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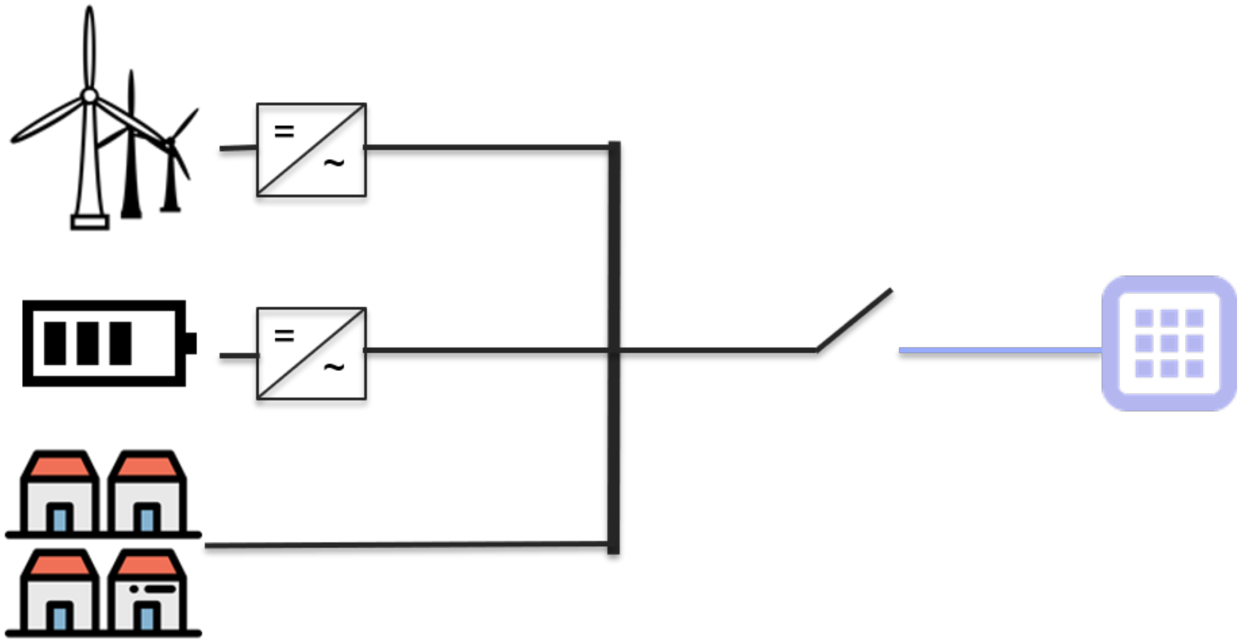

Implementing microgrids in the Swedish power system

Legislative, technical and economical challenges

Bachelor's thesis in Electrical Engineering

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Abstract

The world is about to enter a future where the integration of renewable energy sources within the power grid will play a major part when facing the challenge of reducing global warming. The implementation of microgrids might prove to be a good solution to handle the intermittent generation characteristics associated with renewable energy sources. The Swedish law and regulations does not currently favour the usage of the fundamental technology needed to implement a microgrid.

The purpose of this thesis is to investigate the environmental and economical impact of implementing a microgrid. By making calculations and assumptions on the consumption data for the town of Glesby, a model to find an optimally dimensioned battery storage system is formulated and the economical viability of using a microgrid for the towns already existing wind power plant is presented and discussed. Revenue streams from the concepts of demand flexibility and ancillary services are examined as well.

The report concludes that investing in a microgrid using demand flexibility, supplying ancillary services to the main grid and utilising a properly dimensioned battery energy storage system will be a feasible solution for the future integration of local renewable energy sources. In order to accomplish this, the suggested legislative changes presented in the thesis needs to be made.

Keywords: microgrid, local energy system, energy storage system, demand flexibility, battery, island mode, ancillary services, Swedish power system

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Anton Bergman, Carina Engström, Anton Eriksson,
Josef Johansson and Patrik Pettersson

Gothenburg, May 2018

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Acronyms

AC Air Conditioning. 21
aFRR automatic Frequency Restoration Reserve. 26

BESS Battery Energy Storage System. xv, 1, 2, 8, 10–12, 15–18, 25, 26, 29, 37, 42, 44, 45, 47, 49, 51, 53–57, 59, 60

CAPEX Capital Expenditures. 8, 13, 51

DER Distributed Energy Resource. 16, 24
DER-CAM Distributed Energy Resources Customer Adoption Mode. 24, 25
DF Demand Flexibility. 1, 2, 9, 15, 18, 19, 23, 24, 26, 27, 29, 42, 45–47, 53, 59, 60
DSM Demand Side Management. 18, 19
DSO Distribution System Operator. xv, 8–10, 12, 13, 18, 24, 27, 47–49, 53, 56, 59
DSR Demand Side Response. 18, 19

ENTSO-E European Network of Transmission System Operators for Electricity. 24, 26
ESS Energy Storage System. 1, 2, 11, 15, 51, 59
EV Electric Vehicle. 18, 19, 21

FCR-D Frequency Containment Reserve Disturbance. 26, 27, 43
FCR-N Frequency Containment Reserve Normal. xv, 26, 27, 43–45, 47, 53, 54

GDPR General Data Protection Regulation. 9

HVDC High Voltage Direct Current. 25

Li-ion Lithium ion. 17

mFRR manual Frequency Restoration Reserve. 26, 27

OPEX Operating Expenditures. 8, 13, 51, 57

PCC Point of Common Coupling. 1
PV Photovoltaic. 1, 6, 10–12, 15, 16, 24, 55, 59

RnD Research and development. 13

SE Swedish electricity region. 6, 43, 51
SEK Swedish Krona. 9, 10, 18, 24, 44, 45, 47–49
SoC State of Charge. 17, 43, 44, 53

SvK Svenska kraftnät. 5, 6, 24–26, 43, 45

TSO Transmission System Operator. 5, 8, 24, 27

WP Wind Power. 1, 3, 6, 10–12, 15, 16, 29, 55, 59

1
Introduction

This chapter will introduce the current state of the Swedish power transmission systems and why implementing microgrids might be a viable option. Then, the purpose of the thesis as well as deliminations are stated.

1.1 Background

Many nations around the world have committed to reduce future greenhouse gas emissions by setting common goals through global political agreements. The Swedish government has the ambition to develop the renewable electricity production, with the goal being an 18 TWh increase in yearly production until 2030 and that all electricity produced in Sweden will come from renewal energy sources by 2040 [1]. A major challenge with these commitments is to replace power generation from fossil fuel with renewable sources of energy while still being able to supply an increasing power demand. The discontinuous power generation characteristics as well as the scattered locations associated with renewable energy sources such as Wind Power (WP) and Photovoltaic (PV) is a challenge that has to be dealt with in order to develop a future power grid that is both environmentally sustainable and financially justifiable.

A possible solution to these challenges could be the implementation of microgrids in the national grid. The microgrid is a combination of local loads, an Energy Storage System (ESS), local electricity generation, control systems and a Point of Common Coupling (PCC) that can connect and disconnect the microgrid from the main grid [2]. An ESS consisting of batteries, known as a Battery Energy Storage System (BESS), can compensate for imbalances in production and consumption of electricity within the microgrid and provide ancillary services to the main grid. Some local loads can also be controlled to match the production pattern of the power generators with the concept of Demand Flexibility (DF) [3]. DF combined with a control system and a BESS make microgrids suitable for handling the time varying power output associated with renewable power production.

1.2 Problem description and research questions

This thesis aim to investigate the legal, technical and economical possibilities of implementing microgrids in the Swedish national grid. Investments in microgrid technology need to be backed by the law as well as economically justifiable for the energy companies to be considered viable. The current Swedish legislation does not allow for smaller grids to run independently of the national grid, nor does it give any long term incentives to make investments in new, smarter, technology [4, 5].

In order to analyse the eventual benefits of implementing a microgrid, the report will make calculations and derive models based on consumption and production data from the small town of Glesby, situated north of Gothenburg. Due to the nature of the collective data, the real name of the town can not be disclosed, therefore the fictional name Glesby is used.

Glesby currently has a wind power plant installed in its close vicinity. As of today, the town is only connected to the main grid with a single overhead power line which supplies 1 000 connection points in and around the town. What would happen if a microgrid was built in order to support the current connection? If this replacement would occur, what equipment and methods could be used in order to achieve a microgrid that is both environmentally and financially sustainable? To investigate this, three main areas will be examined:

- What laws and regulations are currently limiting the usage of microgrids in Sweden? How can these be changed in order to alleviate the further development of the microgrid concept?
- What minimum economical investments need to be made in order to have a resilient microgrid containing the adequate BESSs? Are the storage systems able to provide any ancillary services for the main grid that the microgrid is connected to?
- How can DF be used within the microgrid to benefit its overall effectiveness and in turn reduce the total cost of required storage?

1.3 Aim and purpose

To be able to answer and discuss the questions presented in the problem description, some sub tasks will be addressed and solved. First of all, an explanation of the Swedish energy market and a review of its current legislation need to be made. In order to understand what a microgrid is and the technical concepts that have an impact on it, concepts such as ESS, DF and ancillary services also needs to be described.

After examining the theoretical elements regarding the microgrid, a method section will be presented. This part of the report will try to find an optimal size of the storage system required for the microgrid by analysing and modelling the load profile of Glesby from collected data as well as finding potential sources of revenue that ancillary services and DF can provide. Lastly, a summary of the chapter is given by comparing the cost of constructing a new power line and building a microgrid with the optimised dimensions.

The results achieved will be the basis of the discussion chapter where our main questions will be handled. Some ethical dilemmas needs to be addressed in the report as well, mainly the environmental impact the implementation of microgrids might have. Since the report is a literature study, the only predicament is encountered in the method where handling of consumption data for individual households leads to a change of the towns name. This is done in order to protect the integrity of the town and its inhabitants. The report then finally comes to a conclusion drawn from the knowledge gained during its course and future recommendations are made.

1.4 Scope

- Only Swedish regulation in force as of January 1 2018 will be studied. Regulations and directives from the European Union that have not yet been implemented in the Swedish national legislation will be disregarded.
- The report assumes that the population has a positive opinion on adapting the microgrid concept.
- The monetary investment of installing new power production will not be taken into account for Glesby because of the already existing WP.
- An overview of what a control system is as well as its function in a microgrid will be included to get a proper picture of what it involves. This project will not dimension a control system for the prospected grid and we are not going to take the cost of it into account.
- The environmental impact when manufacturing components such as batteries for a microgrid will not be examined in this report.
- Cost for maintenance (both preventive and corrective) will not be part of the calculation due to the lack of data nor will the calculations include the different tax rates. Only the purchasing cost, income from ancillary services, fees from the electric act and deduction rates from the Energy Markets Inspectorate will be included.

2
Legislative background

In order to make qualified suggestions on how to solve the problem description of the report, an understanding of the legislative background needs to be established. First off, an overview of the current Swedish energy market and the laws ruling it is made. Then there is a section where changes and additions that have to be made in Swedish law and regulations to favour the implementation of microgrids is presented.

2.1 The Swedish power market

The Swedish power market was deregulated in 1996 [6, 7]. Today it is a market with open competition between the different companies. The main parties involved on the Swedish power market are [5, 8, 9]:

- Electricity power producers
- The national grid company Svenska kraftnät (SvK), the Transmission System Operator (TSO)
- Electricity retailers
- Regional and local distribution electricity companies, the Distribution System Operator (DSO)
- The electric market (Nord Pool)
- The electricity consumer
- The Swedish Energy Markets Inspectorate *(Energimarknadsinspektionen, Ei)*

The power producers are required to reach an agreement with a distribution company in order to be connected to the transmission or the distribution grid. A company is not allowed to both produce the electricity and own a distribution grid in Sweden, nor to take active part in retailing electricity [5]. Exceptions to these rules can be made if:

i an electric power producer and an electricity distribution company are affiliated within the same corporate group. The corporate group must take special action to make sure that the affiliated companies cannot exchange information in order to receive an unfair market advantage [5].

ii an electric distribution company produces electricity only to compensate for grid losses [5].

The physical delivery process of electricity begin with its production. Generated power is injected into the national transmission grid, transmitted to the regional grid, distributed trough the local distribution grid and finally delivered to the end consumer [10].

Besides the physical delivery process there is a commercial structure. Electricity retailers buy electricity from the producers on Nord Pool, the Nordic electric energy market. From the market, end consumers can sign agreements with the retailers and also compare energy prices on platforms such as *elpriskollen.se* provided by the Swedish Energy Markets Inspectorate [8, 10]. A regional toll is added to the retail price for the customer based on how much electric energy your specific region is producing [11]. There are four electrical regions arranged from north to south [11], partly based on the electric production, see Tab. 2.1. The town of Glesby is located within region SE 3.

Table 2.1: Summary of the relative regional electricity production in relation to the consumption.

Region	**Net-electricity produced**
SE 1 Luleå	Large surplus
SE 2 Sundsvall	Surplus
SE 3 Stockholm	Deficit
SE 4 Malmö	Large deficit

2.2 Review of the Swedish energy regulations

The Swedish energy system and the regulations that surrounds it is built on the idea that there is a nation wide main grid with subgrids in the form of regional grids and as subgrids to these are local grids [12]. Sweden has historically produced almost all domestically consumed electric energy by itself and has mainly been relying on nuclear and hydro power [6]. The Swedish national grid is a natural monopoly. Although Sweden has several distribution companies on the distribution grid level, there is only one, Svenska kraftnät (SvK), for the transmission grid [12]. SvK is a company that is both owned and part of the Swedish government (*affärsverk*) [12]. There are three companies owning the majority of the Swedish regional distribution grids: E.ON Elnät Sverige AB, Vattenfall Eldistribution AB and Ellevio AB and over a hundred companies that operate the local distribution grids [13].

In a microgrid containing only renewable energy sources, there are a number of possible tax exceptions that can contribute a more economically viable system. Every electrical generator which can produce a power output of 50 kW or less is exempted from paying tax on the produced electric energy, but WP and PV have even higher allowed power output levels, 125 kW for WP and 255 kW for PV [14].

There are a number of regulation areas which affects the possibility of constructing a microgrid in Sweden. In the following subsections, specific areas where the current legislation affects the implementation of a microgrid, will be presented.

2.2.1 Network concessions

Before building a power line in Sweden, a network concession need to be granted by the Swedish Energy Markets Inspectorate [5, 9]. It is illegal to not be connected to the distribution grid without special reasons, for example if the grid is on an island far from a connection to the main grid [5, 15]. This fact mean that you are judicially not allowed to run a microgrid that is able to disconnect from the main grid into island mode, which will be a problem for its future usage. There are a number of exceptions to the rule of network concessions regulated in (2007:215) that in theory could be a foundation to an approval of running a microgrid in Sweden, unfortunately none of the exceptions are for residential areas [15].

There are two types of network concessions [5]: line and area concession. An area concession include the operation of power lines in a distinct geographic area and the company being granted an area concession does not need to apply to the Energy Markets Inspectorate before building the new power line (although the company still need to get a building permission from the local authorities, make environmental impact assessments and receive permissions from other government agencies). A line concession is a permission granted by the Energy Markets Inspectorate for a specific power line and a new permission needs to be applied for every new power line. All granted network concession are valid until further notice. Until recently they were only valid for 25 years at a time [16].

2.2.2 Tariffs

As a result of the electricity transmission being a natural monopoly, the Swedish Energy Markets Inspectorate determine a framework on how high fees the distribution companies are allowed to charge the customers connected to their grid every four years [5]. In addition, there are laws that in more detail regulates the fees from the distribution companies [17]. The fees must be fair [17] and are designed to include both a reasonable return as well as cover the cost of maintenance, development and operation of the grid [4].

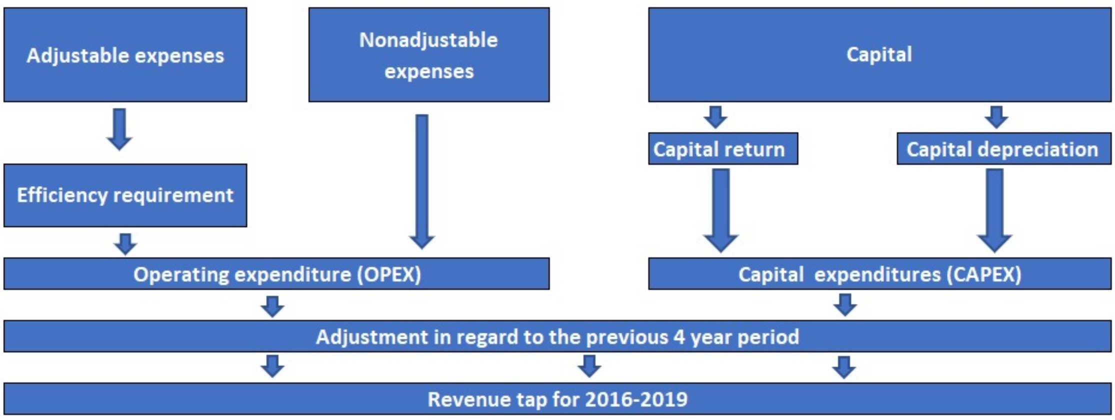

Figure 2.1: A graphic representation of the revenue tap for 2016-2019

The expenditure of the grid companies are normally divided into Operating Expenditures (OPEX) and Capital Expenditures (CAPEX) [4], as seen in 2.1. OPEX consist of adjustable costs such as operation and maintenance of the grid, which is controllable to some extent and nonadjustable expenses, such as government fees and non operational connection cost to the TSO. There is also an efficiency requirement from the Swedish Energy Markets Inspectorate to lower the operational and maintenance cost each year by 1 to 1.8% [4, 18]. CAPEX on the other hand consists of restricted assets, for instance power lines and electric facilities. These can yield a return or be written off as depreciation. Both OPEX and CAPEX are adjusted with regards to the previous 4 year period.

2.2.3 Regulations of energy storage systems

With the rapid progress of battery technology during the last years, the Swedish legislation and tax regulation have not been able to keep up. BESSs are not mentioned in neither the electricity act (1997:857), that regulates all production, transfer and consumption of electric energy, nor the energy tax act (1994:1776) that regulates all taxes in the energy sector, including producers, grid companies and consumers.

There are no precedents from the Swedish judicial system regarding how an BESS consisting of batteries should be interpreted. An BESS is indirectly included in the term electric facility (*elektrisk anläggning*) [5] and as a result, it is included by the safety and operations legislation [5, 19]. It is currently unclear how an BESS should be viewed from a taxation perspective since there are no laws defining them, nor is there any precedent ruling from The Supreme Administrative Court of Sweden (*Högsta Förvaltningsrätten*). However, it is clearly stated that all consumption of electric power is subject to taxation in Sweden [14]. Hence, a BESS will be less economically viable if it is taxed once for the electrical consumption to charge the battery cells and then once again, as production of electric energy when the battery is discharged.

The Swedish National Electrical Safety Board *(Elsäkerhetsverket)* [20] stated that the current Swedish legislation is well designed to regulate both small and large scale BESS facilities from a safety perspective. The biggest risks that have been identified are electric shocks, electrical fires and interference of other units control systems, but they are assessed to be of low probability as long as the current legislation is obeyed. Consequently, no additions or changes to the current electric laws were deemed necessary to ensure the electric safety of an BESS [20].

As mentioned, BESSs are currently not explicitly regulated by the electricity act (1997:857). Its usage may fall under the judicial separation between electric energy producer, distribution company and electricity retailer [21]. A DSO is only allowed to use BESSs in order to compensate for losses in the grid [5]. But, an energy producer or consumer is free to install an BESS as they see fit and the distribution company is obligated to connect the BESS as an electric facility and in turn charge its owner with a fair connection tariff [5, 20].

2.2.4 Regulations of demand flexibility

There are currently no laws in Sweden regulating DF or any similar situation where the DSO is allowed to control a customers consumption for shorter periods of time. Jan-Erik Olsson, Senior advisor at E.ON, confirms that there are no regulations of DF and E.ON have begun small scale test of demand flexibility in their pilot project in Simris.

The lack of targeted laws for DF does not mean that its completely unregulated. An important part of regulation is the EU directive to protect all citizens privacy and data protection: General Data Protection Regulation (GDPR), which will come into effect on May 25 2018 [22]. Due to the complexity and how recent the law is, in combination with the uncommonness of DF on the Swedish energy market, it is not yet clear how GDPR will affect its possible future implementation.

DF can be a significant factor in the implementation of microgrids, since it would make the grid more efficient in its use. Hence, it is unfortunate if DF have no clear regulations at all.

2.2.5 Power outages

The Swedish Energy Markets Inspectorate is responsible for overseeing the quality of all electricity delivered to the end user by the DSO. The definition of delivered quality is split into two subcategories based on paragraphs in the electricity act [5]: delivery assurance, regarding an uninterrupted supply of electricity to the consumer during short (100 ms to 3 minutes) and long (over 3 minutes) time frames and voltage quality, covering disturbances and fluctuations in the transmission grid. A power outage will bring high societal direct and indirect costs, ranging from minor inconveniences for a household to large monetary costs for industries. No outages within responsibility of the DSO is allowed to exceed 24 hours [5]. The Swedish Markets Inspectorate have published a document with regulations and general advice, EIFS (2013:1), containing further demands needed to meet the statutory requirement of high quality electricity transmission. For example a maximum amount of eleven outages per year and installation point as well as protection from falling trees are recommended [23]. There are economical incentives for maintaining a stable grid at both collective and customer level. DSOs able to keep a high delivery assurance can be allowed increased revenue frames, whereas DSOs with a low delivery assurance instead might have it decreased.

Economical compensation for customers affected by power outages is regulated within the electricity act [5], causing the DSOs to balance the costs of damage payment to customers against investing in more resilient grid technology. For outages between 12 and 24 hours, the owner of the net concession (usually the DSO), is obliged to pay 12.5% of the affected users projected yearly electrical cost, with the compensation being at least 2% of the statutory price base amount, which for 2018 is set to 45 500 SEK ($45500 \cdot 0.02 = 910$ SEK) [24]. If the outage lasts longer than 24 hours, an additional 25% is added for every commenced 24 hour period up to a maximum of 300%. Once the power is back and has functioned uninterrupted for two hours, the outage is considered to be over [5].

With the use of a microgrid that take advantage of BESS technology, supplying electricity even during longer periods of outage, a DSO might be able to save money. The BESS will increase the time span given to fix the power outage even for remote villages, giving the DSO a higher level of delivery assurance and therefore allowing a higher ceiling for financial gain. As previously stated it is up to the DSO to find an economical balance point between investing and disbursing.

2.2.6 Micro electric energy producers

In Sweden, the judicial term micro producer *(mikroproducent)* [5] exists, meaning that a physical or juridical person can install small scale renewable energy production such as PV or WP [25]. Small scale in this case refers to the in- and output of energy through the same point of contact connected to the grid, which in this case is an electrical fuse of max 100 A and a production of maximum 30 000 kWh per year [5]. In addition to this, a micro producer is entitled to tax deduction on the production of energy that is sold to the distribution grid by 0.6 SEK/kWh up to 18 000 SEK/year [14].

The electricity retailers who the consumer, which in this case also is a micro producer, buy its electricity from is obligated to receive any excess electricity from the micro producer and pay for it [5]. The micro producer can also reach an agreement with another electricity retailer in order to get a better price for the excess electricity. If the compensation from the electricity retailer exceeds 30 000 SEK/year, the micro producer is obliged to pay value-added tax [14].

2.3 Legislative changes

To favour the real world application of a microgrid, changes in the Swedish law need to be made. In order to make assumptions for the calculations in the rest of the report, this section will suggest changes and additions that can be made to better suit applications of the concept within the Swedish energy system.

2.3.1 Taxation of battery energy storage systems

With new technology comes new type of units and system. Not only for microgrids, but also for the Swedish energy market as a whole where some changes and modernisation of the legislation are needed. With regards to BESSs, a definition is needed in the electricity act (1997:857) 1 ch, to explicitly include BESSs as electric facilities and define what an BESS is in a judicial sense [5], and for microgrids BESS in particular. The Swedish Energy Markets Inspectorate has voiced their concern [26] in this regard, where the lack of a clear juridical definition is problematic. They would like the European Union to define BESS, which would be in accordance with the proposed European energy union [26, 27]. Also, the ministry of environment and energy *(Miljö- och energidepartmentet)* have acknowledged the lack of definition and it has also been pointed out in a recent state public report *(Statens offentliga utredningar)* [28].

An addition in (1994:1776) [14] that clearly states how BESSs are to be taxed and if different types of ESSs should be taxed differently, for example hydro pumps and batteries, is needed. ESSs in the form of hydro pumps have been on the Swedish energy market for quite some time and as such, there are routines and regulations by the Swedish Tax Agency *(Skatteverket)*, but in the case of BESSs, having a fairly recent introduction to the market, the regulations have not been able to keep up [26]. The time that the energy is stored ought to be taken into consideration by the Tax Agency when taxing different ESSs. With a hydro pump ESS, one can store energy for long periods of time, spanning over months, seasons or even years, where BESSs is able to store energy for hours to days. Because of this, it can be argued that it is more justifiable and logical to tax hydro ESSs for both consumption (when water is pumped) as well as production (when the water reservoirs are emptied), due to the fact that the reservoirs can be filled during the spring when the energy prices are low and emptied in the winter when the price is higher [29]. With a BESS on the other hand, this will not be economically viable. BESSs operate within a time frame of one or at the very most a few days, and within a day the electricity price does not fluctuate as much as over an entire year. Of course there are strategic advantages with hydro pumps, but also because of the "buy-low-sell-high" idea, a tax on both consumption and production could in this case be viewed as more of a tax on invest and return.

In a memorandum from the Swedish Ministry of Finance *(Finansdepartementet)* [30], it is proposed that an ESS should only be taxed once, as a consumer when charging from a network with network concession. In part, due to the lack of definition of ESSs, the memorandum can be interpreted in a number of ways. The deputy director at the ministry of finance Ulf Olovsson has stated in an e-mail (dated to 03/06/2018) that the ministry does not intend long term ESS, such as fuel cells, when they refer to energy storage, but only short term such as BESS. Still, this is not stated in the memorandum itself, nor in any available legislative history *(förarbete)* regarding the matter. Depending on the consultation response*(remissvar)*, the changes put forth in the memorandum could be implemented to a proposition from the Swedish government and passed in parliament, thus changing The law of energy taxation (1994:1776). If it gets passed in its current form, changing (1994:1776), 11 ch, 7 and 13 §§ in accordance with the memorandum, it could be interpreted by the Swedish Tax Agency to either:

- i not include any of the current ESSs because there is no definition of it, nor any clarification in the legislative history on which ESSs is intended.
- ii all types of ESSs are included in the new law.
- iii to only include BESSs.

To encourage the expansion of BESSs, either as a compliment to WP and PV or to generally increase the energy storage capacity in the grid, a tax exception up to a fixed amount of kWh could be implemented within the paragraph that already exist for WP and PV in The law of energy taxation (1994:1776) [14]. Another reform to encourage the construction of BESSs, which is mentioned in the public report [31], is to make an addition in the building regulations (1984:1052) to also include BESSs within the lower tax rate, in which the construction of WP is already included [32].

If it is desirable for households themselves to get the energy storage to meet their needs, either to increase the robustness so that every household can manage a few hours of power outage, or as within a larger grid-connected BESSs, contribute to produce a more constant total load. This may in turn lead to an hourly flexible electric price for the consumer to create incentives to charge the household BESS at night when the demand is low and using the stored energy at peak demand where the electricity price is higher. Then, one could grant the installation of household batteries the incentives that is currently granted installation of PV in detached houses. Make an addition regarding BESS to (2009:689) and also include it in the ROT-tax deduction program (*ROT-avdrag*) [31, 33, 34].

2.3.2 Network concessions

The intention of the connection requirement in the electricity act (1997:857, 3 ch, 6-8 §§) indirectly ensure the supply of electricity [5]. One way to change the legislation, yet still ensure the supply of electricity, as well as enabling an isolated microgrid, is to change the electricity act (1997:857), 3 ch, 7 § from a main grid connection requirement to a power supply requirement, which still falls under the existing area concession. This means that a subarea within an area granted area concession, is required to be supplied with power by the DSO who owns the area concession, but not necessary by a connection to the transmission grid. It will give the DSO flexibility to most suitable solution based on the local conditions.

Changing the connection requirement to a supply requirement will most likely result in a need to consequently also change other laws. The energy market as a whole may need to adjust as well, for example the relation and roles between the different parties involved. The tariff system will probably need to be modified, at the very least the criteria of what can be called reasonable fees for the producer and consumers to use the grid. The regional electric toll (see Tab. 2.1) should most likely be modified to at least take the degree of self-sufficiency of a microgrids into account.

One alternative to change the connection requirement is to extend the authority of the energy market inspectorate to be able to approve the establishment of a microgrid. This is already possible today, but the application must meet a set of very specific requirement which are more written with geography limitations in mind, such as a grid on an island [9]. If this change of the connection requirement was implemented the agency could evaluate if a microgrid would be desirable societal point of view, and if so in what extent.

Today, the energy market inspectorate do not have the authority to grant exemption from the current legislation to Research and development (RnD) facilities and test grids [9]. This is something that both the Swedish Energy commission [31] and Copenhagen economics [4] identify as a problem and suggests that the agency should be granted that authority to ensure the long term effectively and development of the Swedish national grid. Currently there are very few incentives for the DSO (see section 2.3.3 for more) on top of the lack of authority to approve operation of RnD facilities to test new technology and concepts [4, 31]

Lastly, a small change is to include transfer of electricity between adjacent buildings that are either part of the same housing cooperative (*bostadsrättsförening*) or are owed by the same juridical person in a well defined area for example a residential area or block without network concessions [5, 15]. For example, to be able to transfer power from a PV that is installed on the roof on one building in a housing cooperative to the other houses as well. A new paragraph in (2007:215) is seemingly the only alteration of Swedish law necessary to implement this reform, which would make the regulations easier and more intuitive.

2.3.3 Tariff system

The DSOs have criticised the current tariff and revenue tap system [4] and argued that the revenue tap, which is set by the Swedish Energy Markets Inspectorate, is ineffective and a blunt tool in a one-size-fits-all manner four years at the time [5, 17]. This, according to the Distribution System Operators, prevents them from purchasing more expensive and effective equipment, that could improve the effectiveness of the grid and in long term lower the total costs [4].

One possible option to reform the current tariff system was presented in [4]. It calls for a new tariff system that is based on the total cost of the grid instead of today's distinction between OPEX and CAPEX [4, 5]. The reformed tariff system could be made similarly to the Finnish system, where the DSO can deduct cost, for experimental equipment, research and development facilities, from the operating income (*rörelseresultat*) up to 1% of the company's total revenue (*omsättning*) [4]. This could also lead to more effective and environmentally friendly grids [35, 36].

A microgrid, when its isolated form the transmission grid, could lead to oligopoly or even monopoly in some cases, unless this is regulated in addition to the already existing general market competition law, (2008:579) [37]. Another way to prevent an unbalanced market within the microgrid is to stimulate the installation of PV that the households themselves own, either if every or many houses put PV panels on their roof or comes together to form cooperatives or *samfällighet* (a Swedish juridical form of ownership tied to a number of local real estates, not the person who is the legal owner of the estate) which in turn constructs PV or WP [38, 39, 40].

Other problems with the current tariff system with regards to microgrids are that the standard costs for investing and operating the grid may differ by large amounts from the actual cost [4, 5]. This is a known problem for the distribution grid companies and is currently preventing them from investing in more technically advanced equipment that could increase the long term efficiency of the grid [4]. If this is a problem today, it will probably be an even bigger problem for a microgrid, because of the microgrids need for modern control systems in order to function effectively. In addition, the calculated standard cost is based on the main grid and it is fair to assume that the actual costs within a microgrid differs quite a lot from that of the Swedish main grid.

3
Technical background

To get an understanding of the the terminology and technical concepts used within a microgrid, the following chapter will introduce key elements such as BESS, DF and ancillary services.

3.1 The microgrid concept

The microgrid is defined as a local grid able to disconnect from the main grid, allowing autonomous operation as well as the possibility to act as building blocks in the main grid [41]. Advantages brought on by using the microgrid concept are increased efficiency and flexibility for the integration of distributed energy resources such as WP and PV, increased grid resilience and reduced transmission losses. The increased efficiency of the microgrid is a consequence of local loads consuming locally generated power, creating relatively short distances between consumer and producer which in turn leads to reduced losses when distributing energy in the grid. When the microgrid is disconnected from the main grid, its autonomous operation is known as island mode.

3.2 Energy storage systems

An energy storage system is needed within the microgrid to make sure that excess energy produced at one time is not lost, and at times of large demand from the loads that electricity can be provided without interruption. The usage of ESS:s can also be motivated by the varying renewable energy technologies such as WP and PV, which are typically producing the most when utilities require little or no electric energy [42]. It is also preferable if a single ESS can provide multiple services simultaneously [43]. One such energy storage form is the battery, see Fig. 3.1. A battery used within grid applications consist of many stacks of smaller battery units, which in turn holds a number of battery cells. The battery technology for power electronics applications is, except for being commercially established [44], suitable for the length of energy storage time needed.

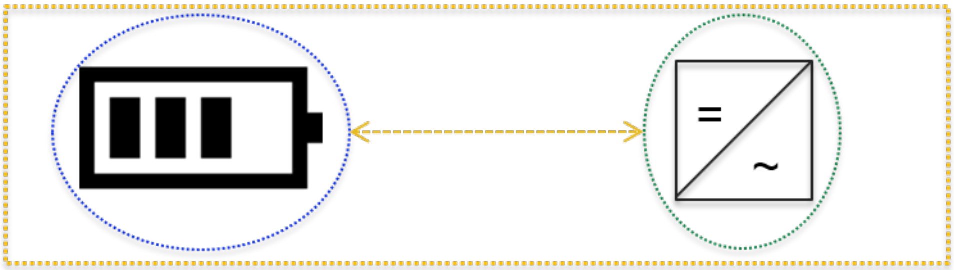

Figure 3.1: The battery energy storage system: Battery management system and inverter control.

3.2.1 Controls and energy storage systems in the microgrid

A microgrid controller is used to control the components within the microgrid in order to keep a high quality of and to assure stable connection and disconnection from the national grid. In [45], a hierarchical control system for microgrids is presented consisting of three control levels: primary, secondary and tertiary. The primary control level is responsible for the fast control response by stabilising the frequency and voltage when the microgrid is operating in island mode. The secondary controller has a slower response and is responsible for the long term energy balance in the microgrid as well as the restoration of frequency and voltage to their reference values after the primary controller has stabilised them. Tertiary control is the slowest control level and is used to optimise the power flow between the microgrid and the national grid when the microgrid is connected to the main grid.

A microgrid relying only on power electronic-interfaced distributed generators, such as WP and PV, for electricity production will have low inertia due to the lack of rotating mass from synchronous generators [45]. Low inertia causes the grid frequency to change quickly when there is an imbalance between power production and consumption. A BESS can be used with primary and secondary controls to stabilise the change in frequency and to restore it to its reference value. How quickly the primary controller needs to stabilise the frequency drop depends on how much the frequency is allowed to deviate, how large the imbalance in power is and the inertia of the microgrid [46].

To keep a constant voltage there needs to be balance between produced and consumed reactive power in the microgrid. Inverters connected to a Distributed Energy Resource (DER) or an BESS can be regulated so that the output current either is lagging or leading the output voltage [47]. This can be used to balance the produced and consumed reactive power in a microgrid. Inverters are used with primary and secondary controls when the voltage begins to differ from its reference value. The primary control stops the voltage change and the secondary control restores the voltage to its reference value [45].

3.2.2 Microgrid batteries

There is a wide range of battery cell compositions already commercialised, such as lead-acid, lithium sulphur, magnesium ion, metal air, nickel cadmium and sodium-type batteries [48]. However, Lithium ion (Li-ion) batteries are widely accepted as the all-around solution for microgrid energy storage needs [49]. A Li-ion battery has a large energy density [50], which can be adjusted by increasing or decreasing the thickness of one cell or by adding or subtracting to the number of cells in it [50]. In addition to the energy density of Li-ion batteries, existing BESS Li-ion based models in production can provide both power and energy functions [51, 52].

The batteries are delivered in containers which consists of both the battery cells themselves as well as safety monitoring and control units. This is done to achieve a lower cost in complex applications, to make the installation process quick no matter where the location of installation is and to also have the required control systems and real-time supervision already incorporated [51, 52].

3.2.3 Battery lifetime prolonging

Longevity of the microgrid-connected battery is preferable since the installation process is costly and grid applications are by default designed to be long term. Hence, controlling the current more precisely is a key factor for long battery life, especially near the battery cell being fully charged [53].

Manufacturers guarantee around 20 years of service from the grid battery [51, 52] and with a sustainable BESS utilisation, such a longevity is possible. The reasons for a decrease in battery capacity in most Li-ion based cells is caused by three main factors: ageing, cycling and elevated temperatures.

The battery age is the term for cycling and temperature effects combined [54]. Increased cycling, especially between a fully charged battery and a fully depleted battery, will shrink the total battery capacity faster [55]. This means that if it is charged near its full capacity many times, that will degrade the battery faster. One solution is to keep the battery charged between a certain percentage of the total SoC. It seems better for the total life of the battery to never have it charged below 25% [54]. 20% is the lowest level of charge that E.ON's Simris battery is kept at. Elevated temperatures can be avoided by making sure the cooling system is working properly.

3.2.4 Pricing of battery energy storage systems

Throughout the recent years, prices for Li-ion batteries have dropped significantly [56]. Still, battery energy storage systems will only become the norm if it costs less than building more transmission lines [42]. In this subsection, an overview of the investments needed to purchase a BESS for microgrid utilisation will be made. In emails exchanged with Trond Beyer (Sales Manager Transport, Telecom & Grid) from SAFT and Elias Afeiche (Sales engineer - Microgrid solutions) from ABB AB (companies producing BESS) they agree that giving standardised prices is difficult. The normal procedure when offering a price from the manufacturer is to first know the load profile of the system and if a power conversion system should be part of the cost, says Beyer.

BESS:s can be categorised into groups based on the C-rate. The C-rate is the discharge rate relative to it's maximum capacity (meaning that a battery with 1C would be discharged in one hour if discharged at discharge current) [57]. If the BESS has higher C-rate, that makes it more expensive.

In a cost analysis of BESSs conducted in 2017 [58], pricing was validated according to the most recent commercial opportunities as well as usage in the microgrid. The analysis is based on surveys, and several interviews with industry participants. Their price interval ranges between 494 USD/kWh ($\approx$ 4 400 SEK/kWh) and 543 USD/kWh ($\approx$ 4 800 SEK/kWh), thus the mean price is 4 600 SEK/kWh [58, 59]. Results represented in this report were not categorised after their C-rate, only the manufacturer price, but they are representative for batteries used in microgrid applications [58].

3.3 Demand flexibility

DF is a concept aimed to create flexibility and make adjustments in consumer power usage by encouraging changes and giving economical incentives in the end user energy consumption pattern [3]. With the recent progress made in the field of smartgrids where parts of the power system are able to communicate with each other, DF is becoming an increasingly practical real world solution, especially within microgrids. Two subcategories are included in the DF concept known as Demand Side Response (DSR) and Demand Side Management (DSM). DSR can be considered a reactive technology where users are given cost incentives and based on these able to decide when energy is to be consumed in the household. DSM allows for the DSO to control end-user consumption by forcing household loads to stop using power at certain periods of time. For this report, the possible usage of DSM within the microgrid will mainly be taken into account.

The main intention of using DF is to shift power consumption off peak hours in order to decrease the required installed power generation capacity, meaning a lower investment in power plants and network capacity need to be made. Peak clipping can be used by reducing utility load during peak power consumption, giving the DSOs control over to what extent home appliances and heating are allowed to run. This brings the net effect of lower peak demand as well as a decrease in total power used. Load shifting on the other hand relies on the usage of loads off-peak, decreasing the peak consumption and moving it to when there is an excess in production. Load shifting maintains the same level of total power usage. Valley filling is closely related to BESSs, utilising the storing of power during off-peak hours in batteries or charging EVs in order to flatten the total demand curve.

DF can also be useful when a microgrid is forced into island mode (if there is a power outage on the main grid for example). Some flexible loads can be turned off to reduce the energy need during the outage and increase the time island mode is possible. To further investigate the possibility of using DF in Sweden, the load profile and characteristics of Swedish houses will be examined.

3.3.1 Household load characteristics

Household loads can broadly be split into two categories, fixed and flexible loads. A fixed load cannot be shifted to another time and there are times when it has to be turned on, e.g lighting and electrodomestics. A flexible load does not have to consume electricity at a specific time of the day and its consumption can be regulated in a smart way to follow the production of weather dependent renewable energy sources like WP and PV. This allows for an easier integration of renewables in microgrids and can possibly lower the required capacity of energy storage. Flexible loads are split into two subcategories, explicit and implicit flexible loads. Explicit flexible loads are best suited for DSM and implicit flexible loads for DSR [3]. The flexible loads included in the two subcategories is presented in Tab. 3.1.

Table 3.1: The two categories of flexible loads.

Explicit loads	**Implicit loads**
House heating	EV charging
Cold appliances	Wet appliances
Water heater	

3.3.1.1 Explicit flexible loads

Explicit loads can be regulated on short notice or even in real time with the help of control systems that get information from the grid and the load itself. The grid informs the controller if there is an excess or deficit in production of electricity. With this information the controller can decide if the load should be turned on or off. If a load has been turned off for a long time and the comfort level of the consumer is about to be affected, the load informs the controller and it is turned on. Explicit flexibility can mainly be applied to three types of loads: house heating, water heating and cooling household appliances [3].

Explicit flexibility of house heating works by down-regulating the heating system (heat pump and radiator) during peak consumption hours and possibly up-regulating during off-peak hours [60]. This can be done with minimal affect on the comfort of the residents since houses have thermal inertia. The drop of internal temperature of a house over time can be calculated through Eq. (3.1)

$$T_i(t) = T_a + (T_i(0) - T_a)e^{-t/\tau} \tag{3.1}$$

where $T_i(t)$ [°C] is the internal temperature of the house after a time t [h], T_a [°C] is the outside temperature and τ [h] is the thermal time constant of the house. For an average Swedish house built in the 1980's, τ = 53 h [61]. How the temperature drops from 22 °C in this type of house with different outside temperatures is shown in Fig. 3.2 using Eq. (3.1).

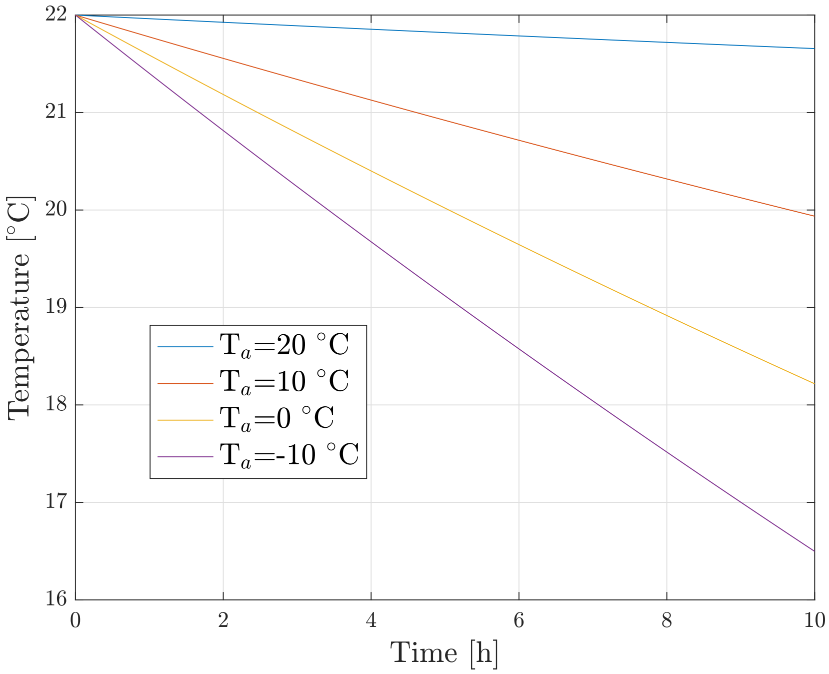

Figure 3.2: Temperature drop in an average Swedish house from the 1980's.

To ensure the comfort of the residents, a limit on how much the temperature is allowed to drop while using explicit flexibility on house heating is set. If the internal temperature is allowed to drop to 20 °C, the heating of a house could be turned of for approximately 3 hours when the outside temperature is -10 °C.

To keep a house at a set temperature the power used for heating needs to be equal to the heat that leaves the house. The power needed to keep a house at a set temperature is calculated through Eq. (3.2)

$$P_{Loss} = P_{Const}(T_i - T_a) \tag{3.2}$$

where P_{Loss} [W] is the heat that leaves the house and P_{Const} [W/°C] is a house dependent constant. The percentage decrease in power needed to keep a house at a lower temperature after a temperature drop can be derived from Eq. (3.3) when the internal temperature drops from T_{i_1} to T_{i_2}.

$$\frac{P_{Loss2}}{P_{Loss1}} = \frac{P_{Const}(T_{i_2} - T_a)}{P_{Const}(T_{i_1} - T_a)} = \frac{T_{i_2} - T_a}{T_{i_1} - T_a} \tag{3.3}$$

Explicit flexibility of water heating works similarly to house heating, but since the water is stored in an isolated tank, it can potentially be down-regulated for a longer period of time. In a study of the flexibility of water heaters in Norway [62], the following results were achieved. An average Norwegian residential water heater holds

200 litres of water, has a heating capacity of 2 kW and it takes approximately 2.3 hours for a full heated tank to drop by 1 °C in temperature when no hot water is being consumed. This type of water heater can be used as an approximation of an average Swedish water heater. The water heater has a temperature range of 4 °C below the set temperature when it is not activated. Meaning that a water heater heated to its set temperature will not be turned on for about $4 \cdot 2.3 \approx 9$ hours if it is not used. The most common cause of the temperature dropping is however that hot water is being used by the household. The majority of hot water consumption occurs in the morning and the evening, leaving two time windows where the water heater needs to regain its set temperature and explicit flexibility could be applied.

Explicit flexibility of cooling household appliances can be used on refrigerators, freezers and Air Conditioning (AC). Refrigerators and freezers can be regulated year round, but modern cold appliances are relatively energy efficient and only consume about 150 W, accounting for around 2% of a family home's peak power demand of about 8-10 kW, limiting the benefit of its flexibility [3]. AC has a high power consumption and may be used with explicit flexibility. However, AC is used to a low extent in Sweden, thus limiting the possibility of implementing AC flexibility [63].

3.3.1.2 Implicit flexible loads

Implicit flexible loads are not controlled in real time, instead they are regulated by behavioural changes in consumption patterns at the user end. This can be done by, for example, giving the consumer price incentives not to use electricity during peak hour. Implicit flexibility is mainly used in Electric Vehicle (EV) charging and wet appliances (washing machine, dryer, dishwasher) [3].

Household EV charging has a high power consumption (ranging from 3.6 kW to 10 kW) and can drastically raise the peak power consumption of a household. The peak power consumption of a small family household without an EV lies around 8 to 10 kW, meaning that charging an EV can nearly double the peak power consumption [3]. Implicit flexibility can give incentive for EV owners to charge during off-peak hours and thereby avoid an increase in the household's peak power consumption.

Washing machines, dryers and dishwashers also have high power consumption. These wet appliances does not necessarily have to run during peak hour. To help consumers avoid using wet appliances during peak hours, a control system can be used which allows the consumers to set a max time when the washing machine, dryer or dishwasher should be done [64]. The control system will start the service (washing machine or dishwasher) when there is excess production of electricity and therefore, reducing the need to store electricity in the microgrid or sell via the main grid.

3.3.2 Load profile of a Swedish household

Between 2005 and 2008, the Swedish Energy Agency did measurements on all loads in approximately 400 Swedish households [63]. The measurements took place in between one to 12 months depending on the household. The data from the measurements were obtained from the Swedish Energy Agency. The data used was seasonally adjusted when obtained and only the measurements made in houses (201 houses) were included. The loads were split into the different load categories. The average load profile is presented in Fig. 3.3.

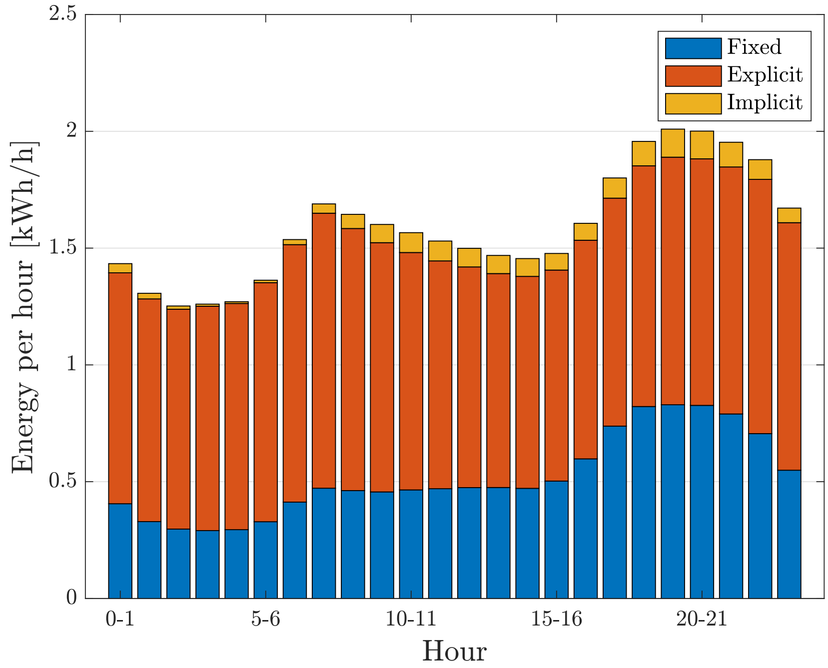

Figure 3.3: Average load profile of the houses measured on by the Swedish Energy Agency.

The data shows that an average day the fixed load ranges from roughly 0.3 kWh/h to 0.8 kWh/h, the explicit flexible load from 0.9 kWh/h to 1.2 kWh/h and the implicit flexible load from approximately 0 kWh/h to 0.12 kWh/h. The relatively large consumption by flexible loads implies that demand flexibility has a good potential in Sweden.

Factors like what heat source a house uses and how well insulated a house is greatly affects the load profile. A house using direct electric heating, for example, is going to have a greater consumption than an equal house without direct electric heating. The data received from the Swedish Energy Agency did not specify what the main heat source were for the different houses and Fig. 3.3 therefore includes houses both with and without direct electric heating.

Fig. 3.3 can be misleading regarding the implicit flexible loads. Since they show an average consumption derived from many households, it looks like the dishwasher and washing machine consumes a low amount of power for a long time, when in reality they have a high power consumption (up to 2 kW) for about one to two hours [3]. A washing machine typically consumes about 0.5 kWh per cycle and runs for about an hour, meaning that it on average consumes 0.5 kW for an hour. A dishwasher also consumes about 0.5 kWh but typically runs for about two hours, meaning that a real load profile for a household could include peaks of 0.25 kW and 0.5 kW coming from the wet appliances [63].

Consumption related to electric heating also has strong seasonal effects which can vary from year to year. When the Swedish Energy Agency monitored the power consumption of 400 households, it was found that during the coldest part of the winter, the consumption related to electric heating was increased by approximately 170 % from the yearly average and was lowered by 80 % during the hottest part of the summer [63]. In Fig. 3.4 the part of the explicit flexible load used for heating in Fig. 3.3 is multiplied by 2.7 and in Fig. 3.5 the part of the explicit flexible load used for heating is multiplied by 0.2.

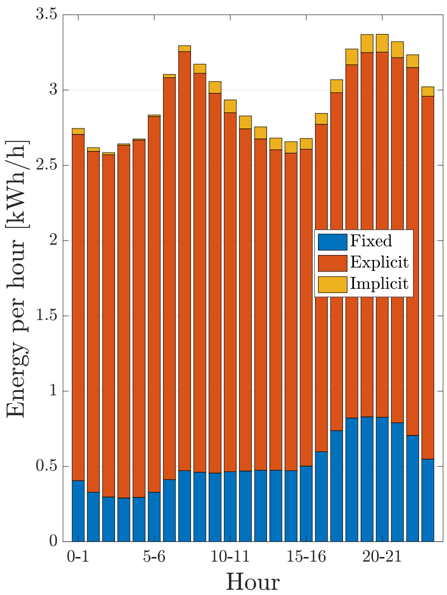

Figure 3.4: Approximated load profile, the coldest part of winter.

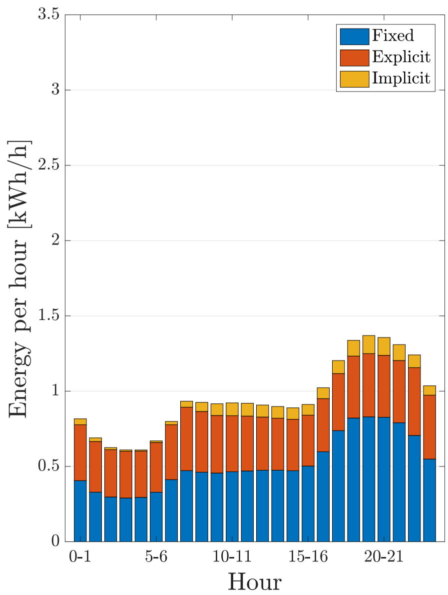

Figure 3.5: Approximated load profile, the hottest part of summer.

Other loads like lighting, cooling appliances and cooking also have seasonal effects, but their variations are minor in comparison to heating and are neglected when accounting for seasonal effects in the load profile.

3.3.3 Cost of implementing demand flexibility

To connect an end-user to a microgrid utilising DF, there might be a need for metering equipment with a time resolution beyond what the household currently has installed. The base and maintenance cost of these units is something that will need to be taken into account as a large number of customers upgrading at the same time will be a big investment. The cost of installing a smart meter with the required peripherals averages €200-250 (≈ 2060-2570 SEK) within the EU [65]. In addition to the primary investments, costs for maintaining data transfer infrastructure, installing the equipment and customer service need to be included.

As a real world example of the cost for a DSO to adapt a household into DF, Stina Albing at E.ON specifies that the equipment used to control water heating and heat pumps, along with its installation, is free of charge for the customer. The price for buying the smart thermostat and water heater control unit used by E.ON, the *Bobbie* and *Ngenic Tune*, new from its manufacturer VUAB is €129 (≈ 1 460 SEK) and 4 995 SEK [66, 67]. Households installing a new heat pump or PV system are given a 30% respectively 50% discount, before any tax reductions or government subsidies, by E.ON. Customers participating in the E.ON flexibility plan are also given a fixed discount of 100 SEK on their electricity bill, as well as flexible compensation depending on how much of their installed capacity have been used to support the grid when requested.

3.4 Microgrid services to the national grid

According to the European Network of Transmission System Operators for Electricity (ENTSO-E), a system service is: "a generic term for services that the system operators need for the technical operation of the power system [68]. The availability of system services is agreed upon between the system operator and the other companies within the respective subsystem." The system in this case being the Swedish transmission grid operated by SvK and the subsystems, all local grids owned by the DSOs.

In order to enable a high quality and safe operation of the electric power system, the Nordic TSOs has set conditions in addition to their respective national regulations for coordinating, connecting and reconstructing electrical installations in a document known as the *Nordic Grid Code* [68]. To keep the system running accordingly, various system services also known as ancillary services, are required to manage elements such as grid frequency, imbalances in voltage and power outages.

A power producer is allowed to trade ancillary services on the balance market. In order to do so, the producer need to be granted balance responsibility (*balansansvar*) by SvK [69]. This responsibility includes factors such as communicating the projected available power for each separate system service, reporting real time measuring data for active and reactive power as well as meeting technical demands for all objects used to provide system control. SvK is in turn obliged to report the planned required control and power prognosis to the producer. The ancillary services are traded on the D-2 or D-1 market depending on whether the contract is procured one or two days before the asked delivery day.

The paper "The impact of ancillary services in optimal DER investment decisions" [70] investigates the inclusion of revenue from participating in ancillary service markets into the microgrid sizing model Distributed Energy Resources Customer

Adoption Mode (DER-CAM). The ancillary services used here are spinning reserve, non-spinning reserve and frequency regulation, which includes both up- and down regulation, since these are the services that there most commonly exists a market for. The result of [70] suggested that using the microgrid for ancillary services could have an impact on its sizing.

3.4.1 Ancillary services provided by energy storage systems

Listed below are the system services included in [71] that are similar to the revenue sources that could be provided by BESS according to [58].

- **Frequency controlled normal operation reserve** is a type of frequency regulation which should correct a divergence of 0.1 Hz within 2-3 minutes. This is currently done by changing the water flow at hydro power stations.
- **Frequency controlled disturbance reserve** is, similarly to frequency controlled normal operation reserve, activated when the frequency drops to 49.9 Hz and then increases linearly until 49.5 Hz. This is currently done by changing the water flow at hydro power stations or, in stages, regulating the power exchange in High Voltage Direct Current (HVDC) links and using gas turbines.
- **Voltage controlled disturbance reserve** is to control the voltage level by restricting HVDC power export. This is only used in the southern part of Sweden.
- **Fast active disturbance reserve** is used to restore frequency controlled disturbance reserve through voluntarily bidding for contracted regulating power from gas turbines.
- **Fast active forecast reserve** is used to restore Frequency controlled normal operation reserve through voluntarily bidding.
- **Fast active counter trading reserve** through voluntarily bidding.
- **Black start** is performed by hydropower plants and a HVDC link between Sweden and Lithuania.
- **Peak load resource** is an active reserve that is not normally used because of the time it takes to prepare it.

The only usage of BESS for the system services mentioned in Sweden is hydro power stations. However, because of the similarities to the revenue sources included in [58], many of these services should have the potential to be performed by other types of BESSs.

Regarding the market for ancillary services in Sweden, SvK has responsibility for the power balance in the Swedish grid which they fulfil by purchasing reserves on the power reserve market in the form of energy and/or power products depending on what payment is based on. A provider of power products is paid an amount per MW for every hour that the product can be activated. Energy products on the other hand are paid a sum per activated MWh when regulating up (providing energy to the grid) and pays a sum per activated MWh when regulating down [72, 73, 74].

- The FCR-N is a power and energy product for small fluctuations of less than 0.1 Hz. In case of larger fluctuations there is the FCR-D which is a power product. A minimum of 0.1 MW is required in order to bid on the FCR-N and FCR-D. Bidding for FCR is done for specific hours and can be done two days or one day before the day that it will be used. The service can be bought back from SvK (returned) at the marginal price after contact with SvK at the auction one day before or during the day it should be used depending on when the bid was offered.
- The automatic Frequency Restoration Reserve (aFRR) is a power and energy product which restores the frequency to 50 Hz and is automatically triggered when the frequency differs. The aFRR should be fully activated within 120 seconds and the bids should be a multiple of 5 MW. Bids regarding the next week, meaning the period from that Saturday until the next Friday, can be submitted before 10:00 AM that Thursday. SvK performs the returns at the marginal price.
- The manually activated reserves should be activated within 15 minutes. This includes the manual Frequency Restoration Reserve (mFRR) which is an energy product on the control power market with voluntary bids of minimum size 10 MW. Also included are two power and energy products similar to mFRR but with a minimum of 5 MW. The power reserve is procured to manage the peak load during the winter through bidding. The disturbance reserve is procured through contracts spanning multiple years and is provided by gas turbines in order to support the grid during short intervals of unforeseen disturbances. In this report the power reserve and the disturbance reserve is represented by the abbreviations mP and mD respectively. Bids regarding mFRR and mP can be submitted 14 days ahead of the hour it will be used and changed until 45 minutes before.

ENTSO-E have made the future recommendation that [75]:
"The TSOs could facilitate market integration of storage by establishing clear technical and market requirements for its participation in the procurement of system services ".

According to an email from an employee at Svenska kraftnät, energy reserves in the form of battery storage is not allowed to participate on the power reserve market in Sweden today but they are currently running a pilot project with the objective to develop a pre-qualifying process for newer types of resources and investigate how BESSs and DF can be used to benefit the frequency regulating ancillary service of FCR-D [76] in accordance to the vision set by ENTSO-E.

Tab. 3.2 compares the revenue sources of [58], the system services in [71] and the current reserve markets in Sweden [74]. The reason that there is not a system service similar for the aFRR market is probably because that market has only existed for a few years.

Table 3.2: Ancillary services.

Revenue sources	System service	Market
Energy arbitrage	-	-
Resource adequacy	Peak load resource	mP
Frequency regulation	Frequency controlled normal operation reserve Frequency controlled disturbance reserve - Fast active counter trading reserve Fast active forecast reserve	FCR-N FCR-D aFRR mFRR mFRR
Non-spinning reserve	Fast active disturbance reserve	mD
Distribution deferral	-	-
Transmission deferral	-	-
Black start	Black start	-
Voltage control	Voltage controlled disturbance reserve	-
Ramping	-	-

3.4.2 Demand flexibility as an ancillary service

Utilising DF as an ancillary service to the main grid has been deemed technically difficult and expensive by TSOs for a long time. With the recent development of faster and more secure communication for coordinating loads within the grid, system services provided by DF will become relevant for a future main grid containing microgrids. The primary service that can be provided by DF is frequency control by lowering the total load within a grid for the needed period of time, in order to balance it out [77]. Explicit loads, such as cooling and heating appliances, enable shorter interruptions that goes unnoticed by the users. These appliances can be controlled by either direct control, where the DSO is able to decide when loads need to be interrupted or indirect control, where users respond to price incentives sent out by the DSO.

4
Method and result

To find the economical investments needed for implementing a microgrid containing an optimally sized BESS, data regarding the existing power production and the derived load profile of Glesby need to be found and analysed. The impact of using DF as well as offering ancillary services to the main grid will also be taken into account. All economical factors will then be summarised for six different cases of possible future power grid solutions.

4.1 Modelling the loads

By using data obtained on the WP production of Glesby and the towns consumption, we can determine the amount of energy the battery should be able to hold (dimensioned after max overproduction), as well as be able to deliver each hour (considering consumption patterns), in the event of an outage on the power line for 24 hours.

4.1.1 Data from Glesby

Electricity production and consumption data for Glesby was obtained from Vattenfall AB. The data has been sampled at every hour during a five year period, from 1 January 2013 at 01:00 to 31 December 2017 at 24:00. During some hours, 244 of the total 43 824, the consumption was zero. These hours as well as hours deviating greatly from the average are assumed to be faulty. Therefore, the consumption of hours with a value lower than 500 kWh/h, a total of 516 hours, have been replaced with the average of that hour for the other four years.

The average electricity consumption was calculated by taking the sum of all consumption at hours correlating to a specific time (0-1 for example) separately and dividing by the number of elements included in the sum. The average electricity production presented was calculated with the same method. The result can be seen in Fig. 4.1.

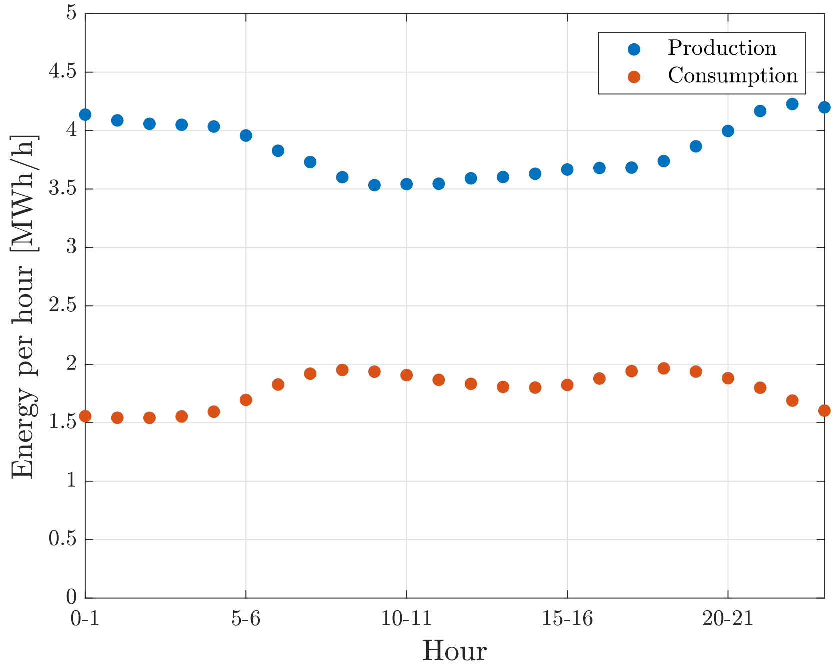

Figure 4.1: Average electricity consumption and production of Glesby

Two peaks can be observed in the consumption pattern. One in the morning centered around the hour between 8:00 and 9:00. The other in the evening centred between 18:00 and 19:00. The average production is approximately twice the size of the consumption. It does not contain any distinct peaks but the production seem to slightly increase in the evening and during the night.

4.1.2 Data from the Swedish Energy Agency

The data obtained from the Swedish Energy Agency, (used in [63] and further explained in section 3.3.2) was used to approximate when and how much different load types consume electricity in the average Swedish household. The loads were split into the categories fixed, heating, other explicit and implicit (other explicit containing all the explicit loads except for heating). The resulting average load profile is presented in Fig. 4.2.

4.1.3 Data from the Swedish National Board of Housing, Building and Planning

Between the years 2007 and 2008 the Swedish National Board of Housing, Building and Planning (*Boverket*) did an investigation on the state of different buildings in Sweden [78]. Energy use and various technical data of the buildings was measured. Out of the measured buildings, 571 were detached houses. With the support from Emil Nyholm, researcher at Chalmers University of Technology, the thermal time constant of the houses was calculated. The highest thermal time constant was 54.8 h and the lowest 5.4 h. The result for all the 571 houses is presented in Fig. 4.3.

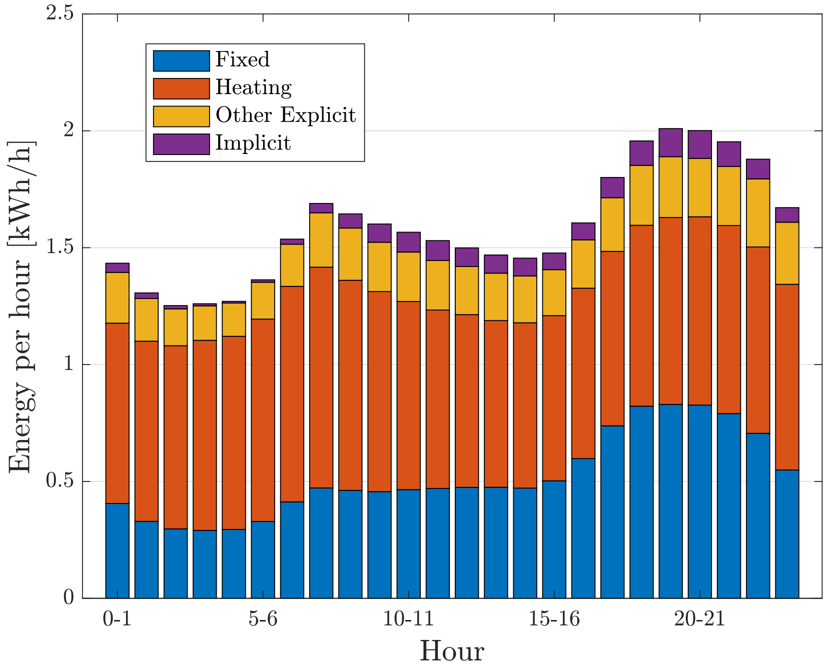

Figure 4.2: Average load profile of the houses measured by the Swedish Energy Agency.

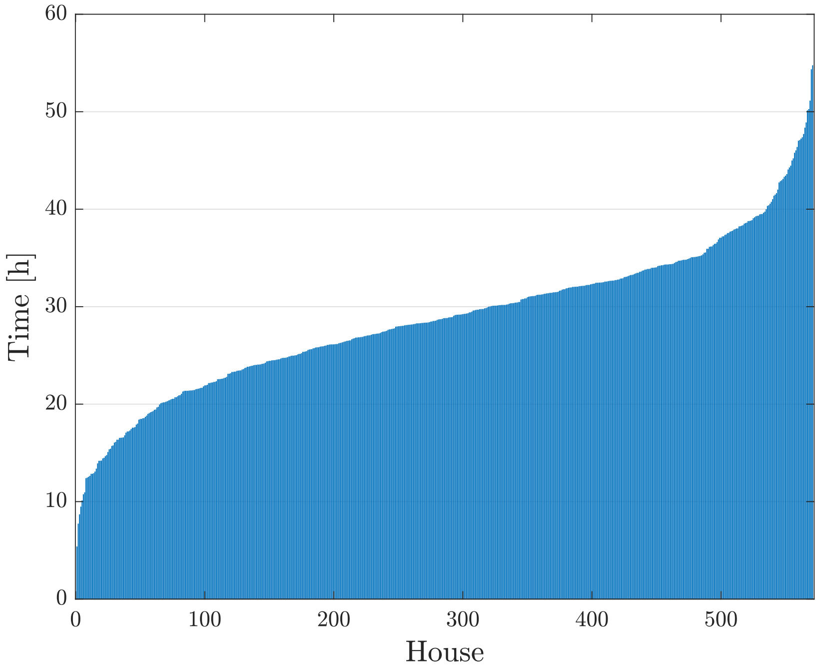

Figure 4.3: Thermal time constant of the measured houses sorted by size.

4.1.4 Derived load profile and production of Glesby

The load profile of Glesby was determined by combining its consumption data with the data from the Swedish Energy Agency. The data was combined by assuming that the percentage distribution between loads for each hour in Glesby was the same as for the data from the Swedish Energy Agency. The average load profile with the loads split into fixed, heating, other explicit and implicit is shown in Fig. 4.4.

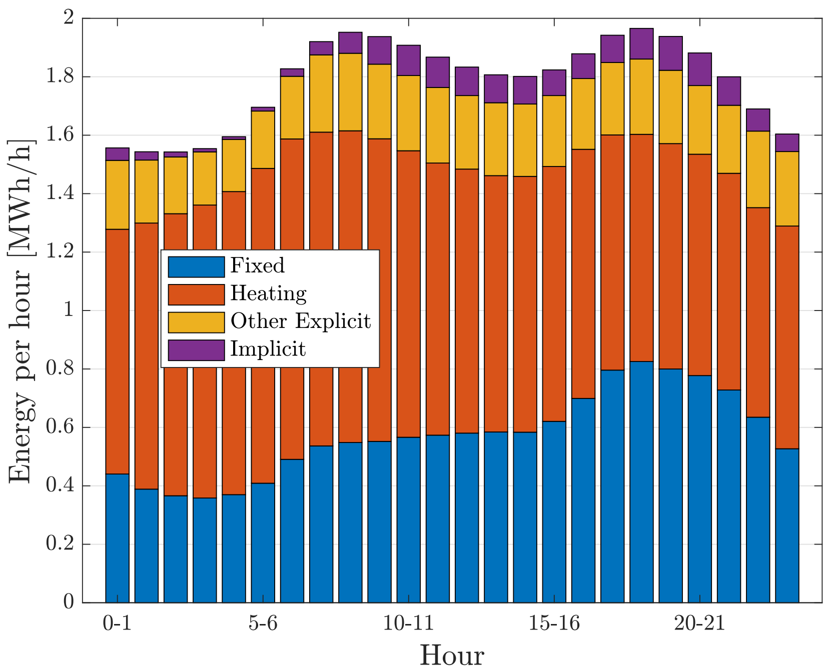

Figure 4.4: Average load profile of Glesby with the type of loads specified.

To determine the seasonal effects on the load profile, it was assumed that only the heating has a seasonal effect and all other loads remains seasonally unaffected. The average load profile for each month was calculated by the data from Glesby without load specifications. This was compared to the average load profile for the corresponding year with load specifications presented in Fig. 4.4. The average daily energy use each month was calculated and deviations from the average daily energy use over the year was assumed to be because of seasonal effects on heating. Fig. 4.5 shows the approximated average daily energy consumption dedicated to heating over a year and Fig. 4.6 the average daily energy consumption.

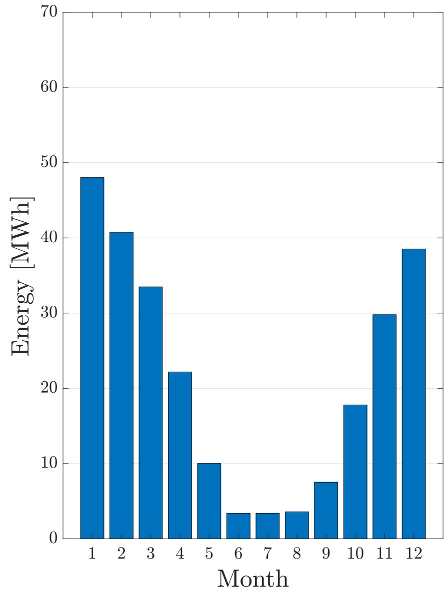

Figure 4.5: The average daily energy consumption dedicated to heating for each month over a year.

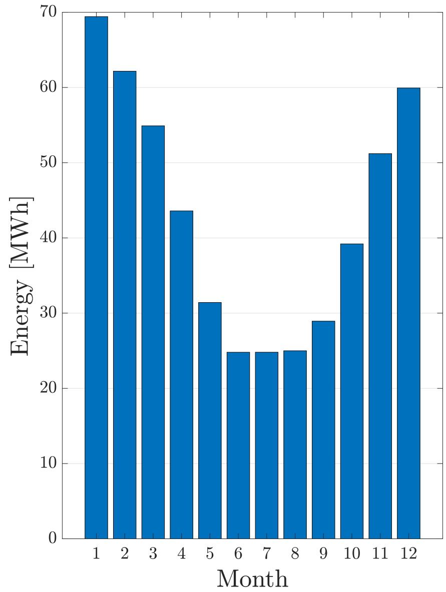

Figure 4.6: The average daily energy consumption for each month over a year.

By dividing the average daily energy consumption dedicated to heating for each month with the average daily energy consumption dedicated to heating over the whole year, the seasonal effects on heating can be acquired. The percentage of the average heating consumption that is being used on average each month is precented in Fig. 4.7.

The largest increase in heating consumption occurs in January, when 224% of the average heating consumption is used. The largest decrease occurs in July, when 16% is used on average.

By combining the load profile in Fig. 4.4 and the seasonal effects on heating from Fig. 4.7, the average daily load profile for each month was calculated. The load profile for January is shown in Fig. 4.8 and July in Fig. 4.9.

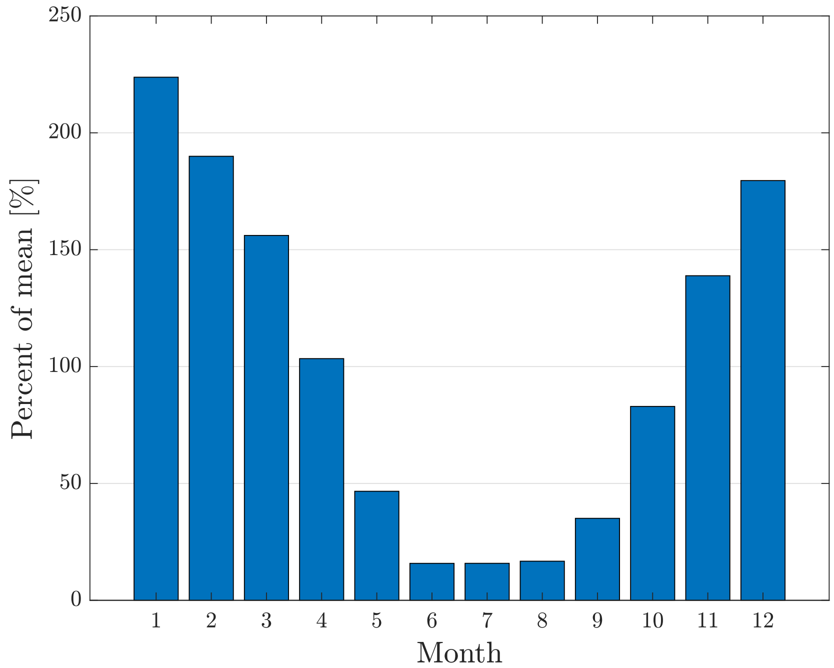

Figure 4.7: Percentage of the average heating consumption used for heating each month.

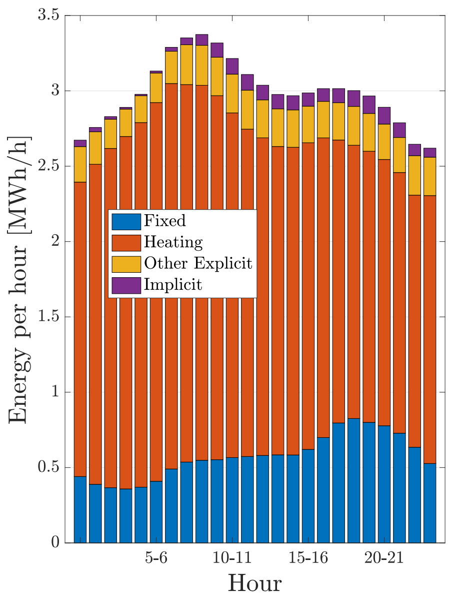

Figure 4.8: Load profile in January.

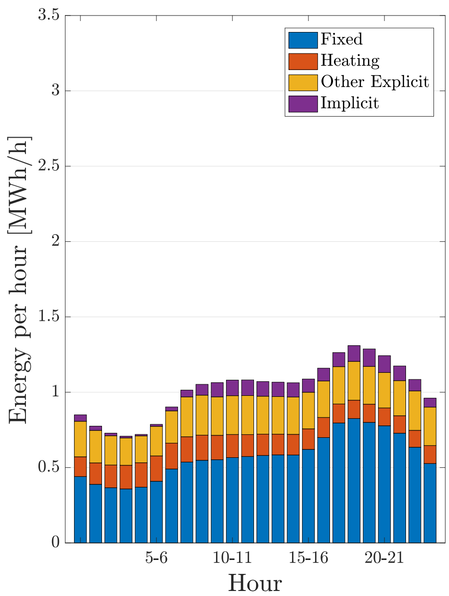

Figure 4.9: Load profile in July.

January is the month with the highest consumption, on average approximately 3 MW. The lowest average consumption is approximately 1 MW and occurs in the month of July.

The wind power production in Glesby has some seasonality associated with it. As can be seen in Fig. 4.10, which shows the average production for a day in January, April, July and December.

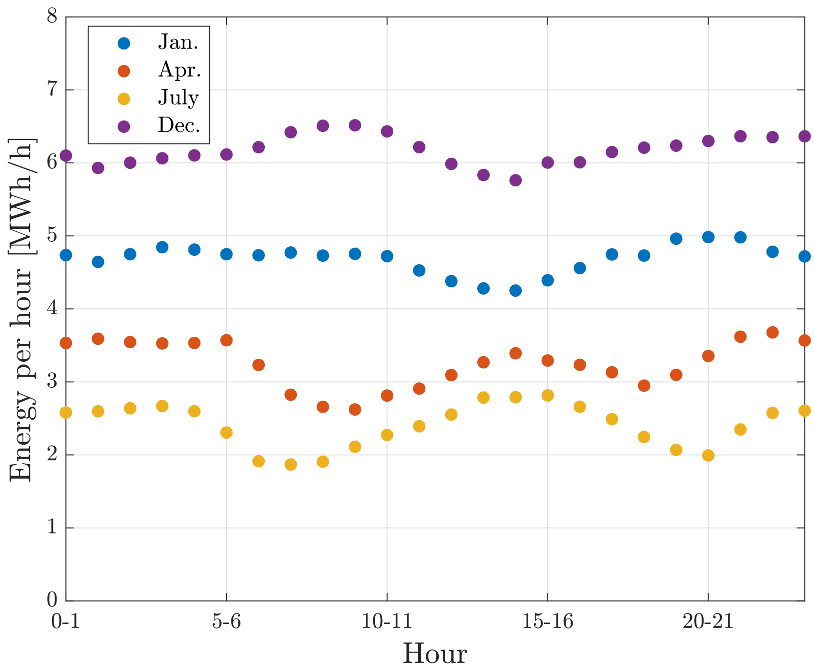

Figure 4.10: Average daily production for January, April, July and December.

The average production is approximately 2 to 3 times as high in December compared to July. The highest production occurs in the autumn and the beginning of winter. How the average daily energy production varies depending on the month is presented in Fig. 4.11.

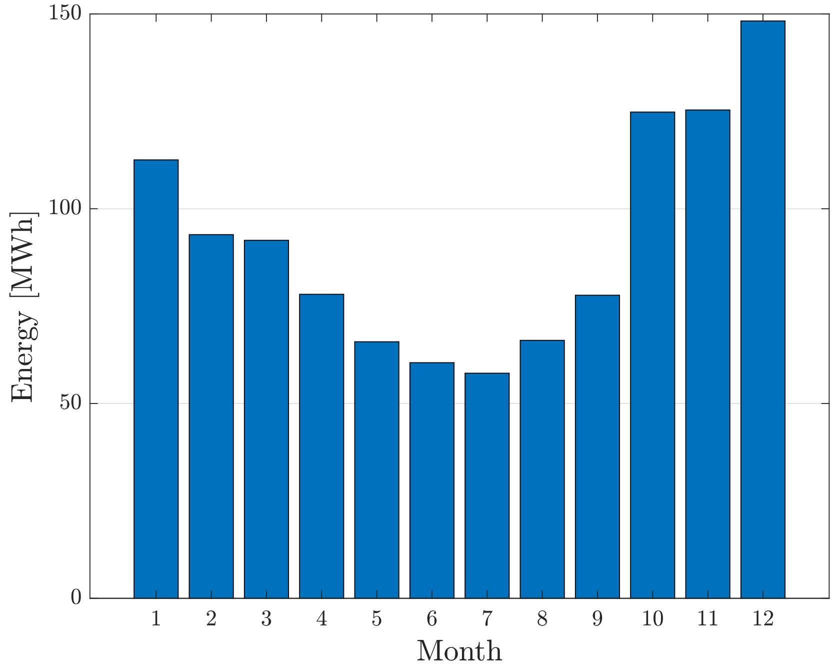

Figure 4.11: Average daily energy production in Glesby each month.

4.2 Optimising the battery energy storage system

To get an overview of how the required energy to manage a 24 hour power outage changes for different periods and the effects of DF, the energy required to supply Glesby with electricity for 24 hours will be calculated for six different cases:

1a) The 24 hour period with the highest consumption and no production. Excluding demand flexibility.
1b) The 24 hour period with the highest consumption and no production. Including demand flexibility.
2a) The 24 hour period with the highest consumption minus production. Excluding demand flexibility.
2b) The 24 hour period with the highest consumption minus production. Including demand flexibility.
3a) The 24 hour period where 0-90% of the highest possible energy demand would be the case. Excluding demand flexibility.
3b) The 24 hour period where 0-90% of the highest possible energy demand would be the case. Including demand flexibility.

4.2.1 Without demand flexibility

The energy need for a 24 hour period is defined as the consumption minus the production over the same period within the microgrid. The energy need for 24 hours in Glesby without demand flexibility is presented in Fig. 4.12.

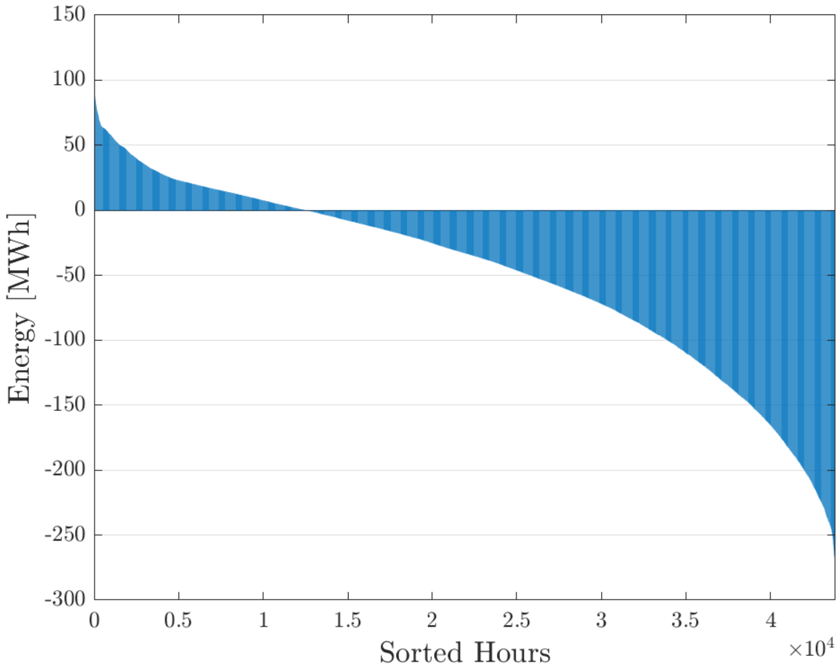

Figure 4.12: The energy need over 24 hours without demand flexibility.

The first data point contains the energy needed from hour 1 to 24, the second data point the energy needed from hour 2 to 25 and so on for all the data from Glesby (5 years) except for the last 23 hours of the data (here named N-22 to N). At hour N-22 when only 22 larger hours are available, hour 1 is used again to replace the last hour. At hour N-21, hour 1 and 2 is used and so on. A negative value means that the production was higher than the consumption during that 24 hour period. The energy need was sorted according to size. This shows that in order to supply electricity for 24 hours during all the possible outage times, the BESS needs to have a minimum capacity of 102.4 MWh (the value at the first sorted hour in Fig. 4.15). To handle an outage in only 90% of the cases however, the BESS needs to have a minimum capacity of 25.9 MWh (the value at the 4 383th sorted hour in Fig. 4.15).

The 24 hour period with the highest consumption began 10:00 on the 21th of January 2016. The load profile with the type of loads specified can be seen in Fig. 4.13.

The minimum required energy in the battery needed to handle a outage during this period, assuming there is no production, is the sum of all consumption in Fig. 4.13. This is equal to 109.5 MWh.

4.2.2 With demand flexibility

To reduce the energy need over 24 hours some of the flexible loads in Fig. 4.13 could be turned off. The implicit flexible load (wet appliances) is assumed to be completely turned off during an outage. The heating will also be turned off until the inside temperature has fallen to a certain value. It is assumed that the normal

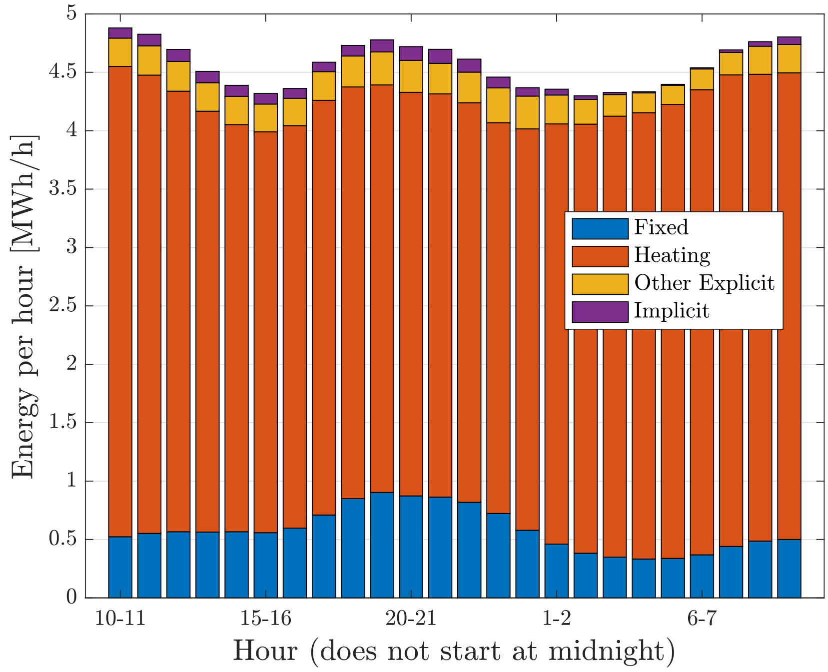

Figure 4.13: The maximum 24 hour consumption without demand flexibility in Glesby.

inside temperature is 22 °C and that it is allowed to fall to 17 °C during an outage. The time it takes for the temperature to drop to 17 °C is calculated by Eq. (3.2) and depend on the different time constants for the houses in Glesby as well as the outside temperature. The data from the Swedish National Board of Housing, Building and Planning was used and the average time constant has been calculated and presented in Tab 4.1 for houses built before 1940, between 1940 and 1980 and after 1980.

Table 4.1: Average thermal time constant for houses constructed in different years.

Year of construction	τ **[h]**	**Percentage of houses [%]**
Before 1940	21.0	25
1940-1980	27.9	25
After 1980	31.1	50

To approximate the thermal time constants for the different houses in Glesby, it is assumed that 25% of the houses were built before 1940, 25% were built between 1940 and 1980 and 50% of the houses were built after 1980. The power needed to keep the temperature at 17 °C is calculated using Eq. (3.3).

Data on outside temperature was not available for Glesby, but temperature data from the nearest weather station ($\leq$ 25 km from Glesby) was available from 2013 to 2017 via [79]. The average temperature during the 24 hour period with the highest consumption, starting at the 21th of January 2016 at 10:00 was -9.0 °C. The average monthly temperature is presented in Tab. 4.2.

Table 4.2: Average monthly outside temperature.

Month	**Temperature [°C]**
Jan	-1.7
Feb	-0.4
Mar	1.7
Apr	5.2
May	10.5
June	13.8
July	16.2
Aug	14.7
Sept	12.0
Oct	7.6
Nov	3.2
Dec	2.1

The other explicit flexible loads only contains water heaters and cooling appliances. In a 24 hour period these loads are not optimal for flexibility, since they can only be turned off for a few hours and consumes more power when turned on again to restore and compensate for the temperature drop. Therefore, the other explicit flexible load will not be regulated during an outage.

In the 24 hour period with the highest consumption the heating can be turned of for 3, 4 or 5 hours depending on the buildings thermal time constant. The load profile for this period with demand flexibility can be seen in Fig. 4.14.

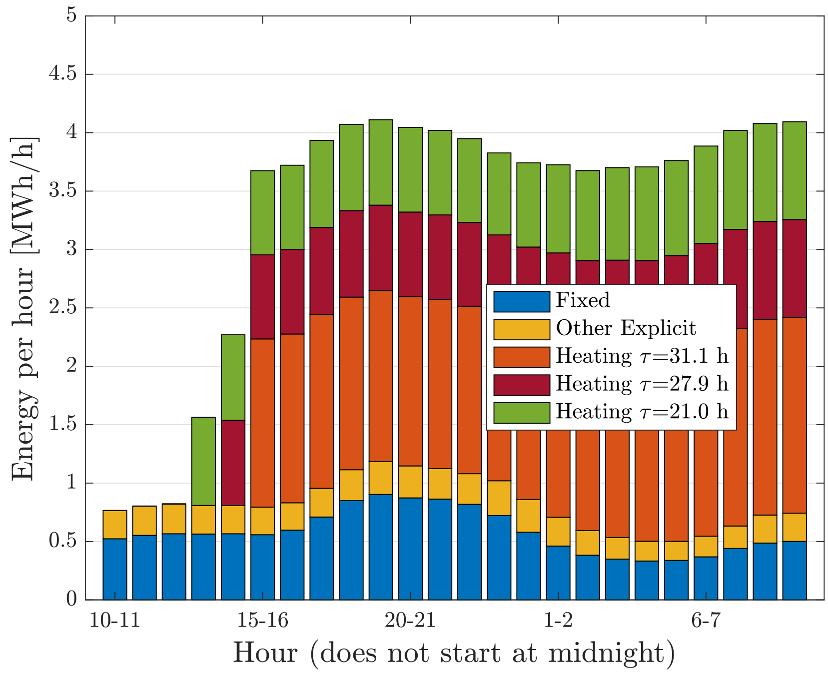

Figure 4.14: The maximum 24 hour consumption with demand flexibility in Glesby.

When demand flexibility is used, the minimum required energy needed from the battery to handle a outage with no production is the sum of all the consumption in Fig. 4.14. This sum is equal to 79.9 MWh.

To calculate how much the consumption can be reduced over a 24 hour period by using demand flexibility it is assumed that the temperature is constant on a monthly basis. It is also assumed that the monthly average temperature in Glesby is equal to the monthly average temperature from the the nearest weather stations data presented in Tab. 4.2. The production was then subtracted from the consumption with demand flexibility and sorted to get the maximum required energy the battery needs to deliver. The result is showed in Fig. 4.15.

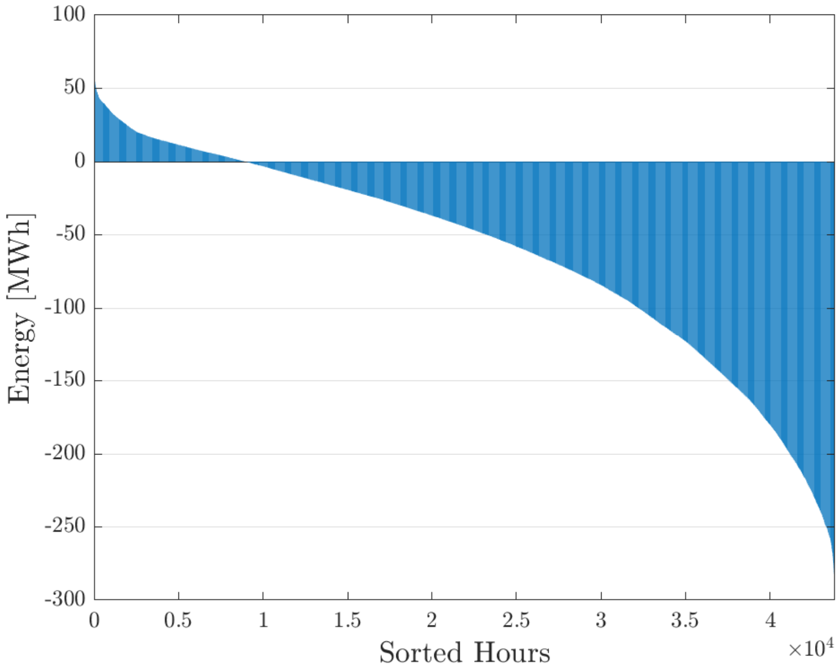

Figure 4.15: The energy need over 24 hours with demand flexibility.

The battery need to be able to deliver 45.8 MWh to handle all the possible cases that an outage can occur (the value at the first sorted hour in Fig. 4.15). To handle 90% of the possible hours an outage can occur, 13.4 MWh is needed (The value at the 4 383th sorted hour in Fig. 4.15). A compilation of the required available energy for the different cases can be seen in Tab. 4.3.

Table 4.3: Required energy available in the BESS to manage the different cases.

Case	**Required energy [MWh]**
1a) The 24 hour period with the highest consumption and no production. Excluding demand flexibility.	109.5
1b) The 24 hour period with the highest consumption and no production. Including demand flexibility.	79.9
2a) The 24 hour period with the highest consumption minus production. Excluding demand flexibility.	102.4
2b) The 24 hour period with the highest consumption minus production. Including demand flexibility.	63.3
3a) The 24 hour period where the energy need is lower in 90 % of the cases. Excluding demand flexibility.	25.9
3b) The 24 hour period where the energy need is lower in 90 % of the cases. Including demand flexibility.	13.4

4.2.3 Battery energy storage system power requirement

The maximum power the BESS needs to be able to deliver when the microgrid is in island mode is assumed to be the highest recorded consumption of Glesby. This assures that the power requirement can be met as long as there is energy available in the BESS. The hour with the maximum recorded consumption was 4.96 MW and the BESS would need a C-rate high enough to handle this.

The maximum power the BESS needs to be able to charge with to handle all the production when in island mode is determined by the maximum production minus the minimum consumption. This is equal to 13.7 MW and it is assumed that a BESS with a C-rate to handle the maximum consumption power will be able to charge the maximum charge power.

4.3 Cost analysis of a microgrid implementation in Glesby

This section contains the calculations and results regarding the investment cost and revenue of the microgrid. The cases that will be considered are the ones with and without DF that can handle 90% of the possible outages. This is because the 10% 24 hour periods that require the most amount of energy would require a disproportionately large BESS capacity. According to Tab. 4.3 that would require a BESS capacity of 13.4 MWh and 25.9 MWh for a system with and without DF respectively.

4.3.1 Cost of implementing battery energy storage systems

The total investment costs calculated based on the price from section 3.2.4 for the BESS is stated in Tab. 4.4.

Table 4.4: Investment cost of BESS.

Battery size [MWh]	**Cost of battery [MSEK]**
13.4	61.2
25.9	118.3

4.3.2 Revenue from ancillary services

The amount of revenue that can be generated from providing ancillary services to the grid is calculated in this section.

4.3.2.1 Choosing ancillary service

Since a battery can begin to provide power fast, but only for a shorter period of time, the best choice of ancillary service would be to provide power to the frequency containment reserve, since it has a smaller demand regarding size. Frequency Containment Reserve Normal (FCR-N) was chosen as the service provided by the battery since it is, contrary to Frequency Containment Reserve Disturbance (FCR-D), reimbursed not only for the power product that can be activated, but for the energy that is used when it is activated as well. There also exist data on the amount of FCR-N that is activated in the different regions which makes it possible to estimate the amount of activated energy.

4.3.2.2 Data from Svenska kraftnät

Four different sets of data are needed in order to find how much revenue could be procured from providing a certain amount of power to the Frequency Containment Reserve Normal (FCR-N).

i The average compensation per MW for power that could be activated during a specific hour.
ii The amount of energy that will be used during a specific hour, both up and down.
iii The highest compensation per MWh for up regulation and the lowest cost of down regulation per MWh during a specific hour. Specific for every Swedish electricity region.
iv The highest price of energy per MWh on the spot market at a specific hour. Specific for every Swedish electricity region.

It is assumed that the participation of the microgrid does not affect any of this data. The first of these data sets can be found at Mimer [80] and the other three at Nord Pool [81]. Data for all hours during the years 2013-2017 was acquired.

4.3.2.3 Model

It is assumed that all bids made on the reserve power market are accepted and that they are at the price levels from the data. The battery should be able to provide power for the entire hour if activated according to an email from an employee at SvK. In order to always be prepared for an outage, FCR-N will be offered every other hour so that the battery can be charged or discharged the next hour. It is assumed that the energy need of the specific hour can be estimated when the bid is submitted. The amount of power, P [MW], that can be offered for FCR-N is calculated based on the amount of energy, E_{max} [MWh], not needed in case an outage occurs during the hour that require the largest amount of energy. This is shown in Eq. (4.1).

$$P = E_{max}/1h \tag{4.1}$$

In Fig. 4.16, hour X is when the battery provides FCR-N and hour X+1 is when the battery is charging or discharging. The bars show the SoC that would be required in case a 24 hour outage occur and the black line shows the highest SoC needed during the two hours. While the red line shows the actual SoC going into the first hour and will deviate if FCR-N is activated. The energy E_{max} is set as the difference between the red and the black line in order for the battery to be able to provide up or down regulation for the whole hour and still be prepared for a 24 hour outage.

In Fig. 4.16, the energy $E_{max} = (100\% - 60\%)/2 = 20\%$ of the batteries total capacity. After the first hour, the SoC will be between 60% and 100%. During the second hour, SoC is changed so that it is between the black line of the next pair of hours and 100% in order for the process to be repeated. Nevertheless, the energy level is always kept above 20% in order to preserve the functionality of the BESS, but no limit is set upwards. Therefore, the black line in Fig. 4.16, for any pair of hours, is never set below 20%. This results in that the energy $E_{max} \leq 40\% = (100\% - 20\%)/2$ of the total capacity.

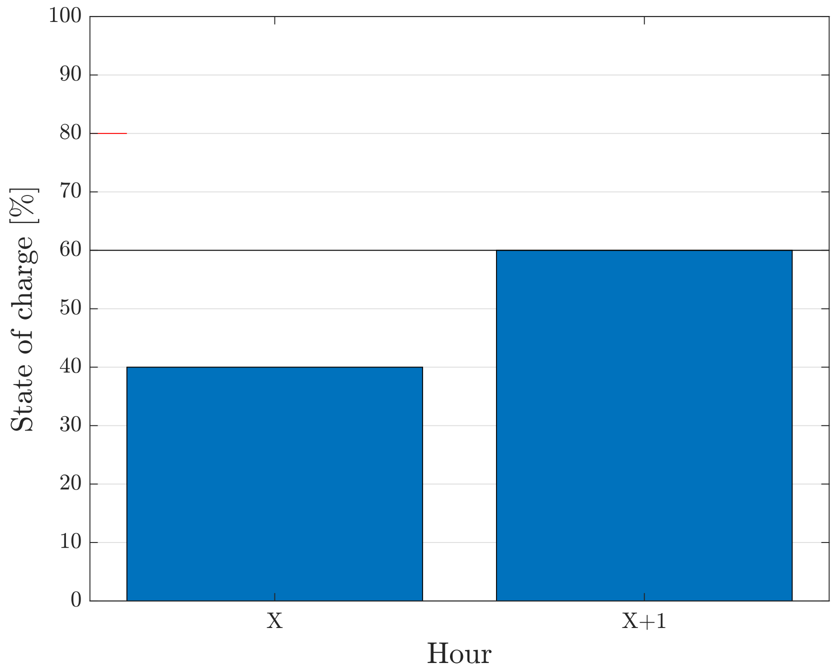

Figure 4.16: The state of charge that is required in case of an outage during two consecutive hours.

The possible revenue R_P acquired from offering activation of the power P is calculated by Eq. (4.2) where C_P [SEK/MW] is the compensation per MW during that specific hour.

$$R_P = P \cdot C_P \tag{4.2}$$

The total amount of power, P_{tot} [MW], that is procured for FCR-N in Sweden is 200 MW [74]. Therefore, the amount of energy that is assumed to be activated for up and down regulation, E_U [MWh] and E_D [MWh], is based on the percentage of the total activated amount in Sweden, E_{Utot} [MWh] and E_{Dtot} [MWh], out of P_{tot} as shown in Eq. (4.3).

$$E_U = E_{Utot} \cdot P/P_{tot} \tag{4.3a}$$
$$E_D = E_{Dtot} \cdot P/P_{tot} \tag{4.3b}$$

If the amount of energy activated in region SE 3 used for up or down regulating, E_{U3} [MWh] and E_{D3} [MWh], during that hour was less than E_U or E_D, then $E_U = E_{U3}$ or $E_D = E_{D3}$ since the battery is located in SE 3. $E_U \approx 0.3 \cdot E_{max}$ on average during the hours that the FCR-N was activated upwards.

While regulating upwards, the revenue from the activated energy is the difference between the energy price that SvK pays for up regulation, C_U [SEK/MWh] and the price on the spot market, C_S [SEK/MWh]. Similarly, when regulating down the revenue is calculated as the difference between the price on the spot market and the cost to purchase energy from Svenska kraftnät while regulating down, C_D [SEK/MWh]. All the data for prices are from region SE 3. Eq. (4.4) shows the total revenue from up R_{EU} [SEK] and down R_{ED} [SEK] regulation for a specific hour.

$$R_{EU} = (C_U - C_S) \cdot E_U \tag{4.4a}$$
$$R_{ED} = (C_S - C_D) \cdot E_D \tag{4.4b}$$

The total revenue for a specific hour R_h [SEK] is calculated through Eq. (4.5).

$$R_h = R_P + R_{EU} + R_{ED} \tag{4.5}$$

The total revenue over a whole year is calculated as the sum of the revenue of every hour that the battery provides FCR-N during that year, as seen in Eq. (4.6).

$$R_Y = \sum_h R_h \tag{4.6}$$

The model was used to calculate the total amount of revenue from FCR-N during the years 2013-2017. By multiplying this by 4, the revenue from FCR-N over 20 years was calculated. The revenue of these two periods are shown in were calculated for case with and without DF. When DF was used, the revenue was calculated for the BESS with both amounts of capacity but only the larger one was used when DF was not used. This is because the BESS with smaller capacity can not handle 90% of the outages without DF. The total revenue from providing FCR-N for 20 years is stated in 4.5.

Table 4.5: Possible revenue from FCR-N during a 20 year period.

Case	**Total revenue [MSEK]**
BESS capacity of 13.4 MWh with DF	84.1
BESS capacity of 25.9 MWh with DF	171.9
BESS capacity of 25.9 MWh without DF	158.7

4.3.2.4 Demand flexibility as frequency regulation

To estimate what loads can be used for frequency regulation, it is assumed that all the explicit flexible load (heating and other explicit) can be used for up regulation and down regulation. The average percentage of Glesby's total load available for frequency regulation each month can be seen in Fig. 4.17.

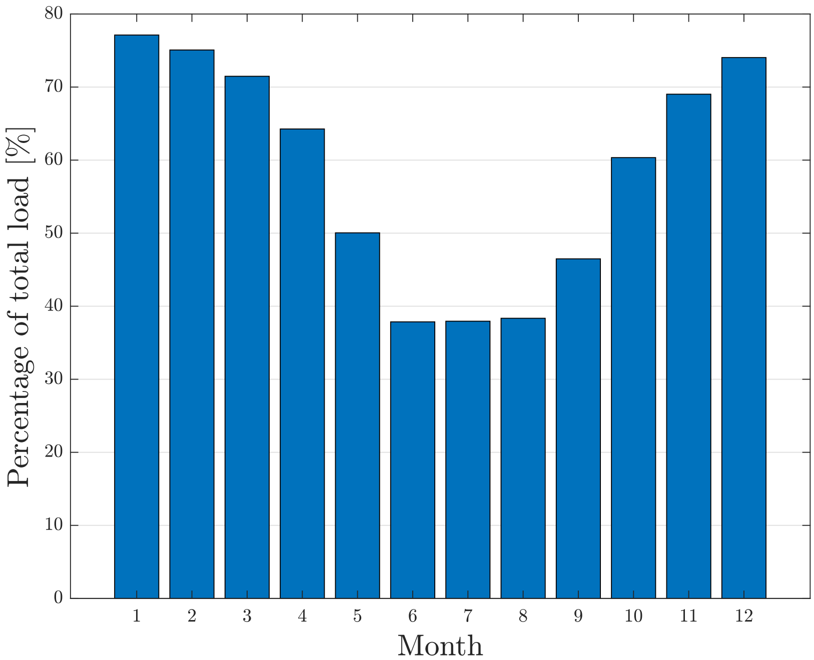

Figure 4.17: The average percentage of the total load available for frequency regulation.

During the winter months, the percentage available for frequency regulation is significantly increased. This can be explained by the fact that more energy is being used for heating during this period and the heating loads are being offered for frequency regulation.

It would be optimal to provide a load for frequency regulation until it can sense that an inside temperature comfort limit is about to be reached, stop providing it and then allow the loads to restore the temperature of its appliance. But with the way that the frequency market is structured in Sweden, presented in section 3.4.1, bids have to be placed on an hourly basis. This means that if a load is offered, it has to be offered for the entire hour. If DF would be used for frequency regulation within the present market, a load could only be offered if it is guaranteed that the temperature comfort limit will not be transcended. If for example the heating load of a house is offered for 3 hours straight and the temperature drops close to the comfort limit, then the load would not be offered the 4th hour. If the frequency market worked in real time the load could have been offered for parts of 4th hour and if that hour required down regulation (consuming electricity) then it might even increase the temperature while being offered.

4.3.3 Cost of implementing demand flexibility

In section 3.3.3 the price for most of the equipment DF requires is presented. Since approximately 1 000 devices are needed, it is assumed that we will get the cheapest price in the smart meters price range (2 060 SEK). In addition to the smart meter, a smart thermostat (1 460 SEK) and a water heater control unit (4 995 SEK) is needed. A control unit for the fridge and freezer is also needed. For the houses using direct electric heating, control units for the radiators are also needed. Therefore the total cost of implementing Demand Flexibility (DF) per household is approximated to 10 000 SEK. Assuming 1 000 connection points in Glesby, the total cost of implementing Demand Flexibility (DF) would be 10 MSEK for the DSO.

4.3.4 Net revenue of services provided by the microgrid

The profit of a microgrid with and without DF is calculated by taking the difference between the revenue of Frequency Containment Reserve Normal (FCR-N) from section 4.3.2.3 and the investment costs of Battery Energy Storage System (BESS) and Demand Flexibility (DF) from sections 4.3.1 and 4.3.3. This is shown in Tab. 4.6.

Table 4.6: Profit of the BESS from providing ancillary services

Case	**Profit [MSEK]**
BESS capacity of 13.4 MWh with DF	12.9
BESS capacity of 25.9 MWh with DF	43.7
BESS capacity of 25.9 MWh without DF	40.4

4.3.5 Cost of power line

According to Per Norberg, professor at Chalmers Technical University and Senior Technical Advisor at Vattenfall Eldistribution AB, the current overhead power line that supplies Glesby with electricity is approximately 24 km long. He states that Vattenfall expects an error rate of 0.5/100km line that causes a power outage lasting longer than 24 hours on this type of power line (overhead and clear of trees). This results in a power outages once every 8-9 years that lasts more than 24 hours from external forces (maintenance not included).

The standard costs for constructing new power lines can be seen in Tab. 4.7 [82]. Considering that the current power line to Glesby is approximately 24 km, the construction cost for replacing the already existing overhead power line with an underground cable can be calculated by Eq. (4.7):

Table 4.7: Table of the standard cost of different types of distribution power lines.

Type of power line	**Price [MSEK/km]**
Overhead	0.55
Underground	2.1

$$24[km] \cdot 2.1[MSEK/km] \approx 50[MSEK] \tag{4.7}$$

and for a new overhead power line by Eq. (4.8):

$$24[km] \cdot 0.55[MSEK/km] \approx 13[MSEK] \tag{4.8}$$

Professor Norberg further explains that longer planned maintenance, resulting in announced power outages lasting more than 24 hours, occurs with a frequency of once every fifth year on the type of overhead power lines that Glesby has. During these planned periods of maintenance, Vattenfall temporarily installs mobile diesel generators in order to avoid extra fees for not supplying the demanded power.

4.3.6 Cost of ensuring power supply to Glesby

Professor Per Norberg states that Vattenfall are looking at a number of options for replacing the current ageing overhead power line to Glesby and its surroundings.

i Do not change the system at all
ii Build a new overhead power line to Glesby
iii Build an additional overhead power line to Glesby, and keep the already existing one
iv Build an underground power line to Glesby to replace the existing overhead power line
v Implement a microgrid as a complement to the current overhead power line to Glesby

As mentioned in section 2.2.5, the electricity act [5] states that the DSO have to compensate their customers in the case of a power outage that lasts for more than 12 hours and the DSO get a deduction on their calculated revenue tap for that area as well [83]. In order to determine the given deduction, the values from Tab. 4.8 with the calculated average power over the total number of hours in a year (8 760 hours) is used. For Glesby the average power over a year is 1.8 MW.

Table 4.8: Table over deduction on the revenue tap for the DSO in the case of an unannounced power outage.

Sector	**Cost per energy unit [SEK/kWh]**	**Cost per power unit [SEK/kW]**
Industry	71	23
Commerce and trade	148	62
Agriculture	44	8
Public sector	39	5
Households	2	1
Electric sector limit point *(gränspunkt)*	66	24

With 1 000 connection points in the Glesby area, a power outage lasting for 4 hours will cost the DSO 0.50 MSEK in reimbursements to the customers [84]. In the case of an outage lasting more than a day (24-72 hours), the cost will be at least 2 MSEK (see section 2.2.5). Without data on how high the network fee is for each electricity customer it is not possible to get a accurate value only a minimum estimation. Professor Norberg states that Vattenfall usually approximates the cost of a power outage by calculating the cost per energy unit and cost per power unit in the corresponding electric sector limit point multiplied with the number of connection points, which in this case means approximately 1.2 MSEK per outage.

Making the same assumption as Vattenfall, that the Glesby power line will fail and result in an unannounced power outage that lasts more than 24 hours once every 8 years, this will result in an extra cost of minimum 3.2 MSEK every time (material, equipment and personel cost to fix the failure is not included). This is equivalent to 0.4 MSEK per year.

4.4 Cost comparison between constructing a new power line and applying a microgrid solution

In Tab. 4.9, the cost for a battery with demand flexibility in section 4.2.1, the cost for building new power lines in section 4.3.5, the cost of an outage once every 8 years in section 4.3.6 and calculated data for the different cases presented in the beginning of section 4.3.6 are presented.

Table 4.9: Summary of the estimated cost for the different cases presented in section 4.3.6 with the data presented in this section, Tab. 4.7 and section 4.3.5.

Case	**Estimated cost [MSEK]**	**Viable long term (20 years)**
i) Do not change the system	0.4 per year	No
ii) Build a new overhead power line	13	Maybe
iii) Build an additional overhead power line	13	Maybe
iv) Build an underground power line	50	Yes
v) Implement a microgrid (BESS of capacity 13.4 MWh with DF)	71.2	Yes
vi) Implement a microgrid (BESS of capacity 25.9 MWh without DF)	118.3	Yes
vii) Implement a microgrid (BESS of capacity 25.9 MWh with DF)	128.3	Yes

5
Discussion

The following sections will summarise the data calculated and presented in the previous chapter. It is then evaluated from a legislative, technical and economic point of view in order to come to a conclusion.

5.1 Regulations

The Swedish power market is not adapted for neither microgrids or BESSs. As previously mentioned there are a number of shortcomings in the current regulations, primarily:

- Lack of definition of ESSs and BESS (1997:857, 1 ch), which lead to complications regarding taxation (1994:1776, 11 ch) and whether BESSs should be defined as production or not, which is decisive if a DSO is allowed to operate them (1997:857, ch 3, 1h §).
- The connection requirement in (1997:857, 3 ch, 6-8 §§), which does not make microgrids a possible substitute for power lines, neither for long or short term.
- The revenue tap and the calculation in OPEX and CAPEX and not the total overall expenses for the DSO. There is also no incentives to invest in neither more effective nor test equipment, because every expense is related to a calculated standard cost from the Swedish Energy Markets Inspectorate.
- If the Swedish electricity region should apply for a microgrid in island mode, and how this would effect the power market

It is difficult to predict the effects of any changes, especially if some and not all of the needed changes becomes reality. For microgrids to become a competitive long-term option for a DSO over constructing power lines, microgrids must be able to run in island mode, otherwise the DSO must both build power lines and a microgrid. Although, a well dimensioned microgrid to a small town could help reduce the cost and dimensions of the power line as well as increase the resilience of the town. In any case a microgrids can still be used as a complement to existing power lines within a distribution system.

The regulation regarding micro producers might also have to be changed, or at least implement an option for the DSO to oppose supplying the excess electricity to the grid in the case of an overproducing island mode microgrid, as there is not enough local consumption to meet it. This is on the other hand very unlikely today. But for the case of a main grid-connected microgrid as in Glesby, this should not be a problem.

In order to meet the Swedish environmental goals, subsidies on household BESSs will be desirable. This would also have a positive effect for the microgrid, as the large BESS designated for the whole microgrid could possibly decrease its needed capacity and usage rate, leading to less wear of the battery. It would also be a very interesting development if residential areas started to form a *samfällighet* (see section 2.3.3) for their own BESS. This could be in the interest of the governments rural growth policy [85] and the resilience mission of the Swedish Civil Contingencies Agency *(Myndigheten för Samhällsskydd och Beredskap, MSB)*. It is possible that the Swedish Civil Contingencies Agency could subsidise this in the same way as their other projects and investments that strengthen the Swedish national resilience.

There might be some complications with regards to the competitive situation in a microgrid, but since the traditional distribution grid is a natural monopoly regulated by the Swedish Energy Markets Inspectorate, a monopoly situation in a microgrid should most likely be able to be regulated by the agency as well.

5.2 Load profile of Glesby with demand flexibility

When approximating the load profile of Glesby, a large number of assumptions were made. Some of these assumptions are simplifications, like the assumption that only the load dedicated to heating has seasonal effects. Other loads such as lighting, refrigeration and cooking also have seasonal effects which were neglected. This might have caused the load profile for months in the summer and winter, when the heating consumption change greatly, to deviate. The load profile of January presented in Fig. 4.8 for example shows a large increase in consumption in the morning and no significant increase in the evening, when a peak is expected according to the load profile in Fig. 4.1. Another cause of this might be that the heating consumption is slightly higher in the morning according to the average load profile presented in Fig. 4.4, so that when the heating consumption is increased by a set percentage each month, it has a higher impact on the morning hours. It is probably not realistic that the heating consumption is much higher in the morning, and a model where the heating is increased as much in total during all the hours of a 24 hour period is probably more realistic.

The data used to approximate the load profile of Glesby with demand flexibility came from different sources and assumptions, which increased the uncertainty of the result. The load profile of Glesby was combined with data from the Swedish Energy Agency to approximate what type of loads that were consuming power. The data from Glesby and the Swedish Energy Agency was from Sweden, but the consumption for different parts of Sweden and different houses can still vary. The houses measured by the Swedish Energy Agency and the houses in Glesby might look very different and the climate may vary as well. Furthermore, the data from the Swedish National Board of Housing, Building and Planning might not reflect the houses in Glesby and the assumption of when the houses in Glesby were built could be inaccurate.

The data from the Swedish National Board of Housing, Building and Planning show a quite low thermal time constant when compared to other sources. In section 3.3.1.1, it is presented that an average Swedish house built in the 80s has a time constant of 53 hours, a number which is much higher than the 31.1 hours that the used data showed as thermal time constant for houses built after 1980. This implies that the time constant in Glesby might be higher than the data used suggests, which would lower the required energy needed during a power outage.

One possible method for lowering the consumption not discussed in this thesis is the possibility for houses with direct electric heating to install efficient heat pumps. This could lower the heating consumption, especially during the winter, and in turn leading to a lower required battery capacity. New houses built in Glesby could also be encouraged to be build with extra isolation so that the heating can be turned of for a longer period of time if an outage should occur. If the thermal time constant is large enough, the heating of a house could be turned of for 24 hours in the case of a power outage, significantly lowering the consumption during an outage.

If a microgrid were to be built in Glesby, it would be beneficial to do specific measurements (like the ones done by the Swedish Energy Agency and the National Board of Housing, Building and Planning) to increase the certainty of the load profile with demand flexibility. This would result in a more exact load profile which assures that the system is not over or under dimensioned.

5.3 Economical viability

If microgrids are to become part of the Swedish power system, they must be economically viable for the DSO in order to become a realistic supplement to the current distribution system. The subsections below treats this with the microgrid being able to provide ancillary services and the different cases in section 4.4.

5.3.1 Ancillary services

As shown in section 4.3.4, the revenue from ancillary services is large enough to cover the cost of both the BESS and buy the equipment for DF and install it. The installation of DF and the increased capacity of the BESS increases the profit. This is despite the fact that the models primary focus is to keep the SoC of the BESS high enough to handle an outage of 24 hours. If the only purpose of the BESS was to provide FCR-N, the profit would probably be even higher, but there would be less protection against outages.

The activated energy per MWh is assumed to be bought or sold on the spot market for upwards and downwards regulation respectively. This might not be the case, since it could bought or sold from other actors. Also, the price per MWh for up and down regulation were the most favourable during each hour, which mean that the revenue from the activated energy probably is lower than calculated.

The model for calculating the revenue from providing FCR-N is quite cautious in the way that it is always prepared to be activated, in either direction, during the whole hour and that an outage could occur during any hour. However, an outage only happens about every eighth year and only about 30% of the available energy, E_{max}, was used during the hours FCR-N was activated upwards. It might therefore be the case that a larger amount of power can be offered to the FCR-N without increasing the risk of an outage to occur when there is not enough energy in the battery. A more thorough study of the amount of activated energy is needed to find if and how much this could be implemented.

The battery will not maintain the same functionality over time, which will result in lower amounts of energy able to be used for ancillary services in turn resulting in less revenue. This was ignored since it was not the focus of the report and a good estimation would have required further research. To not provide FCR-N that could result in the battery being charged close to 100% would probably decrease the rate at which the functionality decreased. If the functionality of the battery were to be studied more thoroughly, a comparison with the loss of revenue from FCR-N could find whether or not it is economically beneficial to keep the battery charged below a certain level. It should be noted however, that even if the FCR-N will not increase the energy level close to 100%. This will still occur during the hours where the full capacity of the BESS is required in order to handle an outage of 24 hours. Another solution could be to purchase a battery with a higher capacity. This would result in a higher investment cost for the battery.

5.3.2 Possible options for Glesby

This section treats the different cases which are presented in section 4.4, which presents the different options for Vattenfall in Glesby.

Case i) is not an option as the existing power line is deteriorating at an accelerating rate due to age, which will require an increasing amount of maintenance. Even then, it is more likely that power outages will become more frequent and it is therefore not a viable option. Case ii) and iii) both require the construction of a new over head power line. For case ii), it will simply replace the existing one, meaning that Glesby still only has one connection to the main grid and remain vulnerable to broken power lines. Case iii) will for a period ensure the delivery of electricity to Glesby by having two separate overhead power lines, but only for a shorter period.

The main problem, that the only existing power line is becoming of age, is still a factor and when the current power line reaches its end of life in a relatively near future, the village still only has one single power line. The new line will be an improvement over the old one, but the problem mentioned for case ii) will still remain for case iii).

The underground cable in case iv), will replace the already existing one. Professor Per Norberg expresses that an underground cable is the only realistic option for Vattenfall where building power line is an option. Since the storm Gudrun in 2005 [86], it has been a strategy for Vattenfall to gradually replace the vulnerable overhead power lines with underground equivalents, both due to less maintenance and as a consequence of the less than 24 hour outage requirement [5].

The least expensive microgrid option, case v), costs 42% more than the underground power line which is the most expensive non-microgrid option. Althouh, as shown in Tab. 4.5, a microgrid with a BESS with the capacity of 13.4 MWh and DF can generate a revenue of 84.1 MSEK over a period of 20 years from ancillary services. The same can be said in both case vi) and vii). A BESS with a capacity of 25.9 MWh can generate a revenue of 158.7 MSEK without DF and 171.9 MSEK with DF. In all of the microgrid cases, the revenue is larger than the initial investment of the BESS and for case v) and vii), with DF, making the microgrid a viable and realistic option. Another advantage with a BESS is that it can provide a buffer to the system for Vattenfall. In the case of an outage the BESS will be able to supply Glesby with electricity for some time.

In the worst case scenario, with minimum production from the WP plant, the BESS should be able to ensure a supply of power for 24 hours for all of the cases in Tab. 4.9. This will give the technicians at Vattenfall 24 extra hours until the law requires them to restore the electricity for Glesby. The disadvantage of case v), vi) and vii) is that the ageing overhead power line to the village still remains and may both result in more maintainace, outages and leads to the complication of providing ancillary services. Although, a microgrid could be a temporary solution during the effective life time of the BESS ($\approx$ 20 years, see section 3.2.3). After this time the technology might have progressed to the extent that an isolated micogrid in Glesby becomes both cost effective and legal, something that will require new BESS technology and changes in the electricity act (1997:857).

5.4 Environmental and socioeconomic impact

Relevant ethical aspects of this report has mainly been environmental and socioeconomic. Any eventual gain from the result have been deemed to have an overall positive impact on future research and regulatory decision making.

5.4.1 Environmental impact

From an environmental point of view, the opportunity for greater incorporation of renewable and clean energy sources (such as WP and PV), as well as decreased grid losses in the power grid will contribute to globally lower the emission of greenhouse gases and the handling of dangerous waste products created by consuming the planets finite resources. An environmental downside when utilising the microgrid concept is the need for Li-ion batteries when installing the required BESS. The extraction of lithium depletes the environment around the mining plants and an increased production of this type of batteries might have a negative environmental impact. Although, metals such as lithium are easy to recycle and the EU has set strict regulations demanding the collection and treatment of used batteries [87]. It has been speculated that the total depletion of lithium wont occur during this century [88], but that its mining and processing still has a high environmental impact, making the recycling and handling of it an important factor in a future power system with a greater need for battery storage solutions.

Manufacturing PV panels involves the use of toxic materials and chemicals, mainly various acids for refining the silicone semiconductors [89] and if the panels does not get disposed of correctly, they are an environmental hazard. Seeing how PV panels consists of relatively rare and expensive materials as well as having a demanding production process, there are significant incentives for its proper future handling, disposal and recycling.

5.4.2 Socioeconomic impact

It is unlikely that a microgrid should have any drastic socioeconomic impact in the foreseeable future. A distribution system, regardless if it is a traditional distribution grid or a microgrid,is non-discriminatory by law [5] and benefits the whole population in an area. Due to the current regulation forbidding the DSO to price discriminatory [5], the rural consumers can not be charged differently from the urban costumers. A microgrid will not change this, but it might make it possible for the DSO to increase its total revenue due to reduced construction and maintenance cost for power lines.

A long-term socioeconomic segregation could be the case if BESS for households and neighbourhoods (*samfällighet*, as mentioned in section 2.3.3). If the part of a population with accumulated wealth can buy BESS and make a profit from trading electricity when the price is low and sell it when the price is high, the economic inequality will increase. In addition to this the households who can afford a BESS will be more resilient to natural disasters and other factors that can cause a power outage.

5.5 Microgrid as an option

It is important to underline that additional costs such as maintenance, personnel and extra equipment is not included in the comparisons made, neither for the power line (both for the already existing one and if a new one were to be built), nor for implementing the microgrid. On the other hand it is also important to highlight the fact that it is a relatively short distance between Glesby and the regional distribution grid. In other parts of Sweden, such as north of Dalälven, these distances can be much larger which in turn means that the cost of a power line will be greater that in the case of Glesby.

As noted in section 4.4, the two viable options for Vattenfall is to either build an underground power line or a microgrid. Although the two BESS of both capacities (13.4 MWh and 25.9 MWh, see section 4.3.2) are expensive, the potential earning from ancillary services over a time period of 20 years are higher than the initial investment.

The profit presented in Tab. 4.6 are higher then can be realistically expected as maintenance, cost of installing the BESS and the cost of a control system for the entire microgrid is not being considered in this estimation, nor inflation which most likely will effect the return over the course of 20 years.

It is interesting and surprising to see that the provision of ancillary services could give such a large revenue over 20 years. If the cost of a BESS were to be included in the revenue tap (OPEX), the cost can be included in the network fee for the grid costumers, which would increase the income even more.

6
Conclusion and recommendations

This project has come to the conclusion that microgrids using BESSs and DF is a viable option for a DSO as an supplement to existing power lines and renewable energy production. Legislative changes is recommended in order to make microgrids a realistic option.

6.1 Regulations

This report recommends a full independent inquiry to investigate the implementation of BESS in the Swedish power system and the future role of the different parties operating on the energy market in order to ensure the power supply with more sustainable energy production with more WP, PV and BESSs. A definition of what a BESS implies is needed and in order to maximise the use of DF in a microgrid, the role and authority of a DSO must be adjusted. Both so that the DSO can legally own and operate a BESS according to the need of the microgrid and a more specific regulation for DF to ensure the security for the customer that the DSO manages.

As mentioned in section 2.3.3, there are a number of possible legislative changes that can be made to enable the implementation of microgrids, but this must be analysed more thoroughly and reviewed in accordance to (2007:1244) [90]. In conclusion, the legislative changes needed can be summarised as:

- Definition of ESS and clear taxation regulation.
- Inquire the implication of changing the current grid connection requirement to a supply requirement under the current area network concession.
- Create government subsidies for BESS to complement the construction of WP and PV, both currently subsidised by the government, in order to make the production more stable less direct weather dependent.

6.2 Demand flexibility

DF can be used to lower the required installed BESS capacity in a microgrid with the purpose of being able to manage 24 hours of island mode. A large percentage of the total load in Swedish houses is flexible and the percentage increases during the winter as heating consumption increases. In the three cases investigated, the required BESS capacity was significantly decreased when using DF. The decrease was approximately inbetween 28% and 49% depending on the case. DF can also allow for a larger percentage of the battery to be used for ancillary services.

When approximating the load profile, house characteristics and temperature of Glesby, a lot of assumptions were made. This increases the uncertainty of the DF result and most of the used data was not from Glesby. To raise the certainty it would be recommended to do measurements and gather data on Glesby, specifically if a microgrid solution were to be implemented. This would lower the risk of over or under dimensioning the BESS and increase the economic viability.

6.3 Investments, batteries an demand flexibility

Implementing a microgrid solution for Glesby in order to handle 90% of any possible outages lasting 24 hours would require a minimum investment of 71.2 MSEK. This includes investment costs for a BESS with an energy capacity of 13.4 MWh and DF equipment. Without DF, a BESS with the capacity of 25.9 MWh would be needed, requiring an investment cost of 118.3 MSEK.

The BESS is not allowed to provide ancillary services on the energy market today, something that might be changed in the future. This would create a revenue which, according to the model used in this project, would be large enough to cover the investments during a 20 year period. The profit also increases with an increased BESS capacity and the implementation of DF.

If the regulations were to be changed and allow for the microgrid concept to be fully used, the final recommendation is to implement DF and invest in a BESS with the capacity of 13.4 MWh. Since it is uncertain if BESS will be able to provide ancillary services and because of the uncertainty regarding the assumptions made the recomendation is to invest in the smaller BESS and DF.

7
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A

Report from study visit of the Simris microgrid

Figure A.1: Happy students in Simris.

A.1 The Simris microgrid

The only microgrid currently operating in Sweden is situated in the small town of Simris, just outside Simrishamn on the east-coast of the Skåne province. E.ON, who are operating and monitoring the microgrid began updating the already existing local grid which included a wind and PV-plant during the beginning of 2017 (see Table A.1 for dimensions of the microgrid). E.ON finished installing the required controllers, batteries and back-up generator to run the microgrid in October the same year. The microgrid disconnects from the main grid every fifth week to enable tests on how it runs during island mode. The Samsung-manufactured Li-Ion BESS is able to supply the microgrid during 30 minutes of maximum peak power and the back-up generator can provide power for 65 hours per 4500 litres HVO (Hydrated Vegetable Oil) fuel.

The project is partly financed with support from the EU innovation program "Horizon 2020", by agreement no. 731289, namely *Interactions between automated energy systems and Flexibilities brought by energy market players* (InterFlex) where 19 DSOs, including E.ON participates.

Table A.1: Dimensions of the Simris microgrid

Type	kW	GWh/year
PV	440	0.45
Wind	500	1.5
Battery	800	0.33 MWh
Back-up generator	480	-
Town of Simris	800	2.1

As of the third quarter of 2017, E.ON is deploying demand side management in some of the households within the microgrid. There are currently 14 households out of 145 signed to contracts with E.ON, with 26 more on the way. The households signing up gets control and monitoring equipment installed for their heat pumps and water heaters, allowing control and optimisation of the load profiles for these households. E.ON offers the users connected to the microgrid multilevel contracts. The first level, *AvtalFlex*, regulates fixed and floating economical compensation whenever E.ON controls the users equipment. E.ON is responsible for installing the smart meters needed. The second level allows installation of control equipment such as the *VUAB*-manufactured units *Bobbie* and *Ngenic Tune* that is installed on the household water heater and heat pump. E.ON can also offer subsidisation on PV and heat pumps if a household wishes to invest in new equipment.

A.2 Questions asked during our visit

Arriving at the microgrid control station in Simris, we met up with Jan-Erik Olsson, *Senior Advisor* at E.ON and Ingemar Leisse, *Senior Specialist Regional Grid Planning and Regional Grid Asset Optimization* also at E.ON. We sat down to take part in a presentation regarding the future plans for the Simris project as well as E.ON's view of the microgrid concept as a whole. Some of the main questions discussed were:

- **Within what levels do you keep the battery charged?**
  30% charged up to 80%. It should be pointed out that these levels are given by the central control system, and may not be precisely how the energy cells within the battery are charged, since they in turn have an internal regulation for material sustainability purposes.
- **How big are the losses from charging and discharging the battery?**
  It depends on different factors but around 5% for the inverter and 10-20% for the battery.
- **Do you use the battery to provide reserves (ancillary services) to the grid and to trade on the spot market?**
  There are two separate systems. It is the technical which is managed by E.ON and the market where for example a household can be connected to the grid but a customer to Vattenfall which means that Vattenfall provide the energy that is sold to the customer but the energy that is used by the customer comes from the solar PV. The battery is not used for ancillary services but it is something that is being looked into.

Figure A.2: Batteries forming the power reserve, stacked on racks.

- **Is the battery and the generator used to compensate for losses in agreement with current legislation?**
  Yes but it is a bit of "hairsplitting" to point out the specific losses.
- **What is the cost of the smart meters?**

Do not know right now but will find out and send it later by email to us. The budget for subsidisation of the smart meters is 1 MSEK.

- **Does E.ON compensate the customers for the demand side regulation?**
Yes, but it is not much.
- **Who pays for the equipment that is installed in the homes and who owns it after the contract is fulfilled?**
It is subsidised by E.ON and the customers can keep it.
- **How did you choose the size of the battery?**
The available power output of the battery was chosen in order to be able to sustain the whole system while the energy was limited by the budget to 30-35 minutes.
- **For how long can the generator sustain the system?**
65 hours.
- **What is the purpose of the project?**
Investigate if the customers want to be able to have locally produced energy and are willing to pay more. The reliability is E.ON's responsibility and especially within small villages on the countryside, microgrids could be a solution.
- **How does the communication work (in DSM)?**
Today, 2G to fiber, mostly through 3G and 4G. In Simris in particular we communicate with fiber. It is best to use whatever works at that location, there is no general solution.
- **We have not been able to find any legislation or other regulations of DSM. Have you found any, and if so how have this affected your DSM project in Simris?**
There is no specific laws that is targeted to DSM, mostly because this is relatively new. On the other hand more general legislation do also apply to DSM, such as the Privacy Act *(Personuppgiftslagen)* and starting from May 25, The General Data Protection Regulation (GDPR). To answer the question, it has not affected the DSM project within the main microgrid project. We try to protect our costumers privacy regardless if they are part of a test project or not.
- **What is your opinion on using demand side management as an ancillary service?**
It will not be very effective and batteries will be much better suited for this purposes rather than relying on smaller loads in the households for services such as frequency regulation.
- **What have been the cost of applying DSM to the households in Simris?**
An investment of 1 MSEK have been made to subsidise measuring equipment and installation costs of the same for all 40 households currently connected to the program. The total cost of the Simris microgrid project is expected to end at around 45 MSEK. But, as Jan-Erik added, it was never meant to return any profit as it is being run as a research project for future promotion and an opportunity to be in the forefront when the demand for microgrid technology eventually takes off.

- **Has everything worked out the way you intended during the deployment of the microgrid?**
  For the major part, yes. The only problems have been the long periods of time needed to arrange and settle the required paperwork and mice chewing on the fibre communication cables running the control system (Fig. A.3). Everything has otherwise been running surprisingly smooth - the system ran as intended on the first startup.

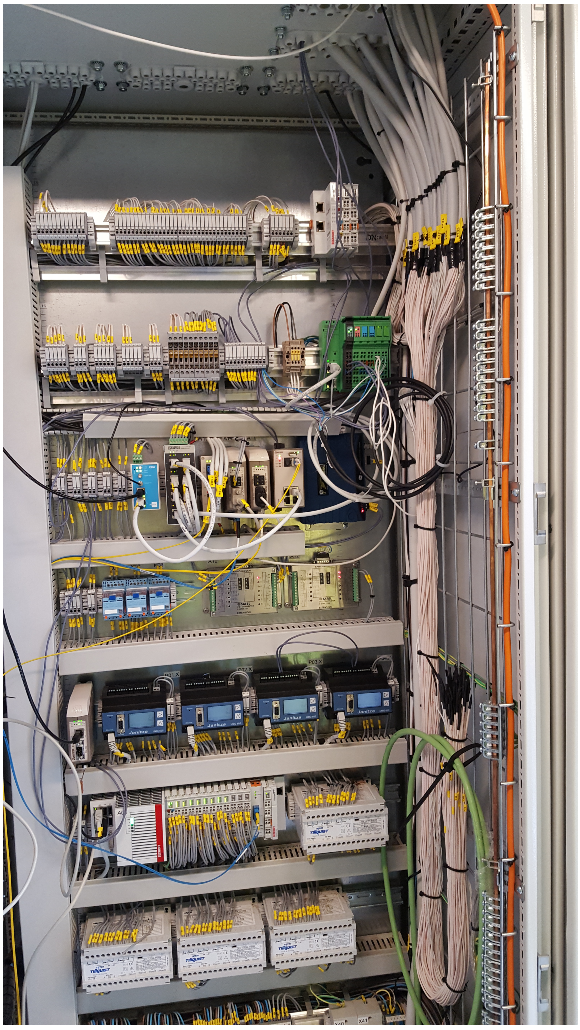

Figure A.3: The cluster of communication links making the microgrid possible.

A.3 Reflections and knowledge gained from the visit

In regards to the Swedish regulations of ESS and DSM, it was very valuable to confirm the groups own conclusions and understanding with E.ON. Both E.ON's microgrid project's working relations with the Swedish market inspectorate, their dialogue, view on the future of the Swedish energy market and lack of regulation regarding DSM, except for more general laws, such as GDPR.

The most important answers were probably the explanation of why the project was conducted and how it was going. Beyond getting to ask our questions it was really interesting to see the different parts of the microgrid (Fig. A.4) and to be shown around by an engineer who had been working with it and knew how it functioned. Most of all, it was a valuable experience, since we were demonstrated a working example of a microgrid in Sweden.

Figure A.4: Control and overview display for the microgrid.