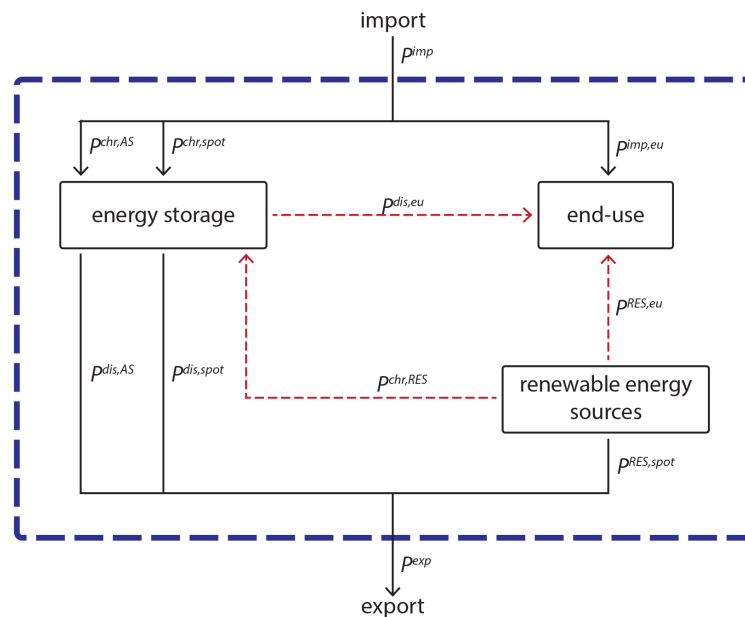




Microgrids in the Swedish Power System

Existing Limitations and Future Perspectives

Master's thesis in Sustainable Energy Systems

KRISTOFFER FÜRST
JONAS NILSSON

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KRISTOFFER FÜRST

JONAS NILSSON

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Supervisor: Saioa Buruchaga Laza, Department of Electrical Engineering, Division
of Electric Power Engineering

Examinor: Peiyuan Chen, Department of Electrical Engineering, Division of
Electric Power Engineering



Department of Electrical Engineering
Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The increasing use of renewable energy intensifies the need to handle the balancing between load and generation of electricity. One way to handle the issue is by implementing local energy systems called microgrids. This thesis proposes a projection concerning the development of the Swedish regulations and if the society of a small region could benefit from a microgrid concept including a battery energy storage. Through literature studies of battery energy storage and regulations of microgrid, a short-term (3-5 years ahead) and a long-term (10-15 years ahead) scenarios were set up. A local electricity distribution system at in a smaller region in Sweden is selected as a case study for a potential microgrid operation. The corresponding social benefits for the distribution system analyzed include the benefit of economic power dispatch and the provision of ancillary service to the main grid. In particular, the provision of normal frequency containment reserve is considered. The social costs include the cost of loss of load and the cost of investment in battery storage systems. Such a social cost and benefit analysis is formulated as a linear programming problem with the aim to select the optimal capacity of the energy storage that maximizes the social welfare.

Our findings suggest that a reduction of the current cost of lithium-ion battery of 85-90%, in the long-term scenario, can have a positive effect on the social welfare. However, the reduction in the long-term is only predicted to be 54%, which makes the investment of the battery economically unattractive. The review of the regulations shows that the current legislation is not in favor of microgrid. However, the situation is about to change. Furthermore, energy storage in Sweden is about to become more beneficial since the double taxation is being removed and there is a discussion of including battery energy storage in the frequency regulation market. The main conclusion of this study is that the society would not benefit from investing in a microgrid for the region in both scenarios since the costs of the battery energy storage is too high. If the cost reduction would reduce more than expected, or if another storage technology would be developed, it could be beneficial for the society. Furthermore, for the reliability of the microgrid, at a battery power capacity above 4 MW does not increase the reliability. At a storage capacity above 50 MWh without participation in the frequency regulation market, and 100 MWh with, does not increase the trade or social welfare of the microgrid. When the microgrid is operated optimally with an energy storage of 4 MW and 50 MWh, the peak power export increases with about 4 MW and the energy import of 2000 MWh/year from the microgrid. This indicates that an economically optimal operation of a microgrid does not necessarily lead to an increase of the self-sufficiency or social welfare of the microgrid.

Keywords: microgrid, energy storage, policies, regulations, battery energy storage, lithium-ion batteries, dispatch model

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List of Abbreviations

BAU	Business As Usual
BESS	Battery Energy Storage System
BOS	Balance Of System
CAPEX	Capital expenditure
CCA	Community Choice Aggregation
DOD	Depth Of Discharge
DSO	Distribution System Operator
Ei	Energy Market Inspectorate
ENS	Energy Not Served
EPC	Engineering Procurement & Construction
ESS	Energy Storage System
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve - Disturbance
FCR-N	Frequency Containment Reserve - Normal
LOLP	Loss Of Load Probability
MILP	Mixed Integer Linear Programming
NPV	Net Present Value
OHPL	Overhead Power Line
OPEX	Operating expenditure
PCS	Power Conversion System
RES	Renewable Energy Sources
SM	Storage Module
SOC	State Of Charge
SvK	Svenska Kraftnät
TSO	Transmission System Operator
VOLL	Value Of Loss Load

List of Nomenclature

α^{Aug}	augmentation cost [% of BESS/year]
α^{EPC}	EPC [% of investment cost/year]
α^{Opex}	OPEX [% of investment cost/year]
Δt	time interval [h]
η^{chr}	charging efficiency of the BESS []
η^{dis}	discharging efficiency of the BESS []
π^{bid}	bid price in the FCR market [kr/kW]
$\pi_{\text{a.c}}^{\text{bid}}$	alternative cost bid price, calculated per month [kWh/h/month]
π^{EPC}	EPC cost [% of investment cost]
$\pi_{\text{y,h}}^{\text{RDn}}$	down regulating price [kr/kWh]
$\pi_{\text{y,h}}^{\text{RUUp}}$	up regulating price [kr/kWh]
$\pi_{\text{y,h}}^{\text{spot}}$	spot price [kr/kWh]
$\pi_{\text{m}}^{\text{spot,min}}$	minimum value for each month of the 2017 spot price [kr/MWh/h]
$\pi_{\text{m}}^{\text{spot,max}}$	maximum value for each month of the 2017 spot price [kr/MWh/h]
π^{tariff}	tariff for electricity [kr/kWh]
$b_{\text{y,h}}^{\text{Dn}}$	Down regulated hour $\in \{0,1\}$
$b_{\text{y,h}}^{\text{Up}}$	Up regulated hour $\in \{0,1\}$
$B_{\text{y,h}}$	bid volume in the FCR market [kW]
B^{min}	minimum power bid volume in FCR-N market [kW]
$b\text{Bid}_{\text{y,h}}$	binary decision variable for bid $\in \{0,1\}$
C^{Cap}	power related cost [kr/kW]
C^{ECap}	energy related cost [kr/kWh]
$C_{\text{y,h}}^{\text{tariff}}$	tariff for net electricity imported [kr]
$E_{\text{y,h}}$	energy level of the BESS in the end of the hour h [kWh/h]
$E_{\text{y,h-1}}$	energy stored at the hour h-1 [kWh/h]
E^{max}	energy capacity of the storage [kWh]

n	maximum number of cycles
$P^{\max}$	power capacity of the storage [kW]
$P_{y,h}^{\text{chr}}$	power import to the energy storage [kWh/h]
$P_{y,h-1}^{\text{chr}}$	power charged at hour h-1 [kWh/h]
$P_{y,h}^{\text{chr,RES}}$	power from the RES to energy storage [kWh/h]
$P_{y,h}^{\text{chr,spot}}$	power import to the energy storage for arbitrage [kWh/h]
$P_{y,h}^{\text{chr,AS}}$	power import to the energy storage for ancillary service [kWh/h]
$P_{y,h}^{\text{dis}}$	power exported from the energy storage [kWh/h]
$P_{y,h-1}^{\text{dis}}$	power discharged at hour h-1 [kWh/h]
$P_{y,h}^{\text{dis,AS}}$	power exported from the energy storage for ancillary service [kWh/h]
$P_{y,h}^{\text{dis,eu}}$	power from the energy storage to end-use [kWh/h]
$P_{y,h}^{\text{dis,spot}}$	power exported from the energy storage for arbitrage [kWh/h]
$P_{y,h}^{\text{exp}}$	power exported from the microgrid [kWh/h]
$P_{y,h}^{\text{imp}}$	power import to the microgrid [kWh/h]
$P_{y,h}^{\text{imp,eu}}$	power import to the end-use [kWh/h]
$P_{y,h}^{\text{load}}$	load to supply the end-user [kWh/h]
$P_{y,h}^{\text{RES,eu}}$	power from the RES to end-use [kWh/h]
$P_{y,h}^{\text{RES,spot}}$	power exported from the RES [kWh/h]
$P_{y,h}^{\text{solar}}$	power from the solar production [kWh/h]
$P_{y,h}^{\text{wind}}$	power from the wind production [kWh/h]
$\text{SOC}_{\min}$	Minimum SOC level [%]

1

Introduction

1.1 Background

As a part of the climate negotiations in 2015, the majority of the world's nations have committed to reduce their greenhouse gas emissions in the Paris Agreement [1]. At the same time, the primary energy demand is increasing in the world. Even though the commitment is pledged by the nations, it is estimated that the primary energy demand will increase by 30% between 2016 and 2040 [2]. In order to meet the increase in energy demand, and at the same time reduce the greenhouse gas emissions, EU has set up an energy framework. By 2030, the share of renewables should be at least 27% of the consumed energy. Similarly, the overall energy efficiency should be increased by 27% [3]. Sweden has set an even higher goal, to be one of the first nations in the world to be fossil fuel free [4]. Furthermore, the goal is to have an electricity system entirely based on renewable energy sources by 2040 [5].

One solution to moving away from fossil-fuel based generation sources to an electric generation system entirely based on renewable energy sources, is to have a massive expansion of wind and solar power. Their intermittent behavior and distributed locations, in combination with the increase in demand, creates both challenges and opportunities to the operation of the electric power system [6]. Microgrid is a concept that is growing in the energy industry, and that can be a part of the solution to the challenges that the electric power system is opposing. It could offer an effective integration between the local load, distributed generators and energy storage system in the electric power system [7].

Energy storage is one of the key components in a microgrid with a high penetration level of distributed energy sources. The energy storage system can improve the stability and the reliability of the network, thereby increasing the security [7]. Batteries are currently the storage system that dominates in microgrids and for distributed generation projects [8].

The benefits of microgrids have encouraged governments around the world to take action towards the development of microgrids [7]. In Sweden, on the other hand, the current legislation is not in favor of the development of smart grid solutions [9]. Consequently, the operation and the potential of energy storage in the distribution system is limited. However, the transition towards 100% renewable energy sources motivates changes in the regulations of the power system [6].

1.2 Aim and goals

The overall purpose of this project is to investigate the future potential in Sweden for microgrid operation. In particular, the aim of this project is to investigate possible changes in regulations and the sizing of battery energy storage system for microgrid operation of a distribution system.

The following steps are set up in order to achieve the aim:

1. Collect the key aspects of the current market/power system regulation that are limiting the deployment of storage in larger scale in the Swedish distribution network and the transition towards microgrid.
2. Analyze and suggest likely changes in regulation of storage in the distribution network, both in the short-term (3-5 years) and in the long-term (10-15 years).
3. Analyze the cost and benefits of battery storage solutions for power systems applications.
4. Construct a short- and a long-term future scenario based on renewable energy penetration and market conditions. This is to investigate the potential savings for investment in storage and microgrid operation for the society.
5. For the short-term and long-term scenarios, analyze the size of the energy storage system. The microgrid should both be able to operate self-sufficiently in island mode, for a period of time, and to be interconnected with the main-grid.

1.3 Scope

The modeling of the energy system includes current data from a small region in Sweden. The objective is to analyze the cost of energy storage and the investment needed for operating the storage. Therefore, not all the costs associated with the microgrid are included. For instance, the costs associated with the investment in generation capacity are excluded, neither the costs of the microgrid controller. Historical data of load and generation are applied in the model, where the load is assumed to be the same for the scenarios. Furthermore, the model is based on perfect foresight where the weather, electricity prices and loads are assumed to be optimally forecasted. Lastly, the potential of controllable loads are not included.

1.4 Method

To construct the future scenarios, the first step is to collect relevant information about the current regulations of the electricity market. The information search contains reviewing of regulatory documents and literature. The second step is to investigate how the regulations will change in a short- and a long-term perspective. The proposal of likely changes will be provided by literature studies of the regulations in other countries and possible changes in current regulations.

A literature study provides the cost of battery energy storage solutions for power systems applications. The energy storage will be analyzed and the power capacity will be dimensioned based on the load and generation.

A distribution system from historical data will be used as a case study for analyzing its potential operation as a microgrid, concerning the load and generation of the smaller region, it is gathered from Vattenfall. The data and the result of the literature studies are the basis for constructing a short- and a long-term future scenario, and how the system will look like for the future market conditions with an increased amount of renewable energy. The scenarios are then compared with the defined reference cases. Given the two scenarios, the investment cost is calculated together with the reliability and dispatch cost. To calculate the reliability and dispatch cost, a model with linear programming is set up in GAMS. The model maximizes the net social welfare for the region and together with the reliability and investment of the scenarios, it is compared with the reference cases.

1.5 Thesis outline

The chapters are summarized below, excluding the introduction:

Chapter 2: Describes the technical background of microgrid and the cost of energy storage. The value streams that can be obtained for these are also reviewed.

Chapter 3: Provides a review of the Swedish electricity market and the current regulations of microgrids. Moreover, the possible changes of the regulations and regulations in other countries are reviewed.

Chapter 4: Provides the set up of scenarios and an explanation of the data used in the model. The developed model is also reviewed and the methodology of providing the value streams obtained outside the model.

Chapter 5: Provides the results of how the society could benefit from a microgrid in the future. This is presented with a discussion of the results.

Chapter 6: A further discussion of the proposed changes of regulations and the microgrid data. Lastly, the model is discussed.

Chapter 7: Presents the main conclusions and future work.

2

Technical background

2.1 Microgrid

The U.S. Department of Energy Microgrid Exchange Group defines a microgrid as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode." [10] (see Figure 2.1 for illustration). The grade of self-sufficiency varies, some microgrids are disconnected from the main-grid without the possibility of connecting to the main grid. Others are connected with a possibility to run independently, where the disconnected mode is referred to as island-mode [11]. This study focuses on the second one.

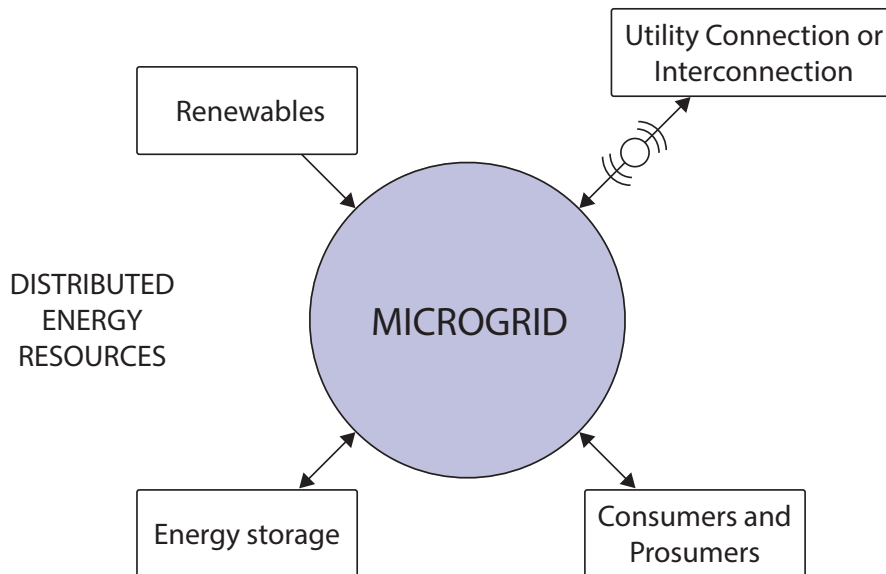


Figure 2.1: Schematic figure over a microgrid system

2.1.1 Microgrid drivers

The microgrid industry predicts a significant growth in the near future [11]. Even though the concept of microgrid has existed for a long time, it is now that the microgrid industry has actually started to grow [12].

This development is driven by different factors. Firstly, cities and states find microgrids attractive due to the increased level of reliability of supply. If a certain area has a highly reliable electrical network, it could attract companies with those requirements [12]. Secondly, typical microgrid components such as solar panels, wind energy and energy storage (usually occurring in microgrids [13], [14] and [10]) have stood for a significant price decrease during the last years [15]. Thirdly, new technology can optimize the resources within the microgrid in a more cost-efficient manner. Lastly, threats from cyber-attacks, natural disasters and terrorist attacks makes the actors more worried about the security of the grid. A microgrid can operate even though the main grid is out of service. Universities, hospitals, certain industries and the military are some of the actors that are in need of a reliable grid [12].

The microgrid has also other benefits such as transmission and distribution electric losses (due to shorter transmission) and grid congestion. The possibility of increasing the use of renewable energy as well as the decrease of grid losses makes it an alternative that could reduce the carbon emissions. Moreover, new capital-intensive investments and upgrades of the current electricity grid can be avoided with the technology [12].

In the Swedish electricity grid, there has been a lack of continued expansion and upgrades during the last 40 to 50 years. Consequently, the grid is old and needs new investments [16].

2.1.2 Components in a microgrid

The loads and generation sources of different microgrids can vary. This thesis focuses on microgrids that include solar energy, wind energy, energy storage and that are interconnected with the main grid. It is assumed that a microgrid controller optimizes the operation of the microgrid network and provides the possibility to operate in island mode [11]. The controller is outside the scope and will not be further reviewed.

2.1.2.1 Point of common connection

The point of common connection is the physical interconnection between the microgrid and the main grid. It makes it possible to trade energy when there is a surplus or deficit of energy within the microgrid [17]. Moreover, the interconnection makes it possible to import energy for storage when there is a low energy price, in order to consume when the electricity price is high. In this way, the total cost can be reduced. [14]

2.1.2.2 Renewable energy sources

Solar power

Solar cells are converting solar irradiation, a renewable energy resource, to electrical energy. It offers the advantage to generate electricity close to the load without releasing carbon emissions [18]. During the last decades, the ownership structure of

energy generation plants has changed. Solar rooftops owned by individual persons or business actors have been common. They are also often operated in the distribution network [15]. However, since the sun does not always shine, the generation of the energy source will have a fluctuating and intermittent characteristic. The energy produced from solar is larger during the day- and summertime in the Nordic countries.

Wind power

To supply wind power, the electric energy is converted from the kinetic energy in the wind. Similar to solar it is a renewable energy and it has an intermittent behavior. But the wind will not always blow at the same time as the sun shines which results in different supply curves. The generation of wind power varies over the seasons, in the Nordic countries there is an increased production of electricity from wind during winter compared to summer [19]. Furthermore, owners of wind power plants in Sweden are typically private individuals, wind power cooperatives or companies. They are usually installed in the distribution grid but bigger wind power plants can also be connected to the transmission grid [20].

2.1.2.3 Energy storage

The supply of energy and power from solar together with wind can, as earlier described, vary over time. This creates a need of energy management and ancillary services (described in Section 2.3.1 and 2.3.2) within the microgrid. Energy storage systems (ESS) can provide this type of services and help to keep a stable operation of the grid [13]. The storage can, with some restrictions, be owned by the customers, the power producers, the system operator or a third-party actor [21], [22].

The investment cost is high for storage in power systems. This makes long lifetime and high cycle rates important factors for the storage in a cost-efficient system [23]. Technical and economic performance varies between the ESS and is therefore suitable to provide different types of services [13].

2.1.2.4 Consumers and prosumers

A microgrid also includes consumers and prosumers if they exist within the defined electrical boundaries. Prosumers are consumers who not only consume electricity, but also generate electricity from on-site generation sources. This generation can for example come from solar rooftops [24]. The microgrid end users include households, industries, agriculture, public sector, trade and service.

2.2 Costs of energy storage system

One of the most usually applied ESS is the battery energy storage systems (BESS) [13]. According to several demonstration projects [25], [26], the BESS is the most common storage solution in microgrid projects. They have the benefits of a fast response, high efficiency, no operational emissions and low maintenance cost [13].

There are various kinds of battery chemistry used in BESS. Lithium-ion is the most common and flow batteries have been started to be used in microgrid operations. However, flow batteries are not as commercialized as lithium-ion batteries. There is an expected cost-reduction of the BESS [27], for Lithium-ion batteries it is partly driven by electric vehicles. Bloomberg Finance estimates that the cost will decrease with 54% by 2030 [28]. Furthermore, the lithium-ion battery is the most utilized BESS technology [13] and the technology that this study will investigate.

The cost of ESS consists of both capital expenditure (CAPEX) and operating expenditure (OPEX) [29]. CAPEX accounts for the largest part [30] and can be expressed as the capital for new investments, or the investments that prolong the lifetime of an earlier investment. OPEX is defined as a continuous cost for a product, business or system [31]. Therefore, the cost of energy storage is also depending on the lifetime of the battery [30].

2.2.1 Battery lifetime

The capacity of a battery will decrease when it is aging and used. When 80% of the nominal capacity is left, the end of life generally is considered to be reached. There are several factors that impact the lifetime of the ESS. One factor is the rate of utilization of the ESS. This can be measured in number of cycles per day, which relates to the amount of energy used by the ESS during a day. Each storage has a different estimated number of cycles that it can manage before the end of life. This number depends on the depth of discharge (DOD). When determining the maximum DOD for battery storage it needs to be considered that DOD and life cycle depend on each other. Maximum DOD is an important factor when evaluating the installed capacity for the technology [30].

The lifetime of the storage also depends on the calendar lifetime. Thus, the end of lifetime depends on the factor that reaches the maximum parameter first. The calendar lifetime is defined as the time where the storage is operational without being cycled [30]. For battery storage, a lower number of cycles per day can result in the end of life due to calendar lifetime rather than cycle lifetime. In that case, the number of cycles are not maximized, which can imply a less cost efficient system [30].

2.2.2 CAPEX

CAPEX for an ESS can be comprised by new investments and replacement costs. The replacement costs depend on the total lifespan of the ESS. If the storage has components that have a lower lifespan than the ESS, replacement cost is needed to be accounted for [30].

ESS includes all the needed components for storing and supplying energy. The cost of ESS can be divided into the power conversion system (PCS), the storage module (SM) and the balance of system (BOS), as can be seen in Figure 2.2. Besides these systems, costs for the engineering procurement & construction (EPC) also emerges [27].

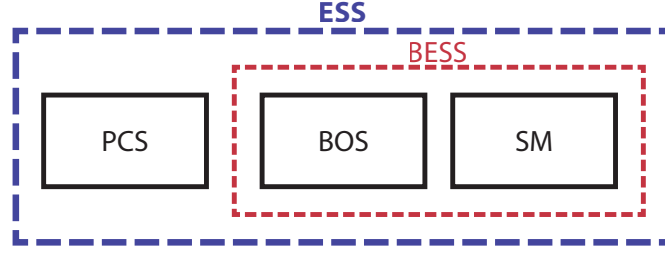


Figure 2.2: Overview of the components in an energy storage system

PCS includes the components needed to provide the interconnection between the BESS and the grid [32]. Within this group of components are the inverter, protection and inverter control included [27]. The CAPEX of the power conversion system can be measured in cost per unit of power capacity [cost/kW] [33].

SM includes the battery module, which in the case of lithium-ion are the cells that are interlinked in modules and packs [34]. In addition, it also consists of the battery management system. The CAPEX of the SM can be measured in cost per unit of delivered or stored energy [cost/kWh] [33].

BOS includes the monitoring and control systems. This helps the BESS to operate in a safe and optimal manner [34]. The BOS includes several components such as: thermal management, containment vessel, monitor and controls [27]. It is usually measured in cost per unit of delivered or stored energy [cost/kWh] [33].

The shipping, grid integration equipment, metering, land and the program are excluded when calculating the costs [27].

2.2.3 OPEX

The OPEX for the EES can be split into fixed and variable costs. The fixed costs depend on the power capacity installed, regardless of the electricity delivered by the storage. It is an average annual calculation of the costs. For the variable cost the opposite is valid and it depends on the energy generated from the storage [35]. The OPEX are usually approximated as an annual percentage of the investment costs [30].

The electricity cost is equal to the amount that is charging the ESS. The losses in the BESS can be seen as an increased OPEX, since extra electricity is needed. When dimension the storage, the discharging and storage losses are needed to be accounted for, in order to provide a certain amount of energy. [30].

2.3 Energy storage value streams

A summary of the value streams the microgrid can provide is summarized in Table 2.1. Later in this section, there is a further review of the value streams.

Table 2.1: Summary of energy storage value streams [27]

Value stream	Description	Market
Energy management		
<i>Peak shifting & load leveling</i>	Allows for matching the load and supply in island-mode and a reduction of high price demand charges in grid-connected mode. Time-shifting of the load using battery discharge and the daily storage of electricity for use when time of use rates are highest	E
<i>Energy arbitrage</i>	Allows for storing electricity at low price periods and selling at high price periods in the wholesales market	W
Frequency regulations		
	Supplies power directly or within a short period of time, to keep the generation-load balance and to get the frequency at a stable level	W
Reactive power & voltage support*		
	Supplies reactive power or voltage support [36]	W
Reliability		
<i>Backup power</i>	Supplies power reserve for end-users when the main grid is failing	E, U
<i>Black-start capability</i>	The capability to re-energize the grid after a total black out.	W

E - End-user, W - Wholesale, U - Utility

* The revenue stream is believed to not need further explanation and is not in a large extend handled in the report.

2.3.1 Energy management strategy

For a microgrid in island-mode, there is no possibility to participate in the electricity market at that given time. It is therefore vital that the generation and services are provided within the microgrid [36]. When the generation from the distributed resources is not enough to cover the load at all times, storage can be used in order to time-shift the load [7]. This principle can be used when connected to the main grid as well, achieving an economical operation of the microgrid. The flexibility of energy trading can also be offered to the main grid [36].

2.3.1.1 Peak shifting & load leveling

When the power supply does not match the demand, time-shifting the load can be a solution. Peak shifting and load leveling are two examples of procedures that can be used to shift the load. This flexibility can be provided by energy storage systems. The main concept is to store energy when the demand is low in order to discharge during high demand periods. Load leveling focuses on flatten out the load curve over a period of time, whereas the purpose of peak shifting is to satisfy the demand at peak periods [7], see Figure 2.3. A consequence of peak and load shifting can be to avoid new investments in the distribution grid by providing extra storage capacity [27].

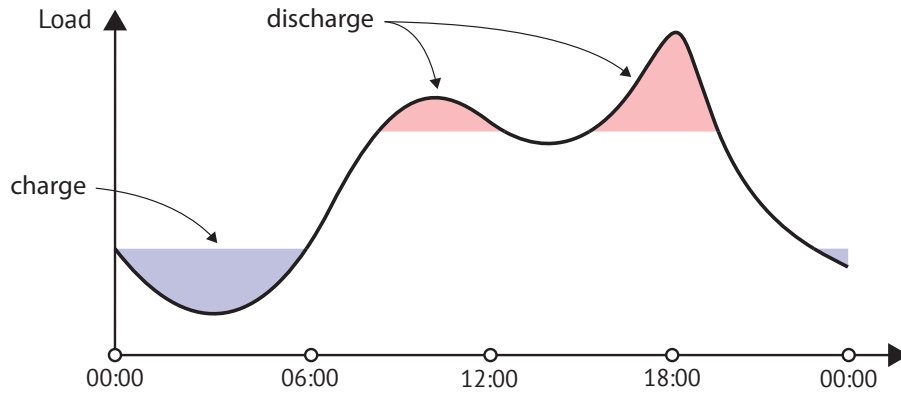


Figure 2.3: Load shifting and peak shifting

For a microgrid in island-mode, the demand needs to be covered by its own generating capacity. The supply then needs to be dimensioned in order to cover the load, including the peak periods [36]. Peak shaving could here be seen as a dimensioning tool, where it could avoid investment costs in new generating capacity [37], e.g. gas turbines or diesel generators. Load leveling is used as a flexibility, storing energy in order to match the load and the intermittent generation [36]. This is also a solution to curtailment when there is an overproduction in the system [38].

In grid-connected mode, by shifting the load, the microgrid can avoid costs for expensive electricity from the electricity market [36]. Lowering the peak demand could also postpone installment of generating capacity and other infrastructures in the main grid [37]. It could also be more economical beneficial than distribution and transmission upgrades [36].

2.3.1.2 Energy arbitrage

For microgrids connected to the main grid, there is a possibility to trade electricity. The function for trading with energy storage is similar to time-shift. But instead of focusing on the time-structure of the load, trading focuses on the price of electricity. The main concept is to store electricity at low price periods, and to discharge during high price periods [36].

The microgrid can determine when it is most beneficial to use its own generating capacity or when to buy electricity from the main grid [11]. The operating costs for the microgrid can for example be reduced by importing electricity during low price periods. The price on the spot market can also sometimes be very high, for example, at peak loads in the main grid. The microgrid can avoid these costs by having a properly dimensioned ESS. Additionally, if the price signals are high, it could be economically beneficial to offer energy to the main grid, thus creating revenue streams for the microgrid [39].

2.3.2 Frequency regulations

In a power system, the generation must at all times be equal to the demand and losses in the system. If there is an imbalance between the load and the supply, the

frequency in the system will deviate from its nominal value [40]. If the frequency is not restored, it may result in tripping of loads and/or generators which could lead to a blackout [41]. The system's frequency serves as a surveillance variable to keep track of the system's balance [42]. The quality and stability of the frequency can be seen as the system's ability to withstand imbalances and disturbances in the load and/or generation [40]. Furthermore, in the traditional electrical power system, the quality can be related to the inertia of the system. This is a form of energy buffer, ready to absorb or inject energy into the system. Therefore, a system with low inertia provides less energy buffer, and the frequency is more sensitive to sudden changes in load or generation. In today's system, inertia is mainly provided by conventional power plants, whereas solar and wind power at the moment are not contributing [41].

Microgrid, as a power system, also needs to manage the frequency when in island mode, in order to maintain a proper stable operation of the network. With a high share of solar and wind power, the mechanical inertia in the system is low [41], and hence the system is more susceptible to suffer from frequency variations. Large variations in the frequency could cause instability issues in the microgrid. One solution to deal with frequency disturbances is to use energy storage [7], see Figure 2.4. This could be used to compensate for a lower inertia in the system, increasing the quality of the frequency in the microgrid [41].

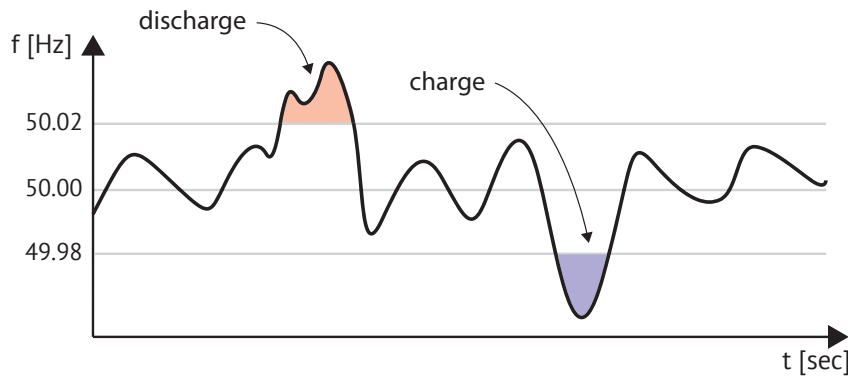


Figure 2.4: Frequency control with energy storage

In the main grid, there are reserve markets for the regulations of the frequency [42]. This means that if the energy storage system in the microgrid has additional capacity, it could offer its reserves to the main grid, creating additional revenues [36]. Due to the fast response time of energy storage and its emission-free operation, it is an attractive option for providing these reserves [37].

2.3.3 Reliability

2.3.3.1 Backup power

Depending on the end-user, the value of backup power¹ could differ. For some, a power outage could have severe economical consequences. This is in-fact one of the main reasons why microgrid projects are motivated, to have a reliable power supply when the main grid fails [11]. The energy storage can then support the microgrid and supply power during these events [7].

The outage cost for the consumer depends on their activities and the duration of outages. One approach to assess this value is to base the value of a customer survey. Another view on the cost of the outage is to consider the cost of energy not supplied [11]. Furthermore, in Sweden, there is a law that forbids power outage for more than 24 hours. The network operators have to compensate for outages lasting more than 12 hours and could have to pay indemnity for the caused damages [43].

2.3.3.2 Black start capability

If there is a black out in the microgrid, it could have a big impact on the economy of the microgrid as well as on the consumer's activities. It is therefore vital to minimize the interruption time of the system. In order to re-energize the microgrid, energy storage plays an important role [44]. The microgrid can also offer black start service to the utility grid, thereby creating additional revenues and improve grid reliability [11].

¹VOLL can be described as the average expense for the consumers due to the outage [7]

3

Regulations of the electricity market and power system

3.1 Electricity market structure

3.1.1 Market players in Sweden

The relevant market players in Sweden for this work are the generation companies, transmission system operator (TSO), distribution system operators (DSO) and consumers.

The generation companies provide electricity that is either sold directly to energy retailers (electricity traders) and large consumers, or on the electricity market. In Sweden, the majority of the electricity produced is actually traded within the spot market, which is a part of the electricity market. Larger consumers normally buy electricity on the spot market, whereas smaller ones buy from a retailer. The retailer is aggregating the demand and then buying electricity on the spot market [42].

A significant part of the Swedish electricity production takes place in the north, whereas a majority of the consumption is in the south and the middle of Sweden. This creates a need for transmission of electricity over longer distances. The grid that operates for longer distances and with a higher voltage level [45] (220-400 kV [42]) is called the transmission grid. It is owned by Svenska Kraftnät, which is the TSO in Sweden and is responsible for the balance as well as the reliability of the system [42]. The distribution grid (below 130 kV) [42] works as an interface between the transmission line and consumer. For this grid the DSOs are both the owner [45] and the responsible operator [42].

The competition in the market for the Swedish electricity suppliers and production of electricity is free [46]. However, the grid sector is regulated by the Energy Market Inspectorate (Ei) and a concession for building and operating a power line is needed [47]. This concession is area dependent and only one network operator has the right to operate within each respective area [48].

3.1.2 Markets in the Swedish electricity system

Nord Pool is a market place where the buyers and sellers can bid for electricity in competition. The Nord Pool includes the Spot market where the actors can bid for electricity per hour, one day before delivery [42].

However, consumption and production can vary from the spot markets trades [42]. In the Swedish electricity grid, the frequency should be 50.0 Hz. In normal operation, this is allowed to deviate from its nominal value by ± 100 mHz [40]. This creates a market for the balancing of the system. In order to achieve balance in the system, the TSO can pay a downward or upward regulating price to the providers of the regulating service [42]. There are also different markets for providing these reserves, i.e. primary, secondary and tertiary reserves. The markets are distinguished by their response time and actuation times [49].

There are two primary reserve markets in Sweden, the frequency containment reserve (FCR) markets, which are automatically activated. One reserve is activated in normal operation between 50.1 and 49.9 Hz (FCR-N) and one in disturbed operation (FCR-D) outside 50.1 to 49.9 Hz. These markets are further described in Table 3.1 [49].

The secondary reserve is activated when the frequency needs to be restored. In Sweden this reserve is called automatic frequency restoration reserve (aFRR) and is activated automatically. There is also a market for tertiary reserves, which is manually activated (mFRR) [49]. This market is further described in Table 3.1.

In the Swedish system, there is today no market for fast frequency reserves [36]. But since the shares of non-synchronous renewable energy sources are increasing, and at the same time the spinning mass in the system is decreasing [40], this will become more and more important. The fast response of BESS could help to support the network in this regard [36].

Table 3.1: Reserve markets in the Swedish electricity system. The minimum capacity is the least allowed volume in the market. The response time refers to the time that a certain share of the volume should be activated in the market. The time ahead describes the time ahead that the offer needs to be made. The minimum sustained power duration and minimum bid volume is also included [50]

Reserve	Min bid volume [MW]	Part response time [sec]	Full response time [sec]	Sustained duration [min]	Energy Com- pensation	Power Com- pensation	Time ahead
FCR-N	0.1	60 (63%)	180 (100%)	60	Up/down	Pay-as-bid	1-2 days
FCR-D	0.1	5 (50%)	30 (100%)	60	-	Pay-as-bid	1-2 days
aFRR	5 ^a	-	120 (100%)	60	Up/down	Pay-as-bid	2 days
mFRR	10 ^b	-	900 (100%)	60	Up/down	-	14 days- 45 min

^a The bid volume is made in steps of 5 MW.

^b The bid volume is made in steps of 10 MW.

3.2 Regulations in Sweden

The obstacles in the regulations for the development of microgrids are related to economical factors and the current configuration of the concession in the electricity grid. Economic obstacles in the regulations relate to the costs and benefits of a microgrid and how it is reflected in the market environment concerning the customer,

TSO, DSO and the society as a whole. The concession in the electricity grid regulates the possibility of operating a microgrid [51].

3.2.1 Obstacles for microgrids and energy storage

In the current Swedish electricity act, some regulations limit the use of microgrids and energy storage. Three major obstacles for microgrid and energy storage could be identified. Firstly, the ownership of energy storage is regulated [21]. The network operator, in a corporate group with more than 100,000 electricity consumers, are not allowed to have any influence in decisions or to be involved in organizations of companies that produce or trade electricity [47]. As a result of that the network operators are not allowed to contact the customers, nor the producers in order to create a microgrid. Furthermore, the DSOs and TSO are not allowed to trade or manage the production of electricity [47] (which energy storage can be classified as according to Ei). The exemption to this is when the operation only covers the electricity losses or in a temporary operation when there is a power failure [21]. With that said, the energy storage that is not used as mentioned above, should be operated by actors at the competition-based market. On the other hand this does not limit the network operators to own and lease storage or the facility of storage [21].

Secondly, the concession is needed to build or operate a power line with some exceptions [47]. An internal grid can be operated in some cases, e.g. when there is within a building, industrial facility, airport, leisure facility, fenced area, establishment, etc. [52]. Hence, in cases as the studied region in this thesis, this is not possible.

Thirdly, the concession owner is almost always obligated to connect an electrical facility to the grid [47]. This can create problems when operating in island-mode.

Lastly, a network operator is only allowed to purchase electricity that is covering net losses and to avoid outage in an open, non-discriminate and market oriented way [47]. A microgrid should, by the definition, be able to operate as a single entity. This is not possible since electricity producers within the microgrid can be favored. If the microgrid is operated in island-mode, the electricity is generated within the microgrid or the energy storage. In that case a cheaper electricity producer outside the microgrid can be unused and therefore discriminated.

3.2.2 Network tariff

The tariff ensures that the network operators get paid from their customers. It covers the costs of development, operation and maintenance in the electricity grid [9]. According to the Swedish electricity act, the tariffs should be designed in a way that promotes both an efficient utilization of the electricity grid and an efficient electricity production and usage. It should also be designed in a objective, efficient and non-discriminate way [47].

The revenue cap (see Section 3.2.4) regulates how much the electricity network companies can get paid from their customers. The network operators can design the tariffs differently. However, larger customers have mainly subscription tariffs based

on the power output (kW), whereas smaller customers mainly base it on the energy output (kWh). Moreover, the tariffs can be fixed or variable and do not always reflect the energy consumption. According to Ei, tariffs that better reflect the costs and demand flexibility in the grid is needed. One way to solve this is by using tariffs that change depending on the demand. However, this type of tariffs is not utilized by all grid companies [9].

A grid company that owns energy storage's does not pay tariffs for the electricity that charge and discharge the storage. However, a commercial actor needs to pay a double tariff for the electricity since it is treated as both consumption and generation. Meaning that there is a tax for the electricity charged and for the electricity that is fed back to the grid [21].

3.2.3 Energy taxes

According to the current Swedish electricity act, the owner of the storage needs to pay tax for electricity during storage of electricity. This concerns the electricity that is consumed during charging of the storage from the electricity grid. But there is also a tax for the energy that gets discharged and transmitted to another actor. Consequently, the same electricity can get taxed twice [53]. If the storage is owned by a grid company and used as the current laws prescribe, the charging and discharging is tax free. The same goes for energy storage's owned by end user that have a maximum production capacity of 1500 kW and is connected to the local grid, in the purpose of own use [21].

3.2.4 Revenue cap structure

Due to the monopoly of transmission, regulations are necessary. This is done by the revenue cap, which regulates the amount that the network operators can get paid by their customers. It should ensure that the customers pay a reasonable price and secure the supply in the long run. The revenue cap is decided in spans of 4 years and the current period is between 2016 and 2019 [9].

The costs of the companies are categorized in OPEX and CAPEX, according to the criteria shown in Figure 3.1. The OPEX consists of two categories, controllable and non-controllable costs. The controllable costs include operation and maintenance costs and every grid company is regulated to lower it by between 1 to 1.82% per year. Non-controllable costs can for example be costs to authorities and TSO and can be distributed to the customers [9].

CAPEX consists of depreciation and return capital that is adjusted. The return capital is determined by the interest rate and is decided by the Ei before each revenue cap period. The efficiency of how the grid is operated and the quality of the grid operation determines the adjustment. It can regulate the revenue cap by maximum $\pm 5\%$. One way for the grid companies to improve the indicator of the efficiency is by investments in smart grid solutions. However, the revenue cap structure has been showed to have a low driving force to this type of investments [9].

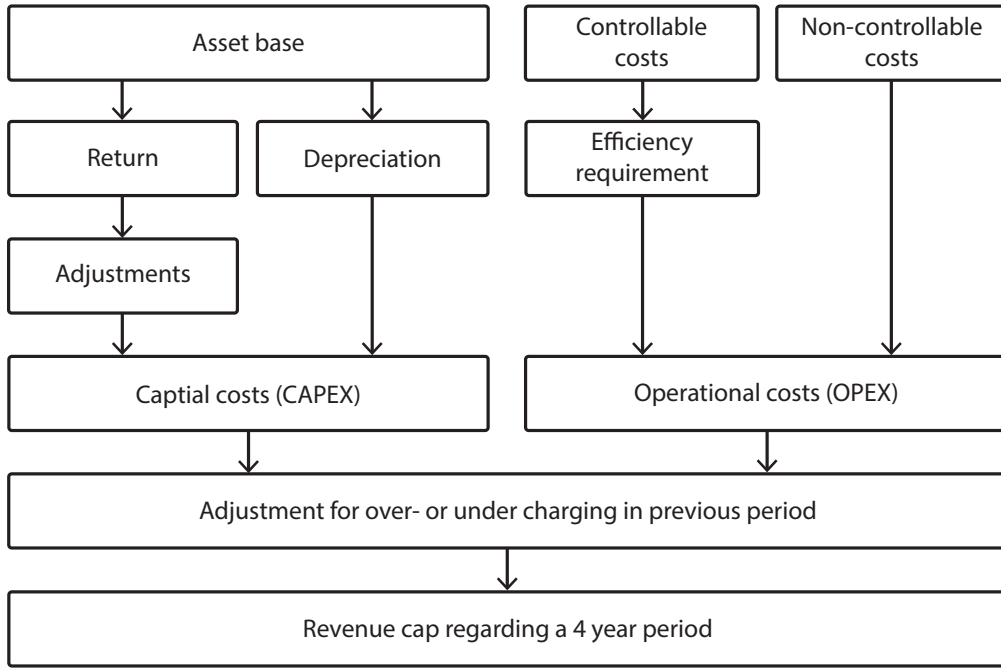


Figure 3.1: Overview of the revenue cap 2016-2019 of the Swedish electricity grid companies

3.3 Regulation in other countries

In order to achieve a development of microgrids, changes in policies are needed. These changes concern the interconnection of the microgrid to the main grid, un-beneficial economic regulations for microgrid owners and the participation in energy markets for microgrids [26]. US, Europe and South Korea are three of the leaders in the development of smart grid [54]. US and South Korea together with Germany are further reviewed in this chapter.

3.3.1 South Korea

South Korea has aimed to be a provider of smart grids and have set goals for a regional smart grid in 2030. Microgrid is one of the smart grid technologies they have set attention to and during 2016, business targets were announced towards the microgrid business [55]. In the country KEPCO, the network operator, has stood for the development of the microgrid concept where the focus has been on two types of microgrids, island- and urban-based microgrids. There are 86 island-based microgrid projects planned by KEPCO, where the project at Gasa Island works as a prototype for these projects since 2013. The cost of the Gasa Island project was divided between KEPCO and The Ministry of Trade. The retail market is needed to introduce more competition if private companies should invest in microgrids [56]. There is also a business license needed to provide transmission or distribution services. However, only KEPCO has been allocated the license to provide such a service [57].

3.3.2 United States

Usually, microgrids within the USA are connected to the main grid. They are using the interconnection with the main grid to sell excess power and to get electricity when the internal resources are unavailable. They are often seen as a desired component within an electricity grid. One problem has been to solve issues regarding how the traditional utilities should backup the microgrid operations financially. The utilities have shown a revenue increase in several years and are concerned about the risk of losing customers. Moreover, the customers and policymakers are worried about the risk of an increase of cost and instabilities for the customers that are outside the microgrids [58].

Multi-Stakeholder Ownership Models are increasing within the US. A property owner can own the site where a third party or a utility owns the energy devices. Projects have shown that third party owners can own certain components and the rights for potential revenues. This can reduce the costs to the consumers and provide services for the utilities [59].

The program Community Choice Aggregation (CCA) offers local communities to be involved in the electricity market. In the program, the city or local government is purchasing the electricity while as the utility maintains the grid services. In 2017 the program was established in seven states and another six was investigating the possibility to provide such a program [60]. In the state of California, CCA can provide sub-rates for microgrid customers and configured distributed-connected resources. Furthermore, a part of the costs for pre-studies can be compensated and the value streams visualized by the program. It can also help to form integrated micro utilities (fewer than 2000 customers) by cooperating with local agencies and the CCA is working under other regulations than electric corporations [61].

3.3.3 Germany

Since the change of energy market regulation in 2005, microgrids have been excluded from some regulatory obligations in the energy industry act. However, this has not led to a constant increase of microgrids in Germany. In order to be an accepted microgrid, several criteria need to be fulfilled. Consequently, the considerations of microgrids in Germany has mainly concerned newly developed industrial or residential areas [62].

A possibility for microgrids in Germany could be to aggregate different customers and loads. This has been done in Mannheim-Wallstadt, Germany, where 1200 inhabitants are interlinked. With a point of common coupling to the main grid, switching between island and grid-connected mode is possible [63].

3.4 Possible changes of the regulations

The aim of this section is to highlight different stakeholders view of how the electrical system in Sweden will or could develop in the future. Changes in regulation, system development plans and long-term goals are included to give a broad spectra of a

possible direction of the electrical system. The section is mainly based on reports that are made for or by ENTSOE [64], Svenska Kraftnät (SvK) [65], the Council of European Energy Regulators [66], Swedish DSOs [6],[67], Swedish Energy Market Inspectorate, Copenhagen economics and the Swedish Energy Agency [68], [69].

3.4.1 A vision for a future grid

There are today several obstacles that hinder the potential of microgrids and energy storage, (as mentioned in Section 3.2). Two of the problems for a future development of the grid is the lack of incentives for the grid operators to invest in smart grid solutions and the lack of aim and vision for a future grid [68], [69], [70]. At the same time, an increased self-sufficiency may result in prosumers and microgrids going off-grid [70]. This could compete with the natural transmission and distribution monopoly [69] and it could potentially affect the role of the grid in the future [70].

It is proposed to create a political aim for the development of the future grid and to solve issues in the legislation and regulation that hinders technical neutrality and the transition towards a modern and smart network [69], [68]. In order to investigate new smart grid solutions and technologies, six different EU grid projects called InterFlex is operated across Europe. One of the InterFlex projects is a microgrid allocated in Simris, Sweden, and it is operated by E.ON, a Swedish DSO. The project will run until 2019/2020 and the goal is to test smart grid technologies in order to increase renewable energy integration [67]. The Swedish Market Inspectorate is also working on long and short-term issues regarding the legislation and regulation of the electricity system [70].

Even though there is no clear picture of the grid of tomorrow, the reports made by/for the ENTSOE, SvK and the Swedish Energy Market Inspectorate indicate that changes must and are about to happen.

3.4.2 Tariff structure and incentives

The current tariff structure in Sweden does not give the network companies incentive to build additional power transfer capacity. Instead there is incentive to minimize the network cost by reducing the transferred power [6]. According to the result from a survey from Copenhagen economics, more than 50% of the network companies in Sweden actually see the cap revenue as an obstacle for smart grid investments and solutions [68].

Based on interviews, surveys and literature studies, Swedish Smartgrids are proposing four different solutions on how the regulations can be changed in order to give incentives for smart grid solutions.

- Firstly, a clear aim and vision for the future grid is needed. The Energy Market Inspectorate should be able to allow pilot and demonstration projects in order to review new tariff and business structures [68]. This should be of first priority to look over according to Power Circle, a advocacy group for the electricity industry [69].

- Secondly, to keep the current regulations as it is but include incentives for the companies to invest in smart grid solutions. This without making it market-like.
- Thirdly, keep most of the current regulations as it is but instead create a more market-like condition [68].
- Lastly, to develop a new regulation model that would give the grid companies more freedom of reaching the regulation targets. This would give incitement for smart grid solutions if it is the most cost-effective solutions [68].

For energy storage in specific, both the distribution and transmission tariff structure should ensure neutrality and it should be able to compete with other technologies on the same level playing field [64].

3.4.3 The role of DSOs and new market players

One of the principles of the DSOs is that they have to act in the public interest where costs and benefits should be taken into account. Therefore, it is important in the case where a new public service is imposed, or new large investment projects, in which there is a net benefit for the end users [66], [65]. The Council of European Energy Regulators is pointing out that in cases where flexible options are more efficient than network reinforcement, incentives are needed for the DSO to invest in these solutions, given that the option is non-discriminatory [66]. This could open up the potential of DSOs owning energy storage as long as it does not conflict with its core activity and on equal and transparent terms. In the case of disruption in the network, the DSO could temporarily contract local generation in order to supply power in off-grid condition areas [66].

Aggregators or other third party actors will in the future be important actors when it comes to energy services as energy storage, production and flexibility management [69]. A possibility to develop microgrids in the future could be to aggregate different customers and loads, which as mentioned in Section 3.3.3, is already a possibility in Germany. There is though still a need to investigate what role different actors should have in the future [69].

3.4.4 System service markets

The markets today are directly or indirectly made for the current electrical system and production mix. With a change currently happening in the production mix, the regulations need to be changed for a future system [6].

SvK in its system development plan for 2040 highlights the increased need for a flexible power system due to the increase of solar and wind power. The TSOs in the Nordic countries are working together for new strategies for frequency regulations. In a new concept created by the Nordic TSOs, aFRR will have a more dominant roll, and mFRR will be used mainly for proactive regulation [65].

ENTSO-E further highlights the need of new system services within the 2030 horizon, whereas energy storage should be able to compete with other technologies [64]. SvK is concurrently investigating the development for a fast frequency reserve (FFR)

market [65]. The need of new markets models and faster resources for primary regulations is also confirmed in a report made for the DSO Skellefteå Kraft [6]. In order to open up the market further, a lower minimum bid volume size in the different markets is proposed [69].

ENTSO-E and the Swedish TSO do not highlight the need for new markets regarding black start capability, reactive power and voltage support.

3.4.5 Double taxation

In the beginning of 2018 the Swedish ministry of finance came with a proposal for a change in the Swedish electricity act. The change intends to handle the double taxation of the electricity for storage systems. According to the proposal the storage actor will get repaid for the taxation of the electricity that is fed back into the grid, which could be beneficial for investing in BESS [53].

4

Data and modeling

4.1 Scenarios

Based on the information gathered in previous chapter, four scenarios have been constructed and summarized in Table 4.1. In order to analyze the different scenarios, a case study is conducted. The area analyzed has currently only one transmission line connected to the main grid, which opposes problems when there are outages on that line. All scenarios are considering the reliability which consists of the social cost for the value of energy not served (ENS) and curtailed energy. There is 15 MW installed wind capacity and the peak demand is 5 MW for the area.

Table 4.1: The set up of scenarios

Scenario	Reference		Short-term	Long-term
	BAU	New line	3-5 years	10-15 years
Microgrid	No	No	Yes	Yes
Transmission line upgrade	No	Yes	No	No
Energy storage	No	No	Yes	Yes
Arbitrage	No	No	Yes	Yes
Ancillary service	No	No	Yes	Yes
Tax of losses in BESS	-	-	Yes	No
Microgrid Operator	-	-	U	U
Battery cost reduction [%]	-	-	36	54
Solar PV increase [% of load]	2.4/4.8*	2.4/4.8*	2.4	4.8

U=Utility

*3-5 years/10-15 years

4.1.1 Reference scenarios

The reference scenarios consist of a business as usual (BAU) scenario and a new line scenario. They are modeled to explore the social welfare in comparison with the microgrid scenarios. Thereby, the generation and load are the same as in the microgrid scenarios. In the reference scenarios, neither the energy storage is included nor is the region working as a microgrid. In the case of an outage, the load cannot be covered and all local generation is curtailed due to the disability to work in island mode.

In the BAU scenario, the area is operated as today, with one overhead power line (OHPL) connected to the main network. For the new line scenario, a new invest-

ment of OHPL is included, this for the distance which today consists of one OHPL connecting the area with the main grid. Installing an additional line can be covered by the tariffs (see Section 3.2.4), and can increase the reliability of the local network, thereby fulfill the N-1 criteria.

4.1.2 Microgrid scenarios

Another possibility to increase the reliability of the local network is to make investments for microgrids. The short and long-term scenarios are modeled with the assumption that it will be possible to operate a microgrid in the type of area explored, as discussed in chapter 3.4. For the short term, it is assumed that it will be possible for the network operator to get exceptions for a microgrid in order to operate and explore the concept. In the longer term, microgrid operation is expected to be allowed to a larger extent. Thereby, the services of the peak and load leveling will be included. The distribution network operator is in the microgrid scenarios still the operator of the microgrid. This since they are currently owning the distribution grid and it seems unlikely that another actor can compete with the price intensive investments needed to operate in this area.

The regulations regarding the economic obstacles for owning an energy storage are currently under development (as described in Section 3.4). Consequently, the double tariff and taxes is removed in the scenarios, which makes it more profitable to invest in energy storage. However, in the short term there is assumed to be energy taxes for the losses in the BESS. In the long-term, this regulation is assumed to be removed. Similarly, as of today, it is assumed that a third party actor can own the energy storage.

For the FCR market in Sweden, the participation of energy storage is discussed (see Section 3.4). In the short term, it is likely to happen and they are thereby included in the scenarios as frequency reserve market. It is also likely that there will be a market in the long term for fast frequency response market where energy storage could participate. But since it is difficult and uncertain to predict the revenues of participating in such a market in Sweden, the frequency regulation is assumed to be represented by the FCR markets.

Markets for the aFRR and mFRR are excluded in the microgrid scenarios due to that the minimum bid volumes are 5 MW and 10 MW and due to lower revenue streams where only the energy delivered is charged/paid, as explained in Section 3.1.2. This would require extra capacity or a large share of the BESS, since it is similar to the peak load of the region. Likewise, the black start capability, reactive power and voltage support markets are neglected due to the current lack of vision for these markets (as stated in 3.4.4).

As described in 4.2.1, the cost of battery energy storage will probably decrease in the future. A larger decrease has been assumed for the long-term scenario in comparing with short term. Likewise, the increase of solar power is assumed to be larger for the long-term scenario.

4.2 Data collection

Main assumptions for the data collection:

- *Hourly time data* - All power data represents the average value during the hour.
- *Historical data* - The data between 2013-2017 of the load, wind generation, spot price and FCR capacity markets represents the future years. To cover the 10-year period, the data is repeated twice.
- *Active power* - Only active power considered, the reactive power is outside of this scope.

4.2.1 Generation and load

The load (Figure 4.1) and wind power production data (Figure 4.2) used in the model are based on real values between 2013-2017, gathered from Vattenfall. Currently, only wind power is installed in the area, hence solar power (Figure 4.3) is modeled based on assumptions. Note that the figures present monthly averages, whereas hourly data is used in the modeling.

The solar power is expected to increase and to cover 4.8% of the total Swedish electricity production by 2030 [71]. Related to the load of the studied region, this corresponds to 750 kW installed peak capacity solar power and is utilized in the long-term scenario simulation. For the short-term scenario, half of this value is assumed.

The model in the report [72] was used to create a projection of solar power generation profiles. The simulation creates the profile by including 8 different solar system types, together with the site-specific meteorological weather data. In order to create the profile, an optimal angle and the direction of south were used. Due to the low rate of solar power in the system (see 4.4) and that the data for 2012 were easy to access from the model, this was used for all years.

The load, generation, net and spot price profile over a week can be viewed in the Figure 4.4. As can be seen, the demand is rather stable and the solar production is low. The fluctuation in net load is thereby mostly affected by the wind power.

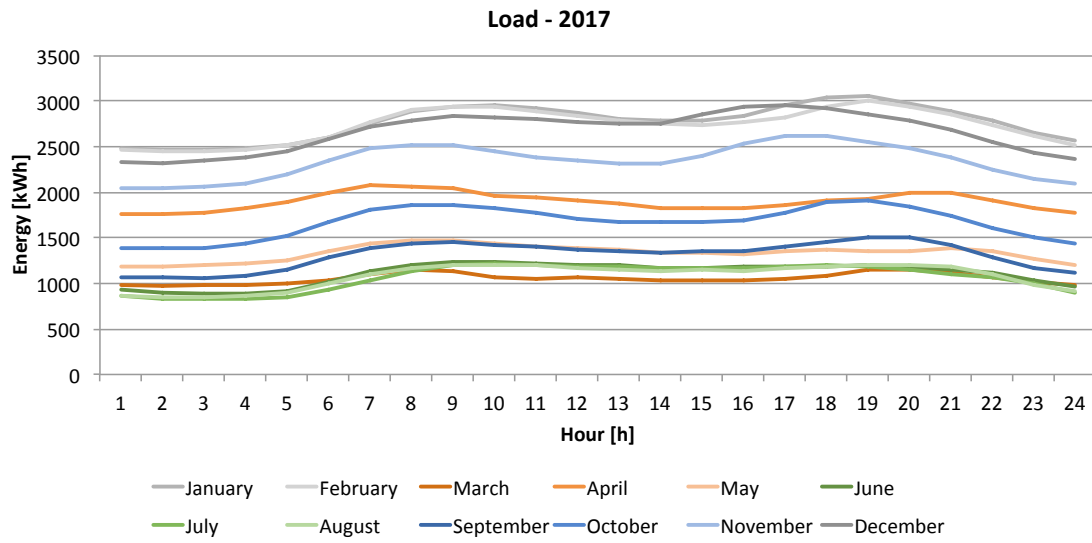


Figure 4.1: Average load 2017 presented per hour. Based on data from Vattenfall

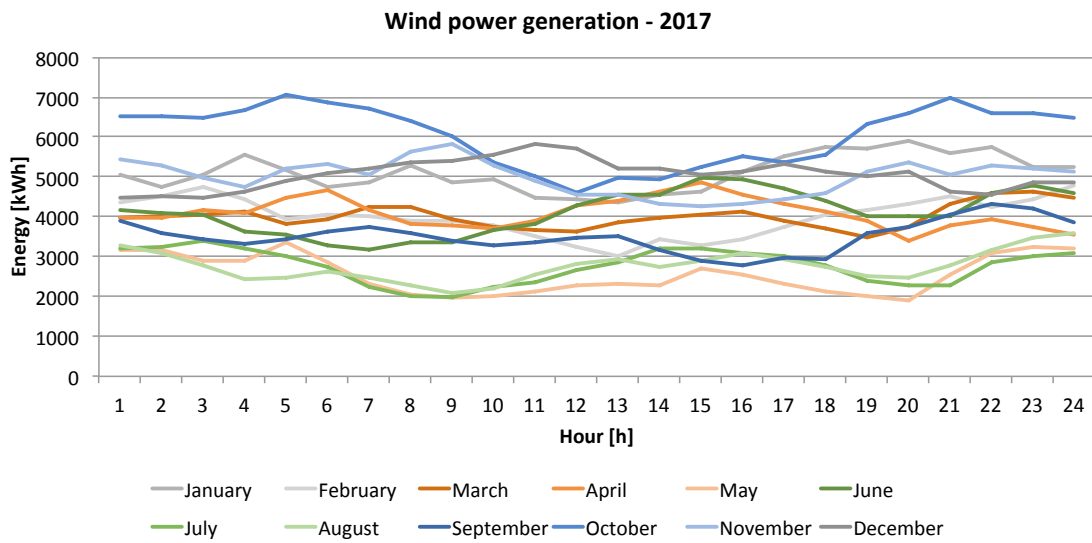


Figure 4.2: Monthly average wind generation 2017 presented per hour. Based on data from Vattenfall

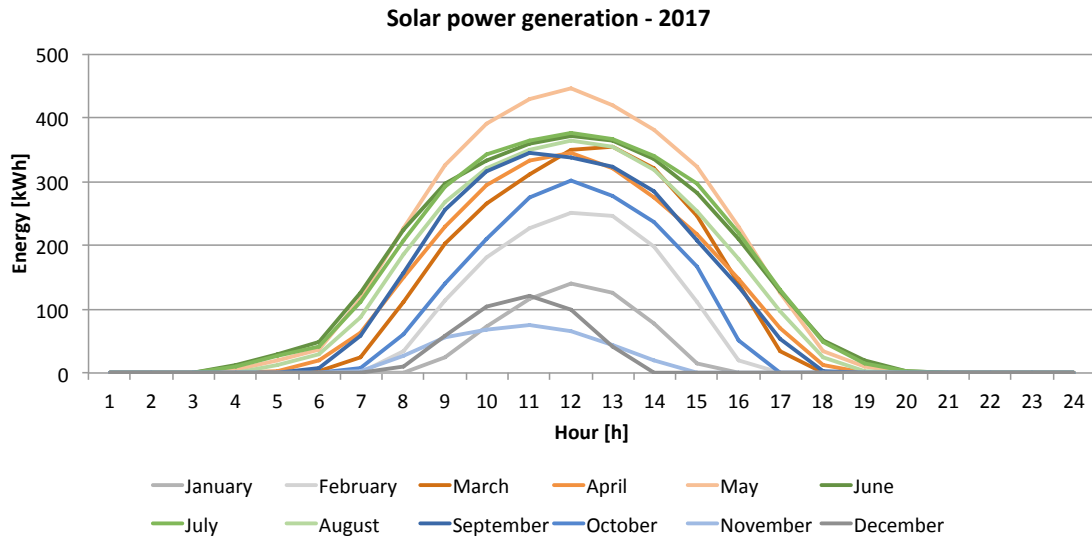


Figure 4.3: Modeled monthly average solar PV production presented per hour. Modeled with an installed peak capacity of 750 kW

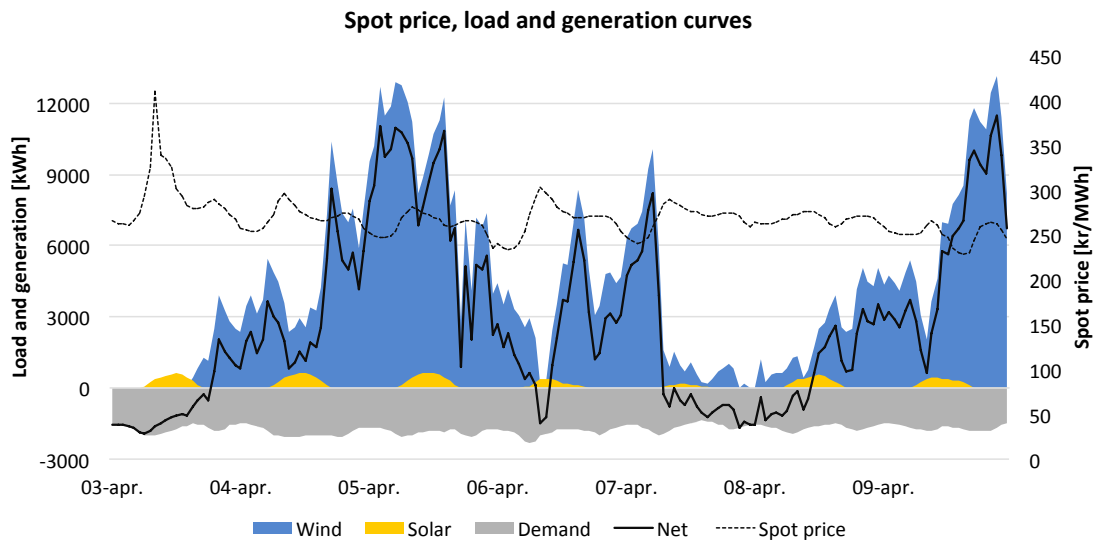


Figure 4.4: Wind, solar (750 kW), load, net load and spot price of one week in April, 2017. Based on data from Vattenfall

4.2.2 Cost of storage

Lazard 3.0 report [27] is used as a reference for constructing the cost of lithium-ion battery energy storage. The cost in this study is estimated to be linear and the 2017 values are presented in Table 4.2. The cost for the investment of the battery is assumed to decrease from the 2017 values by 36% in five years [27], which is utilized in the short-term scenario. For the long-term scenario, a decrease of 54% [28] is applied, which is the estimated decrease between 2017-2030. The augmentation

costs are also included, which represent reparations in order to avoid capacity loss during the battery lifetime [27].

Table 4.2: Data for the life cycle cost calculation of lithium-ion battery energy storage system. The data corresponds to the 2017 values

Parameter	Value
Power related investment cost [kr/kW]	1,300 ^a
Energy related investment cost [kr/kWh]	3,500 ^a
EPC [% inv. cost]	12 ^b
Augmentation cost [% of BESS/year]	3.2 ^a
Round trip efficiency [%]	85 ^a
Total cycles [#]	1,270 ^a
Min state of charge (SOC) [%]	5 ^c
O&M [%/inv. cost/year]	1.5 ^d
Project Life [years]	10 ^a

^a Assumptions based on Lazards LCOS 3.0 [27] and recalculated by the exchange rate from the 19 April 2018 [73].

Assume total charging and discharging capacity are equal ($\eta_{\text{dis}} = \eta_{\text{chr}} = \sqrt{0.85}$).

^b Assumed EPC costs as a percentage of investment costs [27]

^c Assumptions based on Irena [74]

^d The O&M escalation cost is neglected

4.2.3 Electricity markets

The actual prices for spot, up and down regulating markets between 2013-2017 were gathered from Nord Pool [75]. For the average pay-as-bid price in the FCR-N capacity bid market were gathered from [76]. The 2017 profiles can be seen in Figure: 4.5, 4.6, 4.7 and 4.8. Note that the figures present monthly averages, whereas hourly data is used in the modeling. The spot price together with the 2018 tax and tariff level (see Appendix A.1) were used to create the imported electricity cost.

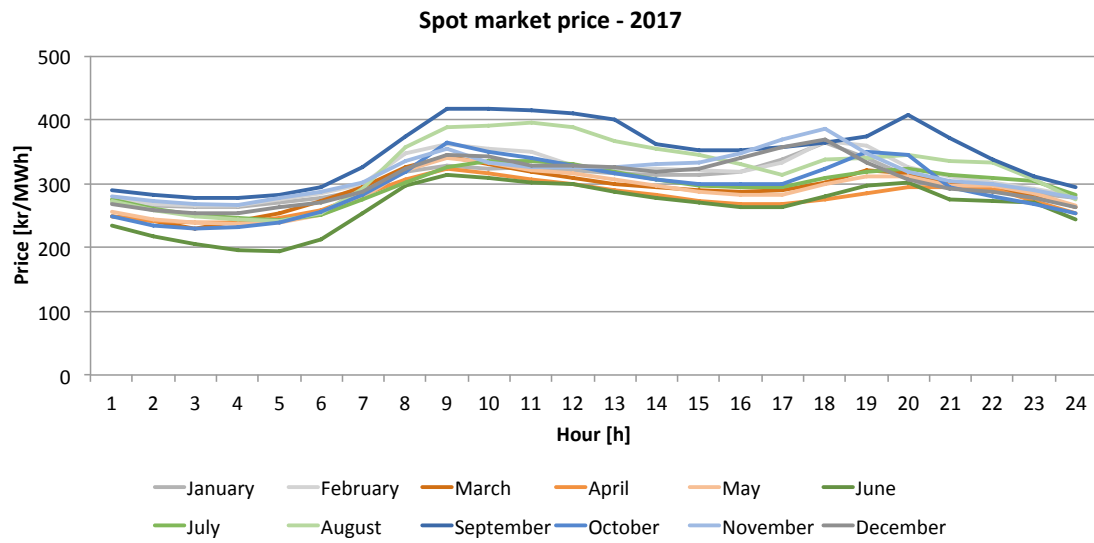


Figure 4.5: Monthly average spot price of 2017, presented per hour. Based on data from Nord Pool [75]

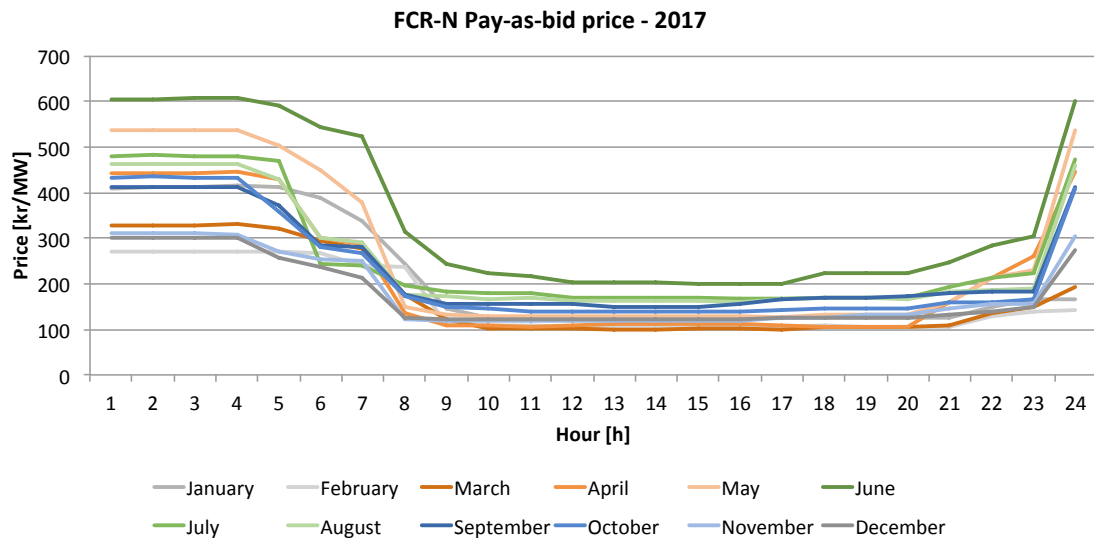


Figure 4.6: Monthly average pay-as-bid for FCR-N capacity market of 2017, presented per hour. Based on data from Svenska Kraftnät [76]

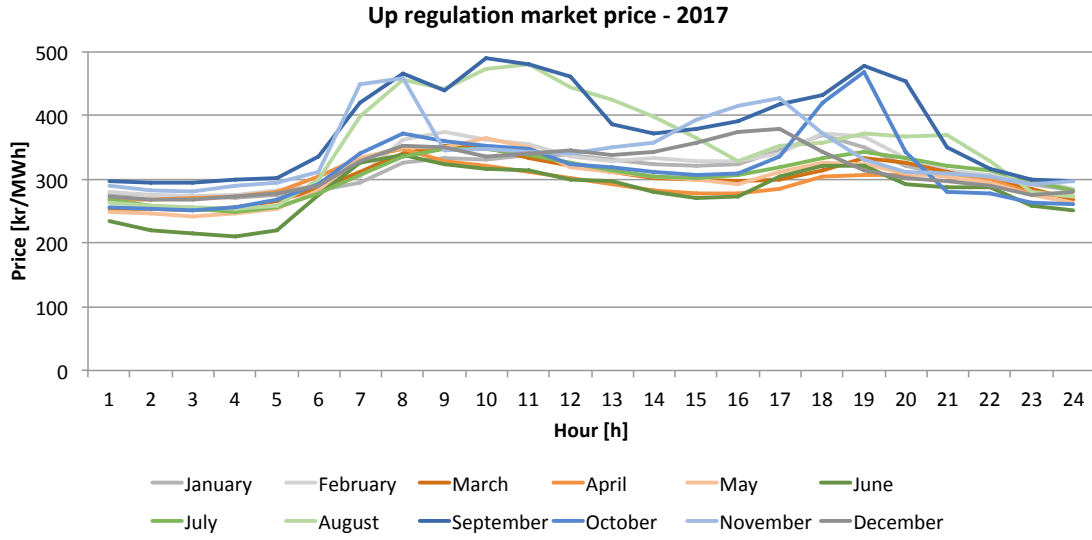


Figure 4.7: Monthly average up regulating market price of 2017, presented per hour. Based on data from Nord Pool [75]

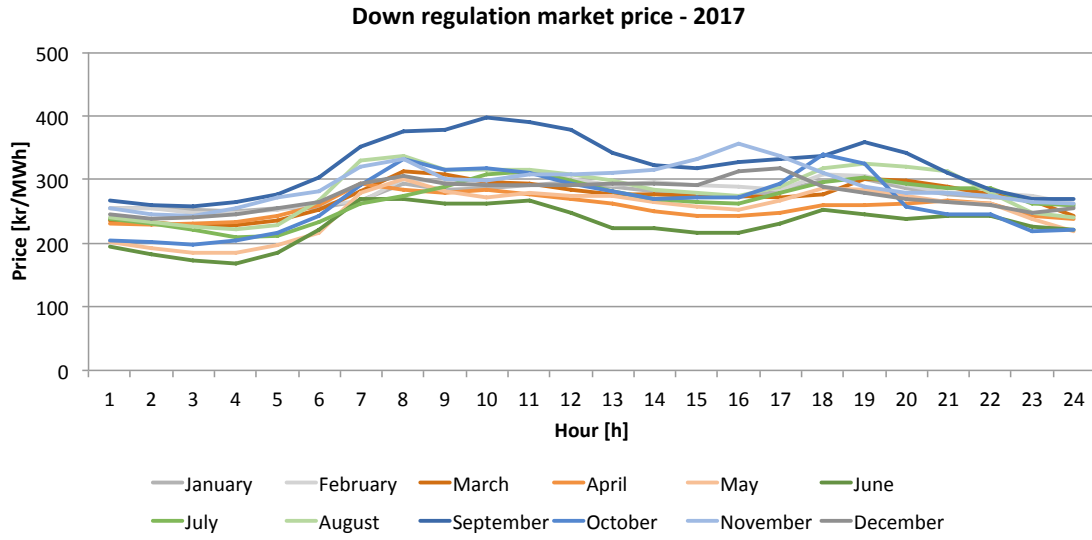


Figure 4.8: Monthly average down regulating market price of 2017, presented per hour. Based on data from Nord Pool [75]

4.2.4 Bid price for energy storage

As described in Section 3.1.2 it is currently not possible to participate in the Swedish FCR-market with BESS. The bid price for the FCR-market is predefined and differs depending on technology [77]. Consequentially, the fixed capacity bid price for BESS was approximated by eight accepted bids from BESS providers in the United Kingdoms enhanced frequency response market (EFRM). The average capacity price gave the result $\pi^{\text{bid}} = 114 \text{ kr/MWh/h}$ [78] and represents the parameter in this study.

The bid can be selected if the FCR-N capacity market (Figure 4.6) is higher then the π^{bid} . If it is lower it is not selected.

Since there is a difference in the electricity market and electricity production mix of U.K and Sweden, the result was compared with an alternative cost calculation (see Figure 4.9). This was made according to the current Swedish FCR balance agreement where the bid price should be based on the actual cost of the regulation, including arbitrage [77]. Consequently, the alternative cost calculation was based on the alternative cost for arbitrage over a month (4.1). In the calculation, the average 2017 spot price data per month (Figure 4.5) was used.

Alternative cost bid price calculation:

$$\pi_{\text{a.c}}^{\text{bid}} = (\pi^{\text{spot,max}} - \pi^{\text{spot,min}}) \cdot \eta_{\text{chr}} \cdot \eta_{\text{dis}} \quad [\text{kr/MWh/h}] \quad (4.1)$$

where:

- $\pi_{\text{a.c}}^{\text{bid}}$ = alternative cost bid price, calculated per month [kr/MWh/h]
- $\pi^{\text{spot,min}}$ = minimum value for each month of the 2017 spot price, where the average of each hour during a month were used [kr/MWh/h]
- $\pi^{\text{spot,max}}$ = maximum value for each month of the 2017 spot price, where the average of each hour during a month were used [kr/MWh/h]
- η_{chr} = charging efficiency of the BESS [%]
- η_{dis} = discharging efficiency of the BESS [%]

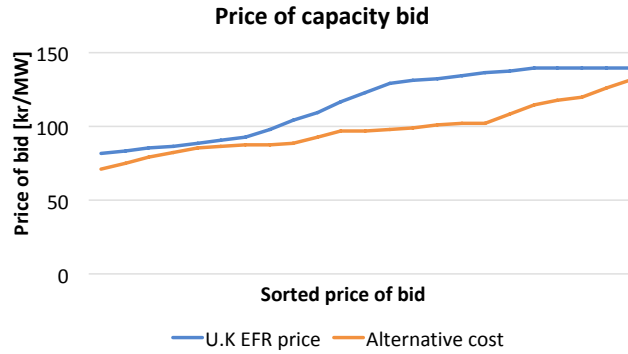


Figure 4.9: The sorted alternative cost of energy storage where a value for each month has been calculated. The sorted 2016 bid prices of United Kingdom enhanced frequency response market (recalculated with the exchange rate according to [79])

4.2.5 Reliability and distribution deferral

With the investments in energy storage, the cost of building a new OHPL is assumed to be avoided. The cost and reliability of the OHPL is based on a similar line connected to the studied region. In this case, trees have been removed close to the overhead line in order to increase the reliability.

The value of lost load is based on the costs for the society during an outage [80]. The average energy and power consumption from the investigated area and Vattenfalls estimations for the OHPL has been used to calculate the cost. In the Appendix A.1 the costs are further described and the data can be seen in Table 4.3.

Table 4.3: Data for reliability and overhead power line

Overhead power line cost [Mkr]	12.8 ^a
Overhead power line life-time [year]	60 ^b
Value of lost load (VOLL) [kr/kWh]	65.2 ^c
Outage probability overhead power line	0.12 ^a
Average duration hour	11 ^a

^a Values from Vattenfall

^b Values from [81]

^c See calculation in Appendix A.1

4.3 Modeling

A common approach to evaluate the cost-effectiveness of an investment is to analyze the benefit against the cost. Cost-benefit analysis focuses on the cost and benefits for the society as a whole, rather than an individual self-interest approach [82]. This type of analysis is commonly used when sizing and analyzing distributed resources and energy storage [14], [83], [84]. Further, it can be a rational decision tool and can be used for policies, project, demonstrations and regulations etc. [82]. The net social benefits can be described as:

$$\text{Net social benefits} = \text{social benefits} - \text{social cost} \quad (4.2)$$

This type of analysis is used in the model and compared to a BAU case, which shows the potential benefits of implementing a microgrid. By optimizing the total cost, the most cost-effective size of the BESS can be achieved.

There are different methods proposed in the literature to optimize a microgrid and sizing distributed energy resources, including energy storage system. Two types that are commonly used are simulation models [85] and optimization algorithms [14], [83], [84]. The general advantages of simulation-based models are that it can model non-linear behavior and the development of the model is simple. On the other hand, it is highly dependent on data input and the results do not necessary show the optimal solution. In contrast, optimization models can guarantee an optimal solution, but can be very computational heavy [83]. Due to the transparency of the optimization model with the given mathematical formulas, and that it can produce an optimal solution, it is more suitable for the objectives of the project.

There are different ways to optimize a model, and it could either be of linear or non-linear characteristics. With a non-linear programming, a more complex and detailed model can be obtained. Non-linearity on the other hand can result in that no solution can be found [83]. With a linear model, a global minimum is

guaranteed [86]. In a state-of-the-art microgrid resource dimensioning model called DER-CAM, a mixed integer linear programming (MILP) model is proposed. The solution includes an economic dispatch and the size of the distributed energy sources [87]. The most relevant work was found in [83], where an expansion of the model, including value streams resulting from activities in the ancillary service markets, is proposed. Similarly, MILP is used in [14] when a energy storage in a microgrid is dimensioned.

Based on a similar approach as DER-CAM, a dispatch model was used in order to evaluate the social welfare for the dispatch, including RES (renewable energy sources) revenues, arbitrage, ancillary service and import of electricity to end user. Furthermore, to evaluate the social costs for reliability (value of ENS and curtailed energy) and investment, a separate analysis was done. This since the dispatch of the system it self, with a fixed battery size, is independent of these costs. By separating these streams, a more perspicuous result could be obtained. To handle the value difference of money depending on time, all value streams are calculated to the net present value (NPV) (A.1), where the discount rate for network operators (see Table A.2) was used.

The revenues and costs are further reviewed in this chapter and the net social benefits can be described as:

$$\text{Net social welfare} = \text{Dispatch} - (\text{Investment} + \text{Reliability})$$

4.3.1 Key assumptions

In order to construct and simplify the model, the following key assumptions are made:

- *Perfect foresight* - The model is based on perfect foresight where the weather, electricity markets and loads are assumed to be optimally forecasted.
- *Price taker* - The trade between the microgrid and the main grid does not affect the spot price or the prices on the frequency regulation market.
- *Comparative analyze* - the social welfare are compared between the different cases in order to compare their net difference. Costs that are equal in the different cases are left out. In specific, tariffs within the local grid; the costs for planed interruptions of the line in the purpose of reparations; other reparation and maintenance costs for the OHPL; and energy tax for the end user.
- *BAU* - The costs for planed interruptions of the line, in the purpose of reparations are neglected.
- *Feed in tariff* - The summation of feed in tariff and the compensation for grid benefits can both give revenues and costs, depending on network operator [88]. Therefore, the exported electricity includes only the spot market price. Similarly the feed in cost or compensation for the BESS are also neglected.

4.3.2 Dispatch model

For the dispatch model, a linear objective function and constraints are formulated. The objective function includes the operational costs and benefits associated with the

microgrid. The constraints include physical limitations and operational constraints. GAMS, a modeling software, was used for the optimization. The software allows for mathematical programming and optimization, formulated in a similar manner as the mathematical expression [89]. See Appendix D for GAMS code.

Figure 4.10 shows the decision variables concerning the power flow. This is not exactly the same as the physical power flow of the system model at a given moment, but gives an overview of how the model is built. For example, when discharge of the battery is scheduled at the same time as down-regulation activation, the power flow would result in a reduced discharge rate of the storage. The model is thereby dispatching the energy resources in order to maximize the social welfare.

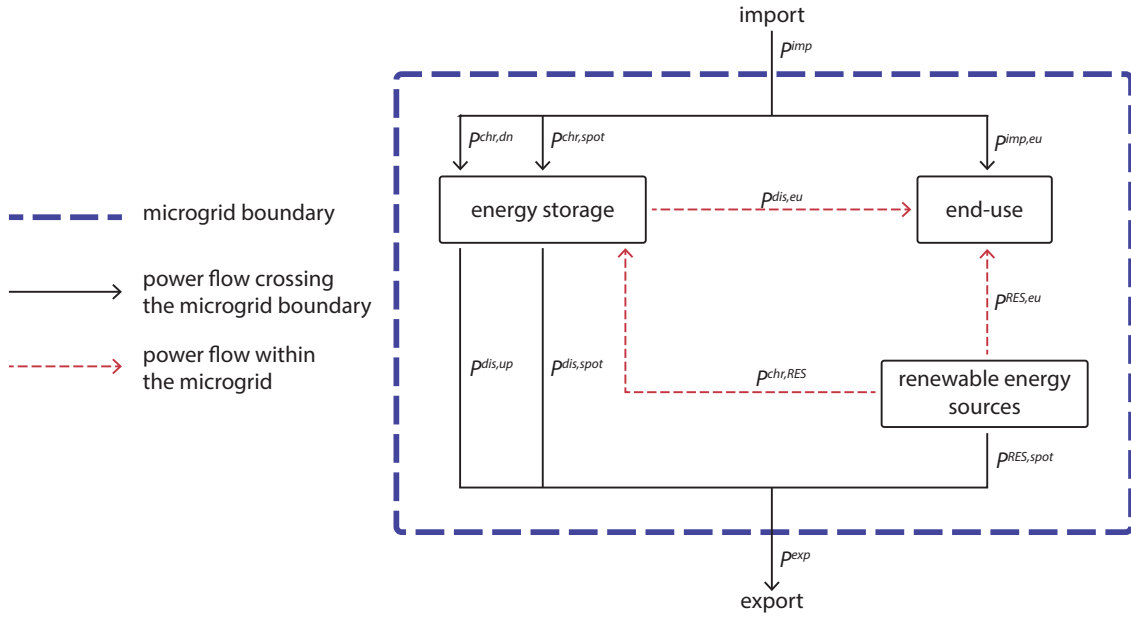


Figure 4.10: Schematic overview of the power flow

where:

$P_{y,h}^{chr,dn}$	= power import to the energy storage for down regulation [kWh/h]
$P_{y,h}^{chr,RES}$	= power from the RES to energy storage [kWh/h]
$P_{y,h}^{chr,spot}$	= power import to the energy storage for arbitrage [kWh/h]
$P_{y,h}^{dis,eu}$	= power from the energy storage to end-use [kWh/h]
$P_{y,h}^{dis,up}$	= power exported from the energy storage for up regulation [kWh/h]
$P_{y,h}^{dis,spot}$	= power exported from the energy storage for arbitrage [kWh/h]
$P_{y,h}^{exp}$	= power exported from the microgrid [kWh/h]

$$\begin{aligned}
 P_{y,h}^{\text{imp}} &= \text{power import to the microgrid [kWh/h]} \\
 P_{y,h}^{\text{imp,eu}} &= \text{power import to the end-use [kWh/h]} \\
 P_{y,h}^{\text{RES,eu}} &= \text{power from the RES to end-use [kWh/h]} \\
 P_{y,h}^{\text{RES,spot}} &= \text{power exported from the RES [kWh/h]}
 \end{aligned}$$

4.3.2.1 Objective function

The objective for the model is to maximize the operational social welfare for the microgrid, taking into account the different value streams. This is expressed in an economic function, as described in (4.3). For an overview, the main costs and revenues are summarized in Table 4.4 below.

Table 4.4: Overview over the costs and revenues included in the dispatch model. The revenues from load shifting is an implicit function, as a result of avoided cost for import of electricity

Revenues (+)	Costs (-)
• <i>Export of electricity</i> - from RES to spot market • <i>Export of electricity</i> - from energy storage to spot market (arbitrage) • <i>Ancillary service</i> - revenues from selected bid • <i>Ancillary service</i> - revenues from activated up regulation	• <i>Import of electricity</i> - from spot market to energy storage for arbitrage or to end-user • <i>Import of electricity</i> - tariff for the physical import of electricity to the local grid • <i>Ancillary service</i> - cost from activated down regulation

Maximize:

$$\begin{aligned}
 C^{\text{tot}} = & \sum_y \sum_h \pi_{y,h}^{\text{spot}} \cdot \Delta t (P_{y,h}^{\text{RES,spot}} + P_{y,h}^{\text{dis,spot}}) \\
 & + \sum_y \sum_h \pi_{y,h}^{\text{bid}} \cdot B_{y,h} \\
 & + \sum_y \sum_h \pi_{y,h}^{\text{up}} \cdot \Delta t \cdot P_{y,h}^{\text{dis,up}} \\
 & - \sum_y \sum_h \pi_{y,h}^{\text{spot}} \cdot \Delta t (P_{y,h}^{\text{chr,spot}} + P_{y,h}^{\text{imp,eu}}) \\
 & - \sum_y \sum_h \pi_{y,h}^{\text{tax}} \cdot \Delta t \cdot P_{y,h}^{\text{chr}} (1 - \eta^{\text{chr}} \eta^{\text{dis}}) \\
 & - \sum_y \sum_h C_{y,h}^{\text{tariff}} \\
 & - \sum_y \sum_h \pi_{y,h}^{\text{dn}} \cdot \Delta t \cdot P_{y,h}^{\text{chr,dn}}
 \end{aligned} \tag{4.3}$$

$\Delta t \in h \quad [\text{kr}]$

where:

Δt	= time interval [h]
π^{bid}	= bid price in the FCR-N market [kr/kW]
$\pi_{y,h}^{\text{dn}}$	= down regulating price FCR-N [kr/kWh]
$\pi_{y,h}^{\text{up}}$	= up regulating price for FCR-N [kr/kWh]
$\pi_{y,h}^{\text{spot}}$	= spot price [kr/kWh]
π^{tax}	= tax [kr/kWh]
$B_{y,h}$	= bid volume in the FCR-N market [kW]
$C_{y,h}^{\text{tariff}}$	= tariff for net electricity imported [kr]

The tax is only charged in the short-term scenario where tax is charged for the energy losses in the energy storage. The tariff cost is based on the actual physical import or export to the microgrid, see (4.4) and (4.5). In addition, $C_{y,h}^{\text{tariff}}$ is a positive variable (≥ 0).

$$C_{y,h}^{\text{tariff}} \geq \pi^{\text{tariff}} \cdot \Delta t \left(P_{y,h}^{\text{imp}} - P_{y,h}^{\text{dis,up}} \right) \quad (4.4)$$

$$C_{y,h}^{\text{tariff}} \geq \pi^{\text{tariff}} \cdot \Delta t \left(P_{y,h}^{\text{chr,dn}} - P_{y,h}^{\text{exp}} \right) \quad (4.5)$$

where:

$$\pi^{\text{tariff}} = \text{network tariff for transporting electricity [kr/kWh]}$$

4.3.2.2 Power balance

The demand and supply must at all times be equal. Otherwise, there is an imbalance in the system and the frequency will deviate. Within the microgrid, there is a local demand and a local generation of power (including energy storage). This needs to be balanced with the import and export of electricity between the microgrid and the main grid. In addition, the microgrid also needs to balance for ancillary services to the main network, which either is an import or export activity. The balance for the entire microgrid can be expressed with following equation.

Demand-supply balance:

$$P_{y,h}^{\text{load}} + P_{y,h}^{\text{exp}} + P_{y,h}^{\text{chr}} = P_{y,h}^{\text{imp}} + P_{y,h}^{\text{dis}} + P_{y,h}^{\text{wind}} + P_{y,h}^{\text{solar}} \quad \forall y, h \quad [\text{kWh/h}] \quad (4.6)$$

where:

$P_{y,h}^{\text{chr}}$	= power import to the energy storage, measured before the BESS [kWh/h]
$P_{y,h}^{\text{dis}}$	= power exported from the energy storage, measured after the BESS [kWh/h]
$P_{y,h}^{\text{load}}$	= load to supply the end-user [kWh/h]
$P_{y,h}^{\text{solar}}$	= power from the solar production [kWh/h]
$P_{y,h}^{\text{wind}}$	= power from the wind production [kWh/h]

Based on Figure 4.10 and a node balance, the following balancing equations can be set up.

Load balance:

$$P_{y,h}^{\text{load}} = P_{y,h}^{\text{dis,eu}} + P_{y,h}^{\text{imp,eu}} + P_{y,h}^{\text{RES,eu}} \quad \forall y, h \quad [\text{kWh/h}] \quad (4.7)$$

RES balance:

$$P_{y,h}^{\text{wind}} + P_{y,h}^{\text{solar}} = P_{y,h}^{\text{RES,eu}} + P_{y,h}^{\text{chr,RES}} + P_{y,h}^{\text{RES,spot}} \quad \forall y, h \quad [\text{kWh/h}] \quad (4.8)$$

Charging balance:

$$P_{y,h}^{\text{chr}} = P_{y,h}^{\text{chr,spot}} + P_{y,h}^{\text{chr,RES}} + P_{y,h}^{\text{chr,dn}} \quad \forall y, h \quad [\text{kWh/h}] \quad (4.9)$$

Discharging balance:

$$P_{y,h}^{\text{dis}} = P_{y,h}^{\text{dis,eu}} + P_{y,h}^{\text{dis,spot}} + P_{y,h}^{\text{dis,up}} \quad \forall y, h \quad [\text{kWh/h}] \quad (4.10)$$

Import balance:

$$P_{y,h}^{\text{imp}} = P_{y,h}^{\text{chr,spot}} + P_{y,h}^{\text{imp,eu}} + P_{y,h}^{\text{chr,dn}} \quad \forall y, h \quad [\text{kWh/h}] \quad (4.11)$$

Export balance:

$$P_{y,h}^{\text{exp}} = P_{y,h}^{\text{RES,spot}} + P_{y,h}^{\text{dis,spot}} + P_{y,h}^{\text{dis,up}} \quad \forall y, h \quad [\text{kWh/h}] \quad (4.12)$$

4.3.2.3 BESS constraints

The energy stored in the battery bank depends on the previous energy level and on the energy charged or discharged. The current status of the BESS can be expressed with (4.13). In order to maintain the minimum SOC-level of 0% and maximum of 100% of the storage capacity (see Table 4.2), it is constrained by the inequality equation (4.14). It also guarantees that energy capacity is available if the bid for frequency regulations is selected. The BESS should also satisfy the maximum charging and discharging power limits, given in (4.15) and (4.16). Lastly, the inequality constraint given by (4.17) makes sure that the cycle lifetime is not exceeded and that the cycles are spread out between the years for the entire calendar lifetime of the BESS.

Energy level in battery bank at the beginning of hour h:

$$E_{y,h} = E_{y,h|h-1} + \Delta t \cdot P_{y,h|h-1}^{\text{chr}} \cdot \eta^{\text{chr}} - \Delta t \cdot \frac{P_{y,h|h-1}^{\text{dis}}}{\eta^{\text{dis}}} \quad \forall y, h \quad [\text{kWh}] \quad (4.13)$$

where:

$$\begin{aligned} \eta^{\text{chr}} &= \text{charging efficiency of the BESS [\%]} \\ \eta^{\text{dis}} &= \text{discharging efficiency of the BESS [\%]} \\ E_{y,h} &= \text{energy level of the BESS at the beginning of the hour h [kWh]} \\ E_{y,h|h-1} &= \text{energy stored at the beginning of hour h-1 [kWh]} \\ P_{y,h|h-1}^{\text{chr}} &= \text{power charged during hour h-1 [kWh/h]} \\ P_{y,h|h-1}^{\text{dis}} &= \text{power discharged during hour h-1 [kWh/h]} \end{aligned}$$

Minimum and maximum energy level:

$$\text{SOC}^{\min} \cdot E^{\max} + \Delta t \frac{B_{y,h-1}}{2} \cdot \frac{1}{\eta^{\text{dis}}} \leq E_{y,h} \leq E^{\max} - \Delta t \frac{B_{y,h-1}}{2} \cdot \eta^{\text{chr}} \quad \forall y, h \quad [\text{kWh}] \quad (4.14)$$

where:

$$\text{SOC}_{\min} = \text{minimum SOC level } [\%]$$

Charging and discharging capacity limits:

$$0 \leq P_{y,h}^{\text{chr}} \leq P^{\max} \quad \forall y, h \quad [\text{kW}] \quad (4.15)$$

$$0 \leq P_{y,h}^{\text{dis}} \leq P^{\max} \quad \forall y, h \quad [\text{kW}] \quad (4.16)$$

Cycle lifetime:

$$\sum_h \Delta h \cdot P_{y,h}^{\text{dis}} \leq n \cdot E^{\max} \quad \forall y \quad [\text{kWh}] \quad (4.17)$$

where:

$$n = \text{maximum number of cycles}$$

4.3.2.4 Frequency regulation market constraints

There are different value streams for participation in the ancillary service market as seen in Section 3.1.2. The battery is assumed to participate in the FCR-N market (see Section 4.1). It is thereby compensated for both power and delivered energy. Note that compensation is given for power capacity if selected, even if it is not activated.

It is further assumed that the BESS is not limited by the response time requirement, as the system should be able to fulfill all requirements for all specified markets. The minimum volume bid constraints for the different services are given in Table 3.1 and the bids are fixed as described in Section 4.2.3. The bid price is the same for both up and down regulation. In addition, when the bid price for the storage is larger than the average cost for that specific hour, the bid is not selected. Note also that in the FCR-N market, the same amount is bid for up regulation as for down regulation. For example, if a bid is made for 2 MW, it should be able to offer 1 MW for up regulation and 1 MW for down regulation.

Minimum/maximum bid volume constraint:

$$b_{y,h}^{\text{bid}} \cdot B^{\min} \leq B_{y,h} \leq b_{y,h}^{\text{bid}} \cdot 2 \cdot P^{\max} \quad \forall y, h \quad [\text{kWh}] \quad (4.18)$$

where:

$$\begin{aligned}
b_{y,h|h-1}^{\text{bid}} &= \text{binary decision variable for bid at hour } h-1 && \in \{0,1\} \\
B^{\text{min}} &= \text{minimum power bid volume in FCR-N market [kW]} \\
B_{y,h|h-1} &= \text{bid volume for up/down regulation selected at hour } h-1 \text{ [kW]}
\end{aligned}$$

Dedicate power capacity for FCR-N market during the following hour after selected bid:

$$P_{y,h}^{\text{chr,spot}} + P_{y,h}^{\text{chr,RES}} \leq P^{\text{max}} - \frac{B_{y,h|h-1}}{2} \quad \forall y, h \quad [\text{kWh}] \quad (4.19)$$

$$P_{y,h}^{\text{dis,eu}} + P_{y,h}^{\text{dis,spot}} \leq P^{\text{max}} - \frac{B_{y,h|h-1}}{2} \quad \forall y, h \quad [\text{kWh}] \quad (4.20)$$

If the bid is selected and there is a down or up regulated hour, this needs to be delivered. The following constraints deliver the service in the activated hour

$$P_{y,h}^{\text{dis,up}} = b_{y,h}^{\text{up}} \cdot \frac{B_{y,h|h-1}}{2} \quad (4.21)$$

$$P_{y,h}^{\text{chr,dn}} = b_{y,h}^{\text{dn}} \cdot \frac{B_{y,h|h-1}}{2} \quad (4.22)$$

where:

$$\begin{aligned}
b_{y,h}^{\text{up}} &= \text{binary parameter - up regulated hour} && \in \{0,1\} \\
b_{y,h}^{\text{dn}} &= \text{binary parameter - down regulated hour} && \in \{0,1\}
\end{aligned}$$

Note that up and down regulation for FCR-N is never activated at the same time.

4.3.3 Investment

As described in the chapter 4.1, the cost of a new OHPL represents the value stream for investment in the new line scenario. For the BAU scenario there is no investment. Moreover, the microgrid scenarios include an initial BESS investment (4.23) and an annual cost for OPEX and augmentation (4.24), which correlates to a factor of the investment. For further details about the cost of the BESS, see Section 4.2.2.

$$C^{\text{inv}} = (1 + \alpha^{\text{EPC}}) \cdot (\pi^{\text{power}} \cdot P^{\text{max}} + \pi^{\text{energy}} \cdot E^{\text{max}}) \quad (4.23)$$

$$C_y^{\text{inv}} = \alpha^{\text{opx}} \cdot (\pi^{\text{power}} \cdot P^{\text{max}} + \pi^{\text{energy}} \cdot E^{\text{max}}) + \alpha^{\text{aug}} \cdot (\pi^{\text{energy}} \cdot E^{\text{max}}) \quad (4.24)$$

where:

$$\begin{aligned}
P^{\text{max}} &= \text{power capacity of the storage [kW]} \\
\pi^{\text{power}} &= \text{power related cost [kr/kW]} \\
E^{\text{max}} &= \text{energy capacity of the storage [kWh]} \\
\pi^{\text{energy}} &= \text{energy related cost [kr/kWh]} \\
\alpha^{\text{EPC}} &= \text{EPC cost [\% of investment cost]} , \\
\alpha^{\text{opx}} &= \text{OPEX [\% of investment cost/year]} \\
\alpha^{\text{aug}} &= \text{augmentation cost [\% of energy investment/year]}
\end{aligned}$$

4.3.4 Reliability

The social cost for the reliability is based on the probability of failure on the OHPL and the probability of the microgrid being able to serve the load in island operation mode. The social cost during an outage on the OHPL can further be divided into the cost for ENS and the revenue loss for curtailed energy. The cost of the lost opportunity to do energy arbitrage with energy storage during an outage is assumed to be neglected.

The cost for not covering the load is equal to the value of ENS. For the energy curtailed there is no income, therefore the revenue loss for energy that cannot be stored or used directly is the spot price times curtailed energy. Note that the dispatch model does not take into account the cost of reliability, but it can be modified in order to calculate this cost. The probability of failure is assumed to be equal during all time periods, therefore the average cost for ENS and revenues from RES is used instead of the spot price in the dispatch model. See Appendix A.1 for further details. The objective function (4.3) can be simplified as:

$$C^{\text{rel}} = - \sum_y \sum_h \pi^{\text{curtailed}} \cdot \Delta t (P_{y,h}^{\text{RES,spot}} + P_{y,h}^{\text{dis,spot}}) - \sum_y \sum_h \pi^{\text{VOLL}} \cdot \Delta t (P_{y,h}^{\text{chr,spot}} + P_{y,h}^{\text{imp,eu}}) \quad \Delta t \in h \quad [\text{Mkr}] \quad (4.25)$$

where:

π^{VOLL}	= value of loss load [kr/kWh]
$\pi^{\text{curtailed}}$	= value of curtailed energy [kr/kWh]
$\Delta t (P_{y,h}^{\text{RES,spot}} + P_{y,h}^{\text{dis,spot}})$	= curtailed energy [kWh]
$\Delta t (P_{y,h}^{\text{chr,spot}} + P_{y,h}^{\text{imp,eu}})$	= ENS [kWh]

In the reference scenarios, it is assumed to be no use of the RES when a fault on the OHPL connected to the main grid occurs. This is due to the lack of off-grid possibility. Consequentially, all the power from RES that was supposed to be generated during an outage is curtailed and no load can be served in the reference scenarios.

For the microgrid scenarios the RES can generate power during a failure of the OHPL. But in the case when the battery is fully charged and there is a net positive energy ($P^{\text{RES}} - P^{\text{load}}$), the RES is curtailed. It can also be curtailed if the net load is larger than the power capacity of the BESS during a failure.

4.3.5 Simple numerical test of dispatch model

In order to verify the model, four simple numerical hand calculations of the mathematical model was made where the expected result is compared with results from the dispatch model. The verification was made in steps of four, adding in complexity (see Figure 4.11). The following steps are presented:

- I. *BAU* - The power for the load ($P_{y,h}^{\text{imp,eu}}$) is imported from the main grid and power from the RES ($P_{y,h}^{\text{RES}}$) is exported to the main network. No economical flow between these two is possible.
- II. *Microgrid* - Energy can flow within the microgrid and import and export is possible.
- III. *Microgrid + bid* - As a first step of adding ancillary services, the bid volume for power capacity is included.
- IV. *Microgrid + up/down regulation* - If the bid is cleared, up or down regulation also needs to be supplied.

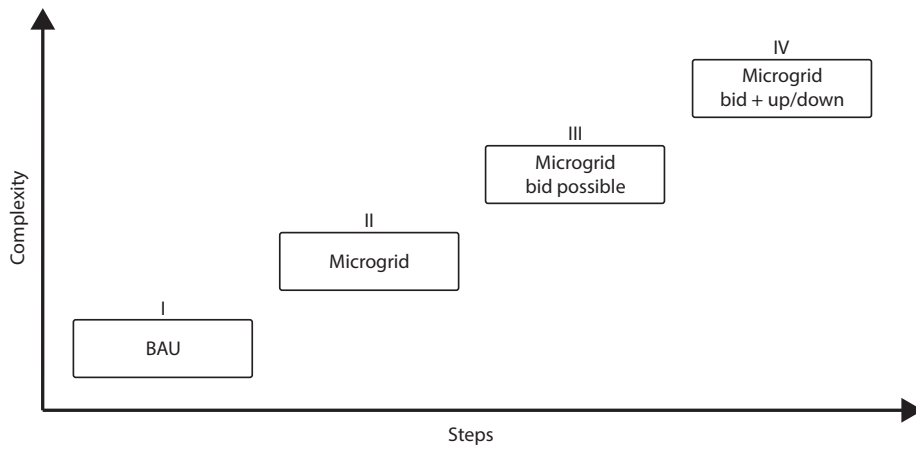


Figure 4.11: Steps for verification of the model, increasing in complexity

There is a large verity of possible settings to test, therefore only snapshot values for the different steps are presented. The verification is made with a charging and discharging capacity of 4 MW and storage capacity of 100 MWh, meaning that the storage capacity is not constrained by the upper limit. The storage is assumed to be fully discharged at hour zero.

4.3.5.1 Step I - BAU

Since no economical flow between the load and generation is possible, all RES are exported to the main grid and the load is covered by import of power from the main grid. The revenues from the RES are based on the spot prices and the cost for imported electricity correlated to spot prices + tariffs.

Table 4.5: Value snapshot of the BAU verification

Hour	1	2
Spot price [kr/MWh]	300	300
Load [kWh]	3,000	3,000
RES [kWh]	7,000	0

The cost calculation and energy flows are presented in Table B.1 in Appendix B. The result is a net social welfare of 186kr for the two hours. The same result can be observed in the dispatch model.

4.3.5.2 Step II - Microgrid

In this step, the energy storage in the microgrid can either be used for arbitrage with the main grid or for load shifting. Depending on the spot price and the relation between load and generation, there are different outcomes. With the input data given in Table 4.6, the following three outcomes are possible ($\pi^{\text{spot}} > 0$):

Table 4.6: Value snapshot of the microgrid verification

Hour [t]	1	2
Spot price [kr/MWh]	300	x
Demand [kWh]	3,000	3,000
RES [kWh]	6,000	6,000

- A The storage is not used - the spot difference is too low.
- B At a minimum spot difference of $\frac{\pi_t^{\text{spot}} - \pi_{t-1}^{\text{spot}}}{\pi_{t-1}^{\text{spot}}} \geq \frac{1}{\eta_{\text{chr}} \eta_{\text{dis}}} - 1 = 18.1\%$, it is beneficial to use the storage to charge from the RES for load shifting/arbitrage.
- C At a minimum spot difference of 25.6% (spot price of 300 kr/MWh and tariff cost of 19 kr/MWh), arbitrage by importing electricity from the main grid is feasible, under the condition that the RES is not enough to cover both the load and maximum charging rate.

Based on the input data above and on the possible outcome for the dispatch (see Table B.2 in Appendix B for further details), a linear relation can be set up (see Figure 4.12). Further, the result from the dispatch model is presented in the same graph, correlated to the optimal outcome.

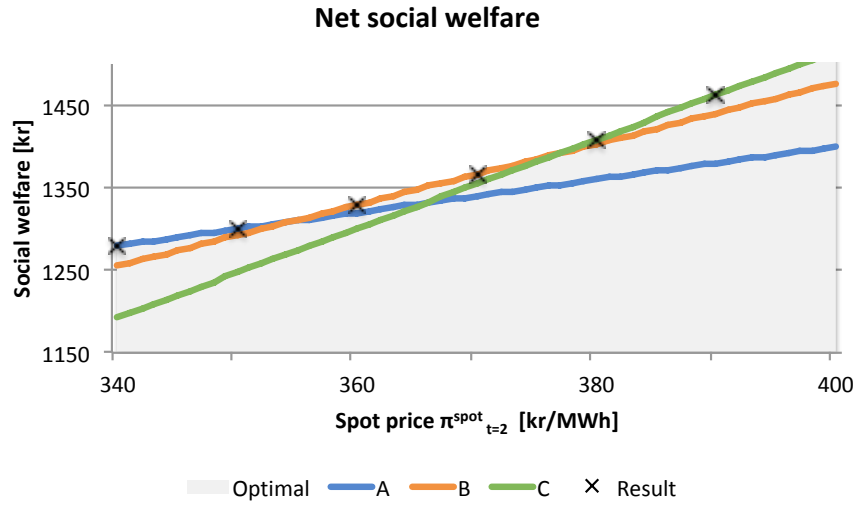


Figure 4.12: Net social welfare as a function of $\pi^{\text{spot}}_{t=2}$

4.3.5.3 Step III - Microgrid + bid

When adding the possibility for bid of reserves, the constraints are extended with minimum and maximum energy capacity. Since the bid includes both up and down regulation, a bid of 1 MW requires 0.5 MWh of available capacity during the next hour, both for charge and discharge. With a power capacity of 4MW and a relative large energy storage, together with the data presented in Table 4.7, the wind can cover both the load and a maximum charge rate of the battery. The need for import is thereby redundant.

Table 4.7: Value snapshot of the microgrid + bid capacity verification

Hour [t]	1	2
Spot price [kr/MWh]	300	x
Demand [kWh]	3,000	3,000
RES [kWh]	7,000	7,000

Based on the settings above and a spot price above zero, there are three feasible alternative outcomes:

- A The spot price at hour two is too low for the revenue from the bid to cover the charging cost at the first hour.
- B Maximize bid - The revenue from the bid is enough to cover the charging cost. Note that in order to discharge the energy storage at hour two, the full capacity can't be offered (see (4.19, 4.20)). In this way, the previous charging expenses can be collect at the second hour.
- C Maximize arbitrage - when the spot price difference is large, it is most profitable to charge at full capacity the first hour and discharge all energy the

second hour. In addition, since the entire discharging capacity (4 MW) is not used in the second hour, it is possible to bid in the first hour for the spare capacity.

Figure 4.13 presents the social welfare, depending on the spot price at the second hour. The result from the dispatch model correlates to the optimum of the hand calculation. For further details, the reader is directed to Appendix B Table B.3.

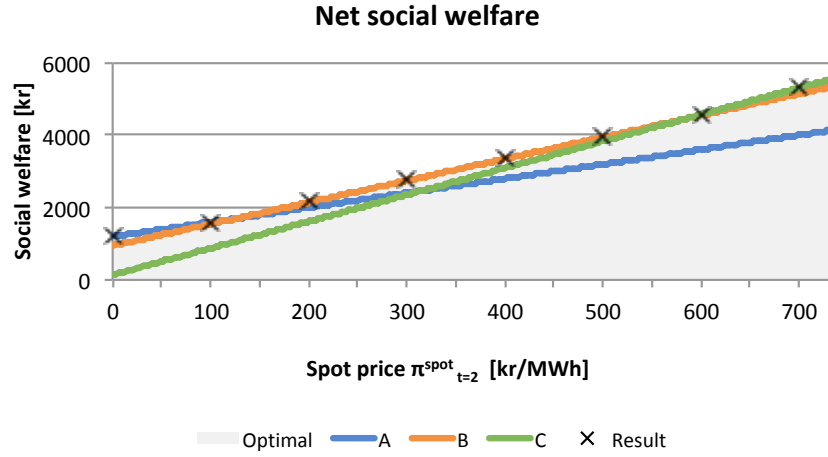


Figure 4.13: Net social welfare as a function of $\pi^{\text{spot}}_{t=2}$

4.3.5.4 Step IV - Microgrid + bid + up/down regulation

In the last step, the constraint of delivered frequency regulation is activated. For simplification, it is assumed to be up regulated hours and that the up regulating price is equal to the spot price for the activated hour.

Table 4.8: Value snapshot of the microgrid with up regulation verification

Hour	1	2
Spot price [kr/MWh]	300	x
Demand [kWh]	3,000	3,000
RES [kWh]	7,000	7,000

Comparing the feasible outcome in step III, only two of these are feasible when adding up-regulation (see Appendix B.1 Table B.4 for further details):

- A The spot price at hour two is too low for the revenue from the bid and up regulation to cover the charging cost at the first hour.
- B Maximize bid (battery capacity $\cdot \eta^{\text{dis}}$) + up regulation - charge maximum the first hour in order to maximize the bid. Compared to step III, the energy storage could be fully utilized the second hour due to up-regulating hour.

C Maximize arbitrage - not feasible. Comparing case B and C, the revenues are equal the second hour. In addition, the first hour, case B gets additional revenue for selected bid.

The result of the outcomes can be seen in Figure 4.14, where the results of the dispatch model correlates to the optimal region of the outcomes.

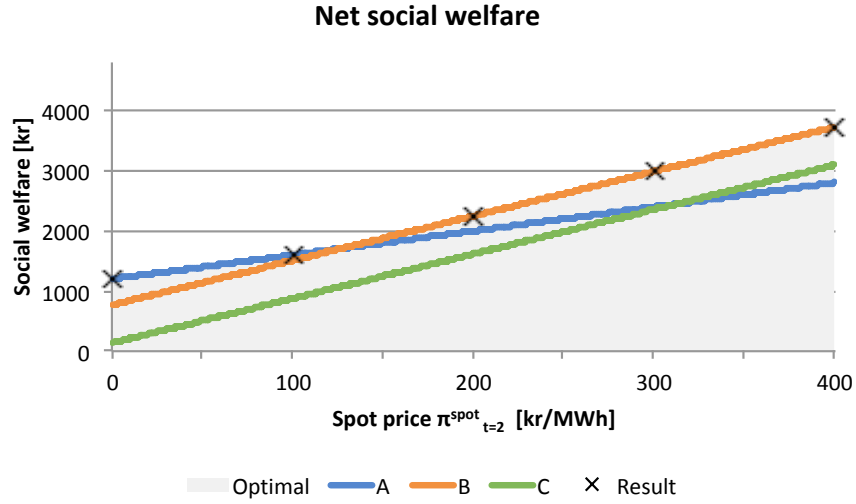


Figure 4.14: Net social welfare as a function of $\pi_{t=2}^{\text{spot}}$

5

Results

The result can be divided into three components, as previously described in Section 4.3. Firstly, the dispatch model, which takes into account the local demand and generation of the RES and the energy storage. Secondly, the reliability cost, including value of loss load and curtailed energy. Lastly, in the new line scenario and microgrid scenarios, investment related costs. These three components added together, equals the total social welfare. The difference between the BAU case and the analyzed case, is the net gain/loss. The result is presented for 10 years, where it is based on hourly values from 2013-2017.

5.1 Reference scenario

The value streams of the reference cases can be seen in the Figure 5.1 where the BAU scenario shows a larger net social welfare (see Appendix C for calculations). This is due to the lower social costs of the BAU reliability in comparison to investing in a new OHPL. Furthermore, the costs of investment and reliability are negligible in relation to the social benefits of dispatch, which can be explained by the high wind power production from the area.

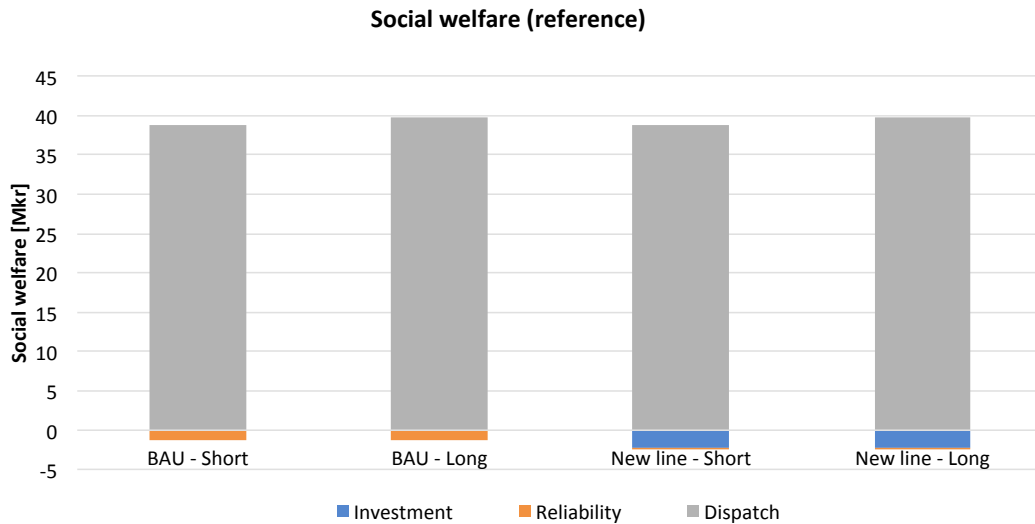


Figure 5.1: Value streams of reference scenarios presented over the 10 year period. The benefits for the two cases are the same, whereas the BAU shows a lower social cost

In reality, it can seem unrealistic to invest in a overhead line that goes in the same corridor as the old one, clean from trees. It is also hard to get permits for creating a new corridor. An investment of an underground cable in the new line scenario was therefore investigated, to see how this could affect the social welfare. This resulted in a four times as high investment cost, seen over the lifespan (see Figure 5.2). However, even with a more expensive line, the cost will be relatively low in relation to the benefits in social welfare for dispatch. An alternative OH line with less reliability for the BAU scenario could result in a significant decrease in social welfare. This indicates that the tree secured OH line used in the BAU scenario is relatively reliable and in another type of area with an OHPL with a reliability as the alternative OH line, the benefits of investing in a microgrid would increase.

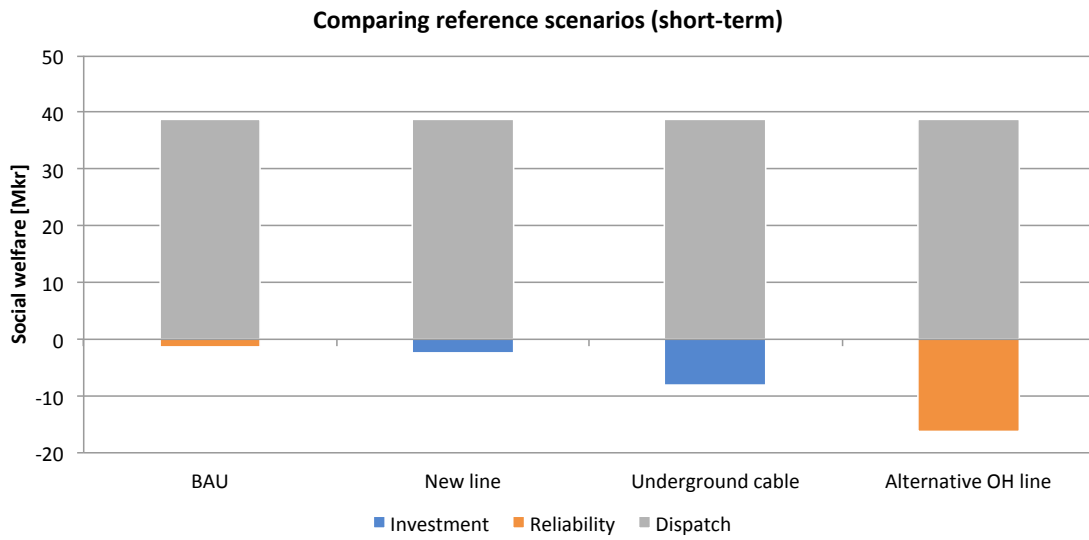


Figure 5.2: NPV of the value streams for the short-term reference scenarios over 10 years. The result is compared with a BAU scenario where the OH line is less reliable (66 kV OH line on Island). A new line scenario is also presented where the investment is a underground cable

5.2 Sizing of the battery energy storage system

The sizing of the battery energy storage system can be based on a technical point of view, i.e. analyze of energy flow, power flow and reliability. It can also be based on an economical point of view, i.e. total social welfare. This section focuses on a technical point of view. Note that the technical point of view still is based on the objective function where the dispatch of the energy is optimized in order to gain a maximized social welfare.

5.2.1 Loss of load probability

By analyzing the loss of load probability (LOLP) in island mode for different power and energy capacities, a minimum requirement for power capacity could be deter-

mined. In other words, the RES are utilized to the maximum together with the loads and battery. By analyzing the capacities in island mode, an under dimensioned system can be avoided. A LOLP of 10% means that the microgrid can be self-sufficient for 90% of the time in case of random outage event. In Appendix A.1 Table A.4, the calculation is further described.

From the Figure 5.3a it can be seen that a power capacity between 4-6 MW gives a marginal difference in LOLP, whereas 2, 3 and 4 MW shows a visible difference. In other words, a power capacity above 4 MW has a negligible impact of the reliability. The load distribution curve (Figure 5.3b) also shows that for most of the hours, 4 MW is sufficient to supply the load, even in a situation of no wind or sun. How long the microgrid can be self-sufficient depends on several conditions, where the energy level in the energy storage is one important factor. It is though important to highlight that for planned outages or for extreme weather condition, there is a possibility to plan the energy storage accordingly.

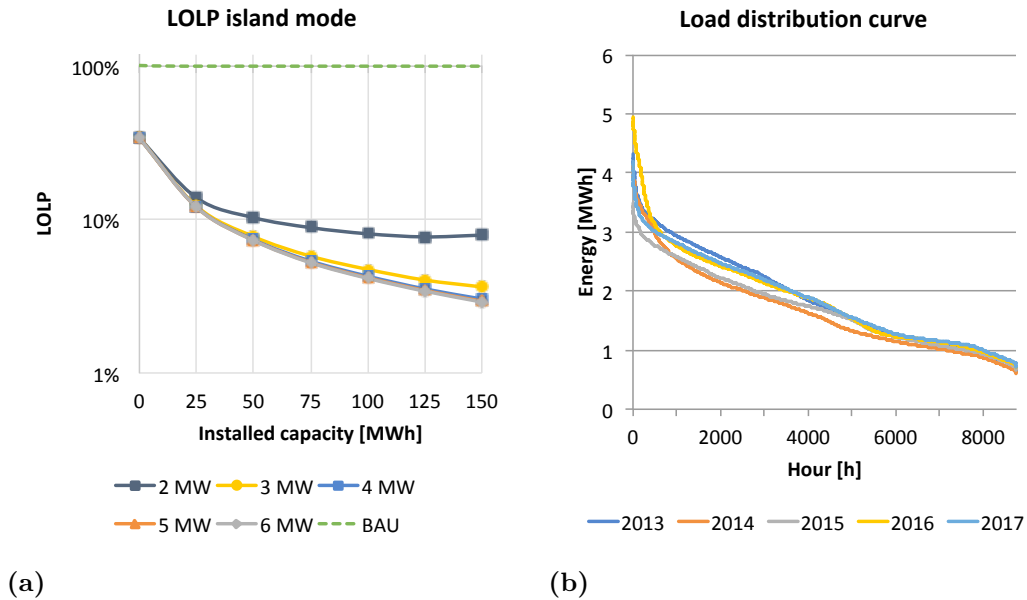


Figure 5.3: (a) The loss of load probability and energy capacity for different power capacities of the battery energy storage system and (b) the load curve for the end user over 5 years

5.2.2 Energy trade

The energy and peak power import/export for the long-term scenario can be seen in Figure 5.4. Since the short-term scenario shows similar results, only the long-term is presented. It can be seen that with a microgrid, the import of electricity is increasing between 13-73%, where with participation in FCR-N market the import of electricity is increasing in the range 93-427% (comparing the BAU line with the 4, 5 and 6 MW lines). With the FCR-N market, the result is clearly differentiated between the power capacities first after 75 MWh. With FCR-N and for a power capacity

of 4 MW a energy capacity above 100 MWh gives no increase in trade between the microgrid and the main grid. Similarly, with no FCR-N market participation a power capacity of 4 MW, gives no further trades at an installed capacity of 50 MWh or higher. This energy capacity would cover the average load of 1.8 MW for 28 hours, if the battery is fully charged and there are no solar and wind production. The result also shows that this battery size would give an increase of energy import of 2000 MWh/year and an export of 1500 MWh/year from the microgrid.

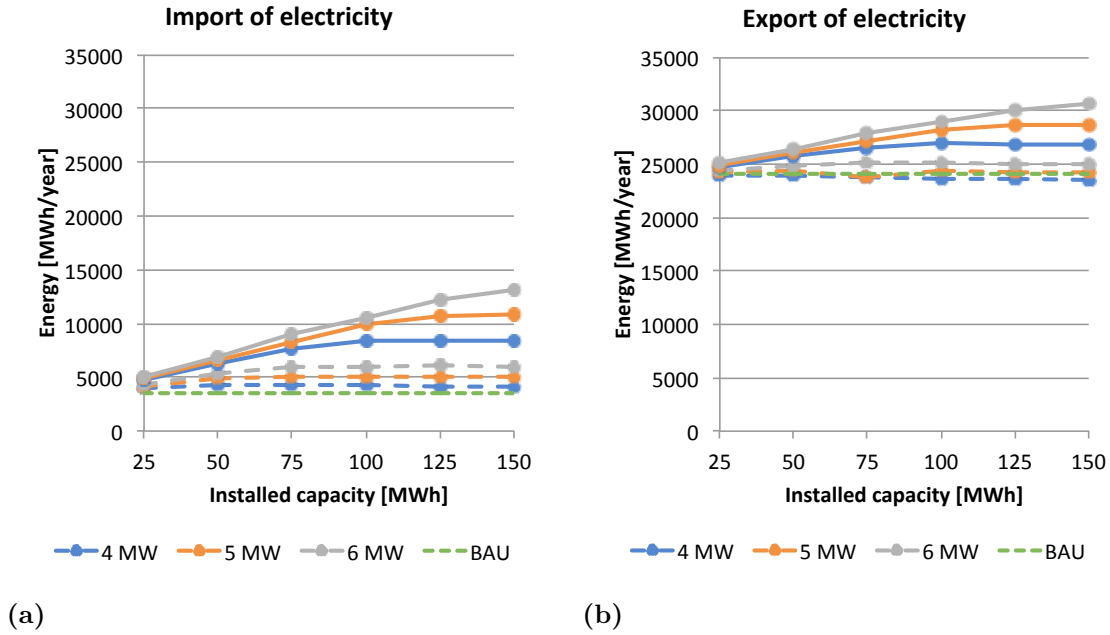


Figure 5.4: The import and export of energy from the microgrid to the main grid for the long-term scenario, with different power and energy capacities of the BESS. Solid line represents dispatch with frequency regulation and dashed line represents without. Green dashed line represent the value of the BAU case. (a) shows the energy import and (b) shows the energy export

In similar manner, the import and export of peak power increases with a higher BESS power capacity in compare with the BAU case, see Figure 5.5. It is important to highlight that no power transfer limit was set, which potentially could create problems if the OHPL limits is reached. With a power capacity of 4 MW of the BESS, the OHPL needs to be able to supply a minimum of 17 MW of power. In relation to the 13 MW for the BAU case.

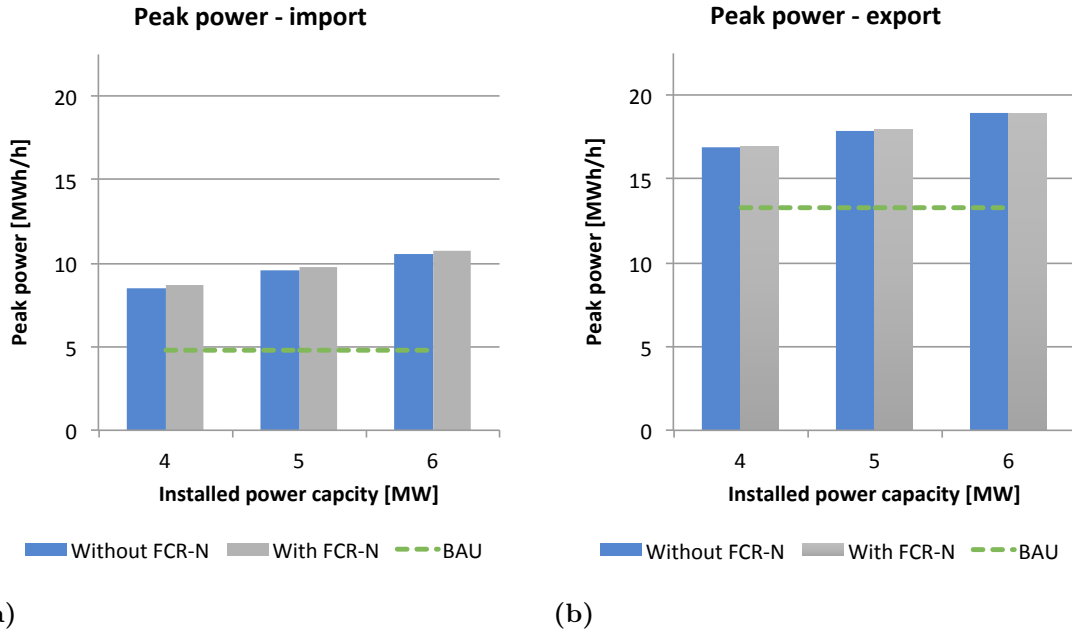


Figure 5.5: The import and export of peak power from the microgrid to the main grid for the short-term scenario, with different power capacities of the BESS. (a) shows the import of electricity to the microgrid from the main grid and (b) shows the export of electricity from the microgrid

5.2.3 Discussion of sizing

To conclude, the results show that from a reliability point of view, 4 MW is sufficient, whereas from a trade point of view, 6 MW could give further exchange with the main network. In energy terms, installing BESS larger than 50 MWh when no participation in FCR-N is included, does not increase the trade between the main grid and the microgrid. Whereas it could be beneficial to have an energy capacity above 50 MWh if FCR-N is included. The FCR-N could though be seen as an additional benefit if spare capacity is available, and not be the sizing factor. This since there are uncertainties in how the FCR-N market for batteries would look like and there are no examples of this in Sweden. It should also be pointed out that in both cases, the forecast is perfectly foresighted, and the bids and up/regulations in the FCR-market is maximized, which most likely would not be the case. Especially since the bids in reality are made in day ahead.

It is also important to highlight that limiting the power transfer limit, most likely will have an effect on the annual traded energy. Consequentially, a lower energy capacity could be enough. Also, aggregated load and generation within the each hour is used. The frequency regulation within the microgrid is therefore not taken into account for, which means that there might not be possible to offer the entire power capacity of the BESS to the main grid. This could result in a lower social welfare and a different optimal size.

5.3 Economical evaluation of microgrid scenarios

5.3.1 Cost of the battery energy storage system

The cost increases with a higher power capacity (Figure 5.6) and according to previous chapter the size of 4 MW could be a suitable size. But when connected to the main grid, there can also be net benefits with increased power capacity, therefore, 5 and 6 MW power capacities are also analyzed.

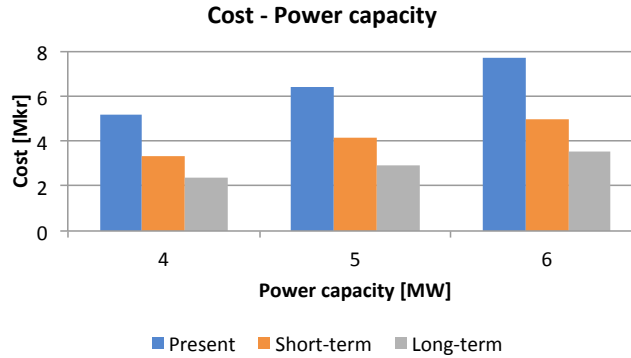


Figure 5.6: The cost for the power related part of the lithium-ion BESS. Short-term scenario is represented by the cost projection of 2022 [27], and the long-term for 2030 [28]

Likewise, the cost increases depending on the energy capacity for the BESS. Six different energy capacities are analyzed, where the cost is presented in figure 5.7. The short-term scenario has a expected cost decrease of 36% and long term 54%.

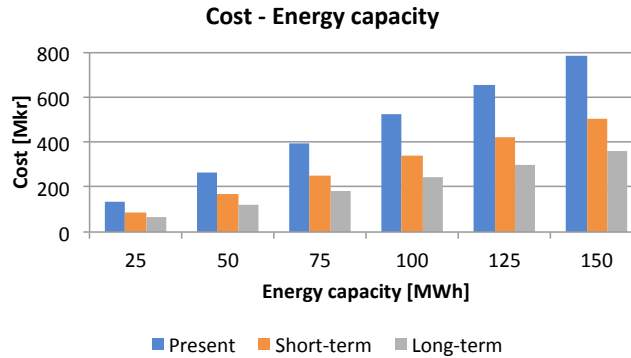


Figure 5.7: The cost (NPV) for the energy related part of the BESS. Short-term scenario is represented by the projection of 2022 years cost and long term for 2030. For NPV of O&M and augmentation cost, see Table C.3 in Appendix C

5.3.2 Short-term scenario

The result from the dispatch model described in Section 4.3.2 can be seen in Figure 5.8. The solid lines show the social welfare with frequency regulation. Since the

dispatch model are not taking into account the probability of activated up/down regulation and that the bids are made day ahead, the dispatch without frequency regulation are presented as well (dashed lines). This shows the span of social welfare that the dispatch could obtain if optimally dispatched. Adding frequency regulation, the battery uses all of its 127 cycles per years (see sensitivity analysis), and the social welfare increases. It can also be seen at even at a very small range, close to 0 MWh of installed energy capacity, there is still a net benefit for the microgrid case. This since the tariffs for the end-user is reduced due to the possibility to send electricity from the RES to the end-user. Even though the physical flow still is the same. For NPV calculations, see Appendix C.

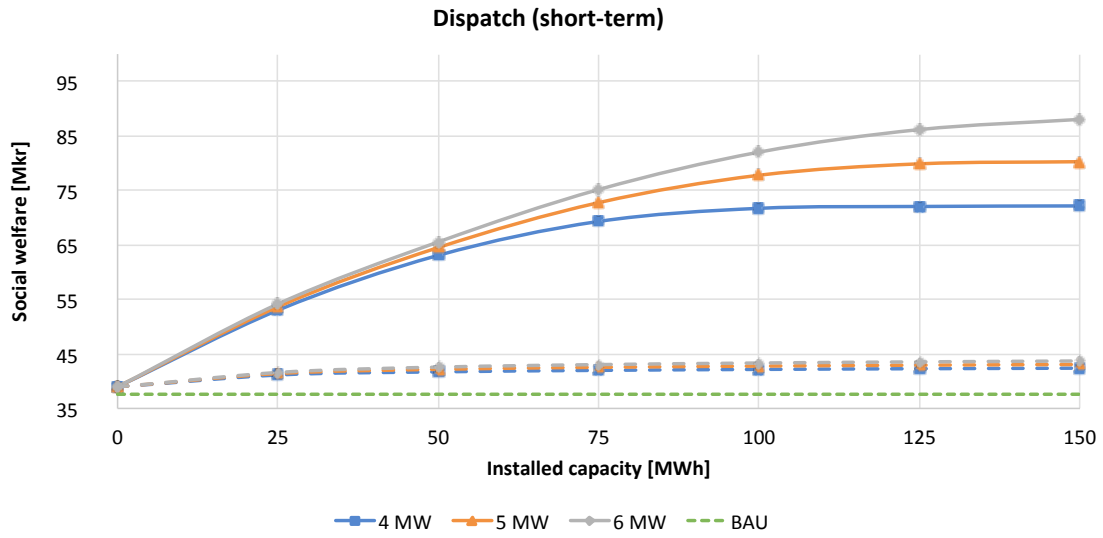


Figure 5.8: Social welfare for the short-term scenario of the dispatch model. Solid line represents dispatch with frequency regulation and dashed line represents without. Green dashed line represent the value of the BAU case. Values are given in NPV, based on a 10-year simulation.

Comparing the social welfare results from the dispatch model with the value of ENS and curtailed energy (see Figure 5.9), the value is negligible in comparison (note the log scale). Only a very small difference between the power capacities can be observed. The reduced cost of lost load (solid line) and curtailed energy (dashed line) can be explained by a high reliability of the OHPL. In the reference case (green line), none of the loads are served and all RES are curtailed during an outage. See Table C.3 Appendix C for NPV calculations.

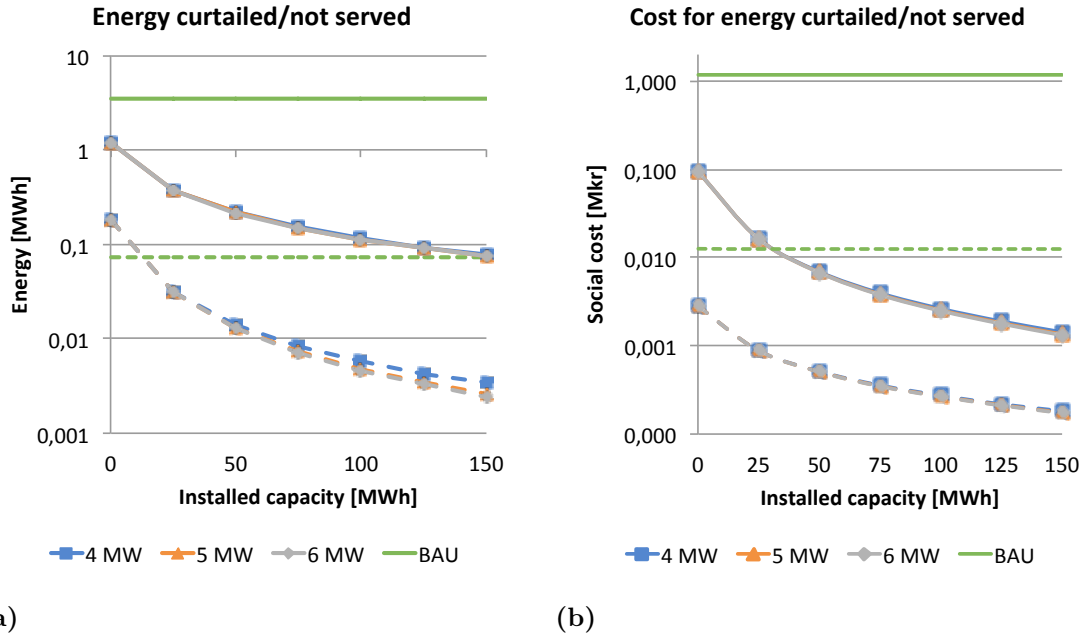


Figure 5.9: The value of ENS and curtailed energy (note the log scale). Solid line indicates the value of ENS and dashed line curtailed RES. The graph is given in NPV, based on a 10 year simulation where (a) shows energy and (b) economics

Adding the social welfare from the dispatch model, the value of ENS, curtailed energy and the cost of energy storage, Figure 5.10 can be obtained. Given the estimated cost of energy storage for the short-term scenario, adding storage gives a negative social welfare for all analyzed power and energy capacities. This includes both with and without ancillary service value streams. For the short-term scenario the results shows a social welfare loss of 150 Mkr in compare with the BAU case.

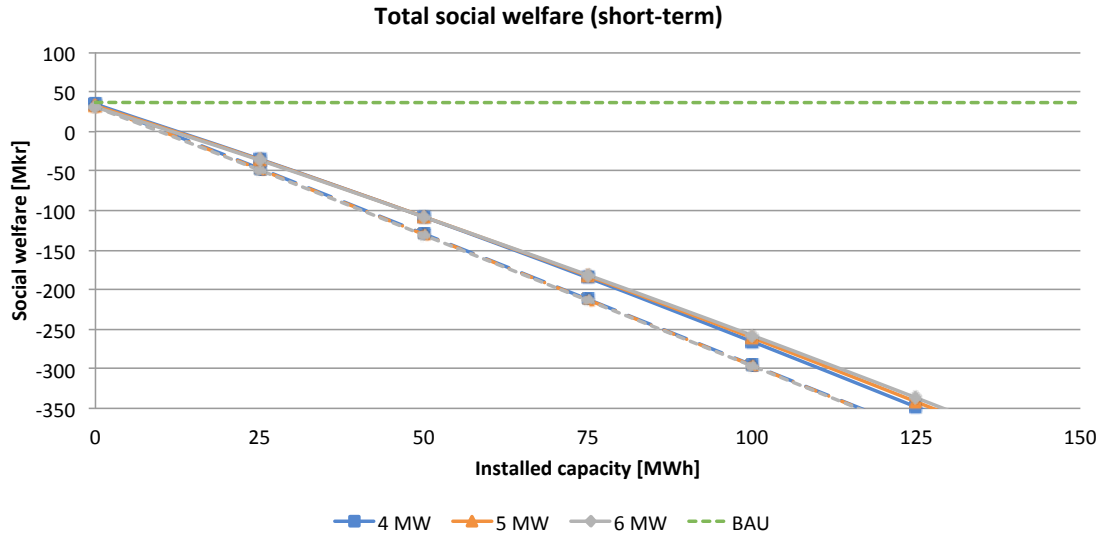


Figure 5.10: Total social welfare including result from dispatch, value of ENS, curtailed energy and investment cost. Result presented in NPV, based on a 10-year simulation. Solid line represents dispatch with frequency regulation and dashed line represents without. Green dashed line represent the value of the BAU case.

In order for the investment to be cost effective, the energy storage cost could be reduced. Figure 5.11 shows the outcome of reduced BESS cost for a 6 MW power capacity. The short-term scenario with 36% reduction is according to the results not beneficial. With optimal dispatch in frequency regulation market, benefits of energy storage could first be seen at a cost reduction above 85%, whereas without participating in frequency regulation market, a reduction above 95% obtains benefits. For 90% reduction from current values with participation in the frequency regulating market, the maximum benefits could be found at 25 MWh of storage. Furthermore, at a 95% price decrease with ancillary service, the optimal energy capacity is found at 50 MWh. If instead the energy storage would come at a zero cost, a storage capacity over 75 MWh is abundant for the analyzed power capacities.

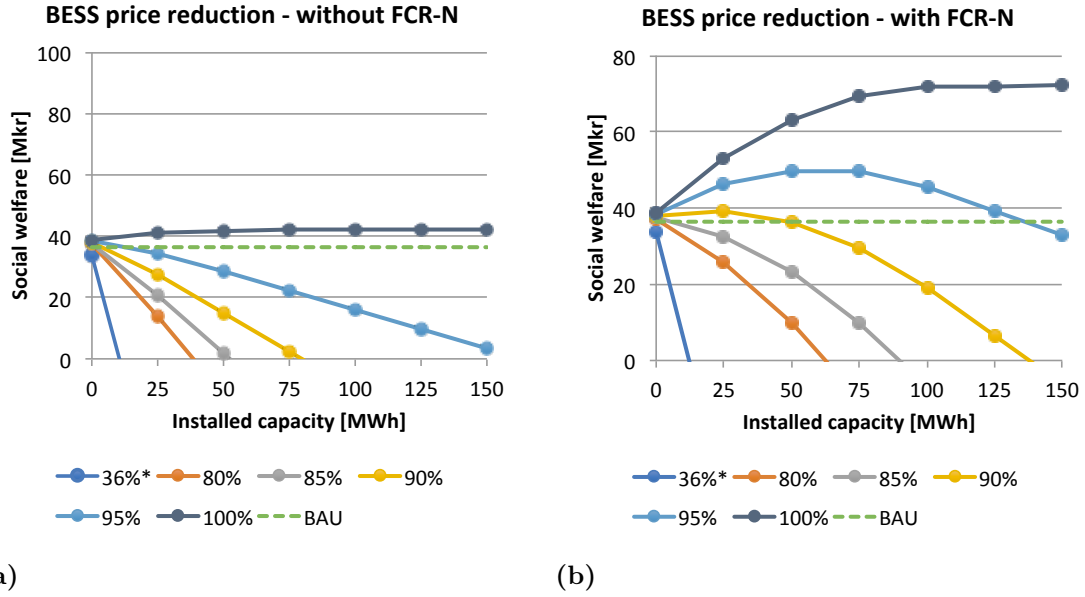


Figure 5.11: Total social welfare as a function of BESS cost reduction from present values. NPV are presented for a power capacity of 6 MW. (a) shows the social welfare without participation in the frequency regulation normal market and (b) shows with participation. * indicates initial value

5.3.3 Long-term scenario

Comparing Figure 5.12 with the results from the short-term scenario (Figure 5.8), it can be seen that the social welfare is increased when the tax for the energy losses in the storage is removed, and the energy storage is seen as a flexibility resource. In compare with the short-term scenario there is an increase of 4 Mkr for 50 MWh of energy capacity and 4 MW of power. By removing the tax, it makes the storage more profitable and there are more incentives for load shifting and arbitrage. This since the economical losses is reduced. At a energy capacity of 35 MWh, there is not a big difference in the welfare between the power capacities, whereas the difference between the sizes increases and fades at 150 MWh. See Table C.3 Appendix C for NPV calculations. .

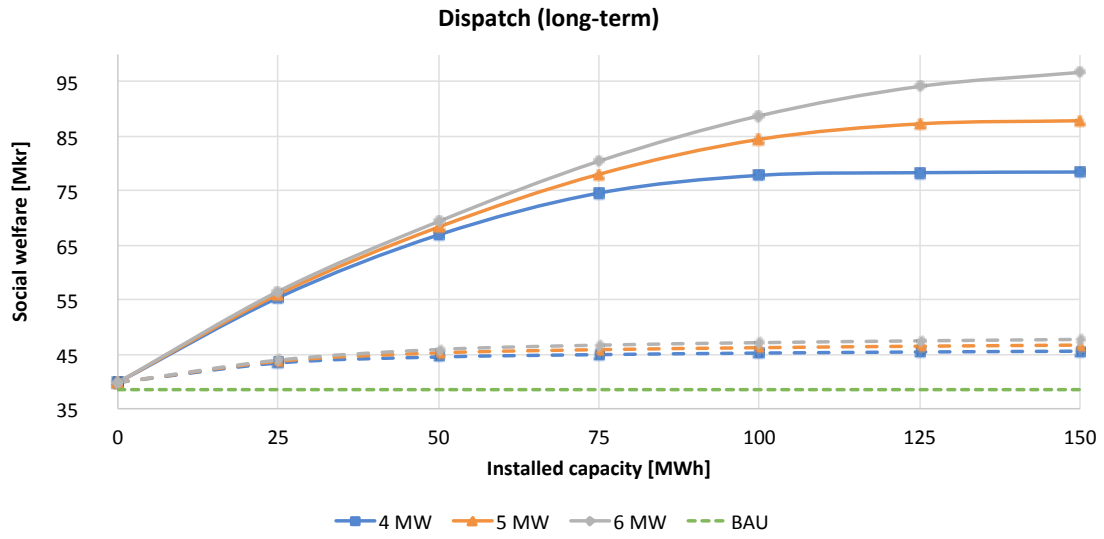


Figure 5.12: Social welfare for the long-term scenario of the dispatch model. Solid line represents dispatch with frequency regulation and dashed line represents without. Green dashed line represent the value of the BAU case. Values are given in NPV, based on a 10-year simulation

The value of loss load and curtailed energy are similar to the short-term case, see Figure 5.10. Between the short and long-term scenario regarding the load and generation, only solar power capacity differs. This would increase the curtailed energy in island mode. But since the results shows that the value of curtailed energy is very small in comparison to other revenues and costs, the graph is not presented for the long-term scenario.

In similarity with the short-term scenario, the cost for the energy storage results in a negative NPV for the social welfare (see Figure 5.13). In this case, the social welfare with energy storage is greater than the short-term and there is a more visible difference with and without participation in frequency regulation normal market. For the long term case included FCR-N with 4 MW of power and 50 MWh installed energy capacity there is an cost of 90 Mkr in comparison to the BAU case. Which corresponds to an increase of 50 Mkr in comparison to the short-term scenario.

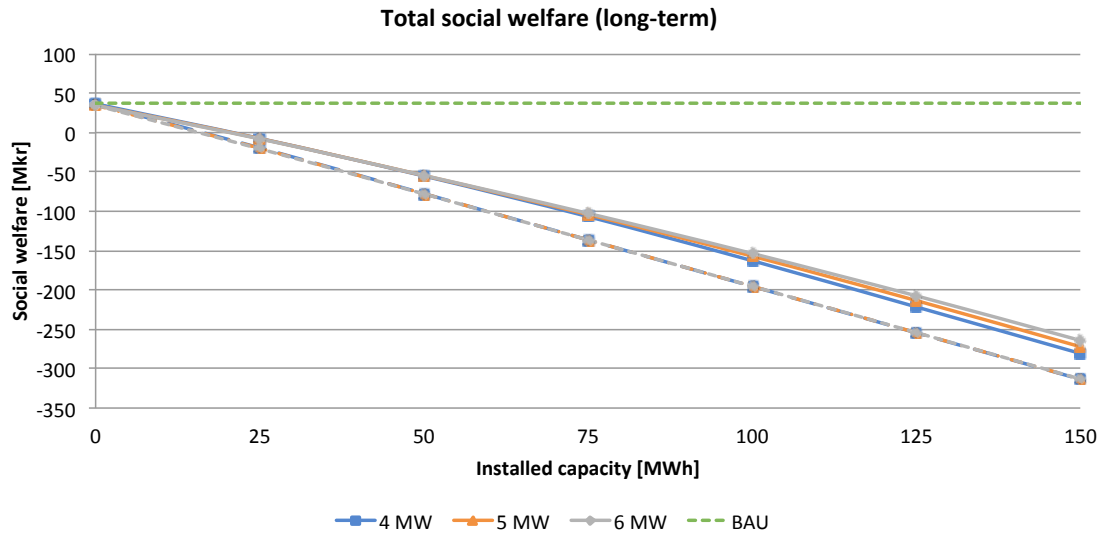


Figure 5.13: Total social welfare including result from dispatch, value of ENS, curtailed energy and investment cost. Result presented in NPV, based on a 10-year simulation. Solid line represents dispatch with frequency regulation and dashed line represents without. Green dashed line represent the value of the BAU case.

For the long term scenario (Figure 5.14) with 54% cost reduction there is still a significant cost reduction of BESS needed to make an increase in social welfare. When compare the short (Figure 5.11b) and the long-term scenario, it can be seen that the cost reduction gives higher social benefits in the long-term case. Similar as the short-term case, there is needed over 85% cost reduction to make the scenario beneficial for the society.

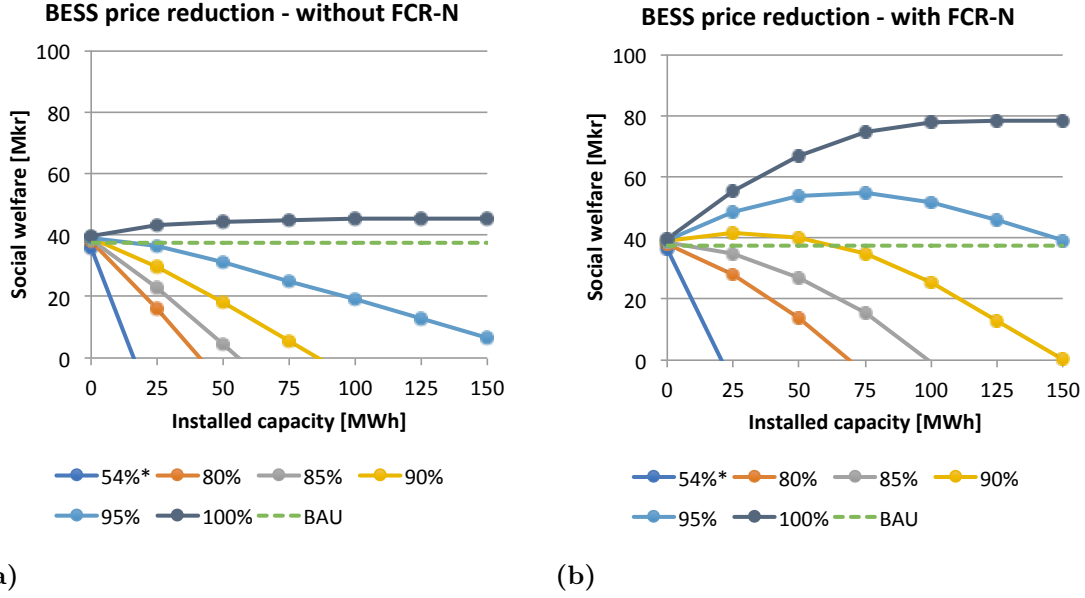


Figure 5.14: Total social welfare as a function of BESS cost reduction from present values. NPV are presented for a power capacity of 6 MW. **(a)** shows the social welfare without participation in the frequency regulation normal market and **(b)** shows with participation. * indicates initial value

5.4 Sensitivity analysis

In order to investigate the robustness of the results, the sensitivity of economic, technical, load and generation parameters were tested. In the analysis of the long-term scenario, a power capacity of 6 MW was used. For the short-term scenario, the effect of the sensitivity analysis is assumed to be similar.

5.4.1 Cycles life length

How the cycle life length of the BESS affects the social welfare can be seen in Figure 5.15, where the case a) is without FCR-N market participation and b) with. In the case with no participation in the FCR-N market, it can be seen that the number of cycles has a low impact on the social welfare. Figure 5.15 shows though that the number of cycles is constrained for the relative low energy capacities. With a storage capacity of 50 MWh, 160 cycles per year would be enough for optimal dispatch, compared to the initial 127 cycles per year. .

When the frequency regulation market is included, the cycle life has a big impact on the social welfare, see figure 5.15. Especially when the installed energy capacity is in the lower end of the analyzed sizes. For 25 MWh installed capacity with FCR-N, the 50 cycles per year corresponds to a social welfare of 53% in relation to the case of unconstrained number of cycles. Whereas 4% without FCR-N market participation. Figure 5.15a further shows the number of cycles that is reached.

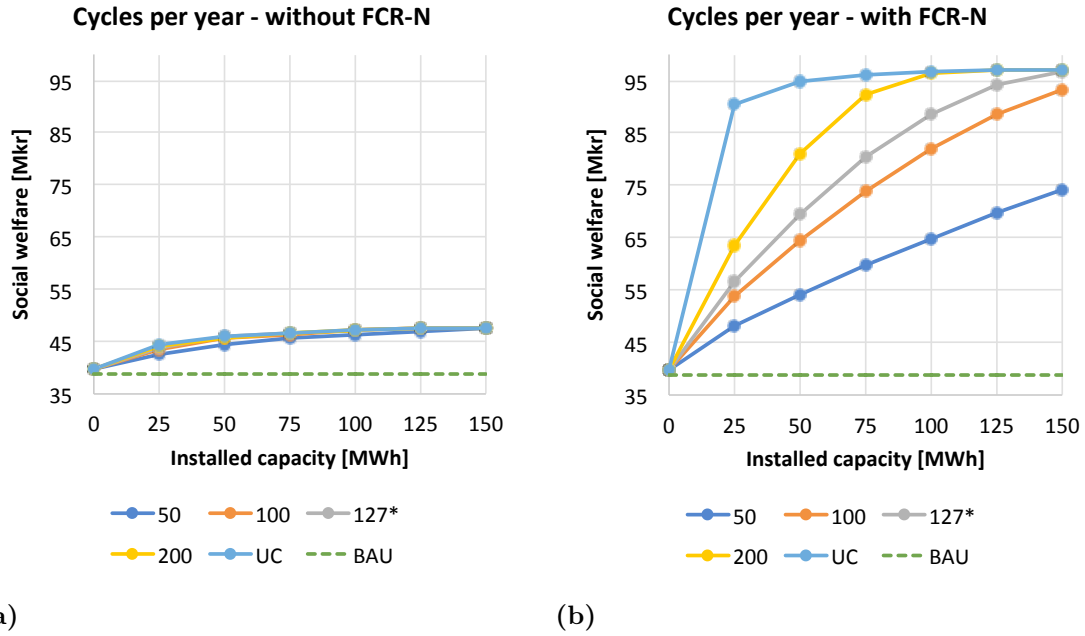


Figure 5.15: Sensitivity analysis for the social welfare as a function of the number of cycles per year, for different installed BESS energy capacities. The analysis is made on the long-term scenario with an capacity of 6 MW. **(a)** shows the social welfare without participation in the frequency regulation normal market and **(b)** shows with participation. * indicates initial value, UC indicates unconstrained number of cycles

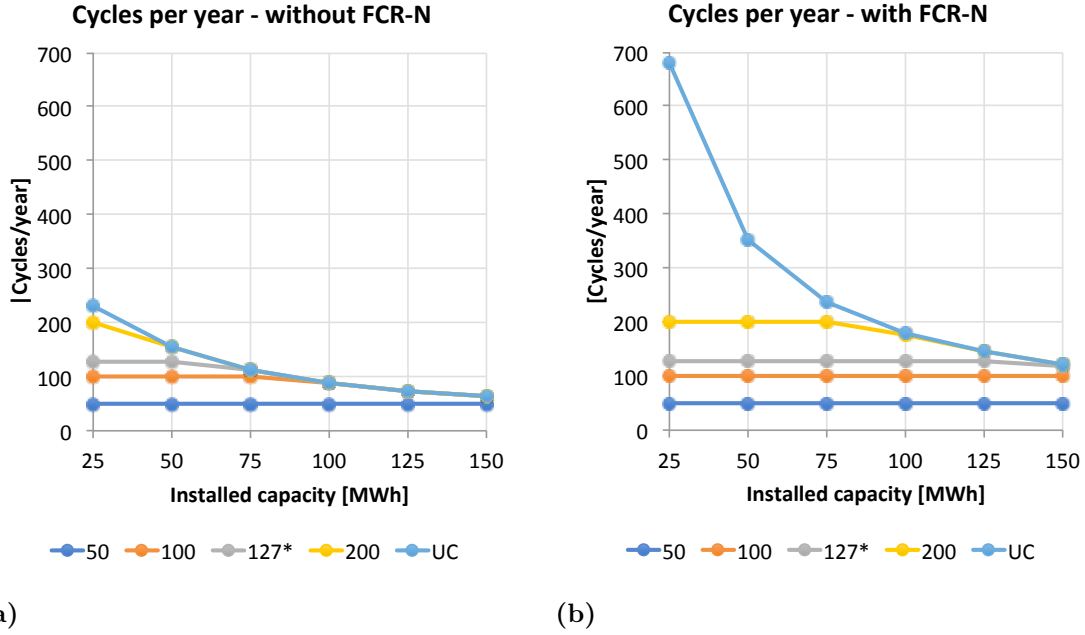


Figure 5.16: Sensitivity analysis of the number of cycles per year depending on bid price for different BESS energy capacities. The analysis is made on the long-term scenario with an capacity of 6 MW. **(a)** shows the social welfare without participation in the frequency regulation market and **(b)** shows with participation. * indicates initial value, UC unconstrained number of cycles

5.4.2 Round trip efficiency

Increasing the round trip efficiency of the BESS, the storage is given economical incentives to be used more frequently, and thereby increasing revenues. The increase of the round trip efficiency, with (Figure 5.17a) and without (Figure 5.17b) participation in frequency regulation market, shows a low impact between in the lower range of installed capacity. Whereas without FCR-N there is a visible difference above 50 MWh and with FCR-N above 100 MWh. Note, since the analysis is made on the long-term scenario, it is no taxes for the energy losses in the BESS.

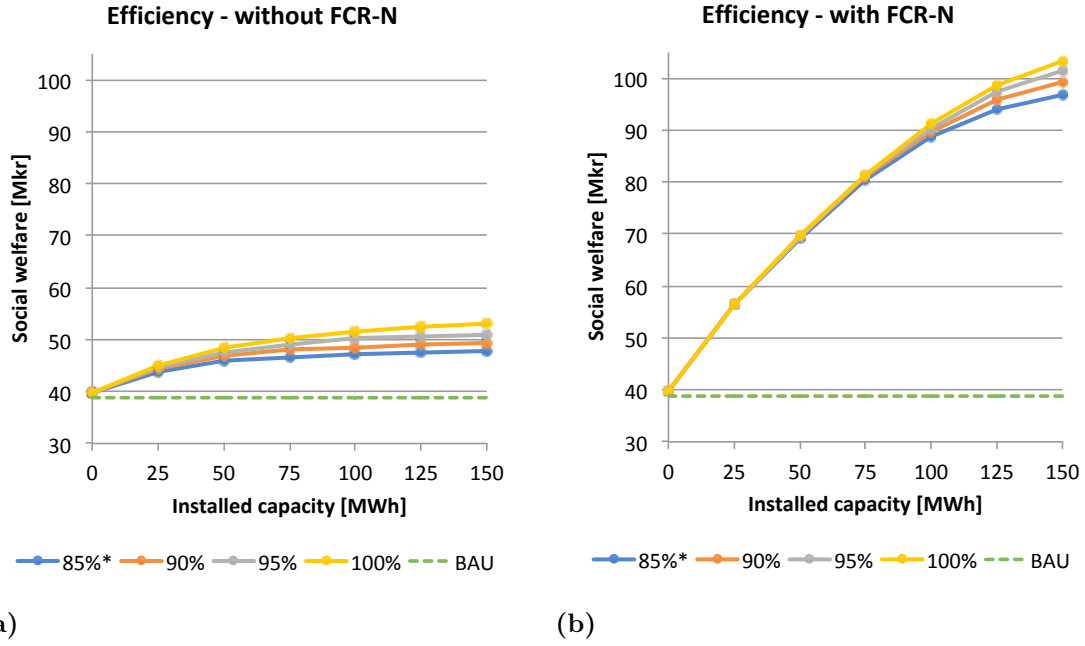


Figure 5.17: Sensitivity analysis for the social welfare as a function of round trip efficiency, for different installed BESS energy capacities. The analysis is made on the long-term scenario with an capacity of 6 MW. (a) shows the social welfare without participation in the frequency regulation market and (b) shows with participation. * indicates initial value

5.4.3 Load and generation

There is a high correlation between annual energy consumption for the end user and the social welfare (see Figure 5.18). The net social welfare between the BAU case (dashed lines) and the long-term case (solid line) is though only changed by 5 Mkr between the steps of $\pm 20\%$. A similar result can be seen when increasing the installed wind capacity (15 MW) with 10, 20 and 30 percent (see figure 5.19). Increasing the solar capacity from 750 kW with 10, 20 and 30 percent will have an even lower impact on the model because of the low share of the total generation. This since the result is similar to the load and wind capacity, but in lower range, it is not presented.

The result can be explained by a high amount of wind in the system and that the profiles for wind and load are the same, even with increased or decreased demand/-values. Altering the profile could have another outcome on the result, but since the simulation is based on five years of data, it is assumed to give a representative profile of wind and load.

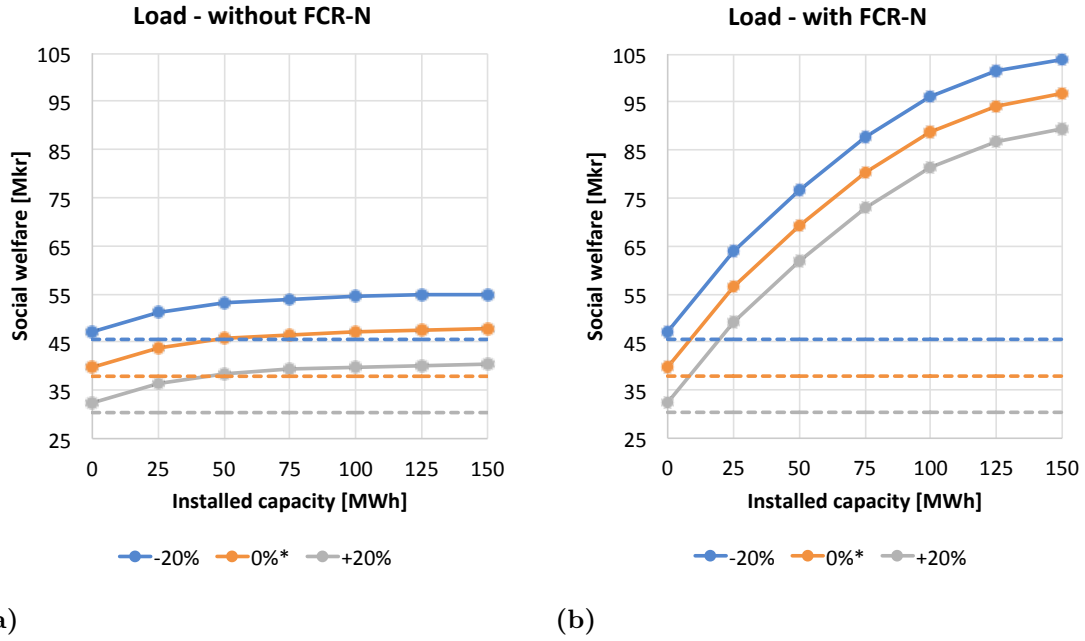


Figure 5.18: Sensitivity analysis for the social welfare with a changed load for different installed BESS energy capacities. Dashed lines indicate BAU case. (a) shows the social welfare without participation in the frequency regulation normal market and (b) shows with participation.* indicates initial value

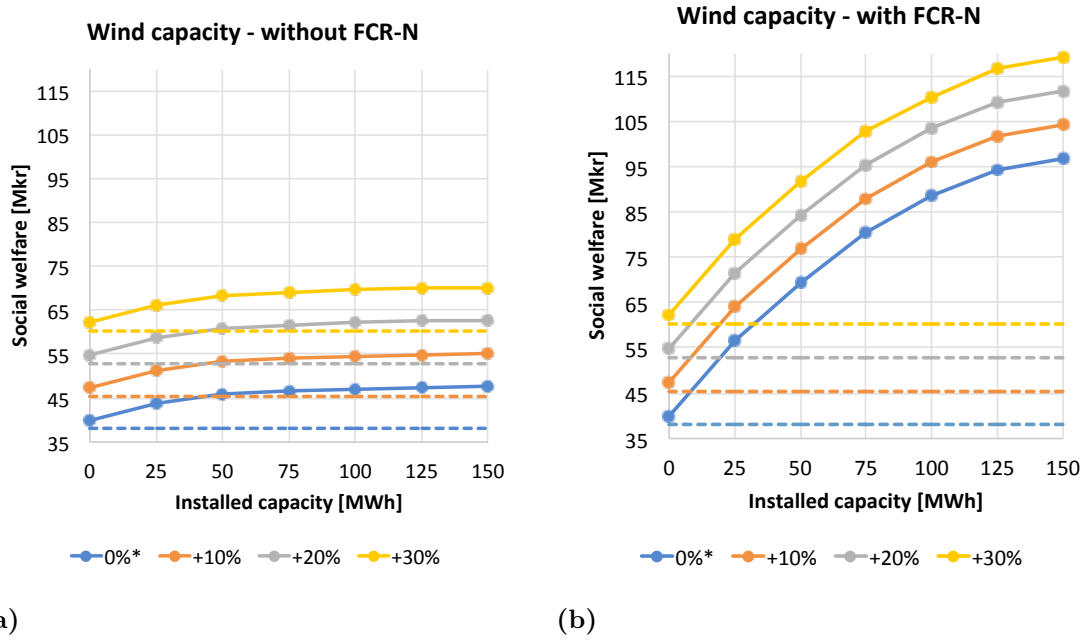


Figure 5.19: Sensitivity analysis for the social welfare with a changed wind capacity for different installed BESS energy capacities. Dashed lines indicate BAU case. The analysis is made on the long-term scenario with an capacity of 6 MW. **(a)** shows the social welfare without participation in the frequency regulation normal market and **(b)** shows with participation. * indicates initial value

5.4.4 Bid price in capacity market

Since the current frequency market are not allowing BESS in Sweden and because there are no guidelines for the cost, it is difficult to predict the pre-defined bid price (Section 4.2.3). From Figure 5.20, it can be seen that the pre-determined bid price (4.2.3) can have a big impact on the outcome of the social welfare for the dispatch. It also shows that for a larger installed capacity the social welfare increases with the bid price, but when the price changes from 150 kr/MW to 200 and 250 kr/MW, the social welfare declines at an energy capacity of 100 MWh and above. However, for a smaller installed capacity a higher bid price gives an increased social welfare. This can be explained by looking at the average pay-as-bid price in Figure 4.7. When the bid price is low, it has a high probability of being cleared, but the revenue per cleared bid is low. When the bid price is high on the other hand, the revenue per cleared bid is higher, but the probability of being selected is reduced.

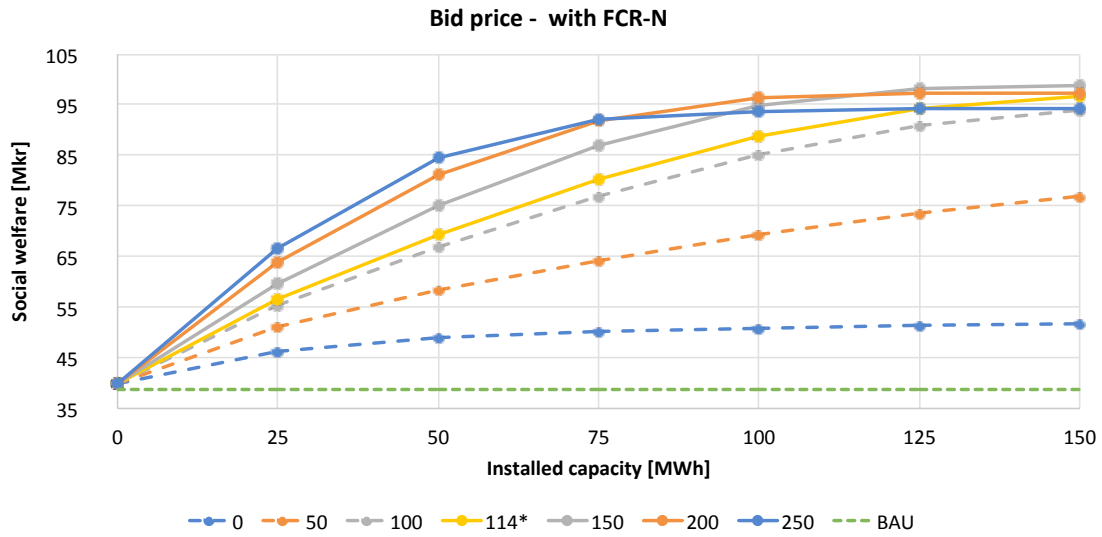


Figure 5.20: Sensitivity analysis showing the social welfare as a function of the bid price for different installed BESS energy capacities. The analysis is made on the long-term scenario with an capacity of 6 MW. * indicates initial value where dashed lines represent bid price under initial value and solid lines over the initial values. Green dashed line represent the value of the BAU case.

5.4.5 Discussion of sensitivity analysis results

The sensitivity analysis shows that the results are sensitive for the number of cycle per year. It is a limiting factor, especially with a low storage capacity compared to the power capacity. The larger the capacity, the more total energy can be cycled. It is though important to highlight that increasing the number of cycles to increase the revenues, most likely also will come at a increased cost for the investment. However, the cost related to maximum number of cycles is something that has not been looked into further.

For a changed amount of load and wind capacity, it can be seen that it does not have a big outcome on the results, compared to the BAU case. Also, the efficiency of the BESS has a relative low effect. Since the number of cycles is a limiting factor, the energy storage cannot be used further on an yearly bases. In the case with changed efficiency, the revenues are increased for arbitrage, but it does not create additional trade due to the cycles.

With FCR-N market participation, the bid price can also have a big effect on the outcome. In addition, since there are no examples of BESS participating today there is a big uncertainty for the estimated price and how the price will be set when the market is available for BESS.

6

Further discussion

6.1 Regulations

It is difficult to predict how the regulations are going to develop. If microgrids will be allowed in the future, as predicted in this report, it is still uncertain how this regulation in Sweden would look like.

Firstly, concerning the ownership, will only the utility have the right to own a microgrid? In this report the authors believe that in the long run the ownership will be open for more than only the network operators. But in this case it will also be a question regarding the revenues and how they will be divided between the actors. Furthermore, if the microgrid is built as in this case, for a larger village or region, does the municipality or network operator have the right to turn the society into a microgrid community? It is a risk that customers and producers in that case will be discriminated, if they are outside the microgrid.

Secondly, regarding the sizes of the microgrid. How big is a microgrid allowed to be regarding the amount of customers, load and generation? If the microgrid is too big the third party microgrid owner can become to have similar functions as the network operator

Thirdly, if a microgrid is seen as a behind the meter, will they pay electricity taxes? Electricity producers in Sweden with a power of less than 1500 kW produced with the purpose of own use, have no taxes today. It is not likely that all the customers within the microgrid will be tax free, but it might be possible with a reduction of the tax, if the energy are produced from RES within the microgrid.

Finally, how should the network operators be compensated when they are supplying backup power to the microgrid? It is possible that it will be an additional rate for connecting or disconnecting the microgrid to or from the main grid, but it is hard to predict how this rate will look like. All the transmission lines with a high lifespan will in the case of less use of the centralized power be a large sunk cost for the utilities. But they should in the same way be ready to deliver power to the microgrids when needed. Since the tariffs should cover the development, operation and maintenance of the network operators, there is a risk that they will be more expensive with fewer customers. It is also a risk that the reliability of power supply decreases since the network operators will have less money to spend on new investments and maintenance. Therefore, the tariffs would need to be designed in a different way.

6.2 Microgrid and value streams

It might be new markets for black start capability, reactive power, voltage support and fast frequency response in the future. Due to the ambitious goals of RES development in Sweden, some of these ancillary services could develop into markets. This can give further benefits and value streams for a microgrid or energy storage owner and it could be more beneficial to invest in a microgrid solution.

Demand response was not included in this study. The revenue from this market could also give additional revenues for the microgrid owner. It would also open the possibility for a smaller size of the BESS, since the customers could reduce their load instead of using the storage.

Another factor that could affect the BESS size is the potential increase of electric vehicles. They could participate in the frequency regulations and thereby affect the BESS size. This would probably also give a higher demand for the region than was counted for in this study.

When countries such as South Korea are making efforts in investing in microgrid business, it will most likely result in cost reduced components. That could bring down the cost of energy storage and open for other possible storage solutions with a higher potential, such as flow batteries. The studied lithium ion-batteries need a large decrease of cost to be a potential alternative in this type of system. Consequentially, subsidy policies could also be needed in order to decrease the cost for storage and make the investment profitable.

The studied system has a large amount of end consumers, which make the load rather stable. It has also a high penetration of wind and low penetration of solar power. Solar has a more regular behavior where a cycle is for 24 hours. Wind power on the other hand can have longer periods of less or more output. This requires an energy storage that can store energy for a longer period of time, since there will be less fluctuations. In that situation it might be better with other storage technologies than BESS, such as pumped hydro. This is on the other hand a technology, which is not possible to integrate everywhere.

6.3 Model

The assumption of perfect foresight in the dispatch model makes it possible to always choose the most beneficial alternative. In reality the forecast error of weather, load and spot price could decrease the revenues. With a perfect forecast it is also possible to predict when to participate in the FCR market and if the capacity bid volume will be activated or not. Moreover, the constraints for participating in the market do only consider the energy level in the BESS one hour before. In reality the operator needs to make a bid in the day-ahead market. All this would make it harder to predict the optimal operation of the microgrid and the benefits would decrease.

The assumption that the microgrid owner is a price taker in the FCR market as well as the spot market, will not affect the potential revenues. The region has a

small demand in relation to SE3, which makes it a reasonable assumption in the spot market. Similarly, the bid volume (MW) in the frequency regulation market is small in comparison to the entire market.

The effect of the reactive power and the losses in the grid were not included in the model. More losses could decrease the total system demand of energy in Sweden. However, due to the arbitrage the energy import is increased to the microgrid. This could increase the total losses since the imported energy needs to be transferred through different voltage levels.

It is beneficial for arbitrage when there is a large fluctuation in RES, load and the spot price. Hourly time-based values decrease the hourly fluctuations in RES and load. Moreover, the spot market fluctuation is probably likely to be larger in the future. This could increase the welfare of the microgrid scenarios.

7

Conclusion

7.1 Main conclusion

The review of the regulations shows that the current legislation is not in favor for microgrid, but there is indication that there is a change happening. First of all, it is highlighted that a vision for a future grid is important in order for investors to take the risk in new smart grid solutions. In addition, the tariff structure for the network companies is not in favor for smart grid investments and it is suggested to change it. As for system service markets, SvK is indicating that energy storage should be allowed to participate in the frequency regulation market. Also, that new markets could be created, e.g. a fast frequency reserve market. Furthermore, there is at the moment a proposal to remove the double taxation for the energy storage.

With the 36% and 54% of lithium-ion battery cost reduction, the results shows that the net social welfare would not be increased in this type of microgrid. In other words, there is most likely no business case for this system with this BESS cost. This is valid for both a short (3-5 years) and a long-term (10-15 years) scenario. Among the parameters, the cost of energy storage gives a large effect of the total social welfare. The study has revealed that the investment in BESS is too high in relation to the benefits. According to the results, a cost reduction of 85-90% is needed in both scenarios to make this type of microgrid beneficial for the society.

Since the cost of BESS is in this range, it is difficult to determine the optimal size of the battery based on an economical evaluation. Instead, technical outcome was used for the optimization of the storage power and energy capacity. The loss of load probability shows that a battery power capacity of 4 MW is suitable for the microgrid. A larger size increases the import and export of electricity, as well as the peak power. Moreover, if a size of 4 MW is utilized and the microgrid is optimally operated, an overhead power line that can handle a minimum of 17 MW is required, which correspond to an increase of about 4 MW peak power. However, if an economical optimization is made, a larger power capacity could be beneficial since it increases the social benefits of the microgrid.

The results show that from a reliability point of view, a power capacity of 4 MW is sufficient, whereas a higher capacity does not increase the reliability. Installing BESS larger than 50 MWh when no participation in FCR-N is included, does not increase the trade or social welfare between the main grid and the microgrid. Whereas with participation, it stops increasing at an energy storage above 100 MWh. With a size of 50 MWh, the import of electricity would increase with 2000 MWh/year and the

export with 1500 MWh/year in comparison with the BAU case. The results shows that this size would give a social welfare cost of 150 Mkr for the short-term scenario and 90 Mkr for the long-term scenario, in comparison with the BAU case. This indicates that an economically optimal operation of a microgrid does not necessarily lead to an increase of the self-sufficiency nor the social welfare of the microgrid.

The results from the sensitivity analysis show that the number of cycles the BESS can be cycled during the lifetime, can have a big effect on the result. Especially with a lower energy capacity. It can also be concluded that with FCR-N market participation, the bid price can have a big effect on the outcome. Since there are no examples of BESS participating today, the bid price is an uncertain factor.

The regulations of microgrid can have big consequences for the society. If the policies do not follows the technical development of energy storage, there is a risk of loss in social welfare, especially concerning the tax of the losses in the storage, which had a big impact on social welfare for the dispatch. Furthermore, the frequency regulation market contributes to a significant amount of social welfare, both in the short and long term scenarios.

7.2 Future work

In order to further investigate the potential of microgrids in Sweden, the following would be interesting to investigate further:

Microgrid with other storage solutions. Since only one type of energy storage was analyzed, the result could be very different with other types of energy storage. It would therefore be interesting to investigate if pumped hydro, hydrogen and other types of batteries as redox batteries, could give another outcome. Pumped hydro and hydrogen storage could provide storage over seasons and could increase the reliability in a cost-efficient manner, whereas redox batteries could have a greater technical potential compared to lithium-ion batteries.

Other types of local network would also be interesting to investigate, since local network can differ a lot with different loads and generation. Especially how a decrease of end customers and thereby an increase of the fluctuations, would affect the results, or if the reliability would be low.

The energy losses for transmission have not been taken into account. Neither has transfer capacity of the utility connection. It would therefore be interesting to see the effect of these, and how the microgrid can reduce the losses in the system.

Lastly, in the case of a positive social welfare, it would also be interesting to see how the revenues could be divided among the different actors.

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Appendices

A

Economical calculations

Table A.1: Economic parameters

	Parameters
Tariff fixed cost [kkkr/year]	400 ^a
Tariff power cost [kkkr/kW/year]	404 ^a
Tariff energy cost [kkkr/MWh]	19 ^a
Tax [kkkr/MWh]	331 ^b
Discount rate, [%]	4.72 ^c
Exchange rate [kkkr/\$]	8.38 ^d
Exchange rate [kkkr/€]	10.45 ^e
Exchange rate [kkkr/£]	11.66 ^f

^a Based on Vattenfalls 2018 tariff cost for cost category T2 in south of Sweden [90]

^b Taxes of 2018 (VAT excluded) [91]

^c The discount rate calculated by Ei for the network operators, during the period 2016-2019 [92]

^d The exchange rate during the 19 of April 2018 [73]

^e The exchange rate during the 8 of May 2018 [93]

^f The exchange rate during the 15 of May 2018 [79]

Net present value calculation:

$$NPV = -C_0 + \sum_n \frac{C_n}{(1+r)^n} \quad [] \quad (A.1)$$

Where:

- r = Discount rate [%]
- C₀ = Initial investment [kkkr]
- C_n = Value stream [kkkr]
- n = Time [year]

Table A.2: Cable and OHPL cost

	OHPL
Length of power line [km]	23.2 ^a
OHPL cost [Mkr/km]	0.55 ^a
Life-time [years]	60 ^b
Total OHPL cost [Mkr]	12.8
10 years OHPL cost [Mkr]	2.3
	Underground cable
Length of underground cable [km]	23.2 ^a
Underground cable cost [Mkr/km]	2.1 ^a
Life-time [years]	40 ^b
Total underground cable cost [Mkr]	48.7
10 years underground cable cost [Mkr]	8.1

^a Values estimated from Vattenfall

^b Values from [81]

A.1 Reliability

Table A.3: Calculation of value of lost load and cost per interruption

	i	Energy cost ^a Ce _i [kr/kWh]	Power cost ^a Cp _i [kr/kW]	Rate of category ^b x _i [%]
Industry	1	71	23	37
Trade and services	2	148	62	24
Agriculture	3	44	8	1
Public sector	4	39	5	6
Household	5	2	1	32
Value off lost load (VOLL)^c [kr/kWh]		65.21		
Cost per interruption (CPI)^d [kr/kW]		24.09		

^a The cost for the society during an unplanned outage, divided in different end customers [94]

^b Average energy consumption rate in Sweden for the different end customers [80]

^c $VOLL = \sum_i (Ce_i \cdot x_i)$
^d $CPI = \sum_i (Cp_i \cdot x_i)$

Table A.4: LOLP

	Data
Length of power line [km]	23.2 ^a
Failure probability current line [# / km / year]	0.005 ^b
Failure probability alternative line [# / km / year]	0.14 ^c
Failure probability underground cable [# / km / year]	0.0003 ^d
LOLP	
BAU ^e , δ_{BAU} [# / year]	0.116
Alternative line ^e , $\delta_{\text{alternative, line}}$ [# / year]	3.248
New line ^f , δ_{line} [# / year]	0.013
Cable ^g , δ_{cable} [# / year]	0.001

^a Values from Vattenfall

^b Based on XLPE Underground Cables from the report [95]

^c Based on 66 kV overhead lines in Iceland from the report [95]

^d Vattenfalls estimation on number of faults that lead to remaining outages

^e LOLP = Length · Failure probability

^f LOLP new line = $\delta_{BAU} \cdot \delta_{BAU}$
^g LOLP cable = $\delta_{BAU} \cdot \text{Length} \cdot \text{Failure probability}$
Table A.5: Energy curtailed and energy not served in island mode during one year. Based on yearly average values from 2013-2017.

	BAU/Line		Alternative line/Cable	
	Short	Long	Short	Short
Wind ^a ($\text{Wind}_{\text{average}}$), [MWh/yr]	35,500	35,500	35,500	35500
Solar ^b ($\text{Solar}_{\text{average}}$), [MWh/yr]	375	750	375	375
Avarage cost curtail ^c (π_{average}) [kr/MWh]	300	300	300	300

^a Values from Vattenfall

^b Modelled values as described in Section 4.2.1

^c Average cost curtailed = $\frac{\sum_y \sum_h \text{P}^{\text{RES}}_{y,h} \cdot \pi_{y,h}^{\text{spot}}}{\sum_y \sum_h \text{P}^{\text{RES}}_{y,h}}$

Table A.6: The reliability cost for BAU, new line, alternative line and underground cable. For BAU and new line the values are the same for both short and long-term scenarios. The presented values for cable and alternative line are for the short-term scenario.

	BAU	New line	Alternative line	Cable
Average duration hours [h]	11 ^a	11 ^a	5 ^b	168 ^b
Average power consumption ^a , P [kW]	1,800	1,800	1,800	1800
Energy consumption during outage ^a , E [kWh]	19,800	19,800	9,000	302400
ENS energy cost ^c [kr/year]	150,000	17,000	1,906,000	15900
ENS power cost ^d [kr/year]	5,030	1,600	141,000	35
Total value of ENS [kr/year]	155,000	19,000	2,047,000	16000
Curtailed, revenue loss ^e [kr/year]	1,600	200	20,000	200
Total reliability cost [kr/year]	156,600	18,800	2,067,000	16,000

^a Based on Vattenfall values

^b Based on XLPE Underground Cables and 66 kV overhead lines in Iceland, [95]

^c Cost of energy = $VOLL \cdot E \cdot \delta_{\text{scenario}}$

^d Cost of power = $CPI \cdot P \cdot \delta_{\text{scenario}}$

^e Curtailed = $\frac{\text{Wind}_{\text{average}} + \text{Solar}_{\text{average}}}{8760} \cdot \pi_{\text{average}} \cdot h \cdot \delta_{\text{scenario}}$

B

Model verification

With no microgrid or energy storage, all wind is sold on the spot market and all demand is bought at the spot market with additional cost for tariffs from the main grid to the local grid. Since the analysis is of comparison nature, the tariffs in the local net and taxes cancel each other out, and is therefore not included.

In the following examples, the following values are used:

- $\pi^{\text{tariff}} = 19 \text{ kr/MWh}$
- $\pi^{\text{bid}} = 114 \text{ kr/MWh}$
- $\eta^{\text{chr}} = \eta^{\text{dis}} = 0.92$

Table B.1: Step I - BAU

Hour [t]	1	2
Energy flow [kWh]		
$p^{\text{imp,eu}} \cdot \Delta t$	3,000	3,000
$p^{\text{exp,RES}} \cdot \Delta t$	7,000	0
Economical flow [kr]		
$p^{\text{imp,eu}} \cdot \Delta t \cdot (\pi^{\text{spot}} + \pi^{\text{tariff}})$	-957	-957
$p^{\text{exp,RES}} \cdot \Delta t \cdot \pi^{\text{spot}}$	2,100	0
Total [kr]	1,143	-957

Table B.2: Step II - Microgrid

	Case A		Case B		Case C	
Hour [t]	1	2	1	2	1	2
Energy flow [kWh]						
$p_{chr,imp} \cdot \Delta t$	2,000	-	-	-	-	-
$p_{chr,RES} \cdot \Delta t^a$	2,000	-	2,000	-	-	-
$p_{exp,RES} \cdot \Delta t$	-	2,000	-	2,000	2,000	2,000
$p_{dis} \cdot \Delta t$	-	3,385.6	-	1,692.8	-	-
$p_{RES,eu} \cdot \Delta t$	3,000	3,000	3,000	3,000	3,000	3,000
Energy level $\cdot \Delta t$	0	3,680	0	1,840	0	0
Economical flow [kr]						
$p_{chr,imp} \cdot \Delta t \cdot (\pi^{spot} + \pi^{tariff})$	-638	-	-	-	-	-
$p_{exp,RES} \cdot \Delta t \cdot \pi^{spot}$	-	2,000x	-	-	-	-
$p_{dis} \cdot \Delta t \cdot \pi^{spot}$	-	3,385.6x	-	1,692.8x	600	2,000x
Total [kr]	-638	5,385.6x	0	1,692.8x	600	2,000x

^a direct revenue/cost is 0

Table B.3: Step III - Microgrid with bid possible

	Case A		Case B		Case C	
Hour [t]	1	2	1	2	1	2
Energy flow [kWh]						
Bid volume	-	-	4000	-	1,229	-
$p_{chr,RES} \cdot \Delta t^a$	-	-	2362	-	4,000	-
$p_{dis} \cdot \Delta t$	-	-	-	2000	-	3,386
$p_{exp,RES} \cdot \Delta t$	4,000	4,000	1,637	4,000	-	4,000
$p_{RES,eu} \cdot \Delta t^a$	3,000	3,000	3,000	3,000	3,000	3,000
Energy level $\cdot \Delta t$	0	0	0	2,174	0	3,680
Economical flow [kr]						
$Bid \cdot \pi^{bid}$	-	-	456	-	140	-
$p_{dis} \cdot \Delta t \cdot \pi^{spot}$	-	-	-	2,000x	-	3,386x
$p_{exp,RES} \cdot \Delta t \cdot \pi^{spot}$	1,200	4,000x	491	4,000x	-	4,000x
Total [kr]	1,200	4,000x	947	6,000x	140	7,386 x

^a direct revenue/cost is 0

Table B.4: Step IV - Microgrid with up regulation

	Case A		Case B		Case C	
Hour [t]	1	2	1	2	1	2
Energy flow [kWh]						
Bid volume	-	-	6771	-	1,229	-
$p_{chr,RES} \cdot \Delta t^a$	-	-	4000	-	4,000	-
$p_{dis} \cdot \Delta t$	-	-		3,386	-	3,386
$p_{exp,RES} \cdot \Delta t$	4,000	4,000	-	4,000	-	4,000
$p_{RES,eu} \cdot \Delta t^a$	3,000	3,000	3,000	3,000	3,000	3,000
Energy level $\cdot \Delta t$	0	0	0	3,680	0	3,680
Economical flow [kr]						
$Bid \cdot \pi^{bid}$	-	-	772	-	140	-
$p_{dis} \cdot \Delta t \cdot p_i^{spot}$	-	-	-	3,386x	-	3,386x
$p_{exp,RES} \cdot \Delta t \cdot p_i^{spot}$	1,200	4,000x	-	4,000x	-	4,000x
Total [kr]	1,200	4,000x	772	7,386x	140	7,386 x

^a direct revenue/cost is 0

C

NPV

Table C.1: Annual NPV of BAU scenarios.

Year	Dispatch [Mkr]				Cost [Mkr]				Total SW	
	RES ^a		End user ^b		Reliability		Investment		SW	
	<i>Short</i>	<i>Long</i>	<i>Short</i>	<i>Long</i>	<i>Short</i>	<i>Long</i>	<i>Short</i>	<i>Long</i>		
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	6.58	6.65	-1.72	-1.66	-0.15	-0.15	0.00	0.00	4.71	4.84
2	5.68	5.75	-0.89	-0.84	-0.14	-0.14	0.00	0.00	4.65	4.76
3	4.68	4.72	-0.70	-0.67	-0.14	-0.14	0.00	0.00	3.84	3.91
4	4.95	5.01	-1.10	-1.07	-0.13	-0.13	0.00	0.00	3.72	3.81
5	5.20	5.26	-1.05	-1.01	-0.12	-0.12	0.00	0.00	4.02	4.12
6	5.22	5.28	-1.37	-1.32	-0.12	-0.12	0.00	0.00	3.74	3.84
7	4.51	4.56	-0.70	-0.67	-0.11	-0.11	0.00	0.00	3.69	3.78
8	3.71	3.75	-0.56	-0.53	-0.11	-0.11	0.00	0.00	3.05	3.10
9	3.93	3.97	-0.87	-0.85	-0.10	-0.10	0.00	0.00	2.95	3.02
10	4.13	4.18	-0.84	-0.80	-0.10	-0.10	0.00	0.00	3.19	3.27
Total	48.6	49.2	-9.8	-9.4	-1.2	-1.2	0.0	0.0	37.6	38.5

^a Revenues of the energy from renewable energy sources, sold on spot market

^b Cost for the energy delivered to end user

Table C.2: Annual NPV of new line scenarios.

Year	Dispatch [Mkr]				Cost [Mkr]				Total SW	
	RES ^a		End user ^b		Reliability		Investment		SW	
	<i>Short</i>	<i>Long</i>	<i>Short</i>	<i>Long</i>	<i>Short</i>	<i>Long</i>	<i>Short</i>	<i>Long</i>		
0	0.00	0.00	0.00	0.00	0.00	0.00	-2.30	-2.30	-2.30	-2.30
1	6.58	6.65	-1.72	-1.66	-0.02	-0.02	0.00	0.00	4.84	4.97
2	5.68	5.75	-0.89	-0.84	-0.02	-0.02	0.00	0.00	4.78	4.89
3	4.68	4.72	-0.70	-0.67	-0.02	-0.02	0.00	0.00	3.96	4.03
4	4.95	5.01	-1.10	-1.07	-0.02	-0.02	0.00	0.00	3.83	3.92
5	5.20	5.26	-1.05	-1.01	-0.01	-0.01	0.00	0.00	4.13	4.23
6	5.22	5.28	-1.37	-1.32	-0.01	-0.01	0.00	0.00	3.84	3.95
7	4.51	4.56	-0.70	-0.67	-0.01	-0.01	0.00	0.00	3.79	3.88
8	3.71	3.75	-0.56	-0.53	-0.01	-0.01	0.00	0.00	3.14	3.20
9	3.93	3.97	-0.87	-0.85	-0.01	-0.01	0.00	0.00	3.04	3.12
10	4.13	4.18	-0.84	-0.80	-0.01	-0.01	0.00	0.00	3.28	3.36
Total	48.6	49.2	-9.8	-9.4	-0.2	-0.2	-2.3	-2.3	36.3	37.2

^a Revenues of the energy from renewable energy sources, sold on spot market

^b Cost for the energy delivered to end user

Table C.3: Annual NPV of the microgrid scenarios with participation in FCR-N market. Snapshot values for a 4 MW power capacity and a energy storage size of 50 MWh is presented.

[Mkr] Year	Dispatch		Reliability		Investment		Total SW	
	Short	Long	Short	Long	Short	Long	Short	Long
0	0	0	0	-0	-129	-91.8	-129	-91.8
1	7.64	8.13	-5.0E-4	-5.0E-4	-5.16	-3.68	2.49	4.45
2	7.62	8.07	-4.8E-4	-4.8E-4	-4.93	-3.51	2.70	4.56
3	6.50	6.89	-4.6E-4	-4.6E-4	-4.71	-3.36	1.79	3.53
4	6.59	6.99	-4.4E-4	-4.4E-4	-4.49	-3.21	2.09	3.78
5	6.80	7.19	-4.2E-4	-4.2E-4	-4.29	-3.06	2.51	4.13
6	6.08	6.46	-4.0E-4	-4.0E-4	-4.10	-2.92	1.98	3.54
7	6.06	6.41	-3.8E-4	-3.8E-4	-3.92	-2.79	2.14	3.62
8	5.16	5.48	-3.7E-4	-3.7E-4	-3.74	-2.67	1.42	2.81
9	5.24	5.55	-3.5E-4	-3.5E-4	-3.57	-2.55	1.66	3.01
10	5.40	5.71	-3.3E-4	-3.3E-4	-3.41	-2.43	1.99	3.28
Total	63.1	66.1	-4.1E-3	-4.1E-3	-171.0	-122	-108	-55.1

D

GAMS code

```

***** Master THESIS PROJECT *****
***** Microgrids in the Swedish Power System *****
***** Existing Limitations and Future Perspectives *****
***** KRISTOFFER FURST & JONAS NILSSON *****
*
***** DATA SET DECLARATION *****
* NO – No microgrid      MG – microgrid      AS – microgrid with frequency
  ↳ regulation participation
$setglobal microgrid_mode      AS
* SHORT – short-term scenario      * LONG – long-term scenario
$setglobal scenario            LONG

* Set input parameters
$setglobal input_P_max          6000
$setglobal input_eta_chr        0.922
$setglobal input_eta_dis        0.922
$setglobal input_n              127
$setglobal input_pi_bid         114

* File name
$setglobal output_file "C:\Users\User\Documents\gamsdir\projdir\RESULTS
  ↳ \X-%scenario%\input_P_max%MW%\microgrid_mode%"

* Percentage change – for sensitivity analysis
$setglobal change_demand        1
$setglobal change_solar         1
$setglobal change_wind          1
$setglobal change_pi_tariff     1
$setglobal change_pi_tax        1

sets
    h                time
                        / 1*8760          all hours of the year /

    y                year
                        / 2013*2017      all years of the investment lifetime /

    battvar          battery properties
                        / P_max           installed power capacity [kW]
                          E_max          installed energy storage capacity [kWh]
                            ↳ ]
                          eta_chr        charging efficiency
                          eta_dis        discharging efficiency
                          SOC_min        minimum SOC-level

```

```

SOC_max      maximum SOC-level
n            cycle lifetime /

marketvar      tariff tax and frequency market properties
/ pi_tariff    energy tariff [SEK per kWh]
  pi_tax       energy tax [SEK per kWh]
  B_min        minimum bid in frequency market [kW]
  pi_bid       price for offering capacity in
    ↪ frequency regulation market [kr per kW]/

unitvar        installed RES capacity and demand properties
/ P_annual_demand annual demand for
    ↪ electricity [kWh per year] * Set the total
    ↪ yearly demand for electricity [kWh]
  cap_wind     installed wind capacity [kW]
    ↪ Set installed wind capacity [kW]
  cap_solar    installed solar capacity [kW]
    ↪ ] Set installed solar capacity [kW] / ;

***** PARAMETER DECLARATION *****
Parameters
* Input data to read from files
  P_demand(y,h)      normalized electricity demand
    ↪ profile [share of annual demand]
  P_wind(y,h)        normalized wind production profile [
    ↪ share of installed capacity]
  P_solar(y,h)       normalized solar production profile
    ↪ [share of installed capacity]
  pi_spot(y,h)       spot price [SEK\kWh]
  pi_FCR(y,h)        average pay-as-bid price [SEK per MW
    ↪ per hour]
  b_dn(y,h)          binary down regulation parameter [1
    ↪ 0]
  b_up(y,h)          binary up regulating parameter [1 0]
  pi_dn(y,h)         down regulating price [SEK per kWh]
  pi_up(y,h)         up regulating price [SEK per kWh]
  P_annual_demand    annual load demand [kWh]
  cap_wind           installed wind capacity [kW]
  cap_solar          installed solar capacity [kW]
  B_min             minimum power bid volume in FCR-N
    ↪ market [kW]
  pi_tariff          tariff for electricity [kr per kWh]
  pi_tax            tax [kr per kWh]
  pi_bid            bid price in the FCR market [kr per
    ↪ kW]

* Model settings
  dT                time interval [h]
  STORAGE_STATUS    with or without microgrid [1 0]
  BID_STATUS        bid allowed [1 0]
  input_cap_solar    solar capacity      ;

***** SCENARIO SETTINGS *****

$if %microgrid_mode% = NO

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        STORAGE_STATUS = 0;
$if %microgrid_mode% == NO
        BID_STATUS = 0;

$if %microgrid_mode% == MG
        STORAGE_STATUS = 1;
$if %microgrid_mode% == MG
        BID_STATUS = 0;

$if %microgrid_mode% == AS
        STORAGE_STATUS = 1;
$if %microgrid_mode% == AS
        BID_STATUS = 1;

$if %scenario% == SHORT
        input_cap_solar = 375;
$if %scenario% == LONG
        input_cap_solar = 750;

***** PARAMETERS *****
Parameter p_batt(battvar)
/ E_max      1000000,
  SOC_min    0,
  SOC_max    1,
  P_max      %input_P_max%,
  eta_chr    %input_eta_chr%,
  eta_dis    %input_eta_dis%,
  n          %input_n%/;

B_min       = 100;
pi_tariff   = 0.019*%change_pi_tariff%;
pi_tax      = 0.331*%change_pi_tax%;
pi_bid      = %input_pi_bid%/1000;

* Parameter decleration
p_annual_demand = 15500000      * %change_demand%;
cap_wind        = 15000         * %change_wind%;
cap_solar       = input_cap_solar * %change_solar%;

* Time-step interval to 1 h
dT = 1;

parameter P_demand(y,h) demand profile;
$CALL GDXXRW.EXE norm.xlsx trace=3 par=P_demand rng=demand!A1 rdim=1
    ↪ cdim=1
$GDXIN norm.gdx
$LOAD P_demand
$GDXIN
P_demand(y,h) = P_demand(y,h)*P_annual_demand;

parameter P_wind(y,h) wind profile;
$call GDXXRW.EXE norm.xlsx trace=3 par=P_wind rng=wind!A1 rdim=1 cdim=1
$GDXIN norm.gdx
$LOAD P_wind

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$GDXIN
P_wind(y,h) = P_wind(y,h)*cap_wind;

parameter P_solar(y,h)    solar profile;
$call GDXRW.EXE norm.xlsx trace=3 par=P_solar rng=solar!A1 rdim=1 cdim
    ↪ =1
$GDXIN norm.gdx
$LOAD P_solar
$GDXIN
P_solar(y,h) = P_solar(y,h)*cap_solar;

parameter pi_spot(y,h)    spot price profile;
$call GDXRW.EXE spotprice.xlsx trace=3 par=pi_spot rng=spotprice!A1
    ↪ rdim=1 cdim=1
$GDXIN spotprice.gdx
$LOAD pi_spot
$GDXIN
pi_spot(y,h) = pi_spot(y,h)/1000;

parameter b_dn(y,h)        down regulation profile;
$call GDXRW.EXE regulation.xlsx trace=3 par=b_dn rng=b_dn!A1 rdim=1
    ↪ cdim=1
$GDXIN regulation.gdx
$LOAD b_dn
$GDXIN

parameter b_up(y,h)        up regulation profile;
$call GDXRW.EXE regulation.xlsx trace=3 par=b_up rng=b_up!A1 rdim=1
    ↪ cdim=1
$GDXIN regulation.gdx
$LOAD b_up
$GDXIN

parameter pi_dn(y,h)        price down regulation;
$call GDXRW.EXE regulation.xlsx trace=3 par=pi_dn rng=price_down!A1
    ↪ rdim=1 cdim=1
$GDXIN regulation.gdx
$LOAD pi_dn
$GDXIN
pi_dn(y,h) = pi_dn(y,h)/1000;

parameter pi_up(y,h)        price up regulation;
$call GDXRW.EXE regulation.xlsx trace=3 par=pi_up rng=price_up!A1 rdim
    ↪ =1 cdim=1
$GDXIN regulation.gdx
$LOAD pi_up
$GDXIN
pi_up(y,h) = pi_up(y,h)/1000;

parameter pi_FCR(y,h)    FCR avarage market price;
$call GDXRW.EXE regulation.xlsx trace=3 par=pi_FCR rng=price_FCR!A1
    ↪ rdim=1 cdim=1
$GDXIN regulation.gdx
$LOAD pi_FCR
$GDXIN
pi_FCR(y,h) = pi_FCR(y,h)/1000*BID_STATUS;

```

```

***** VARIABLE DECLARATION *****
Free variable      C_tot          social welfare - total dispatch
    ↪ cost

                  C_tot_year(y)    social welfare - total dispatch
    ↪ cost per year;

Positive variable

P_imp(y,h)         total power imported
P_exp(y,h)         total power exported
P_chr(y,h)         total power charged to battery
P_dis(y,h)         total power discharged from
    ↪ battery
E(y,h)             energy level in battery

P_imp_eu(y,h)      power imported to end user from
    ↪ electricity market
P_RES_exp(y,h)     power exported from RES to
    ↪ electricity market
P_RES_eu(y,h)      power from RES to end user

P_chr_imp(y,h)     power charged from electricity
    ↪ market
P_chr_RES(y,h)     power charged from RES
P_chr_dn(y,h)      power charged from participation
    ↪ in freq. market

P_dis_eu(y,h)      power discharged to end user
P_dis_exp(y,h)     power discharged to electricity
    ↪ market
P_dis_up(y,h)      power discharge from
    ↪ participation in freq. market

C_tariff(y,h)      cost of tariff (if net import >
    ↪ 0)
B(y,h)             capacity bid for freq. market;

Binary variables   b_bid(y,h)      binary decision variable: bid (ON
    ↪ OFF);

***** EQUATION DECLARATION *****
Equations          obj             main objective function
                  obj_short        objective function short-term
    ↪ scenario
                  obj_long         objective function long-term
    ↪ scenario
                  obj_ENS          objective function no microgrids
    ↪ scenario
                  eq_tariff1       price for tariff
                  eq_tariff2       price for tariff
                  eq_balance       demand supply balance
                  eq_node1         load balance
                  eq_node2         RES balance
                  eq_node3         charging balance

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eq_node4          discharging balance
eq_node5          energy storage balance
eq_node6          export balance
eq_level1         energy level in storage first
    ↪ hour
eq_level2         energy level in storage first
    ↪ hour in year >1
eq_level3         energy level in storage hour > 1
eq_E_min          minimum energy level
eq_E_max          maximum energy level
eq_cycle          cycle lifetime constraint
eq_Chrg           charging capacity limit
eq_Dis            discharging capacity limit
eq_bid1           bid possible if avg FCR price is
    ↪ larger than alt. cost for battery
eq_bid2           minimum bid constraint
eq_bid3           maximum bid constraint
eq_dedicate1      dedicate power capacity for AS
    ↪ one hour after cleared bid
eq_dedicate2      Dedicate power capacity for AS
    ↪ one hour after cleared bid
eq_bUp            up regulation constraint
eq_bDn            down regulation constraint;

***** OBJECTIVE FUNCTION *****
* Maximise social welfare
obj..
    C_tot =E= sum(y, C_tot_year(y));

obj_short(y)..
    C_tot_year(y) =E= sum(h, dT * pi_spot(y,h) * (P_RES_exp(y,h)
    ↪ + P_dis_exp(y,h))) +
        sum(h, dT * pi_bid * 2*B(y,h)) +
        sum(h, dT * pi_up(y,h) * P_dis_up(y,h)) -
        sum(h, dT * pi_dn(y,h) * P_chr_dn(y,h)) -
        sum(h, C_tariff(y,h)) -
        sum(h, P_chr(y,h)*pi_tax*(1-p_batt("eta_chr")*
    ↪ p_batt("eta_dis")))) -
        sum(h, dT * pi_spot(y,h) * (P_chr_imp(y,h) +
    ↪ P_imp_eu(y,h)));

obj_long(y)..
    C_tot_year(y) =E= sum(h, dT * pi_spot(y,h) * (P_RES_exp(y,h)
    ↪ + P_dis_exp(y,h))) +
        sum(h, dT * pi_bid * 2*B(y,h)) +
        sum(h, dT * pi_up(y,h) * P_dis_up(y,h)) -
        sum(h, dT * pi_dn(y,h) * P_chr_dn(y,h)) -
        sum(h, C_tariff(y,h)) -
        sum(h, dT * pi_spot(y,h) * (P_chr_imp(y,h) +
    ↪ P_imp_eu(y,h)));

obj_ENS(y)..
    C_tot_year(y) =E= -sum(h, dT * 60000 * P_imp(y,h)) -
        sum(h, dT * 300 * P_exp(y,h));

***** TARIFF CONSTRAINTS *****

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```

eq_tariff1(y,h)..
    C_tariff(y,h) =G= (P_imp(y,h) - P_dis_up(y,h)) * pi_tariff;

eq_tariff2(y,h)..
    C_tariff(y,h) =G= (P_chr_dn(y,h)-P_exp(y,h))* pi_tariff;

***** POWER BALANCE *****
* Power balance equation
eq_balance(y,h)..
    P_demand(y,h)+ P_exp(y,h) + P_chr(y,h) =E= P_imp(y,h) + P_dis(
    ↪ y,h) + P_wind(y,h) + P_solar(y,h);

eq_node1(y,h)..
    P_demand(y,h) =E= P_dis_eu(y,h) + P_imp_eu(y,h) + P_RES_eu(y,h
    ↪ ) *STORAGE_STATUS;

eq_node2(y,h)..
    P_wind(y,h) + P_solar(y,h) =E= P_RES_eu(y,h) *STORAGE_STATUS +
    ↪ P_chr_RES(y,h) + P_RES_exp(y,h);

eq_node3(y,h)..
    P_chr(y,h) =E= P_chr_imp(y,h) + P_chr_RES(y,h) + P_chr_dn(y,h)
    ↪ ;

eq_node4(y,h)..
    P_dis(y,h) =E= P_dis_eu(y,h) + P_dis_exp(y,h) + P_dis_up(y,h);

eq_node5(y,h)..
    P_imp(y,h) =E= P_chr_imp(y,h) + P_imp_eu(y,h) + P_chr_dn(y,h);

eq_node6(y,h)..
    P_exp(y,h) =E= P_RES_exp(y,h) + P_dis_exp(y,h) + P_dis_up(y,h)
    ↪ ;

***** BATTERY CONSTRAINTS *****
* Energy level: starting value
eq_level1(y,h)$(ord(y) = 1 and ord(h) = 1)..
    E(y,h) =E= p_batt("SOC_min") * p_batt("E_max");

* Energy level: link end value of year y-1 with start value at year y
eq_level2(y,h)$(ord(y) > 1 and ord(h) = 1)..
    E(y,h) =E= E(y-1,h+8759) + dT*P_chr(y-1,h+8759)*p_batt("
    ↪ eta_chr") -dT*P_dis(y-1,h+8759)/p_batt("eta_dis");

* Energy lavel: h > 1
eq_level3(y,h)$(ord(h) > 1)..
    E(y,h) =E= E(y,h-1) + dT*P_chr(y,h-1)*p_batt("eta_chr")-dT*
    ↪ P_dis(y,h-1)/p_batt("eta_dis");

***** MIN ENERGY LEVEL *****
* Minimum energy level
eq_E_min(y,h)..
    E(y,h) =G= p_batt("SOC_min") * p_batt("E_max") + B(y,h-1)/(
    ↪ p_batt("eta_dis"));

* Maximum energy level

```

```

eq_E_max(y,h) ..
    E(y,h) =L= p_batt("SOC_max")*p_batt("E_max") - p_batt("eta_chr
    ↪ ")*B(y,h-1);

*****
* Charging capacity limit
eq_Chrg(y,h) ..
    P_chr(y,h) =L= p_batt("P_max");

* Discharging capacity limit
eq_Dis(y,h) ..
    P_dis(y,h) =L= p_batt("P_max");

* Cycle lifetime
eq_cycle(y) ..
    sum(h, dT*P_dis(y,h)) =L= p_batt("n")*p_batt("E_max");

*****  ANCILLARY SERVICES - FREQUENCY REGULATION  *****
*****  BID CONSTRAINTS  *****
* Bid possible if avg FCR price is larger than alt. cost for battery
eq_bid1(y,h)$(pi_bid > pi_FCR(y,h)) ..
    B(y,h) =L= 0;

* Minimum bid constraint
eq_bid2(y,h)$(pi_bid < pi_FCR(y,h)) ..
    B(y,h) =G= b_bid(y,h)*B_min;

* Maximum bid constraint
eq_bid3(y,h)$(pi_bid < pi_FCR(y,h)) ..
    B(y,h) =L= b_bid(y,h)*p_batt("P_max");

*****  DEDICATED CAPACITY  *****
* Dedicate power capacity for AS one hour after cleared bid
eq_dedicat1(y,h) ..
    P_chr_imp(y,h) + P_chr_RES(y,h) =L= p_batt("P_max")-B(y,h-1);

eq_dedicat2(y,h) ..
    P_dis_eu(y,h) + P_dis_exp(y,h) =L= p_batt("P_max")-B(y,h-1);

*****  ACTIVATED FREQUENCY REGULATION UP/DOWN  *****
* AS - RUp constraint
eq_bUp(y,h) ..
    P_dis_up(y,h) =E= b_up(y,h)*B(y,h-1);

* AS - RDn constraint    P_chr_dn < B(h-1) and < V_RDn
eq_bDn(y,h) ..
    P_chr_dn(y,h) =E= b_dn(y,h)*B(y,h-1);

*****  SOLVER
    ↪ *****
Model master_SHORT / obj, obj_short, eq_balance, eq_node1, eq_node2,
    ↪ eq_node3, eq_node4, eq_node5,
        eq_node6, eq_level1, eq_level2, eq_level3, eq_tariff1,
            ↪ eq_tariff2,
                eq_cycle, eq_Chrg, eq_Dis, eq_E_max, eq_E_min,

```

```

eq_bid1, eq_bid2, eq_bid3, eq_dedicate1, eq_dedicate2,
    ↪ eq_bUp, eq_bDn/;

Model master_LONG / obj, obj_long, eq_balance ,eq_node1, eq_node2,
    ↪ eq_node3, eq_node4, eq_node5,
    eq_node6, eq_level1, eq_level2, eq_level3, eq_tariff1,
    ↪ eq_tariff2,
    eq_cycle, eq_Chr, eq_Dis, eq_E_max, eq_E_min,
    eq_bid1, eq_bid2, eq_bid3, eq_dedicate1, eq_dedicate2,
    ↪ eq_bUp, eq_bDn/;

Model master_ENS / obj, obj_ENS, eq_balance ,eq_node1, eq_node2,
    ↪ eq_node3, eq_node4, eq_node5,
    eq_node6, eq_level1, eq_level2, eq_level3, eq_tariff1,
    ↪ eq_tariff2,
    eq_cycle, eq_Chr, eq_Dis, eq_E_max, eq_E_min,
    eq_bid1, eq_bid2, eq_bid3, eq_dedicate1, eq_dedicate2,
    ↪ eq_bUp, eq_bDn/;

option lp=xa;
option solprint=off;
option optcr=0.1;

solve master_%scenario% using mip maximizing C_tot;
* Write everything to gdx and then selected values to Excel
Execute_unload 'results.gdx';
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 par=p_batt rng=
    ↪ battprop!a1";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 par=p_market rng=
    ↪ marketprop!a1";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 par=p_unit rng=
    ↪ unitprop!a1";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 par=P_demand rng=
    ↪ P_demand!a1";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 par=P_solar rng=
    ↪ P_solar!a1";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 par=P_wind rng=
    ↪ P_wind!a1";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 par=pi_spot rng=
    ↪ pi_spot!a1";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 par=pi_dn rng=
    ↪ pi_dn !a1";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 par=pi_up rng=
    ↪ pi_up!a1";

Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_imp rng=
    ↪ P_imp!a1";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_imp_eu rng=
    ↪ P_imp_eu!a1";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_RES_eu rng=
    ↪ P_RES_eu!a1";

Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_chr rng=
    ↪ P_chr!a1";

```

```

Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_chr_imp rng=
    ↪ P_chr_imp!a1 ";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_chr_RES rng=
    ↪ P_chr_RES!a1 ";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_chr_dn rng=
    ↪ P_chr_dn!a1 ";

Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_exp rng=
    ↪ P_exp!a1 ";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_RES_exp rng=
    ↪ P_RES_exp!a1 ";

Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_dis rng=
    ↪ P_dis!a1 ";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_dis_eu rng=
    ↪ P_dis_eu!a1 ";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_dis_exp rng=
    ↪ P_dis_exp!a1 ";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=P_dis_up rng=
    ↪ P_dis_up!a1 ";

Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=C_tot rng=
    ↪ C_tot!a1 ";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=E rng=E!a1 ";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=B rng=B!a1 ";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 equ=eq.cycle.m rng=
    ↪ =cyclem!a1 ";
Execute "GDXXRW results.gdx o=results.xlsx squeeze=0 var=C_tot_year rng=
    ↪ =C_tot_year!a1 ";

}

```