %	-34.10 %
E_{max} reduction [%]	0.00 %	-1.25 %	-14.01 %	-21.19 %	-35.68 %
P_{max} ratio (24 h:1 h)	1.00	1.06	1.10	1.07	1.17
E_{max} ratio (24 h:1 h)	21.66	23.56	23.44	23.20	24.73

Stormy seasons in Sweden year 2018 and 2019

Table 5.4 shows how the ESS could be dimensioned to handle 1 hour or 24 hours of island operation during a stormy period. These values are based on a specific 1 hour or 24 hour period which entails that the ESS dimensions in general are a bit lower than the peak hour or day of 2018. The dates where the storms occurred were recorded by SMHI [17]. Observing Figure 5.1 and 5.3 it appears that the storms that took place during 2018 occurred just between the heaviest load periods of the year which causes the ESS dimension values be lower than the 68.5th percentile of the ESS dimensions for 24 hour island operation in Table 5.3. When comparing the highest E_{max} 24 hour value for the storm ”Mats” from Table 5.4, 140.55 MWh, to the E_{max} 24 hour value from Table 5.3, 237.50 MWh, they differ with approximately 41 percent. This implies that dimensions of a standby ESS to utilize solely during blackouts for stormy periods will be smaller than a ESS dimensioned to cover all peak net load days during a year, for a microgrid lacking of power generation.

Table 5.4: 1 hour and 24 hour island operation ESS dimensions based on net load data from a village during storms occuring in Sweden during 2018 and 2019

Name	Date	Peak load [MWh/h]	P_{max} [MW]	E_{max} 1 h [MWh]	E_{max} 24 h [MWh]
Johanne	2018-08-10	3.70	3.70	3.70	73.76
Knud	2018-09-21	4.07	4.07	4.07	86.76
Alfrida	2019-01-01	6.62	6.62	6.62	138.50
Jan	2019-02-10	6.95	6.95	6.95	145.13
Julia	2019-02-16	6.23	6.23	6.23	138.58
Mats	2019-02-24	6.50	6.50	6.50	140.55

5.2.2 b) With wind power generation

Case 1 b) presents a scenario where the village microgrid is in island operation together with wind turbines, dimensioning ESS for a 1 hour and a 24 hour case based on hourly data from 2018.

1 hour island operation

In Figure 5.5 the seasonal pattern of the 1 a) case shown in Figure 5.1 is less accentuated but still present. The percentiles are lower due to the power supplied from the wind turbines, but also more compressed, implying that the wind blows more in the winter than in the summer and therefore compresses the individual peaks. The negative hours of net load shows that the grid sometimes generates more power than is needed, implying that an ESS would be able to charge during these hours. It is clear that an ESS dimensioned for the 68.5th percentile faces greater risk of not being able to provide sufficient power even in the warmer months due to the compression of seasonal differences.

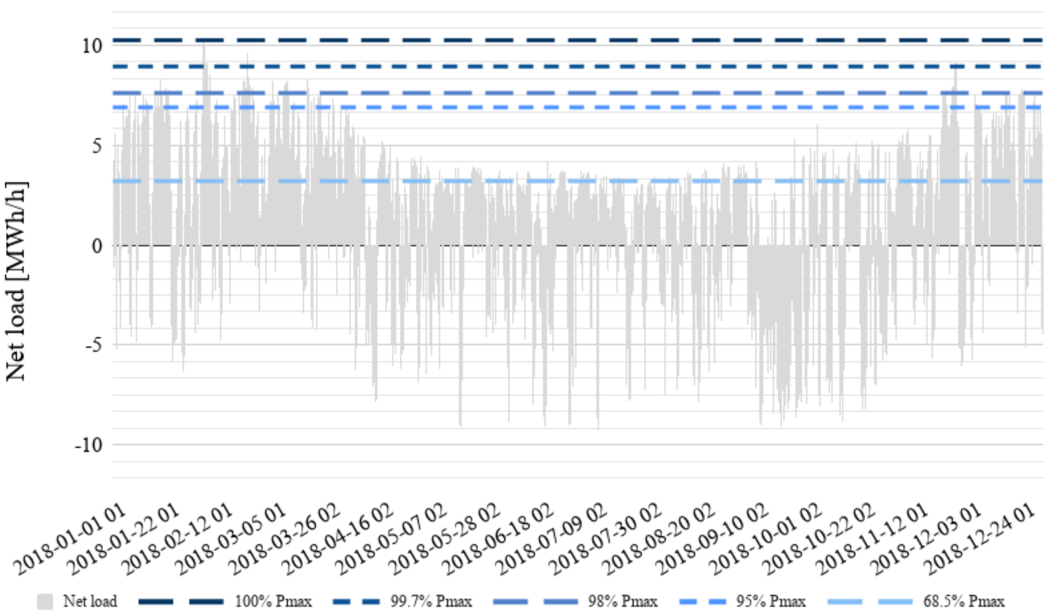

Figure 5.5: Village load with wind power generation over year 2018 presented with dashed horizontal lines showing the different net load percentiles of the ESS dimensions.

The lower amplitude of the curves in Figure 5.6 compared to case 1 a) in Figure 5.2 is due to the wind power generation supplying part of the demand. The narrow peak between 10.25 MWh/h and 8 MWh/h is smaller than the corresponding peak in Figure 5.2. This is due to the peak compression provided by the wind power generation, implying the risk that an ESS dimensioned for the 98th percentile would not be able to cover the demand is smaller with wind power generation than without. An interesting observation is the negative part of the curve that shows the hours where the wind power generation exceeds the load, implying that an ESS could be charged during these hours.

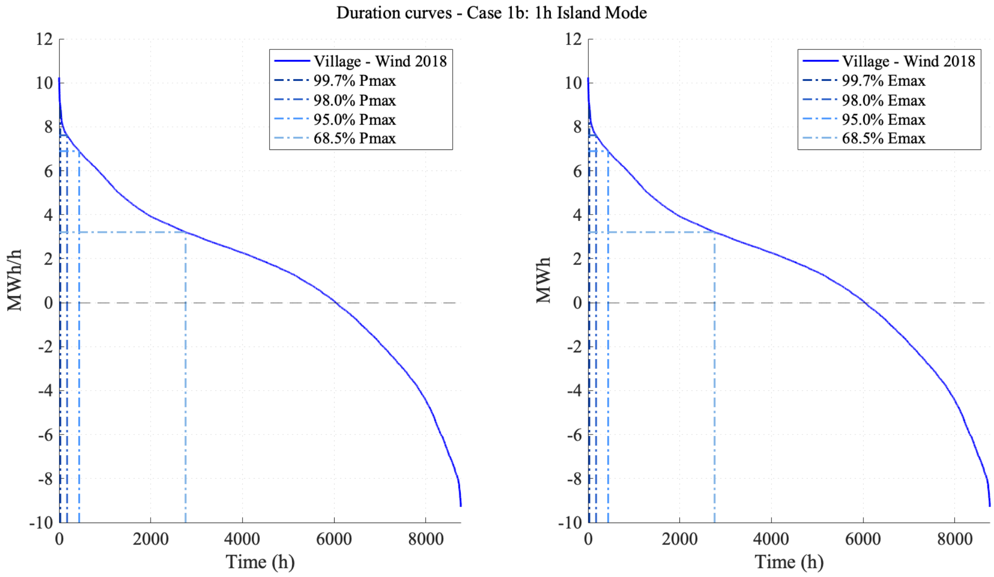

Figure 5.6: Duration curves of the power (left) and energy (right) demand during a one hour island operation with wind power over year 2018. The dashed lines shows different percentiles of the load in terms of power and energy.

Table 5.5 present the net load, $P_{\max}$, $E_{\max}$, and the reduction of the capacity needed for dimensioning an ESS to handle one hour of island operation, in a microgrid including wind power generation, for each percentile of the net load. An interesting result in Table 5.2 is the capacity reduction vs the ESS dimensions in case 1 a) for 1 hour of island operation. One could think that there should be a more significant reduction of the dimensions but since, during some hours of the year, the wind power generation is low compared to the load, this contributes to $P_{\max}$ of the 100th percentile only being 6.56 percent lower.

When examining the 68.5th percentile in Table 5.5 there is a significant reduction compared to case 1 a). Figure 5.5 shows that the 68.5th percentile is covering almost all peak loads during the summer which are significantly lower than the peak loads during the winter season. This is due to less significant load peaks occurring in the 68.5th percentile and the wind power making a bigger impact on those 1 hour periods. To lower the dimensions of an ESS it is not very efficient to install wind power to cover all hours of the year since there will always be some hours of the year when there is no wind.

Table 5.5: Table presenting the capacity decrease for different percentiles of ESS dimensions for 1 hour of island operation during no power generation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak net load [MWh/h]	10.25	8.95	7.61	6.89	3.21
P_{max} [MW]	10.25	8.95	7.61	6.89	3.21
E_{max} [MWh]	10.25	8.95	7.61	6.89	3.21
Capacity reduction [%]	0.00 %	-12.68 %	-25.76 %	-32.78 %	-68.68 %
Capacity reduction vs. Case 1 a) [%]	-6.56 %	-10.05%	-12.63 %	-14.62 %	-48.06 %

24 hour island operation

In Figure 5.7, the compression of percentiles in the 1 hour case shown in Figure 5.5, exhibits a different behavior. The segmentation of the percentiles is due to several 24 hour periods sharing the same peaks, implying that a small difference in the dimensioning of an ESS could have a significant impact. The extended distance from the warmer period peaks of the 68.5th percentile is due to the overall higher power requirements associated with 24 hour period dimensioning explained earlier in this chapter. The implications of this is that for an ESS dimensioned for 24 hour island operations with wind power generation, lower percentiles face a lesser risk of being unable to provide sufficient power during load peaks in warmer periods than one dimensioned for one hour island operations.

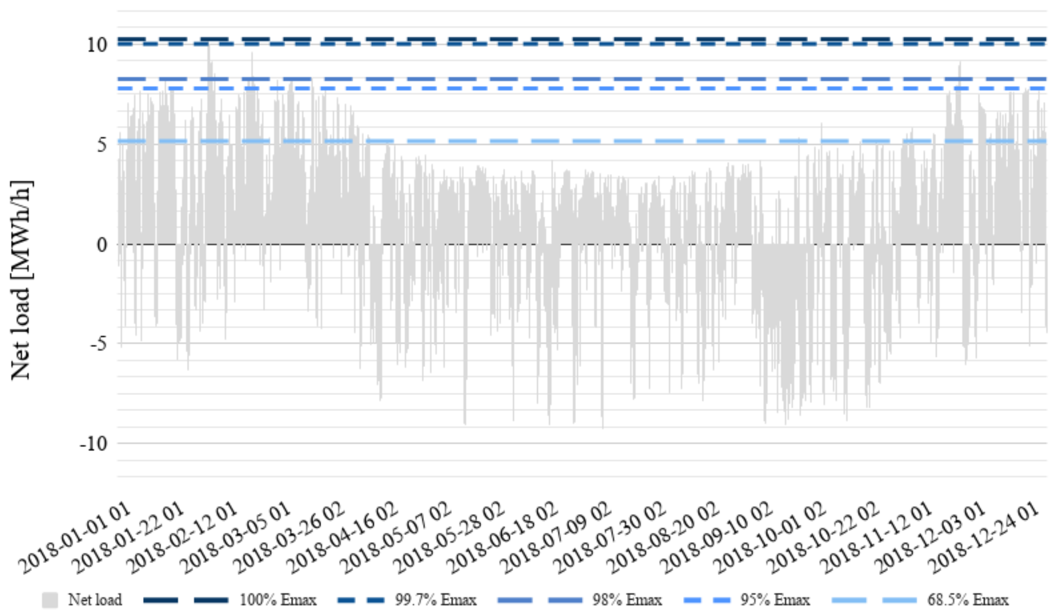

Figure 5.7: Village with power generation over year 2018 presented with dashed horizontal lines showing the different maximum power percentiles of the ESS dimensions. The horizontal axis shows the starting point of a 24 hour period for every hour of the year.

When comparing the left part of Figure 5.8 with the 1 hour case in 5.6, the number of hours with negative values are considerably fewer. This is due to the shared peaks of several 24 hour periods explained earlier, and implies that for an ESS dimensioned for 24 hour island operations, there are fewer hours where charging is possible. The right part of the figure shows the duration curve of the corresponding maximum cumulative energy sum, consumed by the load during 24 hour periods starting at every hour of the year. When comparing the right part of Figure 5.8 with the 24 hour case without wind power generation, a significant decrease in overall curve amplitude due to the power supplied by the wind power generation can be seen. A substantial part of the 24 hour periods have negative net loads. This area between the horizontal axis and these negative values gives an indication of how much energy an ESS would need to be capable of storing if the microgrid would not have the ability to curtail excess power.

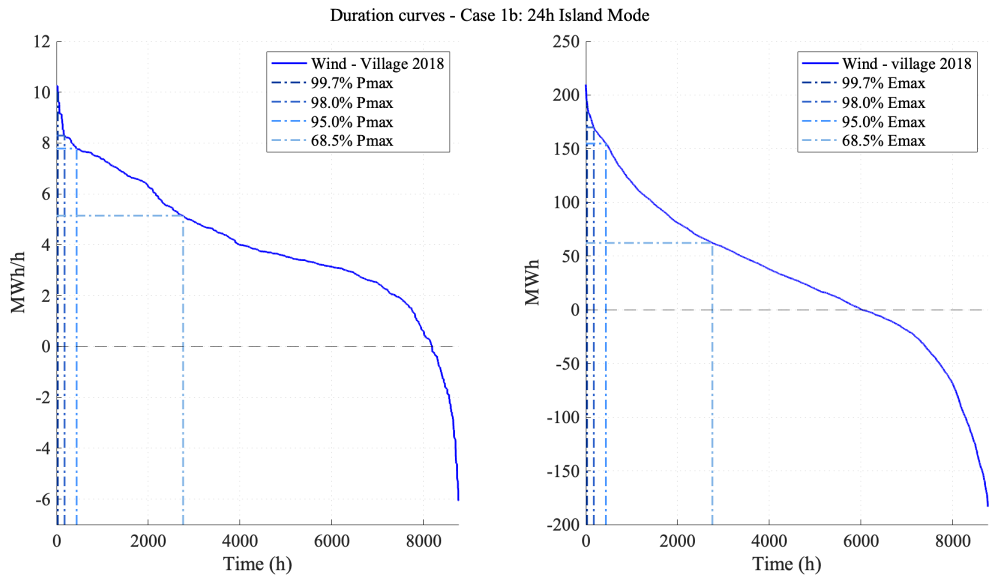

Figure 5.8: Duration curves of the power (left) and energy (right) demand during a 24 hour island operation with wind power over year 2018. The horizontal axis shows the starting point of a 24 hour period for every hour of the year. The dashed lines shows different percentiles of the load in terms of power and energy.

Table 5.6 present the load, $P_{\max}$, $E_{\max}$, and the reduction of each capacity needed for dimensioning an ESS to handle 24 hour of island operation for each percentile of the peak load. The reduction of the $P_{\max}$ and $E_{\max}$ capacity compared to case 1 a) 24 hour island operation, without wind power generation, is also presented. Similarly to the one hour island operation, the most sigificant capacity reduction happens at the 68.5th percentile. Here it is also very apparent that $E_{\max}$ is significantly lower for the 68.5th percentile than the 100th percentile. $E_{\max}$ is reduced by almost 70 percent compared to approximately 35 percent in case 1 a) Table 5.3, without wind power generation. This is also in line with the implications made from Table 5.5, saying that installing wind power in a microgrid mainly affects the 68.5th percentile of the net load values. This concludes that wind power is efficient for lowering the average net load of a microgrid while the peak loads still has to be handled by an ESS.

Table 5.6: Table presenting the capacity reduction for different percentiles of ESS dimensions and the ratios compared to 1 hour island operation, for 24 hours of island operation with wind power generation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak net load [MWh/h]	10.25	8.94	7.61	6.89	3.21
P_{max} [MW]	10.25	10.01	8.25	7.78	5.15
E_{max} [MWh]	209.79	194.02	169.88	154.84	66.27
P_{max} reduction [%]	0.00 %	-2.28 %	-19.48 %	-24.03 %	-49.78 %
E_{max} reduction [%]	0.00 %	-7.52 %	-19.03 %	-26.19 %	-68.41 %
P_{max} ratio 24 h/1 h	1.00	1.12	1.08	1.13	1.60
E_{max} ratio 24 h/1 h	20.48	21.71	22.32	22.47	20.66
P_{max} reduction compared to Case 1 a) [%]	-6.57 %	-5.42 %	-14.25 %	-9.98 %	-28.83 %
E_{max} reduction compared to Case 1 a) [%]	-11.66 %	-17.27 %	-16.81 %	-17.27 %	-56.62 %

Stormy seasons in Sweden year 2018 and 2019

Table 5.7 shows how the ESS in case 1 with wind power generation included could be dimensioned to handle 1 hour or 24 hours of island operation during a stormy period. Due to high winds during stormy periods the peak net load was negative 0.71 MWh/h meaning that the village in this case had its power demand fully fulfilled and surplus power was injected to the upper grid level during all 24 hours of this storm. To handle cases with over production during island operation a grid forming unit has to be installed in order to enable curtailment of surplus power. This also implies that, in this case, no ESS has to be installed in order to cover demand. For the other storms this was not the case.

Name	Date	Peak load [MWh/h]	P_{max} [MW]	E_{max} 1 h [MWh]	E_{max} 24 h [MWh]
Johanne	2018-08-10	0.27	0.27	0.27	0.49
Knud	2018-09-21	1.78	1.78	1.78	3.07
Alfrida*	2019-01-01	-0.71	0.00	0.00	0.00
Jan	2019-02-10	4.73	4.73	4.73	29.76
Julia	2019-02-16	3.00	3.00	3.00	5.21
Mats	2019-02-24	5.29	5.29	5.29	47.71

Table 5.7: 1 hour and 24 hour island operation ESS dimensions based on net load data from a village and wind power generation during storms occuring in Sweden during 2018 and 2019. * In order for island operation to work a grid forming unit has to be installed.

5.2.3 c) Net load at different installed wind power capacity

Case 1c presents a scenario where the villages microgrid is in island operation with installed capacity of wind turbines, operating a 1 hour and a 24 hour operation case and how different installed capacities affects the ESS dimensions. The operation is based on hourly data from 2018.

In Figure 5.9 the impact of increased power generation on ESS dimensions are shown for different percentiles of the 1 hour island operation case. Initially the power and energy demand of all percentiles decreases, for the higher percentiles a certain point marks where an increased wind penetration stops having an impact on the dimensioning of the ESS. The lower a percentile is, the less distinct this point becomes. This pattern fades away at the 68.5th percentile. While still having a significant change in derivative, it is still being impacted by the increased wind penetration. This shows how an ESS dimensioned for higher percentiles still has to provide sufficient power and energy for hours when the wind turbines are not generating any power, while an ESS dimensioned for the 68.5th percentile will not be able to provide sufficient power or energy for these hours anyway and therefore keeps being impacted by the increased wind penetration. This implies that the requirements of an ESS dimensioned for the 68th percentile could be significantly reduced by an increased number of wind turbines.

An interesting result is that the requirements of an ESS dimensioned the 100th and 99.7th percentile increases with the increased wind penetration. This is due to the wind turbines occasionally being inactive and having a negative generation, meaning they contribute to the load. When increasing the number of wind turbines, the negative generation for these hours increases which increases the requirements for the ESS as it has to additionally supply the wind turbines with power and energy.

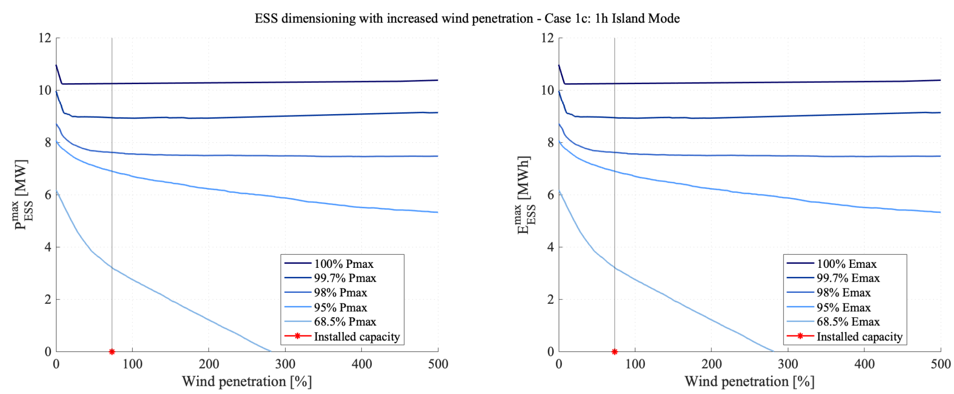

Figure 5.9: Power capacity (left) and energy capacity (right) of the ESS required for 1 hour island operation at different wind penetration levels.

The left part of Figure 5.10 shows an decreasing impact of increased wind penetration on the 68.5th percentile. This is because an ESS dimensioned for this percentile still would have to be able to supply the peak net load of a 24 hour period. The implications of this is that the chance of a 24 hour period with a relatively constant power generation from the wind turbines, is slim.

The increased power demand with increased wind penetration of the higher percentiles explained in the 1 hour island operation case, is now visible down to the 95th percentile. This shows how the increased power requirements of an ESS dimensioned for 24 hour island operations requires it to provide for hours with negative generation from the wind turbines. This implies that the impact on power requirements on an ESS of an increased number of installed wind turbines, is less than in the 1 hour island operation case.

There seems to be an entanglement of the 100th and 99.7th percentiles in the left part of Figure 5.10, but the 100th percentile is, per definition, always at the top. The decrease in distance between them with increased wind penetration is due to more and more of the increased negative generation values entering the 99.7th percentile as they increase in scale, further decreasing the distance until they meet at 450 % wind penetration. This implies that there is not much to be gained by dimenisoning an ESS after the 99.7th percentile in this case.

The right part of Figure 5.10 shows a continued impact of increased wind penetration on the lower percentiles. This is because an ESS dimensioned for the lower percentiles would not be required to supply energy for all the days with less energy generated by the wind turbines. This implies that the requirements of an ESS dimensioned for lower percentiles could be lowered with an increased installed number of wind turbines and that this could be considered in an implementation.

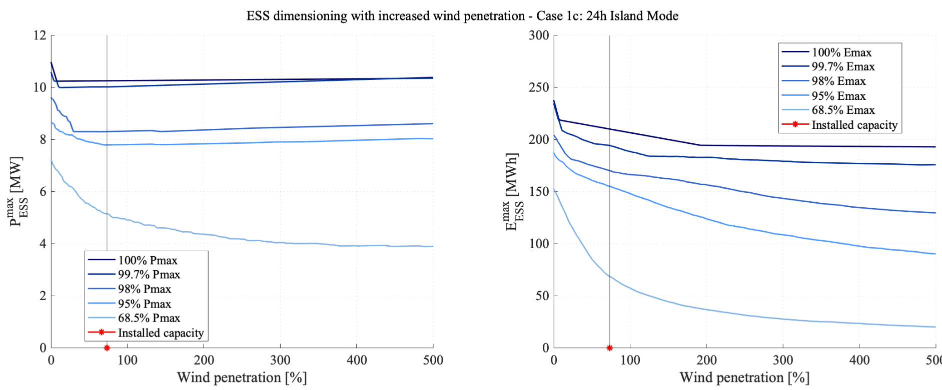

Figure 5.10: Power capacity (left) and energy capacity (right) of the ESS required for 24 hour island operation at different wind penetration levels.

5.3 Case 2: ESS dimensions for a microgrid consisting of a paper mill and a hydro plant

The dimensioning of an ESS for a microgrid consting of a paper mill and hydropower is presented below.

5.3.1 a) Net load without power generation

Case 2a presents a scenario where the paper mill microgrid is in island operation without the hydropower plant, modeling a 1 hour and a 24 hour hour case based on hourly data from 2018.

1 hour island operation

Figure 5.5 shows the time series of the power demand from the paper mill. Different percentiles of the load are also represented in the figure. Minor seasonal variation of the load can be observed with the load being less evenly distributed during the winter time, implying that the heating is partly electricity based. The highest peaks are represented by clusters of peaks during February, April and August. This implies that it could prove hard to predict when an ESS would not be able to supply the demanded power.

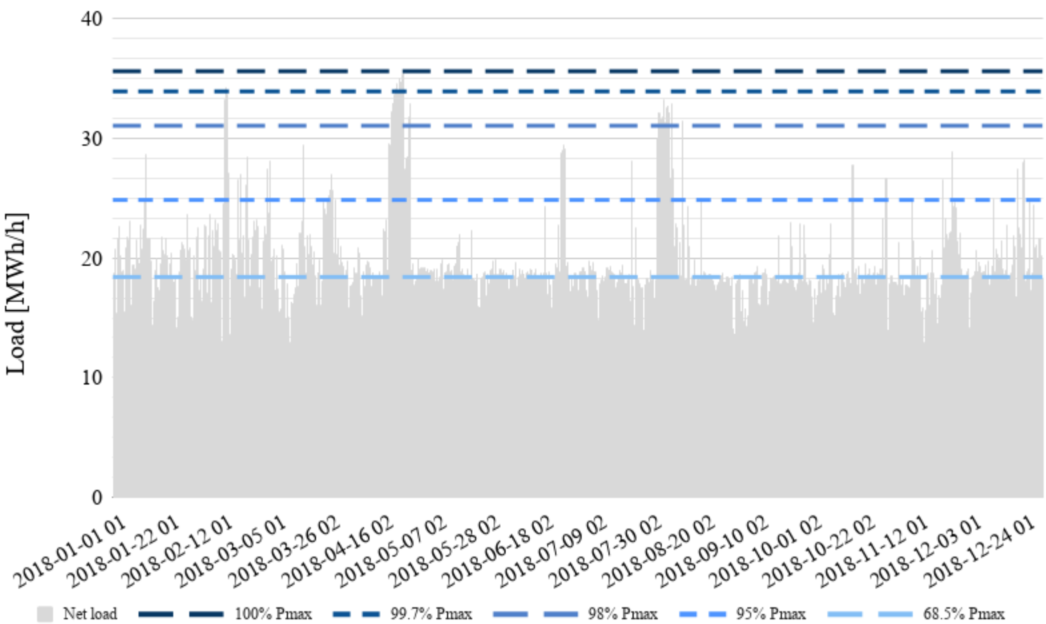

Figure 5.11: Paper mill without hydropower generation over year 2018 presented with dashed horizontal lines showing the different load power percentiles of the ESS dimensions.

The left part of Figure 5.12 shows the corresponding duration curve of the load in Figure 5.11. The figure also indicates the power capacity of an ESS, $P_{\max}$, required to cover different percentiles of the load during a 1 hour island operation. The change of derivative at 19 MWh/h shows that the number of hours an ESS dimensioned for this value would not be able to cover are few and that this point could be interesting in a cost vs. benefit analysis. After the 8,000 hour mark on the horizontal axis, the curve makes a dive to zero. This shows that there is a number of hours where the load drastically reduces, implying that the paper mill is inactive.

The right part of Figure 5.12 shows the duration curve of the corresponding energy consumed by the load for 1 hour island operation, with the corresponding energy capacity of an ESS, E_{max}, indicated.

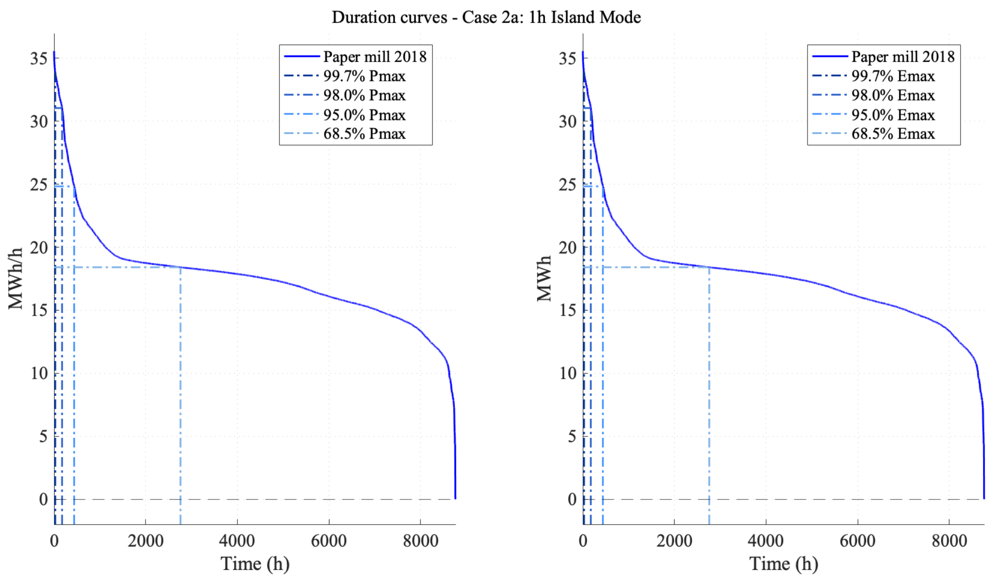

Figure 5.12: Duration curves of the paper mills 1 hour power and energy demand without power generation over year 2018 presented, dashed lines showing the different maximum percentiles of the demand of power in MWh/h (left) and energy in MWh (right).

Table 5.8 below shows how the percentiles of the peak load, P_{max}, E_{max}, and the percentage reduction for each percentile compared the 100th percentile, for a medium sized paper mill without power generation. The most significant capacity reduction happens at the 95th and 68.5th percentile and not as much for the 99.7th, and 98th percentile. This is caused by the paper mill load being quite persistent during the year, and not being affected by seasonal changes. When comparing Figure 5.11 to the results, it is clear that most of the load values peaks at the 68.5th percentile, making it more efficient to dimension an ESS, for 1 hour island operation, for that percentile. As is shown in the Table 5.8 the capacity reduction is almost 50 percent.

Table 5.8: Table presenting the capacity reduction for different percentiles of ESS dimensions and the ratios for one hour of island operation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak load [MWh/h]	35.58	33.90	31.03	24.83	18.41
$P_{\max}$ [MW]	35.58	33.90	31.03	24.83	18.41
$E_{\max}$ [MWh]	35.58	33.90	31.03	24.83	18.41
Capacity reduction [%]	0.00 %	-4.72 %	-12.78 %	-30.20 %	-48.25 %

24 hour island operation

Figure 5.13 shows the time series of the maximum power demand of the paper mill during 24 hour periods starting at every hour of the day. The different percentiles of load are also represented in the figure. The percentiles are higher than in the corresponding time series for one hour load. This is due to several 24 hour periods sharing the same peaks, implying that an ESS dimensioned for a 24 hour island operation would require a higher power capacity. Similarly to the 1 hour time series, the peak distribution implies that it could prove hard to predict at what time of the year an ESS would not be able to supply the required power during a 24 hour island operation.

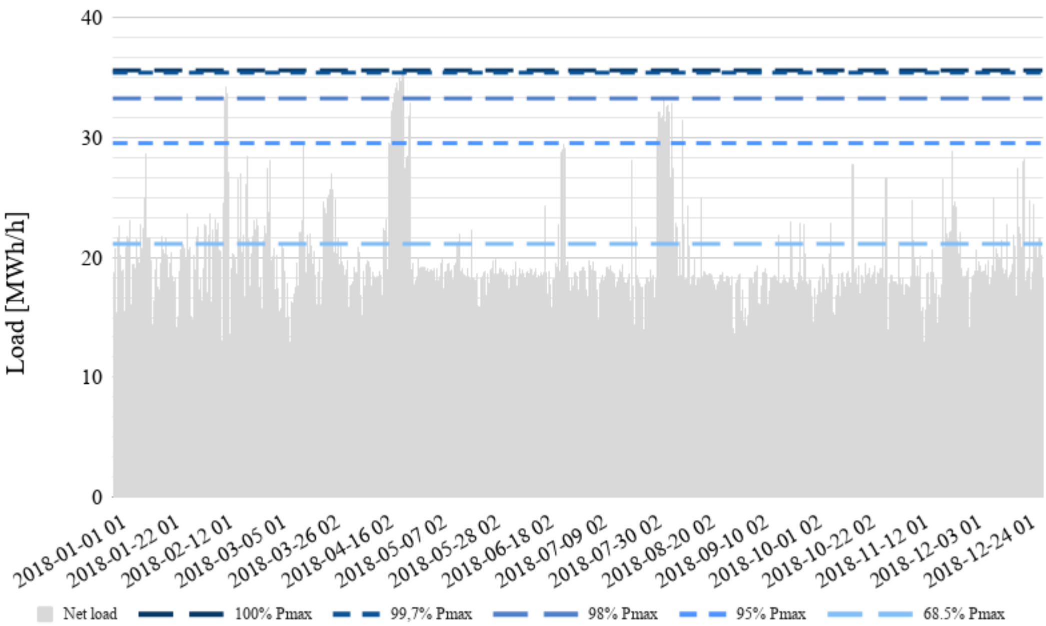

Figure 5.13: Paper mill without power generation over year 2018 presented with dashed horizontal lines showing the different net load power percentiles of the ESS dimensions.

The duration curve to the left in Figure 5.14 shows how many 24 hour periods an ESS dimensioned for a certain percentile of load will not be able to cover over a year, when in island operation. The higher curve amplitude compared to Figure 5.12 is due to a number of 24 hour periods sharing the same peaks. The minimum value of 14 MWh/h shows that paper mill was not inactive during a complete 24 hour period during 2018, implying that the chance of this happening is low.

The right part of Figure 5.14 shows the corresponding duration curve for energy consumed by the load. The minor difference in curve derivative between hour 1,000 to hour 7,500 shows that the energy demand of the paper mill is distributed quite evenly over a 1 year period. This implies a certain predictability in how many 24 hour periods over a year an ESS dimensioned for a certain percentile would not be able to supply.

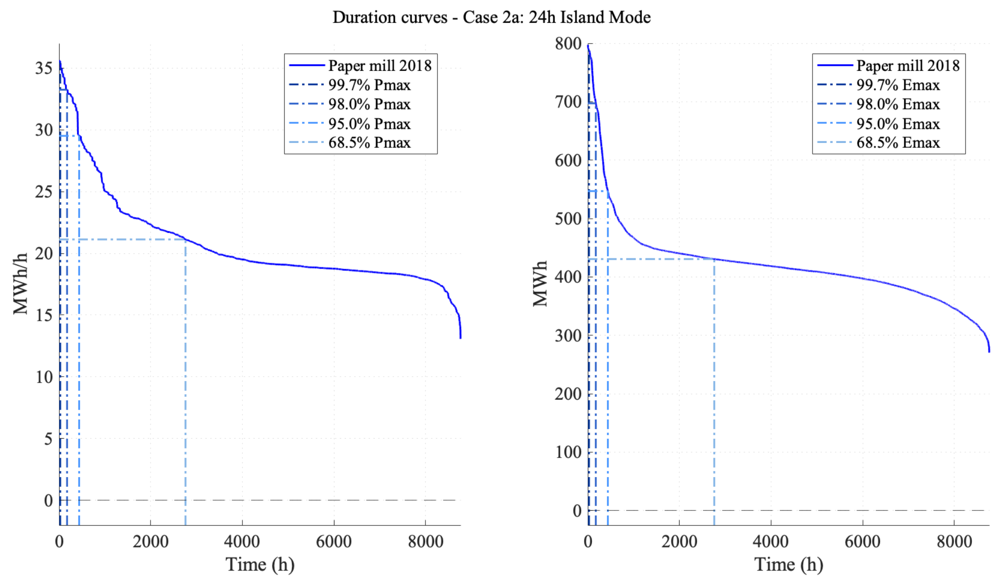

Figure 5.14: Duration curves of the paper mills 24 hour hour power and energy demand without power generation over year 2018 presented, dashed lines showing the different maximum percentiles of the demand of power in MWh/h (left) and energy in MWh (right).

In Table 5.9 different percentiles of parameters regarding 24 hour island operation of the paper mill are shown. The ratios describe how much the percentiles of the different parameters is differing from the 1 hour island operation scenario. In this figure the $E_{\max}$ ratios are quite persistent. They vary around 22.0-23.3 and every value is below 24. Compared to the one hour case, most of the load hours are below the 1 hour percentiles when calculating the corresponding $E_{\max}$ percentile for 24 hour island operation. This implies that it could be more efficient to choose the 95th or the 68.5th percentiles since that results in a significant reduction in both $P_{\max}$ and $E_{\max}$ for the ESS dimensions. Since there is a 5 % probability for having power demand peaks over 29.51 MW during a year, when looking at data from year 2018, the ESS would still be able to handle the 95th percentile of the load during the rest of the year.

Table 5.9: Table presenting the capacity reduction for different percentiles of ESS dimensions and the ratios for 24 hours of island operation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak load [MWh/h]	797.41	787.47	697.06	546.80	430.47
$P_{\max}$ [MW]	35.58	35.38	33.24	29.51	21.12
$E_{\max}$ [MWh]	797.41	787.50	697.26	546.91	430.47
$P_{\max}$ reduction [%]	0.00 %	-0.54 %	-6.56 %	-17.05%	-40.63%
$E_{\max}$ reduction [%]	0.00 %	-1.24 %	-12.56 %	-31.41%	-46.02 %
$P_{\max}$ ratio (24 h:1 h)	1.00	1.04	1.07	1.19	1.15
$E_{\max}$ ratio (24 h:1 h)	22.415	23.233	22.471	22.024	23.383

Stormy seasons in Sweden year 2018 and 2019

Table 5.10 shows ESS dimensions for island operation during storms in 2018 and 2019 for a microgrid consisting of a paper mill and no power generation. Due to the 1 hour resolution, peak load, $P_{\max}$, and $E_{\max}$ will have the same values for each storm. $E_{\max}$ for 24 hours are calculated by using Algorithm 1, explained in the method section. The peak load value of the paper mill during the storm seem to be quite unaffected since they are almost the same during the winter as during the storm "Johanne" in August 2018. It only differs of approximately 3 MWh/h. This implies that the load of the paper mill is not necessarily seasonally dependent.

Table 5.10: 1 hour and 24 hour island operation ESS dimensions based on load data from a paper mill during storms occuring in Sweden during 2018 and 2019

Name	Date	Peak load [MWh/h]	$P_{\max}$ [MW]	$E_{\max}$ 1 h [MWh]	$E_{\max}$ 24 h [MWh]
Johanne	2018-08-10	22.51	22.51	22.51	445.84
Knud	2018-09-21	18.61	18.61	18.61	422.05
Alfrida	2019-01-01	19.32	19.32	19.32	390.70
Jan	2019-02-10	18.62	18.62	18.62	404.70
Julia	2019-02-16	16.53	16.53	16.53	359.79
Mats	2019-02-24	19.06	19.06	19.06	359.85

5.3.2 b) Net load with power generation

Case 2b presents a scenario where the paper mill microgrid is in island operation with the hydropower plant, modeling a 1 hour and a 24 hour case based on hourly data from 2018.

1 hour island operation

Figure 5.15 shows the time series of the hourly power demand of the paper mill together with the hydropower plant. Different percentiles of the load are also represented in the figure. A clear seasonal pattern can be observed in the first quarter of the year. The negative loads shows how the hydropower plant generates more power than the paper mill demands. Thus, the hydropower plant is able to generate more power in this part of the year, since a significant reduction in load cannot be observed in the same period of figure 5.11. The general suppression of loads can be explained by the steady output of the hydropower plant and implies that the risk of an hour where the hydropower plant does not produce any power is low.

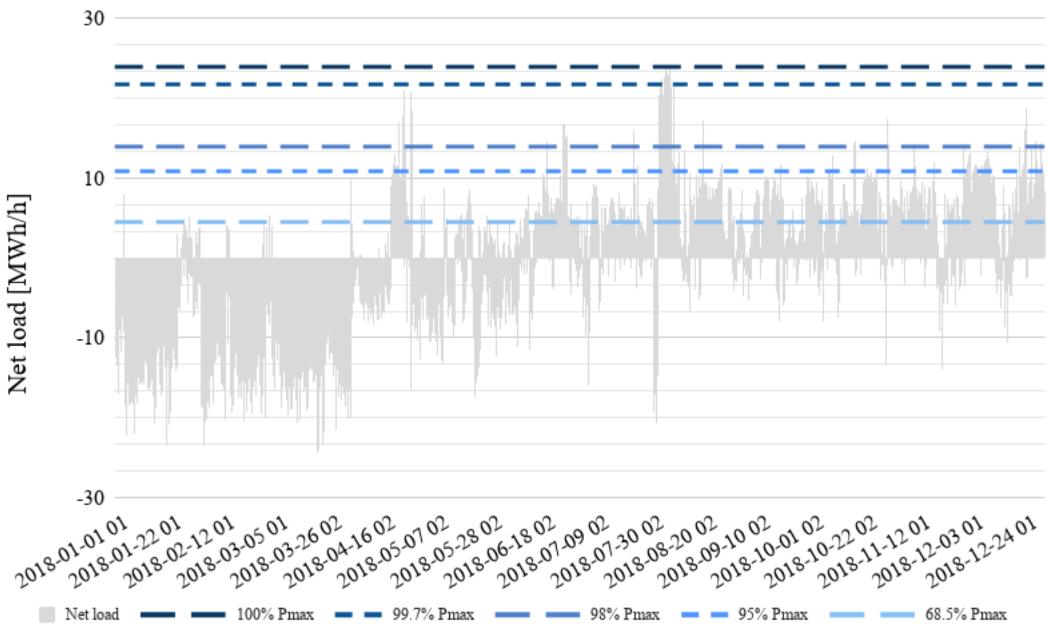

Figure 5.15: Paper mill with power generation over year 2018 presented with dashed horizontal lines showing the different maximum power percentiles of the ESS dimensions.

On the left side of Figure 5.16 is a duration curve showing how many hours an ESS dimensioned for a certain percentile of load will not be able to cover over a year, when in island operation. There is a significant difference when comparing to the corresponding duration curve for the 1 hour island operation in Figure 5.12. The curve is greatly suppressed in its entirety, with close to half of the curve situated in the negatives. These values represent the hours when the hydropower plant generates more power than the paper mill demands, implying that an ESS could be charged during these hours. The change in curve derivative at 10.82 MWh/h is due to the small number of hours where the load exceeds this value, implying that an ESS dimensioned for the 95th percentile would face a relatively small risk of being unable to provide the demanded load over a year, during a 1 hour island operation.

The right Figure of 5.16 shows the corresponding duration curve for energy consumed by the load. The negative side of the curve gives and indication of how much energy could be stored by a capable ESS.

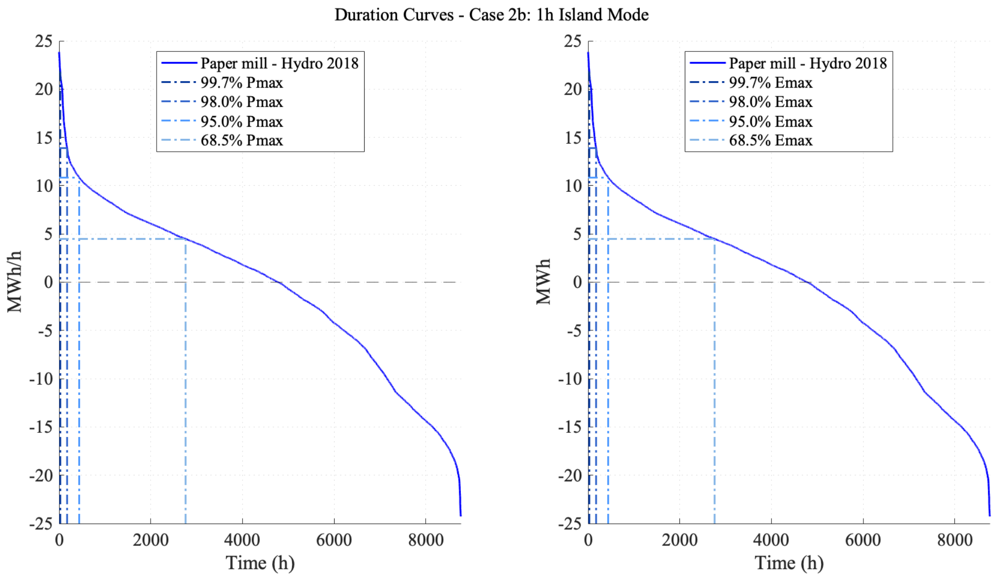

Figure 5.16: Duration curves of the paper mills one hour power and energy demand with power generation over year 2018 presented, dashed lines showing the different maximum percentiles of the demand of power in MWh/h (left) and energy in MWh (right).

Table 5.11 presents the percentiles of the peak net load, $P_{\max}$, $E_{\max}$, and the capacity reduction compared to the 100th percentile, of a microgrid including a paper mill and hydropower generation, during 1 hour island operation. The 68.5th percentile shows a capacity reduction by 81 % of both $E_{\max}$ and $P_{\max}$ compared to the 100 percentile, and a capacity reduction compared to Case 2a, of 75.6 % for the 68.5th percentile. The 100th percentile is also 33 percent lower then in Case 2a. This highlights the need of a stable energy source included in the microgrid, lowering the probability of significant net load peaks during a year.

Table 5.11: Table presenting the capacity reduction for different percentiles of ESS dimensions, and capacity reduction compared to Case 2 a), for one hour of island operation with hydropower generation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak net load [MWh/h]	23.85	21.67	13.89	10.82	4.49
$P_{\max}$ [MW]	23.85	21.67	13.89	10.82	4.49
$E_{\max}$ [MWh]	23.85	21.67	13.89	10.82	4.49
Capacity reduction [%]	0.00 %	-9.14 %	-41.76 %	-54.64 %	-81.17 %
Capacity reduction vs. Case 2 a) [%]	-32.96%	-36.07%	-55.24%	-56.43%	-75.61%

24 hour island operation

Figure 5.17 shows the time series of the maximum demanded load during a 24 hour period starting at every hour of the year. Different percentiles of load are also represented. The seasonal pattern of Figure 5.16 can also be observed here, with a majority of negative hourly loads in the first quarter of the year, implying that an ESS could be charged here. The diminished distance between the 100th percentile and the lower percentiles is due to different 24 hour periods sharing peaks, resulting in overall higher percentiles except for the 100th percentile that always has to cover all loads.

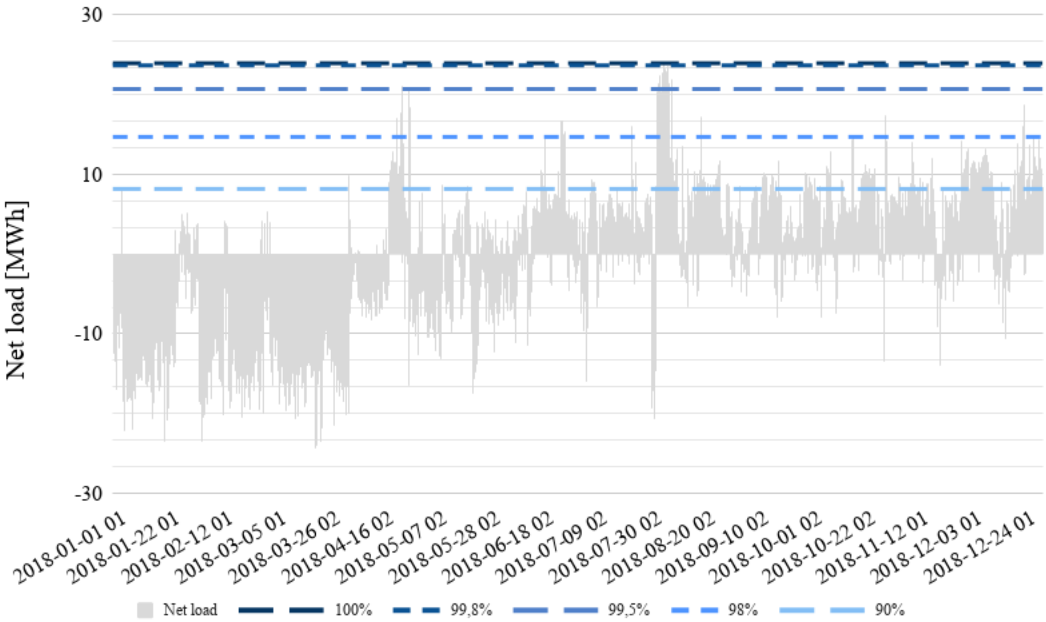

Figure 5.17: Paper mill with power generation over year 2018 presented with dashed horizontal lines showing the different maximum power percentiles of the ESS dimensions.

The left curve of Figure 5.18 shows the corresponding duration curve to 5.11. It shows the maximum load within different 24 hour periods starting at every hour, while also indicating $P_{\max}$ required to cover the different percentiles of load during a 24 hour island operation. The negative curve derivative from the maximum value of 23.85 MWh/h to 15 MWh/h shows that over a year, the number of 24 hour periods with a maximum load load over 15 MWh/h, are few. This implies that the highest load peaks are few but high.

The right part of Figure 5.12 shows the duration curve of the corresponding energy dimension required for a 24 hour island operation, with the corresponding energy capacity of an ESS, $E_{\max}$, indicated for each percentile. The sharp decline from the peak at 500.25 MWh to 287.45 MWh shows that an ESS dimensioned for the 98th percentile would face a very small risk of not having enough energy capacity for 24 hour island operations during any given 24 hour period of a year.

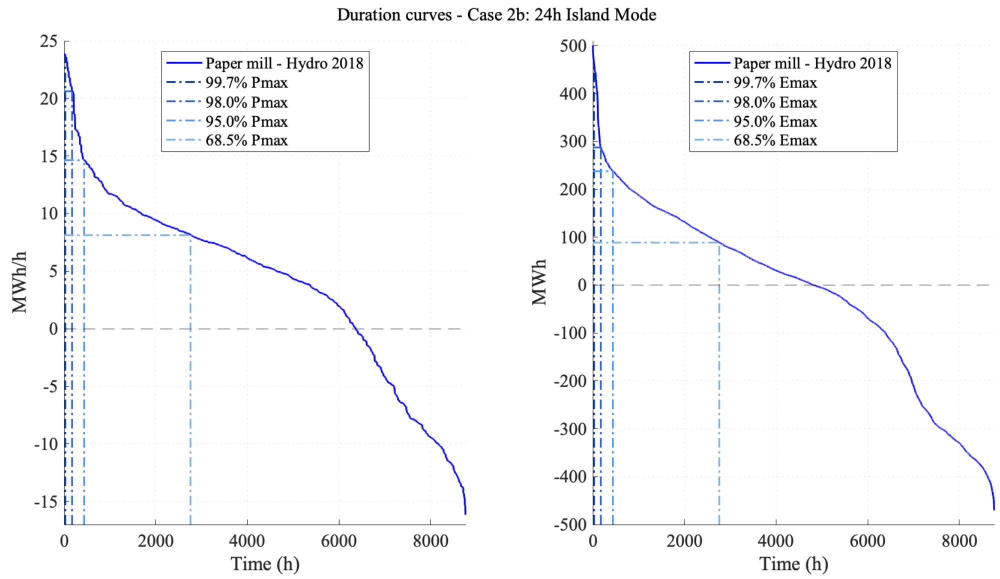

Figure 5.18: Duration curves of the paper mills 24 hour power and energy demand with power generation over year 2018 presented, dashed lines showing the different maximum percentiles of the demand of power in MWh/h (left) and energy in MWh (right).

Table 5.12 presents the percentiles of capacity parameters for ESS dimensions during 24 hour island operation in a microgrid consisting of a paper mill and a hydro plant. As for the 1 hour island operation with hydropower generation, there is a significant reduction in P_{max} and E_{max} compared to Case 2 a) 5.9, starting from the 100th percentile and on-ward. Examining the time series in figures 5.17 and 5.13 it clearly shows that the including the hydropower generation has a significant impact on the over all net load during the year. This explains the apparent reduction in P_{max} and E_{max} compared to Case 2 a) without hydropower and implies that hydropower generation could be a reliable solution for lowering the over all net load in the grid and therefore prevent grid congestion to some extent.

Another interesting result is the P_{max} ratio almost doubling, going from the 100th, to the 68.5th percentile. The sudden increase in ratio is caused by P_{max} being calculated through picking out the maximum net load value during every 24 hour period. This could cause the same value to be P_{max} for up to 24 periods in a row, raising the overall percentiles of P_{max} compared except for the 100th. This is explained further in the method. If another comparison is made with Figure 5.17 and 5.13, it shows that the time series in Fgure 5.17 looks more unstable with sudden significant increases in the net load. This potentially causes the P_{max} for the 24 hour island mode to increase for the lower percentiles, which is shown in Table 5.12. The variations in the net load could be caused by temporary increased demand for the paper mill or temporary power output reductions form the hydropower plant.

Table 5.12: Table presenting the capacity reduction for different percentiles of ESS dimensions, the capacity reduction compared to Case 2 a) 24h island operation, and the ratios compared to 1 hour island operation, for 24 hours of island operation with hydropower generation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak net load [MWh/h]	23.85	21.67	13.89	10.82	4.49
$P_{\max}$ [MW]	23.85	23.60	20.63	14.64	8.13
$E_{\max}$ [MWh]	500.25	464.94	287.45	238.41	96.02
$P_{\max}$ reduction [%]	0.00 %	-1.06 %	-13.52 %	-38.63 %	-65.91 %
$E_{\max}$ reduction [%]	0.00 %	-7.06 %	-42.54 %	-52.34 %	-80.81 %
$P_{\max}$ ratio (24 h:1 h)	1.00	1.09	1.49	1.35	1.81
$E_{\max}$ ratio (24 h:1 h)	20.974	21.451	20.699	22.028	21.405
$P_{\max}$ reduction vs. Case 2 a) [%]	-32.96 %	-33.31 %	-37.95 %	-50.40 %	-61.50 %
$E_{\max}$ reduction vs. Case 2 a) [%]	-37.27 %	-40.96 %	-58.77 %	-56.41 %	-77.69 %

Stormy seasons in Sweden year 2018 and 2019

Table 5.13 shows ESS dimensions for island operation during storms year 2018 and 2019 for a microgrid consisting of a paper mill and hydropower generation. Comparing the $P_{\max}$ and the $E_{\max}$, for 24 hour island operation, for the storm ”Johanne” and ”Alfrida”, it shows that ”Alfrida” has a higher $E_{\max}$ of 129.60 MWh compared to an $E_{\max}$ of 120.03 MWh during ”Johanne”, while ”Johanne has a higher $P_{\max}$ of 13.12 MW compared to 8.79 MW for ”Alfrida”. This implicates that during the Storm ”Alfrida” the demand was more persistent then during ”Johanne”.

Table 5.13: ESS dimensions based on one hour and 24 hour island operation with net load data from a paper mill and a hydropower plant during storms occuring in Sweden year 2018 and 2019

Name	Date	Peak load [MWh/h]	$P_{\max}$ [MW]	$E_{\max}$ 1 h [MWh]	$E_{\max}$ 24 h [MWh]
Johanne	2018-08-10	13.12	13.12	13.12	120.03
Knud	2018-09-21	2.27	2.27	2.27	14.48
Alfrida	2019-01-01	8.79	8.79	8.79	129.60
Jan	2019-02-10	10.43	10.43	10.43	103.89
Julia	2019-02-16	5.62	5.62	5.62	30.48
Mats	2019-02-24	7.78	7.78	7.78	69.74

When comparing Table 5.10 to Table 5.13 it shows that the ESS dimensions enabling island operation is significantly lower but compared to Table 5.7, in Case 1 b), there is still a significant need for a relatively big ESS.

5.3.3 c) Net load with paper mill load increase

Case 3c models a scenario where the power demand of the paper mill increases due to the electrification of processes, showing the changes in demand on the ESS for 1 hour and 24 hour island operations, while marking the grid congestion limit when grid connected without an ESS. The model includes the hydropower plant.

The left side of Figure 5.19 shows the required power capacity for an ESS dimensioned for different load percentiles during one hour island operations. There is a large margin from the ESS requirements to the grid congestion limit, this indicates that the current grid is sufficient for a 100 % load increase. The right side of Figure 5.19 shows how the required energy capacity for an ESS dimensioned for different load percentiles during 1 hour island operation changes with increased paper mill load.

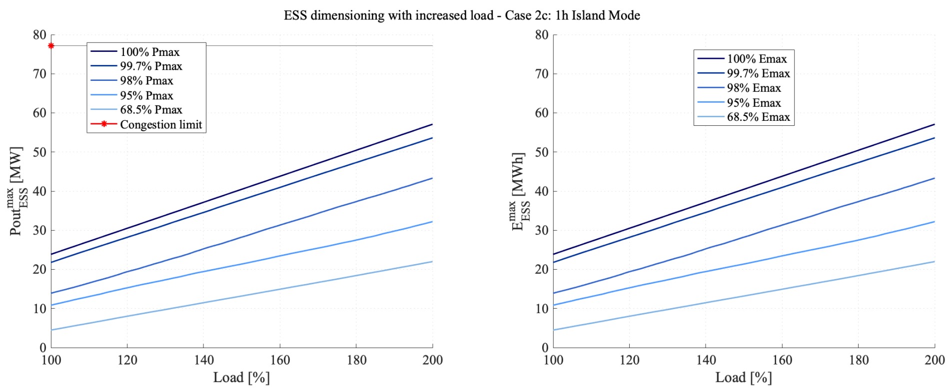

Figure 5.19: The curve shows how the required power and energy capacity of an ESS dimensioned for one hour island operations is affected by increased load of the paper mill due to an electrification of the production process, shown in percentages of load increase. The red star marks the congestion limit. Required power capacity shown to the left and required energy capacity shown to the right.

In Figure 5.20 the change in required power (left) and energy (right) capacity for an ESS dimensioned for 24 hour island operation are shown with a percentage of load increase from 100 % to 200 %. The red marker in the figure to the left shows the congestion limit represented by the maximum output from the hydropower plant together with the maximum outtake (140 %) from the connected substation. The sharp linear increase of 98 % percentiles in the right hand Figure of 5.20 can be explained by the load increase pushing negative values to the positive side, increasing the cumulative sums and therefore further increasing the energy demand.

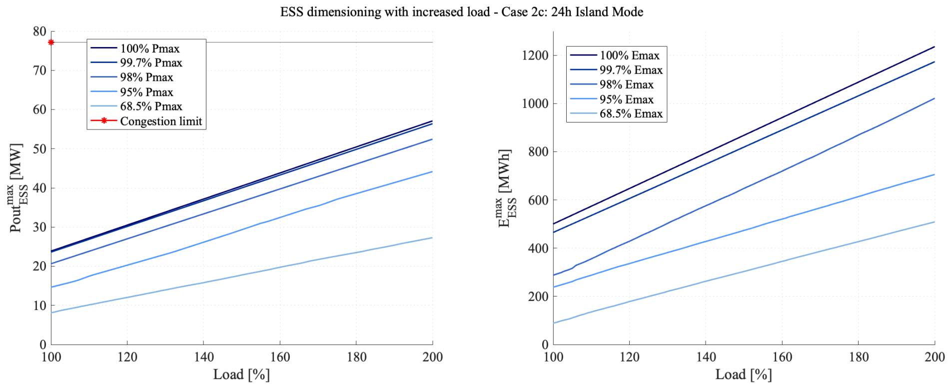

Figure 5.20: The curve shows how the required power and energy capacity of an ESS dimensioned for 24 hour island operation is affected by increased load of the paper mill due to an electrification of the production process, shown in percentages of load increase. The red star marks the congestion limit when grid connected and without an ESS.

5.4 Case 3: ESS dimensions for a combined microgrid

In this section, the dimensioning of an ESS for a microgrid combined of all components mentioned in previous sections is presented. In other words, the microgrid consists of a village, a paper mill, wind power, and hydropower will be presented.

5.4.1 a) Net load without power generation

In case 3 a), ESS dimensions for 1 hour and 24 hour island operation is modeled without power generation representing a windless day where the hydropower plant is offline.

1 hour island operation

Figure 5.21 shows the time series of the hourly power demand of the combined microgrid without wind power or hydropower generation. Different percentiles of the load are also represented in the figure. A seasonal variation is observable, showing higher demand in the winter. This implies that only a part of the heating for the combined grid is electrical-based, and furthermore that the risk of an ESS not being able to cover a 1 hour island operation is greater in the winter time. However, significant peaks are scattered over the summer period. This shows that, though a lesser risk than in the winter time, there is still a non-negligible risk of the ESS not being able to cover a 1 hour island operation in the summer.

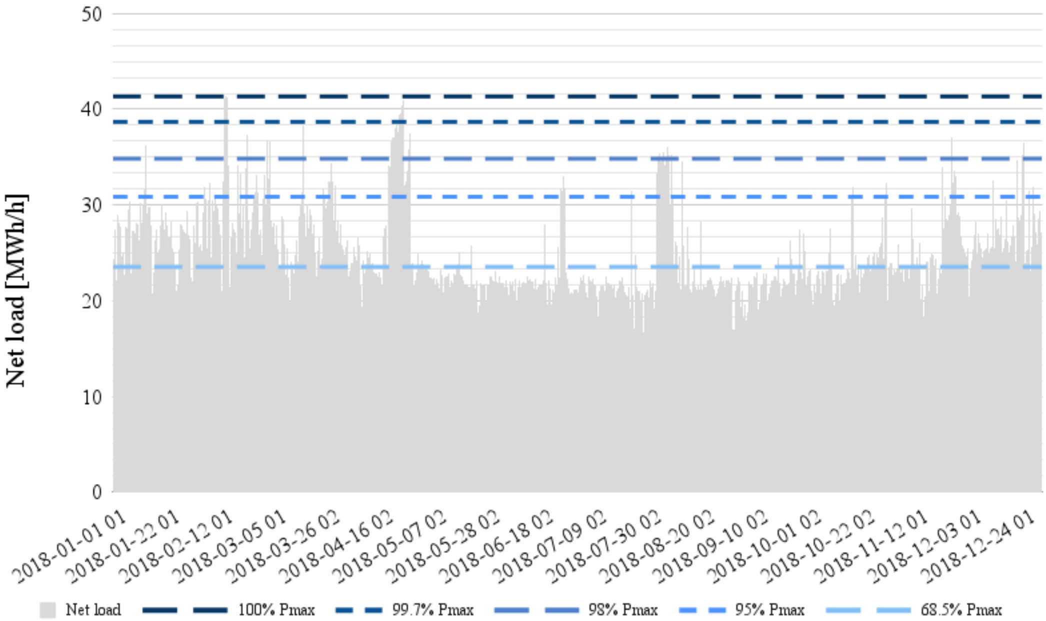

Figure 5.21: Total net load without generation over year 2018 presented with dashed horizontal lines showing the different load power percentiles of the ESS dimensions.

The left part of Figure 5.22 shows the corresponding duration curve to Figure 5.21. The figure also shows the required P_{max} of an ESS required to cover different percentiles of the load during 1 hour of island operation. The gradual change in curve derivative during the first 2,000 hours of the horizontal axis shows that a non-negligible number of hours requires a capacity of more than 24 MW from the ESS.

The right part of Figure 5.22 shows the duration curve of the energy consumed by the load for 1 hour of island operation. The corresponding energy capacity of an ESS, E_{max}, are also indicated. The percentiles ranges from 41.33 MWh down to 23.55 MWh, giving an indication of the required energy capacity of an ESS dimensioned for a 1 hour island operation.

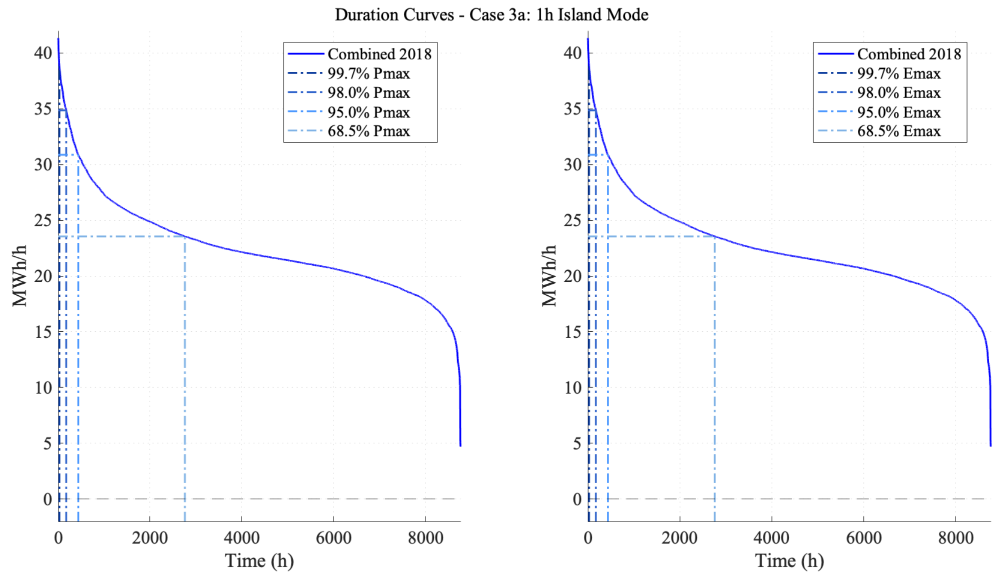

Figure 5.22: Duration curves of the combined grids 1 hour power and energy demand without power generation over year 2018 presented, dashed lines showing the different maximum percentiles of the demand of power in MWh/h (left) and energy in MWh (right).

Table 5.14 presents dimensions for an ESS to handle different percentiles of net load for a microgrid, consisting of a paper mill and a village, to run in island operation for 1 hour. As for the previous cases, the most significant capacity reductions occurs at the 95th and the 68.5th percentile. This is also due to the highest peak loads belonging between the 98th percentile and the 100th percentile which can be seen in 5.22. With the load of the paper mill and the village combined, the dimensions for the ESS increases significantly since the average load of the paper mill is approximately three times higher than for the village.

Table 5.14: Table presenting the capacity decrease for different percentiles of ESS dimensions for 1 hour of island mode operation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak net load [MWh/h]	41.33	38.70	34.83	30.86	23.55
$P_{\max}$ [MW]	41.33	38.70	34.83	30.86	23.55
$E_{\max}$ [MWh]	41.33	38.70	34.83	30.86	23.55
Capacity reduction [%]	0.00 %	-6.36 %	-15.73 %	-25.33 %	-43.02 %

24 hour island operation

Figure 5.23 shows the time series of the power demand during from the combined microgrid for 24 hour periods starting at every hour of the year without wind power or hydropower generation. The seasonal variations of the 1 hour case in Figure 5.21 persist but the percentiles are higher due to some 24 hour periods sharing the same peaks. The seasonal variations implies that the risk of an ESS dimensioned for a certain percentile not being able to supply the required power demand generally is higher in the winter time. The clusters of peaks in May and August shows that this risk is higher also for warmer periods for lower percentiles.

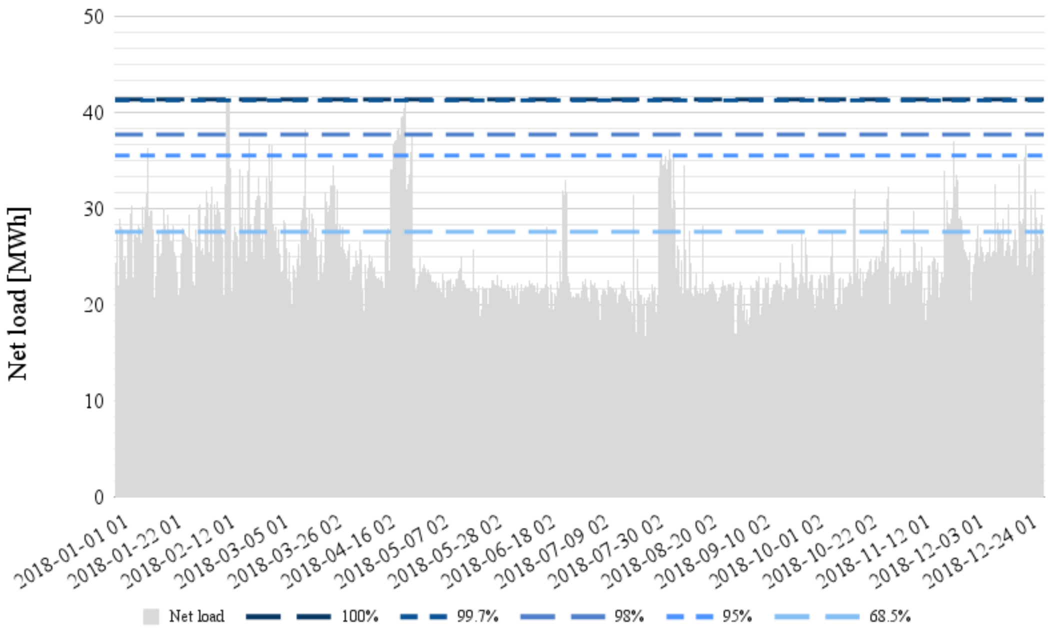

Figure 5.23: Total net load without generation over year 2018 presented with dashed horizontal lines showing the different net load power percentiles of the ESS dimensions.

The left side of Figure 5.24 shows a duration curve of the power capacity requirements of an ESS dimensioned for different load percentiles of the combined grid in 24 hour island operations without wind power or hydropower. The curve shows a significantly higher minimum value compared with the 1 hour case, implying that the chance of the paper mill is being offline during a complete 24 hour period during any part of the year, is very low.

The right side of Figure 5.24 shows a duration curve of the maximum cumulative energy sums required by the grid during 24 hour periods starting at every hour of the year. The figure also shows the energy required by an ESS in order to cover different percentiles of energy demand by the grid. The change in curve derivative at 780 MWh shows that the number of 24 hour periods an ESS would be required to provide more energy than that is low. Compared to the 1 hour case to the right in Figure 5.22, the curve has a significantly higher amplitude. The overall higher amplitude of the curve is due to the longer time periods that the ESS would be required to provide power to the grid for. This gives an indication of what energy storage capability would be needed in order to supply the grid for a 24 hour island operation for different percentiles.

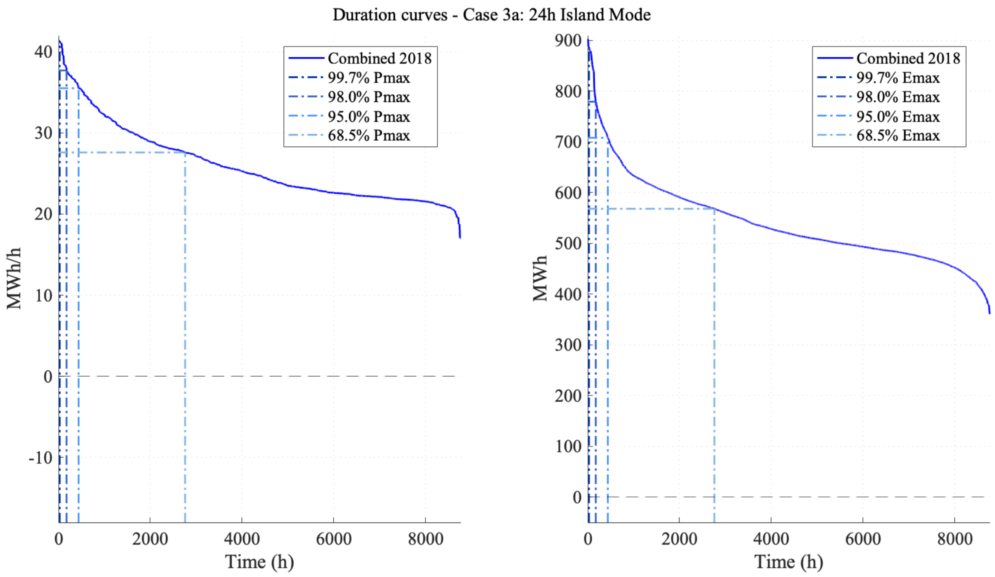

Figure 5.24: Duration curves of the combined grids 24 hour power and energy demand without power generation over year 2018 presented, dashed lines showing the different maximum percentiles of the demand of power in MWh/h (left) and energy in MWh (right).

Table 5.15 presents dimensions for an ESS to handle different percentiles of net load for a microgrid, consisting of a paper mill and a village, to run in island operation for 24 hour. It also presents the ratios comparing P_{max} and E_{max} to 1 hour island operation. When comparing the percentage of reduction for P_{max} and E_{max} on every percentile versus the 100th, it does not defer that much from the decrease of the percentiles at the top row of the table. This is caused by mixing two loads. If more persistent loads, like the paper mill, were included in the load mix it would follow the percentile decrease even more precisely since the peak loads become less significant. This would contribute to more capacity of the ESS being used during island mode operation.

Table 5.15: Table presenting the capacity decrease for different percentiles of ESS dimensions and the ratios for 24 hours of island mode operation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak net load [MWh/h]	41.33	38.70	34.83	30.86	23.55
P_{max} [MW]	41.33	41.25	37.69	35.50	27.82
E_{max} [MWh]	903.01	886.43	779.31	708.17	568.41
P_{max} decrease [%]	0.00 %	-0.20 %	-8.82 %	-14.10 %	-32.69 %
E_{max} decrease [%]	0.00 %	-1.84 %	-13.70 %	-21.58 %	-37.05 %
P_{max} ratio (24 h:1 h)	1.00	1.07	1.08	1.15	1.18
E_{max} ratio (24 h:1 h)	21.847	22.907	22.374	22.947	24.137

Stormy seasons in Sweden year 2018 and 2019

Table 5.16 shows ESS dimensions needed for covering the demand of the village and the paper mill combined, without any power generation and disconnected from the main grid during storms. As expected, these ESS dimensions are the largest among the stormy season cases presented in this report. What differs this case from the other cases is that the highest demand is measured during the storm ”Jan”. This implies that when adding loads to the grid the ESS profile changes since every load behaves differently during the same time period but in 2018, which can be seen when comparing Figure 5.3, 5.13, and 5.23 during the same time periods. However, $E_{\max}$ for 24 hour island operation does not vary as much as it does for Case 1 and Case 2, during stormy periods. This can also be explained by having more loads combined to streamline the usage of the ESS capacity.

Table 5.16: 1 hour and 24 hour island mode ESS dimensions based on net load data from a village and a paper mill during storms occuring in Sweden during 2018 and 2019

Name	Date	Peak [MWh/h]	$P_{\max}$ [MW]	$E_{\max}$ 1 h [MWh]	$E_{\max}$ 24 h [MWh]
Johanne	2018-08-10	25.76	25.76	25.76	519.60
Knud	2018-09-21	22.23	22.23	22.23	508.33
Alfrida	2019-01-01	25.83	25.83	25.83	529.20
Jan	2019-02-10	25.38	25.38	25.38	549.83
Julia	2019-02-16	22.54	22.54	22.54	498.37
Mats	2019-02-24	25.21	25.21	25.21	500.40

5.4.2 b) Net load with power generation

Case 3b models a scenario where the combined grid enters 1 hour and 24 hour island mode operations with the hydropower plant and the wind turbines.

1 hour island operation

Figure 5.25 shows the time series of the hourly power demand of the combined grid with wind and hydropower generation. Different percentiles of the load are also represented in the figure. The seasonal variations of the year shows that the power demand is mostly net negative in the first quarter of the year and generally net positive for the rest of the year. This implies that the risk of an ESS dimensioned for a certain percentile of load in 1 hour island operation to not be able to provide the required power by the grid, is generally higher between May and December. There is an overall observable suppression of load due to the power generated by the wind and hydropower. This implies that local energy production has a significant impact in reducing the required sizing of an ESS dimensioned for 1 hour island operations.

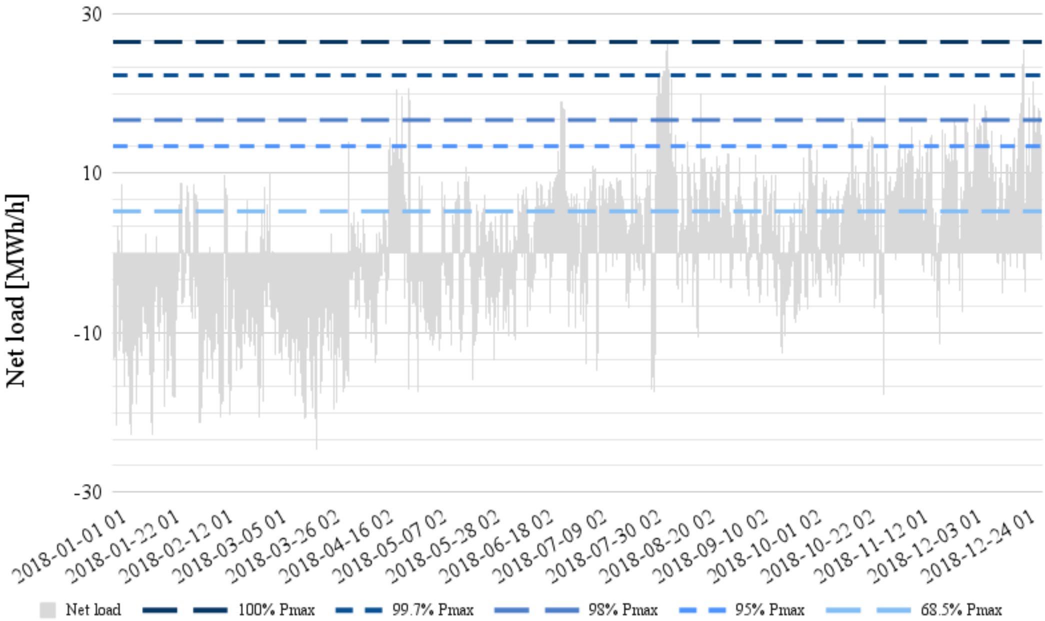

Figure 5.25: Total net load without generation over year 2018 presented with dashed horizontal lines showing the different maximum power percentiles of the ESS dimensions.

In the left part of Figure 5.26 the duration curve of the power demand of the combined grid in 1 hour island mode operations with wind and hydropower generation is presented. The required power capacity of an ESS for different percentiles is also represented in the figure. The peak value is 26.44 MWh/h compared to 41.33 MWh/h in case 3 a) Figure 5.22. This shows how the local power and energy production suppresses the curve and emphasizes the influence on ESS dimensions wind and hydropower generation has. The negative parts of the curve represents hours where the power generation exceeds the power demand. These surpluses implies that an ESS could be charged during these hours.

The right part of Figure 5.26 shows the duration curve of the corresponding energy required for a 24 hour island operation. The corresponding energy capacity of an ESS, $E_{\max}$, is indicated for each percentile. An interesting result is that close to half of the curve is negative. This gives an indication of the amount of excess energy produced. An ESS able to store the excess energy could dramatically decrease the dependency on external grid reliability for the microgrid when not in island operation.

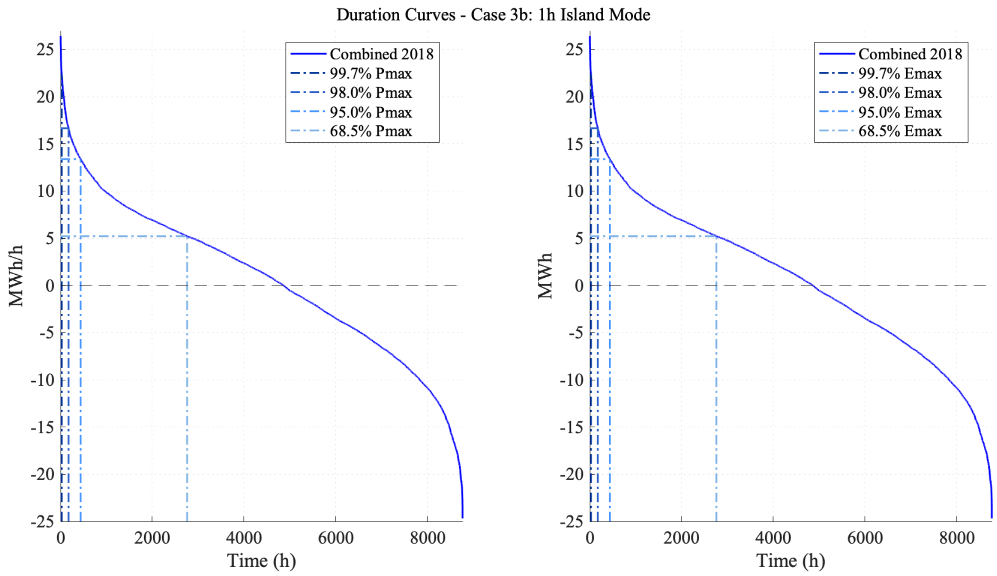

Figure 5.26: Duration curves of the combined grids 1 hour power and energy demand with power generation over year 2018 presented, dashed lines showing the different maximum percentiles of the demand of power in MWh/h (left) and energy in MWh (right).

Table 5.17 presents dimensions for an ESS to handle different percentiles of net load for a microgrid, consisting of a paper mill, a village, wind power, and hydropower generation, to run in island operation for 1 hour. When examining the 95th and the 68.5th percentile of E_{max} and P_{max} it is apparent that adding power generation accelerates the capacity reduction of the ESS. It enhances when observing the capacity reduction compared to Case 3 a) which indicates on a additional reduction of approximately 78 percent. This implicates that adding more loads and energy sources to a microgrid could potentially reduce the dimensions further, for an ESS during 1 hour island operation.

Table 5.17: Table presenting the capacity decrease for different percentiles of ESS dimensions and the ratios for 1 hour of island mode operation with hydro- and wind power generation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak net load [MWh/h]	26.44	22.27	16.65	13.38	5.21
P_{max} [MW]	26.44	22.27	16.65	13.38	5.21
E_{max} [MWh]	26.44	22.27	16.65	13.38	5.21
Capacity reduction [%]	0.00 %	-15.76 %	-37.02 %	-49.39 %	-80.29 %
Capacity reduction vs Case 3 a) [%]	-36.04%	-42.45%	-52.20%	-56.64%	-77.88%

24 hour island operation

Figure 5.27 shows the time series of the maximum power demand of the combined grid during 24 hour periods starting at every hour of the year. Different percentiles of the load are also represented in the figure. There is a clear seasonal variation showing mainly negative power demands in the first quarter of the year, and mainly positive power demands from April to the end of the year. This is due to the power generated by hydro being higher in the first quarter and can be explained by the winter ice melting and increasing the water levels in watercourses. This implies a potential for seasonal storage of energy.

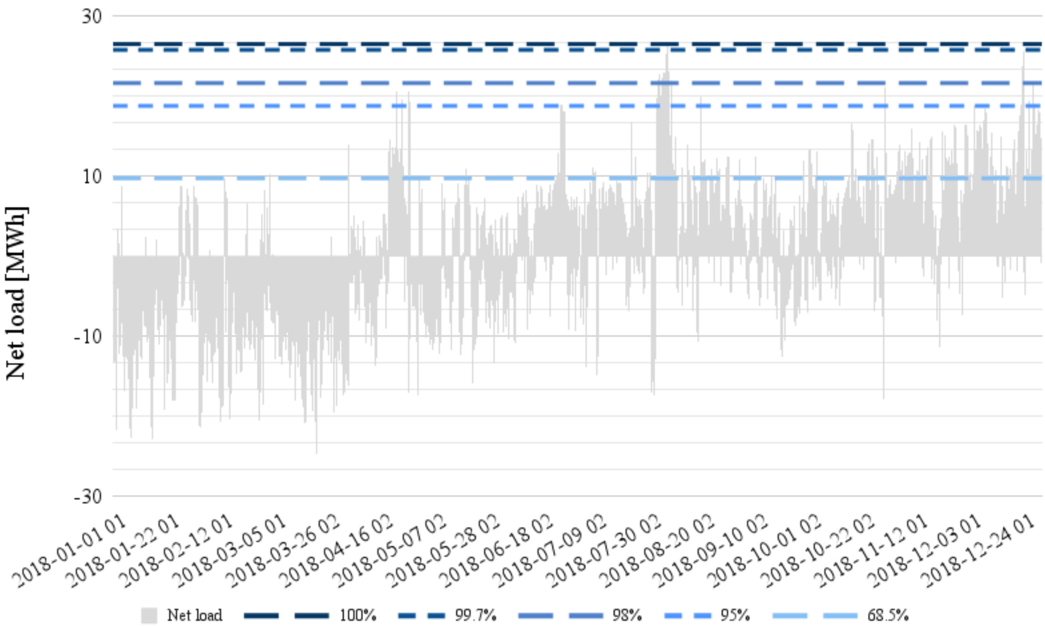

Figure 5.27: Total net load without generation over year 2018 presented with dashed horizontal lines showing the different maximum power percentiles of the ESS dimensions.

The left part of figure 5.28 shows a duration curve of the maximum power demand of the combined grid during 24 hour island mode operation together with wind and hydropower generation. The dashed lines shows the required power capacity for an ESS dimensioned for different percentiles of load. A sharp decrease of the maximum value compared to case 3a in figure 5.24 implies that local electricity production can lower the requirements on an ESS and therefore the microgrid implementation costs. The negative parts of the curve shows twenty four hour periods where the power generated is larger than the demand of the paper mill and village, implying that an ESS could be charged during these 24 hour periods.

The right part of figure 5.28 shows the corresponding duration curve for the maximum cumulative energy sum consumed by the load, with the energy capacity requirements for an ESS dimensioned for different percentiles shown in dashed lines. This figure gives an indication of how much energy storage capacity an ESS would require in order to provide sufficient energy for the grid during a 24 hour island operation. An interesting notion is that the majority of $E_{\max}$ days are negative and that the absolute peak values far outweigh the positive ones. This implies that the dimensions of an ESS for a microgrid without the ability to curtail excess power would increase significantly. This also implies that an ESS capable of storing the excess energy could significantly decrease the microgrid dependency on external grid reliability when grid connected.

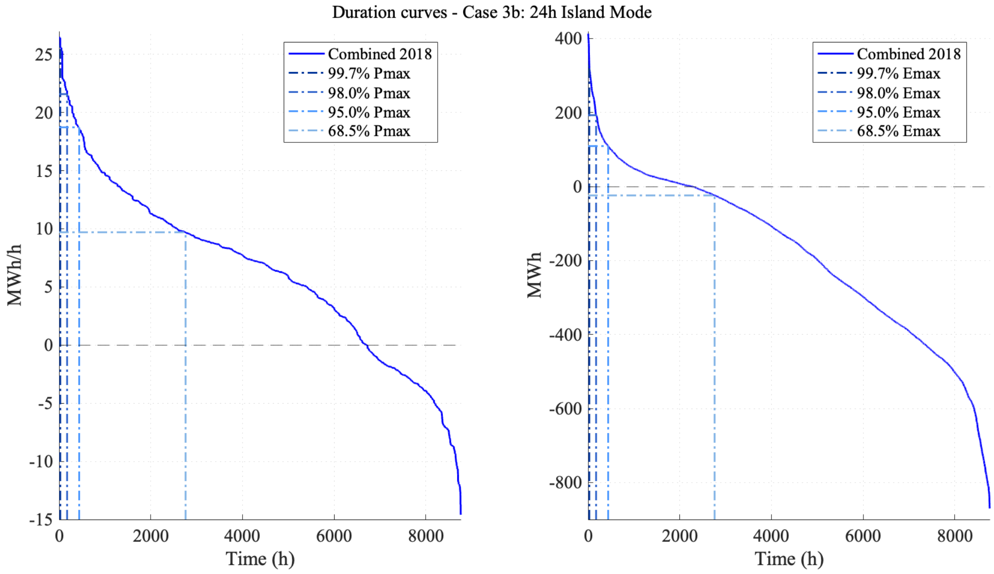

Figure 5.28: Duration curves of the combined grids twenty four hour power and energy demand with power generation over year 2018 presented, dashed lines showing the different maximum percentiles of the demand of power in MWh/h (left) and energy in MWh (right).

Table 5.18 presents dimensions for an ESS to handle different percentiles of net load for a microgrid, consisting of a paper mill, a village, wind power, and hydropower generation, to run in island operation for 24 hours. The results from this table also indicates on significant capacity reductions similarly to the results from Table 5.17. What is interesting in this scenario is that the ratio, for $E_{\max}$ compared to 1 hour island operation, is fairly low, compared to Table 5.15, during every percentile. This can also be explained by the mix of loads and power generators combined compressing the over all net load hours during the time period. This clearly implicates that a mix of components in the microgrid is preferable.

Table 5.18: Table presenting the capacity decrease for different percentiles of ESS dimensions and the ratios for 24 hours of island mode operation with hydro- and wind power generation.

Percentile [%]	100.00 %	99.70 %	98.00 %	95.00 %	68.50 %
Peak net load [MWh/h]	26.44	22.27	16.65	13.38	5.21
$P_{\max}$ [MW]	26.44	25.71	21.58	18.72	9.70
$E_{\max}$ [MWh]	521.43	455.41	365.50	293.30	112.28
$P_{\max}$ decrease [%]	0.00 %	-2.76 %	-18.36 %	-29.19 %	-63.29 %
$E_{\max}$ decrease [%]	0.00 %	-12.66 %	-29.90 %	-43.75 %	-78.47 %
$P_{\max}$ ratio (24 h:1 h)	1.00	1.15	1.30	1.40	1.86
$E_{\max}$ ratio (24 h:1 h)	19.724	20.451	21.951	21.919	21.556
$P_{\max}$ reduction vs Case 3 a) [%]	-36.04%	-37.68%	-42.73%	-47.27%	-65.12%
$E_{\max}$ reduction vs Case 3 a) [%]	-42.26%	-48.62%	-53.10%	-58.58%	-80.25%

Stormy seasons in Sweden year 2018 and 2019

Table 5.19 shows ESS dimensions needed for covering the demand of the village and the paper mill combined with hydro and wind power generation in 24 hour island operation during stormy time periods. Comparing the $E_{\max}$ dimensions, for 24 hour island operation, for storm ”Knud” and ”Johanne”, taking place within just two month in the late summer, the results deviates significantly. Since the load of the village and the wind power having less of an impact on the over all net load in this scenario, this could be the explanation to the apparent deviation. The village and the wind power are the elements that are mostly affected by seasonal changes while the paper mill and the hydropower generation is more persistent. This could also be seen for ”Julia” and Mats”, which deviates significantly too. This could contribute to difficulties when planning for which periods during the year to use the ESS for other services.

Name	Date	Peak [MWh/h]	$P_{\max}$ [MW]	$E_{\max}$ 1 h [MWh]	$E_{\max}$ 24 h [MWh]
Johanne	2018-08-10	9.76	9.76	9.76	61.44
Knud	2018-09-21	3.25	3.25	3.25	7.65
Alfrida	2019-01-01	6.92	6.92	6.92	76.10
Jan	2019-02-10	8.24	8.24	8.24	90.64
Julia	2019-02-16	5.06	5.06	5.06	22.93
Mats	2019-02-24	8.72	8.72	8.72	72.31

Table 5.19: 1 hour and 24 hour island mode ESS dimensions based on net load data from a village, a paper mill, hydropower generation, and wind power generation during storms occuring in Sweden during 2018 and 2019

Comparing Table 5.19 to Table 5.13 in Case 2 b) it shows that for every storm, except for ”Mats”, the ESS dimensions are lower while covering the 24 hour demand during island mode operation. This implies that when combining the two grids and including the power generation it lowers the overall ESS dimensions. For 1 hour island mode operation the ESS dimensions are lower for every storm except for ”Knud” and ”Mats” aswell.

5.4.3 c) Net load with increased paper mill load and increasing wind power penetration

Case 3c models a scenario where the paper mill power demand is increased by 50% due to the electrification of processes, while showing the impact on required ESS dimensions for different load percentiles by increased wind penetration.

The left side of figure 5.29 shows how the combined grid power requirements of an ESS dimensioned for 1 hour island operation changes with increased wind penetration, due to the installation of additional wind turbines. The figure shows the change for an ESS dimensioned for different percentiles of load. The model assumes a 50 % load increase from the paper mill. There is a continous dive of the 68.5

percentile, this is due to that an ESS dimensioned for this percentile of load would not be required to cover hours where the power output from the wind turbines is low. This implies that for lower percentiles, the dimensions of the ESS could be significantly decreased with increased installed wind capacity. A similar dive cannot be observed for the higher percentiles as these are required to cover more hours of low power generation from the wind turbines.

The right side of figure 5.29 shows how the corresponding energy capacity requirements for the ESS changes with increased wind penetration due to an increasing number of wind turbines installed. The change of requirements demanded of an ESS dimensioned for different percentiles of the load is shown. The model assumes a 50% load increase from the paper mill. The continous dive of the 68th percentiles in the power capacity graph transfers to this one, as lower percentiles does not cover hours where the power generated from the wind turbines are as low as in the higher percentiles. This implies that an increased number of installed wind turbines also could decrease the energy requirements on an ESS dimensioned for a lower percentile.

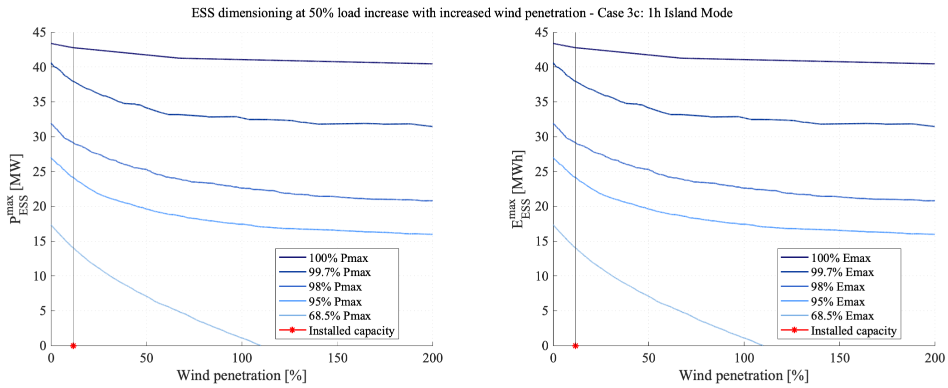

Figure 5.29: The curves shows how the requirements on an ESS dimensioned for 1 hour island operations, is affected by increased wind capacity shown in percentages of wind penetration, with a 50% increase of paper mill load. The red star marks the present wind penetration. The left part of the figure shows the power requirements and right part the energy requirements.

The left part of figure 5.30 shows how the combined grid power requirements of an ESS dimensioned for 24 hour island operations changes with increased wind penetration, due to the installation of additional wind turbines. The figure shows the change for an ESS dimensioned for different percentiles of load. The model assumes a 50% load increase from the paper mill. The continued dive of the 68th percentile observed in the 1 hour case is gone. This is because the curve shows the maximum power capacity required during a 24 hour period, implying that the power output from the wind turbines is irregular and always low sometime during any given 24 hour period. The diminishing distance between the 100th and 99.7th percentiles is due to hours where the wind turbines are inactive and has negative power generation and therefore increasingly contribute to the load with a higher annual wind penetration. The negative generation on these hours increasingly influences the maximum power demands of the 24 hour periods and therefore changes the 99.7th percentile. For short periods, similar behavior can be observed in the 98th and 95th percentile while they show an overall diminishing tendency until 450% wind penetration. For an ESS dimensioned for the 98th percentile, a 450% increase in wind penetration results in a decrease in required ESS power capacity of more than 10 MW. The implication of this is that the change in required power capacity of an ESS dimensioned for 24 hour island operations should be considered when installing additional wind turbines.

The right part of 5.30 shows how the required energy capacity of an ESS dimensioned for 24 hour island operations changes with increased wind penetration, due to an increased number of wind turbines. The required ESS energy capacity is shown for different percentiles of load. There is a overall downward trend of all percentiles up to 410% wind penetration. This shows how the microgrid integrates an increased wind power generation and implies that a diversified microgrid with different types of loads and generators can utilize an increased number of wind turbines and therefore requires less energy capacity from an ESS dimensioned for 24 hour island operations. The downward trend disappears in the 100th percentile at 410% wind penetration, indicating that at some point the cumulative energy sums determining the energy capacity requirements of the ESS, stops decreasing. This is because the increased wind penetration only affects cumulative energy sums including hours when the wind turbines generate power. At some point of scaling, a cumulative sum including hours where the wind turbines does not generate any power will overtake a initially higher sum that includes hours where the wind turbines does. This implies that for an ESS dimensioned for the 100th percentile of 24 hour island operation, there is a limit for the impact of increased wind power generation.

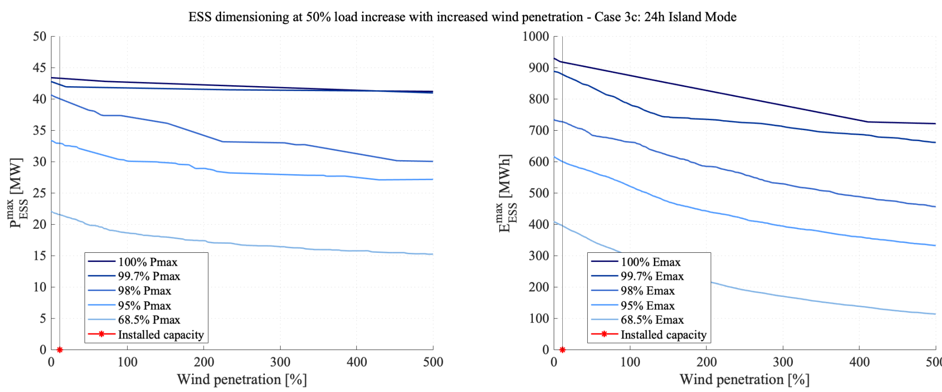

Figure 5.30: The curve shows how the power and energy requirements on an ESS dimensioned for 24 hour island operation is affected by increased wind capacity shown in percentages of wind penetration, with a 50% increase of paper mill load. The red star marks the current wind penetration. The left side shows the change in power requirement for different percentiles, and the right side shows the change in energy requirement for different percentiles.

5.4.4 d) Power exchange for the combined microgrids

The power exchange and the net load for the microgrids during year 2018 can be seen in Figure 5.31 below. In this case it is assumed that there is a cable, or serveral cables, connecting the two microgrids with a total capacity of approximately 30 MW. The power exchange, the red column diagram in 5.31, is calculated by taking microgrid 1's net load plus microgrid 2's net load per hour. This shows that in the beginning of the year until approximately the end of March, most of the excess power produced from the hydropower could cover the unfulfilled demand of the village in Microgrid 1.During the other half of the year the netload of the second microgrid is mostly positive and the netload of the first microgrid is periodically negative. This could be used to lower the power demand of the upper grid level and lower the risk for congestion.

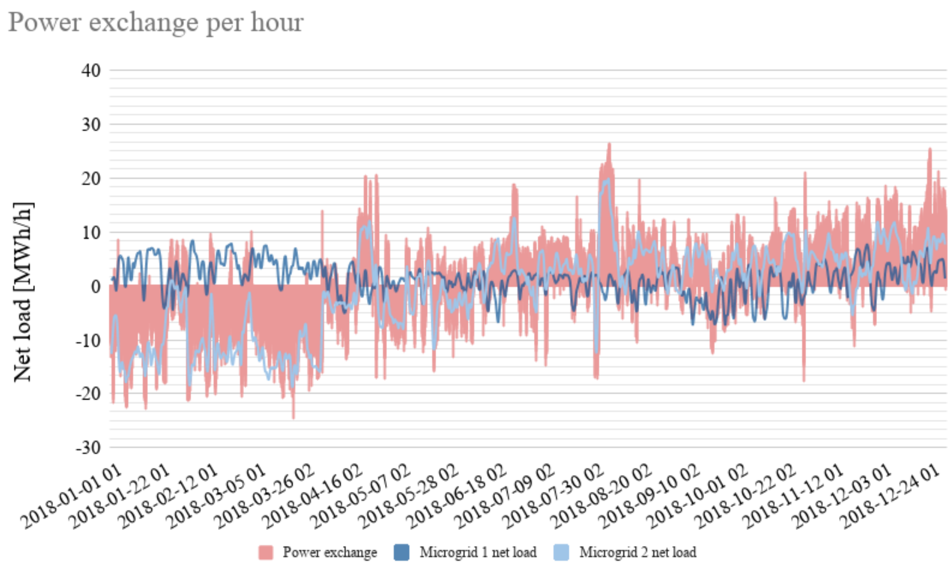

Figure 5.31: Power exchange per hour between "Microgrid 1", consisting of a village and wind power generation, and "Microgrid 2", consisting of a paper mill and hydropower generation. Negative power exchange meaning injection to the grid and positive meaning extraction from the grid.

Table 5.20 shows the net load for the sepearate microgrids and the combined scenario, the energy extracted from the upper grid level, the energy injected to the upper grid level, the total power exchange to the upper grid level for each microgrid, and the sum of the power exchange for the two microgrids. The sum of Microgrid 1's net load is positive and the sum of Microgrid 2's net load is negative and the total net load of the two microgrids combined is positive. This implies that even with an ESS installed, that can streamline the power exchange within the microgrid, would not be enough to supply the microgrids, if they were connected, with power during 2018 since the net demand is positive. However, the connection bewteen the microgrids could increase the power capacity for the paper mill in Microgrid 2 during hours when the village demand is low. This could potentially enable the paper mill to increase its production capacity without improvements to existing the existing connections to the upper level grid.

Table 5.20: Table presenting the power exchange between "Microgrid 1", consisting of a village and wind power generation, and "Microgrid 2", consisting of a paper mill and hydropower generation.

Microgrid 1: Total net load 2018 [MWh/h]	11592
Microgrid 2: Net load 2018 [MWh/h]	-5742
Total net load 2018 [MWh/h]	5850
Microgrid 1: Energy extracted from grid year 2018 [MWh]	20281
Microgrid 2: Energy extracted from grid year 2018 [MWh]	27651
Microgrid 1: Energy injected to grid year 2018 [MWh]	8689
Microgrid 2: Energy injected to grid year 2018 [MWh]	33392
Microgrid 1: Total power exchange [MW]	28970
Microgrid 2: Total power exchange [MW]	61043
Total power exhange for both microgrids 2018 [MW]	90013

5.5 Key findings and discussion

Below, the key findings and discussion regarding the case study is presented

ESS capacity reduction due to including local power generators

In all three cases it is apparent that including local power generation reduces the required ESS capacity dimensions for both 1 hour and 24 hour island operation. ESS dimensions handling the 95th and 68.5 percentile of net load show the most significant reductions of the ESS capacities. The probability of experiencing sustained peak net loads, belonging to the 100th percentile, during the year is fairly low. Therefore it could be beneficial to not dimension the ESS to handle all percentiles of net load. Rather, it could be dimensioned to handle the 95th percentile or lower.

Comparing Table 5.6 from Case 1 to Table 5.12 from Case 2 , this shows that the percentages of capacity reduction, for E_{max} and P_{max}, are more significant in Case 2. This is probably caused by the paper mill load and hydropower generation being more consistent compared to the village load and the wind power generation in Case 1. This indicates that a stable power generation and load is preferable in the microgrid while dimensioning an ESS to handle island operation.

Dimensioning an ESS to cover the 98th percentile for every cases could contribute with savings of around 12 to 40% depending on the case. This means that if the ESS was dimensioned to cover 100 % of the cases, about 12-40 % of ESS energy capacity load would be unused for most hours during the year, especially if there is low probability of an outage taking place. This excess capacity could be used for other services, such as peak shaving the loads within the grid to free up capacity within the microgrid for heavy industries like the paper mill. This minimizes the energy extracted from the upper lever grid during the year.

The impact of a stable power source on ESS power and energy capacity requirements

When comparing the percentiles shown in the duration curves of the hourly demands of power and energy in case 1 b) (5.6) and case 3 b) (5.26), it is visible how the lower percentiles in the two cases approach each other. An ESS for 1 hour island operation in case 1b would require a power capacity of 7.61 MW for the 98th percentile 3.21 for the 68.5th percentile compared to 16.65 MW and 5.21 MW, respectively for case 3b. The power capacity of an ESS dimensioned for the 98th percentile in case 1 b) would need a 9.04 MW or 118.8% increase to be able to handle the same percentile in the combined grid, while an ESS dimensioned for the 68.5th percentile of case 1 b) would need a mere 2 MW or 62.3% increase to handle the same percentile in the combined grid. This shows how the stable output of the hydropower plant suppresses the majority of peaks and diminishes the requirements of an ESS while maintaining the same risk of being unable to provide the required power, even though the average load is more than 4.5 times higher.

The impact of increased wind penetration on different microgrids

Looking at the increased wind power generation shown in figure 5.9 in case 1 c) it is clear that for a 1 hour island operation, the impact is bigger for lower percentiles. Considering power capacity requirements, the same is true for the 24 hour case of 1 c) in figure 5.10 while there is a higher impact on the energy requirements of an ESS dimensioned for 24 hour island operations. This indicates that a larger dimensioned ESS can better utilize the increased energy generated by the wind turbines. When comparing case 1 c) with case 3 c) in figure 5.29 it is clear that the combined grid is able to better utilize the increased wind power generation, both in terms of power and energy. This shows how the different types of load and production are able to compensate each other, implicating that a diversified grid better utilizes increased wind power generation as well as uneven outputs from the wind turbines.

Seasonal patterns

A clear seasonal pattern is shown in the net load time series in Case 1. It is also shown in Case 3 consisting of the combined microgrid, although its not as prominently shown. Observing Case 1, without power generation (Figures 5.1 and 5.3), and with power generation (Figures 5.5 and 5.7), a similar pattern is found in all cases. The seasonal difference reduces with the stable output of the hydropower plant in figures 5.11, 5.12 and with increased diversity of loads and generation types, as shown in figures 5.25 and 5.27 in case 3b. This implies that a mix of loads and energy sources with different load, and generation profiles could lower the capacity dimensions for an ESS to handle island operation.

Extreme weather events

During storms the power and energy requirements of an ESS drops dramatically for the cases with installed wind power. During storm Alfrida in case 1b (table 5.7) the power demand turns negative indicating that the ability to enter island mode alone, without an ESS, could improve grid reliability during the storm, in case of damages further up in the grid hierarchy.

Another thing to keep in mind is that wind power does not operate at too high wind speeds. During 2018 and 2019 the wind speeds during the storms was within the wind power operation range. This is seen when comparing the dates of the storms to the same dates in the time series figures for Case 1 when wind power production is included, for example in Figure 5.5. But if the wind speeds was higher during the storms the wind power plants might have to shut down during the most windy hours of the day. Therefore it might be more sensible to dimension the ESS to be able to handle a certain percentage of the total load during island operation. Looking at the data gathered from 2018 and 2019 the probability of this happening during stormy periods in this village is zero, indicating that this might not be a problem today but for the future with increasing extreme weather events caused by climate change. Control systems for microgrids can also rely on weather data and are able to forecast incoming storms, dry periods or very cold weather [102]. By forecasting weather changes it can manage the size of the energy reserve based on the probability of an extreme weather event taking place at the location of the microgrid. This also enables the energy and power capacity of the ESS to be utilized during periods of low probability of extreme weather occurring.

Peak shaving potential

When observing the time series for every case, it is clear that there are different seasonal and daily variations, especially in the cases including wind power generation. This suggests that if the power and energy capacities of an ESS could be dimensioned for storing the excess energy, the ESS could be utilized for peak shaving both hourly and seasonally. The marked congestion limit in grid connected mode, marked on the left side of figure 5.19 and 5.14, shows that there is considerable distance to the limit, indicating that grid congestion is not of immediate concern in this case. However, if the load would increase further an installed ESS could be utilized to temporarily increase the congestion limit and thus shave the peak.

Potentially increased grid reliability for loads within the microgrid

The 1 and 24 hour periods with negative net loads in the duration curves of all b) cases with power generation indicate that the available power supply is more than sufficient to satisfy the demanded load during these periods. This means that a microgrid capable of island mode operation would be self sufficient in case of a power outage. An ESS could be charged with using excess energy during these periods. However, if the excess power during these hours is too high, the cost to dimension an ESS capable of handling the input power level and the amount of excess energy could be high.

Plausible ESS dimensions

To measure the plausibility for the calculated ESS dimensions for each case, a comparison to the ESS installed in Uppsala [37] by Vattenfall, can be made. The power capacity of the ESS is 5 MW and the energy capacity is 20 MWh. With these dimensions the energy capacity of Case 1 and 2 with power generation for 1 hour island operation can be covered if choosing a lower percentile for the power capacity. If the power capacity of the ESS is dimensioned to handle 1 hour of island operation instead of being used to peak shave, this could contribute to an ESS able to handle Case 1 and 2. This implies that by dimensioning the power and energy capacity of an ESS for lower percentiles of the load profile, a broader spectrum of possible implementations could be achieved while still increasing the grid reliability for the microgrid connected loads.

5.5.1 Sources of error

In this section, the sources of error of the case study is discussed.

The impact of ESS state of charge on ESS lifetime

The case study has not taken potential life time shortening of the ESS, due to the state of charge, into account. There could be cases where charging a ESS to its maximum energy capacity or discharging it to its minimum energy capacity shortens the lifetime of the ESS. An actual implementation of a microgrid ESS would have to take this into consideration when estimating the required power and energy capacity of the ESS.

Sample size

The case study is based solely on one year of data and a smaller sample results in less accurate results. Also, significant annual differences may occur. An overall colder year would result in overall higher power and energy capacity requirements of the ESS. This would increase the risk of the ESS not being able to supply sufficient power and energy, if based on the results of this case study. Additionally, the load of the village and paper mill may vary, though the impact on ESS dimensions of an increased paper mill load is accounted for in cases 2 c) and 3 c), a load increase of the village is not. As the electrification of society continues, the power and energy demands will rise.

Time resolution of data

As the case study is based on hourly measurements, the results do not account for variations in shorter periods of time. A case study based on minute by minute measurements would be significantly more accurate and show more of the momentary variations. Significant short term variations could potentially overpower an ESS.

Not comparing enough different renewable energy sources and loads

For a more complete assessment of the impact of renewable energy sources on a microgrid ESS, the case study would be required to include other power sources such as solar PVs.

Not including the energy storage capabilities of hydro power plants

As some of the cases include a hydro power plant, the case study would show a more accurate picture of the requirements of an microgrid ESS dimensioned for island operations, if the regulatory capabilities of the hydro power plant were included in the results. Also, the potential energy storage capabilities of the hydro power plant are disregarded and should be included for an accurate assessment. If possible, storing energy in the form of more water further upstream would probably be more effective than storing it in batteries, as it wouldn't suffer conversion losses.

6
Conclusion and future studies

The thesis has explored how different parameters affect the power and energy capacity of an ESS in a microgrid, as well as identified what drivers and barriers there are to implement microgrids as a complement to the main grid.

The primary drivers identified for implementing a microgrid are:

- Microgrids can facilitate the integration of renewable energy resources into the grid.
- Local grid reliability can be increased by the microgrids' ability to operate in island mode.
- In grid connected mode, the microgrid can provide services to the main grid
- Lead times for implementing microgrids are shorter than lead times for reinforcing the grid.

The primary barriers identified for implementing a microgrid are:

- Swedish laws and regulations do not favor energy storage or island mode operation
- Lack of financial incentives to own energy storage due to costs, taxes, lifetime and maintenance

Furthermore, the thesis has concluded that current legislation prevents implementing microgrids in the Swedish distribution grids. New laws and regulations have been drafted, however, and when they do come into force, microgrids will be best utilized in remote areas with low reliability.

The model for estimations of required ESS capacity in terms of power and energy and the implementation of this on an existing load and generation profile shows that:

- Local power generation significantly decreases the required power and energy capacity of an ESS dimensioned to enable functional island operations for both 1 hour and 24 hour periods.
- Loads with persistent demand and power generators with an even generation profile reduce net load peaks, leading to power and energy capacity reductions for ESS dimensions.
- A diversified microgrid with different types of loads and electricity production requires less power and energy capacity of an ESS dimensioned for island operations than a homogeneous microgrid consisting of only one type of load

and electricity production.
- In several cases, the ability to disconnect from the main grid and be able to function in island mode could increase grid reliability for the loads in the microgrid.

Future studies

An interesting future study is to continue on the grid connected scenario (Case 3) for the two microgrids in this case and simulate and analyze different services that the ESS can be used for. A new case could be based on a power exchange simulation over the substations while using, for example, peak shaving as a service for the microgrid, and/or the upper level grid. How would this affect the congestion limit for the substation and would this enable the paper mill to increase its production capacity?

Another potential future case study similar to the one conducted could be made where the requirements on power and energy capacity from the ESS also included negative peaks, in order to utilize excess energy. It could also be interesting to investigate how different kinds of ESS could mitigate the capacity need of each other.

It would also be interesting to further investigate whether it is beneficial to install a microgrid or not by more thoroughly studying efficiency of control systems, potential of load flexibility, and more exact costs analyses all components required in a microgrid. Furthermore, the electricity market continuously changing, and there are laws and regulations impacting the power grid that have been drafted but not yet entered into force. When these laws do change, it would be interesting to further investigate implementing microgrids since it would be more relevant from a legal perspective.

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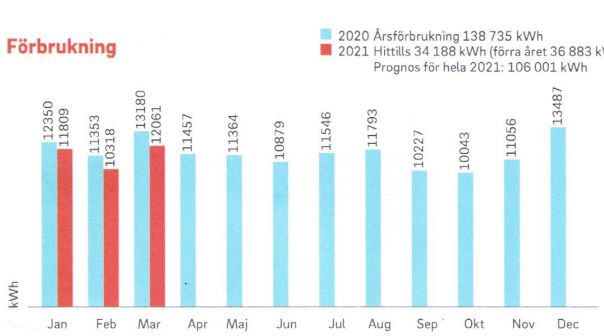
A

Appendix 1



Om ni förbrukar lika mycket i år som vid samma tid förra året (11 457 kWh), och med nuvarande pris skulle beloppet nästa gång bli cirka 9000 kr.

Avtal	Kundnumme[redacted]
Elnätsabonnemang	50 A, Elnätsområde Syd
Elavtal	Annan leverantör
Fakturan gäller	[redacted]
Fakturadatum	[redacted]
Avtalskonto	[redacted]
Anläggnings-id	[redacted]
Områdes-id	OLD

Specifikation	
Elnätsabonnemang månadsavgift, 1 223 kr	[redacted]
Elöverföring, 12 061 kWh à 17,04 öre	[redacted]
Energiskatt, 12 061 kWh à 35,60 öre	[redacted]
Totalt E.ON Energidistribution 7 571,91 kr (9 464,89 kr inkl moms)	
Summa exkl moms	[redacted]
Moms 25%	[redacted]
Öresutjämning	[redacted] kr
Belopp att betala	[redacted]

Elmätare		505 163 913 780 315 5
Datum	**Mätarställning**	**Förbrukning**
Avläst 2021 02 28	[redacted]	
Avläst 2021 03 31	[redacted]	

E.ON Energidistribution AB (Momsreg.nr/F-skatt SE556070606001) har överlåtit fordran till E.ON Kundsupport Sverige AB (556744-4301). Bolagens adress och säte: 205 09 Malmö.
Dröjsmålsränta: referensränta +8 procentenheter. Utlandsbetalning: SWIFT ESSESESS, IBAN SE625 000 000 005 746 100 14 50.

Figure A.1: Electric bill of small grocery store located in SE4

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