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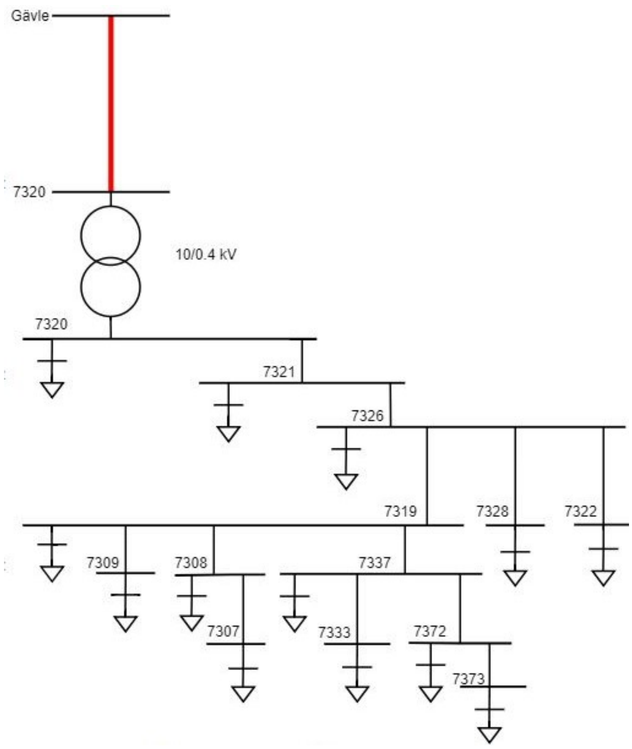

Batteries vs Cables

Possibilities of batteries in the distribution system as substitute for cable reinforcements while maintaining reliable electricity distribution

Master's thesis in Electric Power Engineering

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Department of Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

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Master's Thesis 2018
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Cover: Grid configuration at the present in Furuvik, one of the investigated cases.

Typeset in LaTeX
Gothenburg, Sweden 2018

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Abstract

Reinforcement of the grid is today usually done by cables, but alternative reinforcement methods such as energy storage systems (ESS) are increasing. One of these solutions could be battery energy storage systems (BESS), which can provide additional benefits by supporting the grid. In this thesis the question of whether batteries also could be a profitable solution for distribution system reinforcement is investigated, while considering both investment costs and other benefits.

This thesis is based on two cases. The first, a residential area where an overhead line distributing power would be insufficient for an estimated demand increased of 50% from the current peak load of 1257 kW. The second, a small educational industry with a current peak load of 13.55 kW, which is not able to accommodate an estimated demand increase of 40% due to the connected cable and fuse limit. The two cases were investigated considering reinforcement by both cable and BESS (Li-ion and NiMH), and to generalize the cases a demand level of $100-200\%$ was evaluated for both cases. To incorporate future scenarios electric vehicle (EV) integration was investigated, considering both uncontrolled and scheduled charging to see the impact of demand response (DR). These cases were evaluated in the software GAMS, where a model containing inputs and constraints was created. The objective functions used for evaluation were to minimize the current, minimize total system losses and maximize the integration of EVs. Inputs to the model were: load and cable data, structure of the two grids and data on movement patterns of vehicles. Constraints in the model were: voltage and current limitations, state of charge (SOC) of the batteries, equations consisting of power flow as well as power losses and line loading limits.

From comparing the reinforcement solutions over multiple power demand levels batteries were shown more advantageous when there is a lack of power, and it could also be seen that batteries could provide more benefits when placed close to the customer. When integrating EVs it was seen that scheduled charging could accommodate about four times more EVs than uncontrolled charging for both the cable and battery solutions. From this thesis it is conclusive that there are multiple factors, e.g. variations in the load profile and the demand level, which play a large role when selecting the most beneficial grid reinforcement strategy. All benefits that batteries can provide, which cables cannot, were not accounted for in this thesis, and hence the final conclusions may be inconclusive as no income possibilities were considered.
Keywords: Reinforcement, Battery energy storage system (BESS), Cables, Optimal power flow (OPF), Electric vehicle (EV), Case study, Demand response (DR).

Acknowledgements

Firstly we would like to give a special thanks to Power Circle, especially Anna Wolf our supervisor, for all her help and support during this thesis. We would also like to give a special thanks to David Steen our supervisor at Chalmers for all his help, guidance and patience during this thesis, and also to our examiner Anh Tuan Le, for his help and support. Finally we would like to thank all the people helping us with data and information. Thanks to David Jakobsson at Gävle Energi and Jonas Wågenberg at Kalmar Energi for providing us with grid and load data, advice and information about grid reinforcements, and also and Daniel Köbi at Jämtkraft for providing us with information about charging of electric vehicles. Thanks to Christian Ölund at Nilar and Manuel Weindorf at GE Power for providing us with relevant specifications, data and information regarding batteries, and thanks to Ola Herrloff at Kalmar Airport for providing information about the current situation at Kalmar Airport.

Elin Bergstedt, Sofia Nyström, Gothenburg, June 2018

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List of Abbreviations

BESS	Battery Energy Storage System
BMS	Battery Management Systems
CRF	Capital Recovery Factor
DOD	Depth of Discharge
DR	Demand Response
DSI	Demand-side Integration
DSM	Demand-Side Management
EMS	Energy Management System
EPC	Engineering, Procurement and Construction
ESS	Energy Storage System
EV	Electric Vehicle
GAMS	General Algebraic Modelling System
HV	High Voltage
ISO	Independent System Operator
Li-ion	Lithium ion Battery
LMP	Loational Marginal Price
LV	Low Voltage
MV	Medium Voltage
Ni-Cd	Nickle Cadmium Battery
NiMH	Nickel Metal Hydride Battery
OPF	Optimal Power Flow
PCS	Power Conversion System
PF	Power Factor
PSO	Particle Swarm Optimization
PV	Photo Volatic
RoR	Rate of Return
RTO	Regional Transmission Organization
SOC	State of Charge

1

Introduction

A large part of the national grid in Sweden today is very old, and there is a growing need for renewal and reinforcement of the power system. This renewal and reinforcement need becomes even higher when considering the increased use of renewable energy sources, as well as the need for grid support technologies. Reinforcement is today usually done by investing in new cables, but the price of these investments are expensive, and a more affordable option is sought after. With a decreasing price in alternative methods , other alternatives such as battery energy storage systems (BESS) could possibly be used.

This thesis investigates if batteries are an economic option for grid reinforcements, and if so during which circumstances that BESS would be preferable over cable reinforcements from a financial and system stability point of view. To solve this problem, an optimal power flow (OPF) model was developed in a mathematical optimization program called GAMS. In GAMS, simulations for different locations and settings were evaluated and a comparison between the benefits with cable reinforcements and battery storage was carried out.

1.1 Background

The national power grid in Sweden today is to a large extent very old and needs to be renewed in order to meet the challenges of tomorrow. Most of the existing grid was built during the 1950's and the consecutive 20 years. During the years since then the electricity demand has increased due to both population growth and changes in society towards a larger electricity dependency [1]. One of these changes is the continuing growth in numbers of electric vehicles (EVs), which add to the total electricity demand and solidifies reliance on generation and security of the grid. This all means that there is an increasing need for the old grid to be replaced and renewed. Motivated by the adjustments needed to prepare the grid for these changes in production and consumption patterns, the electricity grid fees increased by 7.5% during the year of 2017 in Sweden [2].

At the same time as the grid is aging, the share of power generated by renewable sources has increased as the technological development has continuously been moving forward, and costs regarding these technologies have dropped [1], [3]. With the increased amount of renewable technologies connected to the grid, the need for support becomes greater due to their intermittent behaviour. One of these support technologies are energy storage systems (ESS) such as batteries, which can be used to balance the increased fluctuations in power generation and demand in the system [4].

Batteries are, after pumped hydro, the largest technology for storage applications, and can also be a suitable choice in locations where pumped hydro is not an option. As batteries can be varied in size and distributed in the power system they could be a good choice when investigating how to replace expensive cable reinforcements. In the selection process for which type of battery to use, lithium based technologies such as Lithium-Ion (Li-ion or LIB), led-acid batteries and nickle based batteries such as Nickle-Cadmium (Ni-Cd) and Nickel Metal Hydride (NiMH) are commonly used alternatives [4], [5]. Li-ion batteries are however one of the most popular solutions due to their decrease in price during several years. This is highly related to the increased use of Li-ion batteries in automotive applications, where the price of complete battery installations decreased with 80% between the years of 2010 and 2016 [6].

Since the cost of batteries is decreasing, using ESS to reinforce the grid is becoming a more attractive option in some cases. However, to decide the most suitable options today is done by assessing the different circumstances from case to case. The assessment is, among other, done by looking at costs and consequences related to the customer's consumption and grid stability [7]. A simplification of this process could make the choice more tangible for the investor. One way of simplifying this process is to find indicators which could show when batteries or cables are the most suitable options.

For a new customer to connect to an access-point in the grid, there is always a connection-fee which varies in size depending on the type of connection and the distance to the closest access-point. If a customer is in need of reinforcement, reconstruction or extensions, it is the customer who is responsible for the additional costs for the project, not the grid owner [8]. However, to manage the needed reinforcement several solutions are applicable, although at different price levels [4]. Some of the solutions that are used today are to decrease consumption, connecting new cables or using ESS [9]. As reinforcement by cables can be expensive, customers may instead choose to move to a better location, shut down the project or consider investing in their own energy production and ESS [7].

Studies within the area of grid reinforcements and battery storage solutions are available and have proven BESS to be a competitor in certain areas, while in others shown it is still not a cost effective. Studies that show areas where BESS can be beneficial for the grid are [10], [11], while [12], [13] points out limitations that BESS still has to overcome before it can become an alternative to traditional methods.

1.2 Aim

The aim of this thesis is primarily to evaluate two specific cases and determine if an investment in cable or BESS would be the most economically beneficial solution for reinforcement, while also considering additional benefits that BESS can provide. Secondly the aim is to generalize the results by using a larger level of demand increase, in order to find indicators for when which type of reinforcement is more beneficial. An additional case with EV integration was created to evaluate the impact charging of EVs has in the created solutions and the impact of demand response, by comparing uncontrolled and scheduled charging.

1.3 Problem/Specific tasks

To achieve the aim of this thesis, there were several problems that needed to be solved. Three different cases were investigated, where two of them, Kalmar and Furuvik, are located at different places in the grid where there at the moment is a need for reinforcement due to a planned increase in load demand. The third case is a future scenario with an increased use of EVs integrated in the Furuvik case.

These cases were compared with both battery and cable solutions, and the comparison evaluates the total costs for the battery vs cable solutions for all cases as well as the associated benefits. Battery storage was used for demand-side management (DSM), where the batteries were optimized for peak load shaving. The batteries were sized to fit with the planned load increase (the capacity that is normally used for a specific amount of load), and the lifetime of the batteries were based on specifications from the battery providers. The cost of the batteries was discounted for the same number of years as the lifetime. This all had to be done in order to find indicators. To be able to reach these results, an OPF model was developed in GAMS.

To reach the aim of this thesis, the following specific tasks were carried out:

1. Gathered and evaluated data for the grid, loads, transformers and the relevant cables and/or overhead lines of the different locations, as well as data for the batteries and EVs that were to be implemented in the simulations.

2. Created an OPF model in GAMS for the separate locations where the different solutions could be compared regarding costs, benefits and power losses, while considering all relevant constraints which include load flow, line limits, voltage amplitude, active and reactive power limits, battery storage and EV characteristics.

3. Processed and evaluated the results from GAMS in Matlab and Excel to create comparable results by generating visual aids such as figures. The results were

then used in order to find indicators, resulting a case-specific as well as a more general recommendation, on during which circumstances reinforcements can beneficially be replaced with battery storage. A sensitivity analysis for different battery lifetimes and interest rates in relation to annual cost was performed as well.

1.4 Scope

In the scope of this thesis, the evaluation of the economic benefits when using battery storage or cables was only performed on some specific locations in the Swedish distribution grid where there at the moment is a need for reinforcement, or places where reinforcements may be investigated. Three different cases were created and analysed for the purpose to find indicators showing during which circumstances that battery storage is beneficial, and to perform a cost/benefit analysis.

1.4.1 System circumstances

The simulations were only performed during steady-state conditions. Frequency deviations were not accounted for in this project, since the size of the different locations were considered small enough to not have noticeable frequency fluctuations in steady-state. The voltage deviations in the system were analysed, and with the implementation of a BESS, investigated if the voltage deviations were decreased in the different locations. Network congestion, total system losses and peak power imported were also analysed, and to which extent they would be affected by the BESS and the placement of the BESS.

1.4.2 Data

The load and grid data used in this thesis were provided by Gävle and Kalmar Energi for two different specific locations and years. The load data has hourly resolution. The phase angle used in the simulations will be the same for all cases, chosen to equal a power factor (PF) of 95%. The specifications for batteries were provided by Nilar and GE for NiMH and Li-ion batteries respectively, and data for driving patterns of EVs was provided by David Steen, Post Doc at Chalmers in the area of Electrical engineering.

1.4.3 Days chosen for simulations

The simulations for the different cases was performed for six specific days chosen from one year:

- The day with maximum peak consumption
- The day with minimum valley consumption
- The day with maximum average consumption
- The day with minimum average consumption
- Selected day 1 which represents an average day
- Selected day 2 which represents an average day

These days were specifically chosen to represent different situations in the grid, ranging from extremes to average, to be able to account for different load and weather variations that can occur and represent one year. Since only one specific year was used, the results of the simulations does not cover all possible loads and weather conditions, but provides an indication on seasonal variations and how these are handled with battery storage and cable reinforcement.

1.4.4 Cost/benefit analysis

The costs and benefits in the cost/benefit analysis that were being considered are:

- Total investment cost
- Annualized cost (over 40 years)
- Total power losses
- Cost of power losses
- Voltage deviation
- Network congestion
- Peak power

These benefits are only considered from a general grid operation point of view. This is since end-customer data was not possible to obtain for all cases, which also means that the benefits home-owners would receive from BESS implementation could not be analysed.

The only benefits that will be given an economic value are the investment cost and the power losses, where the electricity cost is taken from the average Swedish spot market price for the year 2017, which was 301.3 SEK/MWh [14]. The annualized investment cost is calculated by using the Capital recovery factor (CRF), with an assumed interest rate of 5% for both cable and battery investments. This means that the annualized costs might differ from what the real annualized cost would be with a correct interest rate, but will however give an indication about the magnitude of the annualized cost.

The different cost that the other benefits would generate, negative or positive, will not be investigated. The results from this thesis will thereby not be a complete cost/benefit analysis. This is due to the fact that some of these costs are complicated to extract, and also depends on whom that will earn or lose money from these benefits. The extent of these different benefits will however be compared for the different solutions, and a discussion on the impact they would have will be provided.

Investment costs for the reinforcements, such as cables and transformers, were gathered from the planning directory in the EBR-catalogue KLG 1:12, which is based on average costs and contracts in the beginning of 2012. This means that the calculated costs are only an estimated average, but will give an indication of what the real investment cost could be.

1.4.5 Transformers

The transformers used in the simulations are transformers on the 10/0.4 kV level, in the interval of $800 - 100$ kVA rated power. For these transformers, the losses related to the resistance were neglected. The losses related to the inductance however were taken into account, with an assumed inductance value of 5% of the rated power, which was used to calculate the transformer losses. The investment cost for transformers accounts for the material costs, numbers gathered from the planning directory in the EBR-catalogue KLG 1:12.

1.4.6 Cables

The cables used for the simulations are new cables with similar characteristics to the ones normally used when replacing cables and/or reinforcing the grid. The size of the new cables is minimized in the model, but large enough to accommodate for the maximum current needed at the relevant buses during the maximum peak load, size chosen from Draka's product catalogue [15]. Cables selected are however not dimensioned with the short circuit current which results in inaccuracy of the sizes. The investment cost for cables accounts for the cost related to labour, material, machinery, equipment and other, numbers gathered from the EBR-catalogue. Costs regarding service of the cables will not be taken into account, since the depreciation period for cables is 40 years and the cables are assumed to be in functional condition during this time.

1.4.7 Batteries

The battery types used for the simulations are Li-ion and NiMH batteries. The size of the batteries is large enough to accommodate for the maximum current needed during the maximum peak demand, to be able to perform peak load shaving in the different cases. This means that only a few different batteries were used in the simulations. When mentioning the batteries and assessing the effects, the aspect of short circuit currents is not included. As they are not and the short circuit currents is an important part when dimensioning a system there are limitations to the sustainability of this thesis' solution.

The data and specifications for these batteries were provided by Nilar (NiMH) and GE (Li-ion) as well as the investment costs. What the investment cost given by each company includes is presented in table 1.1. The total costs regarding BESS were supposed to match the depreciation time for cables of 40 years, since the battery solution is supposed to be valid as long as the cable solution, which means that a sufficient number of batteries and service of these batteries were included. The number of years that the different batteries were supposed to be functional was also used as the depreciation time.

Table 1.1: List of components and services included in the battery investment cost.

NiMH	**Li-ion**
Battery pack	Battery pack
Inverter	Inverter/Power Conversion System (PCS)
Transformer	Transformer
Battery Management System (BMS)	Energy Management System (EMS)
Power cabling	Balancing of system
Installation costs	Engineering, Procurement and Construction (EPC)
Housing	

It can be noted that the total cost of batteries probably will be much lower in the future than today and that it can be speculated in establishments of special tariffs and other deductions, which all could bring down the investments costs [6], [16]. These are however not aspects which are investigated thoroughly in this thesis and will possibly result in wrongful re-investment costs. This could make the batteries seem like a less beneficial choice in some cases. As batteries are able to perform other services than cables there are multiple areas where batteries can bring in money to increase their overall benefits, some of which are described in 2.2.1. All of these are not covered in the result of this thesis such as; ancillary services and trade on the NordPool spot-market. As a result of this, the solution and estimation for if battery storage would be more profitable now and in the future will only be an indication and comparison of how investments in batteries today compared to in the future would look like.

1.4.8 BESS implementation problem

As of today, the use that grid operators have of storage technologies such as batteries is limited, since transmission and distribution operators are not allowed to control or own energy storage equipment [4]. The consequences of this problem will not be investigated deeply. However, a short description regarding obstacles and limitations for battery storage is presented in in chapter 2.3.2, and in chapter 6.3 a discussion of the extent of this problem and possible solutions can be found.

1.5 Organization of thesis

This thesis consists of seven chapters including Chapter 1 Introduction. The information that can be found in the following chapters are:

- Chapter 2: Information and background about reinforcements in general, how batteries can be used in the distribution system and additional information about different types of batteries, existing projects and previous work, as well as demand response (DR) and how EVs can be used as demand response.

- Chapter 3: The method used in this thesis, described in different steps, as well as development of the simulation model used in GAMS.

- Chapter 4: A description of the cases that were investigated, input data and alterations that had to be made, the days chosen to simulate and additional sub-cases, as well as the assumptions that were made.

- Chapter 5: The case results and a comparison of the different solutions, the results of the additional sub-cases and a sensitivity analysis.

- Chapter 6: A discussion on the results, the impact the assumptions made could have on these results, the benefits of BESS not considered and the implementation problem around BESS as well as sustainability and ethical issues.

- Chapter 7: The conclusions made in this thesis as well as suggestions for future work.

2

Background and methods for reinforcement in the distribution system

This chapter discusses the theoretical background behind reinforcements in the distribution system, which contains distribution system planning, usage of battery energy storage systems (BESS) and demand-side management. In section 2.1 the main theoretical background behind distribution system planning and reinforcements in the distribution system will be explained. Section 2.2 describes how BESS can be used in the distribution system, placement of batteries as well as sizing and the characteristics of different types of batteries. Section 2.3 describes the obstacles present today that hinder the implementation of BESS, and also some examples of BESS that are in use in different parts of the world. Section 2.4 explains how DR can be used in the distribution system, the different benefits with DR and how it can be used as a replacement/postpone method for reinforcements.

2.1 Planning of a distribution system

The planning of a distribution system can be carried out in different time aspects, from long-term to short-term, and can be categorized into three different categories: long-term planning, network planning and construction design [7]. The purpose of long-term planning, also called strategic planning, is to determine the optimal network layout, what investments that are required and the timing of these investments to be able to reach maximum benefits. Long-term planning consists of major investments in the future and the main network configurations [7].

Network planning is planning at an individual level considering investments that should be done in the near future, whereas construction design refers to the structural design of each component in the network. In this stage, all available materials have to be taken into consideration, as well as their costs [7]. All of these planning categories has some things in common, that they all need to take into account the consequences that future changes will have. These future changes could be an increased amount of load in different areas, the price levels of different materials and energy variations, as well as that the use of different technical innovations could increase [7].

When performing any type of planning for a distribution system, the two main aspects to consider are the technical performance needed and the resulting total costs. To be able to solve this problem [7] mention three main tasks, which are:

1. Defining a technically feasible solution. This includes calculations for deciding whether the appropriate regulations will be fulfilled, e.g. the maximum permissible voltage drop or the minimum fault current.

2. Estimating the cost of each circuit or item of equipment. Often this will be based on a unit length of cable, or trench excavation, or the cost of buying and installing a particular circuit breaker or transformer.

3. Ensuring that different types of costs can be sensibly compared. This requires that the costs of the various options being considered are in a form which enables acceptable comparisons to be made. To do this the various annual costs and individual capital investments are converted to annuities, or preferably to present worth values, to obtain total costs which can then be compared in order to decide on an agreed course of action.

To be able to evaluate the general technical conditions of a network, studies regarding the network's performance during load and fault conditions has to have been performed. For this, computer-based information systems are used. Usually the customers current $[A]$ or apparent power $[kVA]$ ratings are used to derive the load data [7].

Since the electrical system in industrial countries are quite developed and electricity supply has been in practice for over a century, the supply systems and corresponding policies in these countries are well established. Due to this, there should be significant technical and/or financial benefits to justify the replacement of old policies with new ones [7].

The engineering life of the different components in a network system can divert and also be difficult to estimate. Some of the equipment in power systems can be useful and in service for up to 40-50 years [7]. This means that investment planning does not only have to consider the present circumstances in the system, but also the possible change in future loads in the considered network. The change in future load can not be predicted exactly, but it should be estimated in the design and planning phase [7].

Because of this it is also complicated to decide which time span that should be used to analyse how any vital policy change could affect the system over the different components lifetimes [7]. To be able to solve investment planning problems during these circumstances, it is however admissible to use the simplified cost/benefit analysis for a long-term plan, where the time span used is normally one to two years. For this type of analysis to be valid, some sort of sensitivity analysis has to be made to account for possible unknown factors in the future [7]. Sensitivity-analysis studies have shown that the major causes for wrongful investments are due to error forecasts of future load levels [7].

For low voltage (LV) networks, investment planning becomes more complicated. The lead time that customers such as households and industries provide regarding an increased supply level are usually short, which means that a detailed investigation over a long-term time period is not possible for LV networks [7]. However, when investigating the approximated loads for a few years ahead the need for reinforcement can be indicated by an excessive voltage drop, as well as an inadequate short-circuit current. The inadequacy of the short-circuit current causes protective devices to operate unsatisfactorily, which is undesirable in a distribution system [7].

When planning any type of system reinforcement, the analysis has to account for the required amount of supply, quality of supply and periods of time when the supply might not be possible to deliver to the customers [7]. This means that the analysis has to investigate how supply can be affected by the loss of different pieces of equipment and voltage fluctuations, while considering safety aspects as well [7].

2.1.1 Reinforcement of the grid

One of the main customer concerns regarding power supply is the reliability of electricity. For the supply authorities however, this is financially and technically impossible [7]. If a customer is in need of 100% secure supply, like for example a hospital, it may be cheaper for them to invest in their own back-up supply, such as on-site generation to protect some of their loads against total power loss, compared to obtaining an adequate number of electricity-supply in-feeds from several various substations [7].

Reliability by itself is not a strong enough motivator for reinforcement investments. Other factors that must be considered when investigating different investment options are all the related costs, such as investment costs, maintenance cost, costs related to losses and the number of power that is not supplied [7]. While an increasing number of components in the network can contribute to minimizing the system losses, every new component also increases the risk of failure in the system [7].

The total cost of reinforcing the grid can be directly related with the costs of power and energy not supplied [7]. This means that the total cost will be a summation of all related costs, and that the cost should be minimized according to

$$min\ C = \sum \Big(C_i + C_l + C_m + C_o\Big) \tag{2.1}$$

where C_i is the investment cost, C_l is the cost related to losses, C_m is the maintenance cost and C_o is the cost of outages [7]. In practice, the longest time period for assessing investment and operation costs in the distribution system should be between $10-15$

years. If the rate of return (RoR) of the different considered options is similar, either a longer time period is assessed or a sensitivity analysis is usually carried out [7].

In high voltage (HV) and medium voltage (MV) systems, transformers can be highly functional after 50 years of installation, which also can be said for MV cables, where some of them are later being used at voltage levels double the originally designed value [7]. There have also been cases where MV switch-gear has been replaced 90 years after its installation, where at the time it still was in fully working order [7]. Even though some old equipment is still useful, replacing them with newer equipment can be economically beneficial in terms of lowering the losses, increased reliability and less frequent maintenance needs [7].

2.1.2 Replacement of equipment

Distribution system planning usually contemplates the peak load demand, but feeders can be overloaded if not customized to a load growth beyond the peak value. If feeders in the distribution system are overloaded during a too long time interval, the equipment might be damaged due to a more rapid deterioration, and might be in need of replacement [17]. Changes in weather and surroundings also greatly impact the ambient conditions of feeders, which means that different components actual current capacity might differ from the rated steady-state current during some specific ambient conditions [17].

Due to this, the thermal overloading capacity of a feeder must be thoroughly investigated before it is subjected to actual physical overload. However, different feeder components generally have large thermal masses, and since the ambient conditions for feeders normally are better than the worst possible scenario, feeders can usually be overloaded for a restricted time before the thermal maximum level is reached [17].

Replacement of equipment enables the possibility of providing a long-term development of the system in question, which should be the main aspect when replacing old equipment, rather than only replacing it with a new equivalent product. It is also often possible to simplify the system, and in doing so increase the system reliability and decrease investment costs [7]. When considering replacement of any type of equipment, it should also be taken into consideration whether it would be economically beneficial to up-rate the new equipment, due to a planned or an eventually planned higher voltage level in the network system in the foreseeable future [7].

The main and most expensive types of equipment in the power system that can be in need of replacement is overhead lines, cables and transformers. In table 2.1 a comparison of costs between overhead lines and underground cables is presented in ratio, also comparing (a) built-up areas and (b) normal soil conditions, where it can be seen that for higher voltage levels, overhead lines are considerably cheaper [7]. In table 2.1, EHV represents voltage levels above 300 kV.

Table 2.1: Ratio of underground-cable to overhead-line costs, at each voltage level (where (a) represents built up areas, and (b) represents normal soil conditions).

EHV	HV	MV(a)	MV(b)	LV(a)	LV(b)
15-25:1	10:1	5:1	2:1	5:1	1.5:1

This comparison takes into account all the life-time costs, consisting of capital investment cost, costs associated with reliability as well as the area conditions for the line to be placed [7].

2.1.2.1 Underground cables

Underground cables have a relatively large thermal mass when considering the thermal mass of the environment of the cable [17]. This enables the possibility for overloading during some specific circumstances. If the ambient temperature is low due to cold weather conditions, the cable can be overloaded for a longer time interval than if the ambient temperature is high, during the right circumstances up to several hours [17]. If the ambient temperature would be high and there would be a high load demand, there is a large risk that the cable would be deteriorated, and possibly damaged [17].

Due to the insulation of a cable, the construction of a cable is far more expensive than of an equivalent overhead line. The installation costs are higher as well since cables are usually installed underground, either directly if there are good soil conditions, with backfill if the ground material is unsuitable, or in pipes, depending on the voltage level [7]. The total investment cost of cable reinforcements has a relatively high threshold value, mainly due to the high installation cost of a cable which contributes to the majority of the investment cost, according to the EBR-catalogue. Due to this, grid owners might over-dimension cables when investing in them [18], since the difference in cost for different cable sizes does not vary significantly.

When replacing cables, the main aspect to consider is the high costs related to cable investments. Since there are no diagnostic technique to examine the condition of the cable, the lifetime of the cable is usually seemed as reached when there is a sudden increase in faults [7]. If the cable to be replaced are located in a pipe or duct, it may be possible to use the same channel, but if the cable is placed in a trench it is usually not possible to use the same trench, due to system security reasons during the replacement time [7].

According to [19], even though there is a good potential for recycling of underground cables, they are generally not recovered and recycled at the end of their lifetime. Instead, they are often left in the ground. This results in a loss of resource and potential from a life cycle point of view. The reason for the low recycling rate in Sweden is according to Christer Forsgren at the recycling company Stena:

> *"Today it's often more costly to recover the cable than what you get for it"*

stated during an interview with the popular science journal NyTeknik in 2005 [20]. This was discovered during a master thesis conducted at Stena Metall by a student from Linköping University, which also stated that cable material, like copper and aluminium, worth 16 billions SEK lies beneath the ground. As a solution to this problem, Christer Forsgren further stated that:

> *"The cables that are being installed underground now must be placed in a way so that they will be easier to extract and recycle in the future."*

2.1.2.2 Overhead lines

Since overhead lines only utilizes air as insulation, the associated thermal mass is also low (directly dependent on the line mass/unit length). This causes the performance of them to be much more affected by weather conditions than for cables, and consequently also more sensitive to overloading [17]. The largest influencing factors for the rated current of an overhead line are the solar radiation, ambient temperature and the wind speed [17]. Due to this relatively low thermal mass, when compared to cables and transformers, overhead lines can only be overloaded for a short amount of time before they would risk to deteriorate, generally only up to 30 minutes [17].

Overhead lines use air to insulate conductors for the major part of its length, except for small sections connected to insulators on the line supports. This low level of insulation and simple construction results in very low insulation costs compared to underground cables, especially when looking at MV and HV levels [7]. When replacing single-phase overhead lines in LV and MV systems, the new overhead lines should be able to be used for higher voltage levels, and also allow for conversion to three-phase circuits, to prepare for changes in the future [7].

When it comes to recovering of overhead lines, the opportunities for recycling are favourable sine most of the parts are placed above ground, which means that the metallic components in conductors and masts can be recovered economically [19]. In a life-cycle perspective, this means that recycling of this metal will produce a net benefit. Especially when it comes to the recycling of copper conductors, this results in a reduced manufacturing need in the future [19].

2.1.2.3 Transformers

The rated capacity of a transformer and thereby the maximum allowed load level at steady-state conditions depends on the ambient temperature and the cycling of the transformer, where increased ambient temperature leads to decreased rating [7], [17].

A high ambient temperature can also lead to a faster deterioration of the winding insulation, which will shorten the lifetime and usefulness of the transformer [7].

The windings and the core of most transformers are insulated with oil, placed in a tank [7]. The power losses of a transformer can be separated into no-load and load losses, also called iron and copper losses. These losses represent the heat sources of the transformer, and can increase the temperature in the iron core as well as the transformer windings. The heat is then being transmitted to the insulating oil surrounding the core and windings [7], [17]. This oil-insulation creates a large thermal mass for the transformer, which results in that the transformer can be overloaded for a relatively long time period, up to a few hours [17].

Besides aging of a transformer caused by the ambient temperature and cycling, there are other factors that can affect the amount of time that a transformer is operational and in service. These factors could be an up-rated level of the distribution system voltage, or an increased load demand [7]. Since these factors would put higher pressure on the system and the transformer, this could lead to that transformers are being replaced long before the electrical and/or mechanical lifetime of the transformer has been reached, since it is not able to efficiently handle the new more demanding circumstances [7].

For transformers it is also difficult to predict the time of failure, since the relationship between deterioration of insulation and dielectric losses has not been established [7]. Due to the high price of transformers, replacement can not be justified solely on the eventual reduction of losses or maintenance costs. However, when there is a need for replacement, these aspects should be taken into consideration [7].

Transformers can be represented by shunt and series impedance. Smaller distribution transformer has a larger series resistance than reactance, and larger power transformers has larger reactance and negligible resistance [7]. For the larger power transformer, the resistance has only a small effect on the voltage-drop, but the resistance should be taken into consideration when calculating real power and energy losses [7].

2.1.3 Power flow and losses

To be able to establish the capacity of a distribution network system during all possible load conditions and network configurations, load-flow studies need to be performed [7]. Load-flow studies on MV and LV networks are simpler than studies in HV networks in the aspect that the networks are generally radially operated, which has a less complex arrangement. These types of networks does however have a higher number of load points, and the information available on the different load points is usually non-instantaneous consumption of the different units at LV levels [7].

To reduce the amount of losses in a system all control variables needs to be within their limits, where the control variables are: voltage magnitude, real generated power, injected reactive power and transformer tapping [21]. When all these variables are within allowed limits, no other quantities will be violated during steady-state operation. This can be referred to as the system equality and inequality constraints [21].

The losses in a network system can be categorized into fixed and variable losses. Fixed losses refer to losses due to magnetization currents of items like transformers and reactors, normally referred to as iron losses [7]. These losses are consistent and occur during all hours of operation.Variable losses refer to losses due to current flowing through all the different equipment items in the system, normally referred as copper losses [7].

2.2 Batteries in the distribution system

As the amount of intermittent power production in the system is increasing challenges with their behaviour are arising. To solve these challenges, ESS could be one of the solutions [5]. Within energy storage solutions there are multiple different technologies available, which vary in suitable application areas. The largest shareholders on the market today are, in the following order; pumped hydro, compressed air, fly-wheel, lithium-ion batteries, molten-salt batteries and lead acid batteries [5]. Pumped hydro and compressed air stood for 99 % of the energy storage capacity in the world 2015, and is by 2030 still expected to dominate the market [5]. However, by 2030 [22] expects that 50 % of all investments into energy storage will be in batteries.

2.2.1 Battery application areas

In a report made by the Rocky Mountain Institute [10] different areas of use for batteries are explained. In this study 13 areas were found where batteries could bring value. The areas could be used on their own or combined to fully use battery's capacity. By combining and using the battery to full capacity they become more appealing from a cost-effective aspect, an aspect they today in most cases lack [10]. As an example, when the battery is solely being used for *Demand Charge Reduction* or *Distribution Deferral*, the capacity of the battery is only used up to 50% resp. 1% of its full capacity.

The different applications for a battery can be divided into who the stakeholder is. Stakeholders in battery applications are; utility services, Independent System Operator (ISO)/Regional Transmission Organization (RTO) services and customer services [10]. Utility services are investments directed to prolonging the time before a new investment into the distribution and transmission infrastructure is needed, by investing in efficient and distributed energy resources. Utility services also include how the system can defer transmission congestion and properly make use of the system [10].

The benefits of batteries for utility services are described by the following terms:

- *Resource Adequacy*
  To meet the demand during peak hours adequate solutions for levelizing between generation from immediate production and the demand are needed. Investments can then be done to increase the production or transmission from areas, but investing in energy storage can decrease the risk of over-investing in a specific area.

- *Distribution Deferral*
  By adding storage into the system, upgrades and investments can decrease in size or be postponed.

- *Transmission Congestion Relief*
  As the ISO charges users of a congested line during affected times of the day, batteries can in these cases provide relief in high demand areas and decrease congestion levels on affected line.

- *Transmission Deferral*
  Much like the distribution deferral, transmission deferral by batteries is provided by the fact that utility investments in the system can be avoided.

ISOs/RTOs relations to batteries is that they can be benefited by the ancillary services that the batteries can provide. Ancillary services are those which keeps the power flow continuous, supports the transmission, such as frequency control, spinning and operating reserves. The services provided by batteries for ISOs/RTOs are the following:

- *Energy Arbitrage*
  With batteries electricity can be bought during low locational marginal prices (LMP) and stored to be sold during high LMP.

- *Frequency regulation*
  In the load-generation relationship 1:1 is the goal, but when deviations from this occur, strategies put in place to level the relation are needed. These strategies are also called frequency regulation and could either be activated automatically and immediate, or manually after a certain time interval. Batteries can be a part in leveling the balance by injecting capacity to combat generation deficit or storing generation excess to combat excess generation.

- *Spin/Non-spin reserves*
  These reserves comes from dormant generators which easily can be started, generators not running on full capacity or ESS. The spin reserves can provide the system with additional power immediately and non-spin reserves within typically less than 10 minutes.

- *Voltage support*
  The regulation of voltage is needed to keep the power flow continuous in the

grid. This can be done by adjusting to the reactive and active power need of the demand using ESS.

- *Black start*
  If a large fault occurs and parts of the grid is off, black start is needed to bring the grid up again. This is done by starting so called black start generators, which are generators independent of the surrounding power grid which can inject the power needed to start power stations, and subsequently the grid.

Customer services are the services provided when the battery is placed behind the meter, and the customers are thereby so called behind-the-meter customers. The services and benefits of batteries placed behind the meter do not only apply to the customer but also to the ISO/RTO and utility services.

For customer service there are four benefits which batteries can provide directly:

- *Time-of-Use Bill Management*
  As the price of electricity fluctuates in correlation with the demand, behind-the-meter customers can reduce their electricity bill with batteries by not having to buy power to the same extent when the demand is high.

- *Increased Photo voltaic (PV) Self-Consumption*
  To decrease transport of power and increase self-consumption of distributed PV generated power, installment of batteries can provide a better utilization of the installed PV in areas where transmission is unfavourable.

- *Demand Charge Reduction*
  Installed behind-the-meter batteries for industrial customers can provide benefits for their power quality management. It can also lower their peak-usage by injecting stored energy from the battery over a specific limit and thereby lowering or chopping of their demand peaks. This would lead to a lower demand charge for the customer.

- *Backup Power*
  For residential customers batteries are beneficial as they can provide a daily backup in case of a black out.

2.2.2 Battery placement

Placement of batteries in the power system is an important factor when economical benefits and equipment utilization is taken into account. As the Rocky Mountain Institutes report states, to receive the most benefits from battery storage it should be placed as close to the end-customer as possible, preferably behind-the-meter [10].

The placement is not only important due to the financial and utilization aspects as wrongful placement can result in voltage violations, low or over-voltages, in the power system [23]. Rocky Mountain Institute recommends the needed size of the BESS to be divided into smaller units and distributed between all consumers in an area and placed behind the meter, in order to reap the most benefits in the system. If it however was to be placed at a single location and hence be centralized, the placement needs to suit the system it is placed within. Therefore, the decision of where to place BESS into the system is important, to create the best possible power flow. In order to place the battery in the right position, the loss sensitivity can be used, which is retrieved by using the Newton Raphson method (power flow analysis). The bus with the highest negative sensitivity during the load flow analysis is the most optimal placement for the BESS. The negativity is measured both for whole buses and for all phases on each bus. If the most negative bus does not coincide with the phases, placement of the battery should then be determined by the most negative sensitive phase and placed at that bus. In the case that the most negative sensitive bus however would be a bus connected to a transformer, the second to most negative bus would be the best placement for the battery [23].

Another method for deciding the placement for BESS is by using an impedance matrix, where every bus is represented and the changes due to voltage variations are easily obtained. It operates faster than power flow analysis as it can allocate changes at specific buses and generate the resulting changes at remaining buses while avoiding iterative algorithms, such as in the Newton Raphson method [24]. When applying the impedance matrix as the solution two cases are searched for. The first being at which bus the minimum reactive and active power delivered by a battery while still having effect on the voltage regulation, and the second at which bus a battery can provide maximum voltage regulation while still having a low active and reactive power input [24].

2.2.3 Battery sizing

Besides the placement of BESS in a system, the sizing of these batteries is also important. Customization of the battery size for the intended application is done by using load signatures from the current system, evaluating the placement of BESS and then running simulations to evaluate how large the batteries needs to be in order to fulfill the need [23].

To calculate the optimal size of the BESS particle swarm optimization (PSO) can be used. PSO is a method which essentially uses iterations while taking all important data into account to reach the best solution. This method is suited for power systems as it can solve large-scale nonlinear optimization problems in an efficient way [23].

Another method for calculating the minimum size of a battery while receiving the maximum benefits is explained by H. Nazaripouya et.al. in [24]. By assessing all currents at every bus of a system, using the impedance matrix as in the case of placement, the minimum possible size of the BESS can be found. By looking at the maximum real and imaginary part of the current going in and out from a battery at each bus, the minimal current required is found and then used to scale the battery.

2.2.4 Battery types suitable for stationary energy storage

Batteries are being used in multiple different sizes, in a vast variation of sectors and are embedded in many of the items used every day. Within the concept of batteries there are several different types but they all work from the same principle, movement of ions from the anode through a separator with electrolyte to the cathode. Some of the more common types are lead acid or variations where nickle or lithium are the main material. Within the two large category's, nickle and lithium based, there are several commonly used technologies [5]. For nickle, Ni-Cd and NiMH are two commonly available types of which Ni-Cd have dominated the market until Li-ion technologies replaced them in several applications. Li-ion batteries has an anode and cathode of lithium mixed with other elements, where common elements are cobalt, magnesium and phosphate [5].

The previous stated variations of battery-technologies are all used in practice to this date, but they are suited for different applications. Lead acid batteries have been and are today a large player on the market of stationary applications, such as starter and standby capacity as they are cost-effective and robust. Ni-Cd batteries are, as lead acid, used in UPS and airplane applications as they perform on a mature technology whiles having high endurance and discharge current [25]. However, as Cd is hazardous for the environment and the element have been prohibited by the European union in consumer products as well as a law for recycling has been introduced, in the aspect of Ni-based batteries NiMH have taken their place [25], [26]. This as the NiMH battery is applicable for the same tasks as the Ni-Cd but uses non-toxic components, are easily recycled while having a higher specific energy.

Li-ion batteries are replacing the previous mentioned batteries in most areas due to their light weight and high energy density [25]. Although they are more expensive than NiMH and lead acid, they can compete in price if comparison is done with price-per-cycle. This as they reach a higher number of cycles during its lifetime. However, they lack in robustness compared to the other types and needs protection equipment such as extra circuits in order to prevent thermal runaways when stressed [25].

Although there are several types of batteries that are applicable for grid support and stationary use, only Li-ion and NiMH are further described in this section as defined in the scope, chapter 1.4.

2.2.4.1 Lithium-ion batteries

Lithium batteries are selected when choosing battery type due to their long hold-capacity of charging, high energy density, low maintenance and low weight [27]. These attributes make them applicable for a large variety of applications and have pushed older technologies away. Li-ion batteries are generally found in most mobile devices carrying a battery such as phones, computers, cameras and EVs, but also in aerospace applications and in BESS. The future of Li-ion BESS investments are large in central and eastern Europe, and was the largest category for planned investments by 2016 [28], [29].

As mentioned in section 2.2.4, in Li-ion batteries the lithium is placed in the cathode combined with other materials such as cobalt, magnesium and phosphor, but in the anode it is combined with graphite [5]. The different types of cathode-materials gives the final battery different characteristics where the cobalt version covers the largest part of the market. In the future however magnesium versions may take the place [5].

In the tables 2.2 and 2.3 below, specifics on Li-ion batteries in general, and more specific information about different types of Li-ion batteries are declared and compared [5]. From table 2.3 it can be seen that the Li-ion battery with a cathode of manganese oxide (LMO) and anode of titanium oxide (LTO) has the highest amount of number of cycles, but also the lowest energy density and the highest cost [5].

Table 2.2: Specifications on Li-ion batteries in general.

Battery type	**Capacity MW**	**Operating time**	**Efficiency %**
Lithium-ion	0,001-0,1	min-h	85-99

Table 2.3: Comparison of Li-ion battery variations.

Cathode material	**Anode material**	**Energy density Wh/kg**	**Number of cycles**	**Cost 2014, SEK/kWh**
Iron phosphate (LFP)	Graphite	85–105	200–2000	3850–5950
Manganese oxide (LMO)	Graphite	140–180	800–2000	3150–4900
Manganese oxide (LMO)	Titanium oxide (LTO)	80–95	2000–25000	6300–15400
Cobalt oxide (LCO)	Graphite	140–200	300–800	1750–3500
Nickel-Cobalt-Aluminum (NCA)	Graphite	120–160	800–5000	1680–2660
Nickel-Manganese-Cobalt (NMC)	Graphite, silicone	120–140	800–2000	3850–5250

From this table it can also be seen that cobalt oxide (LCO) cathode with an anode of graphite has the highest energy density and second to lowest cost, but quite low number of cycles [5]. Due to these overall good characteristics, cobalt is the most used material for the cathode, and will from now be the only discussed Li-ion battery type. There are however other materials that are gaining ground, especially among BESS where the use of lithium iron phosphate (LiFePO4) batteries is expanding [28], [29].

During the last years Li-ion battery faults have been noticed by the media, and large companies have had to recall large batches of products [27]. The faults have resulted in products catching fire or melting which have made the general public and sensitive industries require guidelines for battery usage [25], [30]. For example, airplane companies have put in rules and restrictions of battery volumes on board the planes [30]. When batches of products have been recalled the faults have related to manufacturing faults [31]. However, it is not only manufacturing problems that causes faults, but temperature and voltage level sensitivity [27], [32].

Li-ion batteries are not able to charge below 0°C without causing harm to the battery, resulting in a decreased performance [32]. Another affect of charging at low temperatures is that the anode experiences lithium metal plating which leads to a shorter lifetime and power potential. The power potential is lowered as during the metal plating of the anode, it becomes close to having the same characteristics of a lithium metal battery. This makes them less optimal for applications in colder climates [32].

The Li-ion batteries sensitivity regarding voltage levels is related to its inability to be completely discharged [27]. If completely discharged the battery is no longer functional. This problem is however controlled by adding a controller which prevents the battery from fully discharging. Li-ion batteries sensitivity problems can overall be controlled and faults can be prevented with a BMS [27].

The recycling process of Li-ion batteries is an ongoing field of research due to financial and sustainability reasons [33]. Incentives for recycling are however small or week, since there is only a small economical benefit for the material recovering firm and the electrode materials are not scars. As the continuous growth in demand on Li-ion batteries recycling may become more important in a near future. When Li-ion batteries are recycled today the reasons are often to recycle electrode materials, primarily cobalt and lithium due their cost, or due to regulations in the area forcing it [33]. As extraction of cobalt is an incentive for recycling, development of batteries containing cheaper materials could reduce the interest in recycling. One of these materials is phosphate which would bring the economic gain down. The main reason for the small economic benefits of recycling is that most methods are advanced and often expensive when regarding time consumption, energy use and equipment. There are although companies who makes profit from recycling and the EU is invested into research and development of batteries [33].

Another way of prolonging the lifetime and increase the sustainability of Li-ion batteries is to use them for different applications [22], [34]. In the automotive industry a battery's lifetime is considered reached when the peak power is below 80% of the original level. Instead of then recycling the battery and retrieving the raw materials, it can be used as static energy storage [22], [34].

Out of the total amount of resourced lithium each year, 35% is used in batteries and the mineral is found in several parts of the world, embedded in the brine or as crystals in the pegmatite [27]. To retrieve the lithium mining processes are needed, which alter the environment around the mine and possibly can destroy land for animals in the area and close by communities [27]. Discussions on the responsibility of actors are regularly a topic in courtrooms and governments in order to implement sustainable solutions for all material mining [35]. The lithium triangle, the geographical area where Bolivia, Chile and Argentina meet, holds 56% of the lithium resources on earth [27].

With the amount of lithium needed to create a Li-ion battery the market for mining has increased drastically, especially since Tesla announced to be building a Li-ion battery factory in 2014 and with the following surge from other companies [36]. With the increased need, Chile and Argentina have increased the possibility for companies to start mining in these countries, on the expense of the aboriginal communities. Although they are receiving financial compensation for the land and it creates jobs in some communities, one of the already scars resources in the area is exploited and the consequences are unknown. The resource needed is water, which is necessary in the process as washing of the final product, and during the resourcing as water needs to be evaporated [27]. Adding to the problem is that the saltwater lagoons have decreased in the mining areas as well as they have been experiencing drought for years [37].

One of the most common types of cathode material for a Li-ion battery is the composition $LiCoO_2$ (LOC), where Co stands for cobalt. Cobalt is a highly discussed material for ethical and environmental reasons due the mining process and location of where it is done. The majority of all cobalt is mined in The Democratic Republic of the Congo, a country which is under violence, political stress and has been declared by the United Nations (UN) to be in urgent need of humanitarian relief [38]. The conditions at the mines have been reported to be hazardous to the workers, many of which are self-employed or children. Miners often (between 17 – 40 % in Congo) use hand tools, have no access to proper safety equipment and are in constant risk of the tunnels caving in [39]. Additionally, as they lack proper standards for a work environment, cobalt is not treated by the miners properly which may lead them to be in risk of breathing problems and thyroid conditions, problems which are undergoing studies [39].

Concluded studies regarding metal-levels in fish close to mining areas, number of cases where children to miners are born with defects and pollution levels have been recorded and studies to look for correlations are ongoing [39]–[42]. However, seen in patients with metallic prostheses containing cobalt and in rabbits injected with the metal, effects on the nerve system are common which shows as blindness, hearing problems and peripheral neuropathy [43].

As the minerals used in LiCo-batteries exist in Sweden, the Swedish agency Growth Analysis recommends moving the mining business to Sweden. This as it would both ensure a more sustainable mining process and decrease the reliability on other countries to provide the minerals [35]. Currently 85% of all rare earth metals are resourced in China while 25% of all raw materials are used in Europe, a region which resources 3% of all raw materials [27].

2.2.4.2 Nickel–metal hydride batteries, NiMH

From recent studies the energy density of NiMH batteries has experienced an increase and is in laboratory environments reaching the lower levels of common Li-ion battery types. A project conducted by the Advanced Research Project Agency-Energy (ARPA-E) were able to create a NiMH-cell with an energy density level of 127 WH/kg and as they continue their work they are aiming for 148 WH/kg [44]. Arguments have been made that NiMH batteries after installment with all necessary surrounding equipment reach the same equivalent power density as Li-ion due to the fact that Li-ion batteries demand more equipment, such as fire hazard protection [25].

The NiMH battery consists of an anode and cathode separated by a separator and electrolyte. During the last couple of years new technologies within material science has led to breakthroughs for NiMH batteries, which in turn has led to that new material combinations for the anode and cathode has been developed. In current technology the anode often consists of a so called AB_5 structure where the A can be a combination of magnesium, Mg, and rare earth elements and the B is nickle, Ni. This combination is superior to previous AB_5 structures as it is better in aspects of energy storage capabilities, lower rate of self-discharge and contributes to more stable cycles [45]. For the cathode, a common solution is where a mix of elements (Ni/Co/Zn) is pasted on a Ni-foam, using a wet method. Although the wet-method is most commonly used, dry-methods have been developed which have shown to increase the energy density [46]. Between the cathode and anode is the separator and electrolyte, the separator can be made out of grafted polypropylen or polyethylene non-woven fabric and the electrolyte a strong base such as aqueous potassium hydroxide, KOH [46], [47].

Due to its structure NiMH batteries are rugged and suitable for applications in places where longevity and stability is favoured, such as in space applications and ESSs for grid applications. Capacity degradation is however common, which is the result of internal reactions [47], [48]. Capacity degradation is separate from faults due to physical abuse or short/open-circuit faults and can either be reversible or irreversible [47].

For NiMH batteries the most common irreversible fault is that the electrolyte dry out, a problem which can be caused by high pressure internally [47], [48]. However, this can be solved by refilling the cell with new electrolyte, a solution that restores the capacity to the initial value. Other capacity degrading issues are related to reactions between the materials in the cell. For example, if the anode is compromised the electrical conductivity is decreased and when the cathode loses the original structure, the internal resistance is increased. High stress on the cell causes increased electrode expansion and distortion which may result in breakage [47].

Reversible capacity degradation is mainly caused by self-discharge. The self-discharges can for large scale operations be controlled by implementation of re-charging algorithms and hardware. Self-discharge is for NiMH batteries temperature depended, which is shown by the increased number of self-discharges when temperature moves up from $-5°$C, where the frequency is zero [49].

Another problem that can be solved with controllers and monitoring of the battery is what happens when the state of charge (SOC) and depth of discharge (DOD) reaches 100% or over. When the battery reaches these levels of SOC and DOD, oxygen is generated in the cell, a reaction which leads to a lowered capacity respectively higher impedance [48], [50]. An example of this effect has been seen in NiMH batteries used in EVs, where a NiMH battery which has an increased DOD from 10% to 90% resulted in a decrease in number of cycles from 5000 to 500. When comparing Li-ion to NiMH batteries in the aspect of monitoring, NiMH batteries needs less monitoring as they only require surveillance of the whole battery pack, whereas Li-ion needs monitoring on every cell due to its larger sensitivity to 100% DOD and SOC [50].

Even though NiMH batteries are considered as being non-toxic and non-dangerous compared to other types of batteries there are concerns. One is the electrolyte, KOH, as it damages metals and when in contact with skin result in burns. These reactions occur as KHO reacts with water and therefore also moist air [51]. The second concern is not directed to humans and during the operation, but to the environment as Ni harms plants [51].

NiMH batteries may have a long lifetime as they are able to be re-activated and recycled when the capacity level has decreased. The re-activation can be done by re-filling the cell with new electrolyte, as described earlier, but also by adjusting the anode and cathode when the capacity is decreasing. This can be done by first cleaning the electrodes via adding a sulfuric acid which is electrified, and then reversing the chemical reaction which has lowered the capacity of the electrodes by adding other chemical solutions [52]. However, caution is needed when opening up the cell as a flammable reaction may occur when the anode comes in contact with CO_2 [53].

When the battery is completely spent dismantling can be done in order to retrieve the metals and re-use them. In a study [54] made at the University of Chemistry and Technology in Prague, it was shown that over 90% of a majority of the metals could be obtained. In most cases the loss of nickle and cobalt from the input to output with their method was in majority of cases 5% and had a lowest level of 0.5% loss.

As some elements used in the anode of the NiMH battery are classified as rare earth elements, sustainability aspects of the usage of these elements could be valuable to consider. However, rare earth elements is not a measurement of the abundance of these elements as the intentions of the term when invented, grouped together elements that were unfamiliar and hard to extract from the surroundings [55]. In general the elements in the list are as abundant as other elements used in industrial settings such as copper, nickle and zinc, and the least abundant in the group is around 200 times as abundant as gold [55]. In the anode of the battery a mix of these elements contribute to the over all performance and from [56] a common mix i described; Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd) and Samarium (Sm) [57]. The abundance of these differ but Ce is almost as abundant as copper placing its abundance at $26th$ place of all elements, Nd is about as common as nickle, copper and cobalt, and Sm can be found in up to 2.8% of the Earth's crust [58].

Described in chapter 2.2.4.1 is the complexity of the Co industry and the impacts it has on society and its sustainability. As Co is used in the cathode of the NiMH battery, the sustainability aspects of Co also applies to NiMH batteries. In contrary to the Li-ion

In a NiMH battery the nickel content vary dependent on the technology used, but from [54] where several different NiMH batteries were investigated, it was found that around 50% of the total electrode was made out of nickle. Nickle is an abundant element on Earth and extracting it is done in several countries over the whole globe. Although it is abundant the main countries for mining are Russia, the Philippines, Canada, New Caledonia (France), Australia and Indonesia [59]. During later years the mining process and its effects has been questioned which has lead to plants shutting down and harsher regulations been putt in place [60]–[65]. Mines in Australia, Russia and the Philippines have been ordered to shut down or invest in safety measures in order to still get to operate due to these regulations and new government officials [61]–[63], [65]. One of these mines which have started to modernize the operation is situated in Norilsk, Russia. A city among the most polluted in the world where the level of blood illnesses is 44% more common in children than in the entire region of Krasnoyarsk [60]. Additionally, to the higher number of cases of blood illness in Norilsk, nervous system illnesses and bone/muscle system illnesses are 38% respectively 28% more common in the city. For humans in general, nickles carcinogen properties have been known for decades and then especially via cancer types related to the inhalation system [66]. It is however not only humans who are affected by nickle directly or from bi-products. The sulphur emitted as smoke from the chimneys during production creates acid rain which affects the growth possibility for plants near the operation cites, as well as provoke cough among citizens [67]. Another problem is the need of remedies for the soil pollution caused during mining and production which is expensive and is not always prioritized by the companies [67], [68].

2.3 Battery usage and limitations today

The power system is in a transition, with an increasing share of variable power sources, distributed energy production, ESS, EVs and smart grid technologies. These new trends causes challenges, but also opportunities for the energy system [3]. Previously, there was a clear division between production, distribution and consumption, but this division is becoming increasingly inexplicit with the introduction of prosumers, microgrids and the possibility to aggregate storage, flexibility and production [3]. This creates a new playing field with new rules, but also the possibility to solve problems in new ways, by for example using local energy systems and BESS to increase the resilience of an energy system. This could lead to that reinforcement investments in the grid can be postponed or avoided completely. Due to the current circumstances and legislation however, the ability to implement BESS is limited, which complicates the integration of these types of solutions [3].

2.3.1 Obstacles with smart grid technology and components in Sweden

In Sweden today, there are several obstacles that has to be overcome for a successful integration of smart grid technologies. A report conducted by Power Circle AB [3] states different types of obstacles, and also contains a survey on this subject. One of these obstacles is the Swedish electricity network control, which is quite restricted and limiting in the aspect of investing in new and unexplored techniques, rather than traditional [3]. Some of the participants in the survey also claimed that the electricity network control is more detail controlling now than it has been before, and that it is adjusted to old traditional techniques. This could then lead to grid companies adjusting themselves more to the electricity network control, than to what that could benefit their customers [3].

Investments in power equipment usually requires very long depreciation periods, which is reasonable when considering traditional techniques, but does not promote investments in new technologies. The industry is also pressured into only making efficient investments due to decreasing electricity prices and increasing distribution prices [3]. The network operation is generally based on risk minimization, which results in only a little to none driving force for grid companies to try out and invest in new solutions [3]. As of today there is also no possibility for grid companies to get any funding for research and development (R&D) in their revenue framework. This also result in that the opportunity to implement and test new business models and techniques in terms of pilots is limited [3].

The possibility to test tariffs on a part of the network is restricted due to the requirement for non-discriminatory tariffs, and to introduce new tariff structures in a network without small scale testing is by the majority of the network companies in the survey considered to be very risky [3]. Another obstacle mentioned by the participants was the limited time and resources to study what meaning the revenue framework regulation would have on their investment decisions [3].

Second to economics and regulation, other mentioned obstacles was lack of competence, culture, external relations, organization and disinterest from the management [3]. To be able to overcome these obstacles, survey participants mentioned enthusiasts and precursors to be important factors. It was also mentioned in the survey that everyone in the industry knows what needs to be done, but without engaged and driven workers, nothing in this area will be done [3].

2.3.2 Obstacles with BESS implementation

With an electricity network system, the end customers pay a grid fee for the transmission of their electricity. There can also be a fee for generators which has to be paid for them to be able to get access to the grid. When considering ESS such as BESS in this perspective, it can be seen as both a consumer, when it is charging, and a producer, when it is discharging [4]. Therefore, different countries in Europe handles ESS in different ways, depending on their policies. Many countries have fees for both charging and discharging ESS, while some countries have removed these fees for some specific ESS types [4]. The European Commission suggested (2016) that network operators should not be allowed to own ESS. Exceptions could be made if no other investors than network operators were interested, but then only for a restricted time [3].

2.3.2.1 Limited energy laws in Sweden and resulting complications

The laws regarding usage of ESS in Sweden is to date not very clear, not the current nor the ones that are to come, which causes barriers for a large scale usage of ESS [3]. It is not legal for network operators to own ESS, unless it is solely used for the purpose of covering or replacing electricity losses due to outages [5]. This means that the laws regarding ESS such as batteries has to change in order for such alternatives to become an attractive and viable option for network operators [5].

Network operators who owns ESS under the previous mentioned restrictions are excepted from the network charge and electricity taxes. If a commercial actor wants to invest in and utilize ESS however, they not only have to pay output and input tariffs for the electricity charged and discharged, but also electricity taxes for the electricity going into the batteries [3]. Further, the end customer will also pay taxes for the sold electricity that is re-entered to the grid. This double taxation is a clear obstacle for the success of BESS [3]. However, in February 2018 the Ministry of Finance released a memorandum on several issues and among them was the double taxation on electricity [69]. To remove the additional cost, which affects a number of companies both taxable and non-taxable, it is suggested that a refund on the tax payed on the electricity re-transferred to the same concession-grid as taken from should be applied to the non-taxable. This would be the non-taxable and hence the storage-suppliers responsibility as it would be a larger administrative burden on the grid-company than the storage-supplier. For taxable, such as producers and grid-owners, the tax should not be applied to electricity which is not transferred to other taxable if tax is previously paid. The reformation starts on the 1^{st} of January 2019, but will be retroactively used from the 1^{st} of January 2018 [69].

2.3.3 Existing projects and implementations of BESS

Implementations of BESS has previously for most parts been used as back-up systems for vital societal functions, such as hospitals. Projects and implementations with this purpose today are common and use mature techniques. The size of these projects varies from small to single households back-ups, to the currently larges once which has a capacity of 100MW [70]. Projects partly based on BESS are increasing in size, capacity and numbers. In the following sections 2.3.3.1, 2.3.3.2, 2.3.3.3 and 2.3.3.4 a few selected projects both based in Sweden and larger once from other parts of the world are presented.

2.3.3.1 Simris, Sweden: Li-ion

Up and running since October 2017 in the village Simris in the south of Sweden is a local energy system with the possibility for island mode operation [71]. Initially the placement of the project was supposed to be on an island outside of Timrå, in the mid-east of Sweden, but due to problems with building permits plan B was put in action [72]. Plan B was the village Simris, a village with around 140 inhabitants, outside the city Simrishamn [72], [73]. This place was selected as Simris had a suitable grid structure and an already operating solar park and wind power station. Additionally, not only the technical aspects were suitable but also the social ones, as the inhabitants had an interest in green locally produced power. The cost of the project came to be 35 million SEK, which was by 50% founded by the owner company E.ON, and 50% by the European union in form of the projects InterFlex and Horizon2020 [74].

Simris has an annual consumption of 2.1 GWh and the power generated by the solar park and wind power station generates 85% of the consumption [73]. Thereby, it is not disconnected from the main grid at all times but the goal of the project is to be completely disconnected every fifth week [72]. The battery's role in this system is to balance the grid and increase the power quality along with decreasing demand peaks when the main grid is connected. To handle these tasks a Li-ion battery from Samsung at a size of 833 $kW/333\ kWh$ was chosen [73], [75]. Additionally to the previous described tasks, the responsibility of the battery is to release a fault current when a problem occurs in the system in order to release the relays and protect the system [76].

From the start, the project's two test weeks have been completed at the time of writing, where the goal was to run in island mode between 08:00-16:00 during the first week, and between 08:00-20:00 during the second week. The goal for the first test week was hence to be disconnected for 40 hours, and the second week for 60 hours. Due to seasonal and weather conditions the goal for the first week was not reached, 34.5 hours island mode, and overreached for the same reasons during the second, 61.26 hours island mode [75].

2.3.3.2 Microgrid Torsebo, Sweden: Li-ion NMC

The Microgrid Torsebo project was started by Vattenfall in March 2017 in a village called Torsebo, located in the southeast of Sweden. This area has been subjected to problems related to voltage levels, mainly due to the operation of a PV plant in the area in combination with an old low voltage network which was not compatible with this type of operation [77]. Due to this, Vattenfall wanted to investigate how a BESS can handle and improve these voltage variations. The project is only a test and demonstration project. Commissioning of this project is planned in the beginning of July 2018, and the equipment will be removed after the test period of one year [77].

The aim of the Microgrid Torsebo project is to earn knowledge about the benefits that BESS can provide to the grid. The hope is that the BESS can improve the quality of electricity and of distribution in a low voltage network, and if so be an alternative to the traditional reinforcement method [77]. The BESS chosen is ABB's Powerstore, a Li-ion NMC battery which is supposed to regulate the voltage level in the low voltage network between ± 5%. It is also supposed to perform peak load shaving and minimize the amount of energy exported from the area, while also being able to keep the low voltage network in island mode during an interruption in the overlying grid [77].

Even though the project was started about a year ago, the equipment has not yet been installed. This is due to the fact that BESS equipment for low voltage networks are not easy to purchase, and only a few suppliers offers these types of products [77]. The BESS usually offered and the related power electronics are usually customized for higher voltage levels. Delivery time for these types of products are also quite long [77]. In the long term, Vattenfall can see a lot of application areas for BESS, and that this type of technique can be a compliment to speed up the implementation of renewable power production [77].

2.3.3.3 Hornsdale Power Reserve, Australia: Li-ion

On July 7th 2017 it was announced that an agreement between the South Australian Government, together with the US company Tesla and the French renewable energy company Neoen was conducted, that would result in the installation of the worlds largest battery to date [70]. CEO of Tesla Elon Musk stated that the battery would be delivered within a 100 days, or it would be provided free of charge, the start day being the day when the grid interconnection agreement had been signed [70]. On November 25th, the battery was fully installed and tested with its first charges and discharges into the grid, and on December 1st the Hornsdale Reserve project was fully completed and put into operation [70]. The facility consists of 100 MW/129 MWh Tesla Powerpack battery system which at December 1st 2017 was the largest Li-ion battery in the world, and can provide electricity to 30 000 homes during peak discharging. It utilizes a land area of almost one hectare and is located by the Hornsdale Wind Farm [70].

The aim of the Hornsdale Power Reserve project is to provide a battery storage facility that can stabilize the electricity grid in South Australia, while also supporting the integration of renewable power sources. Other properties of the system is the ability to prevent load-shedding events, provide frequency control and short-term network security services [70]. A part of the battery will also be used for trading in the electricity market, to store energy when the demand is low, and discharge energy when the demand is high. This will decrease the need for expensive gas-plants, and push down the electricity prices [70].

2.3.3.4 Dalian, China: Vanadium flow battery

Currently under construction by Rongke Power in Dalian, China is the largest chemical based ESS, with a capacity of 200MW/800Mwh when complete in 2020 [78]. The technology used for this large battery is vanadium flow, which is a mature technology best used in large scale applications, such as power grid support, and is from a longevity aspect possible to deliver close to twice of a Li-ion battery simultaneously as having non to minimal degradation during their first 20 years [78]–[80]. With a cycle life of above $13\ 000 - 15\ 000$ and with a frequency of use is once every day, the lifetime in years equals to 41 years which makes it competitive to cables, with a depreciation time of 40 years [78], [79].

In the case of the site in Dalian the batteries are manufactured in a close-by factory run by UniEnergy Technologies (UET) [78]. UET are aiming to not only supply this project from the factory, but also other large vanadium flow battery projects with their yearly production rate of 300 MW/1200 MWh, according to the vice-president of business development and marketing Russ Weed [80], [81]. After the installation is finished in 2020 the main power company will take over the operation and coordinate this ESS with others in the area to optimize the usage. When up and running the purpose of the ESS it to support grid stability, be a resource during black start and help with up to 8% of load shaving during high demand [78]. Additionally, the battery will make it possible to increase the wind power production as it now is limited and curtailed.

2.4 Demand response

The ongoing changes in the electricity generation mix and the increasing demand of electricity will all lead to a growing peak demand. This will in turn lead to network congestion and can risk the security of the electricity system [82]. These challenges can be mitigated by the use of demand response (DR), which can be a number of different procedures that utilizes locally produced energy, load and energy storage to improve the operation of the power system as well as strengthen the quality of the power supplied [82]. To decrease the peak demand, procedures of DSR economically motivates customers to move their consumption to off-peak hours, which can reduce the systems generation capacity requirement [82], [83]. By moving the load consumption to off-peak hours, this facilitates the handling of voltage variations and load management in the network, but DSR can also be used to shift the consumption depending on the conditions of power supply [82].

DSR can be used in all subsystems of the grid, which includes power generation, the transmission and distribution systems [83]. By supplying ancillary services from larger industrial loads and utilizing the generators that has a lower marginal cost, such as renewable power sources, to decrease the balancing cost, the use of DSR can enhance the efficiency of the power system [82], [83]. This means that DSR can also be used for the purpose to reduce the cost and need for reinforcement in the distribution system [83]. However, the impacts that DSR has is specific for the locations that it is used in, which entails that the reduced need for reinforcements in one location where DSR is used, might lead to more demanding requirements of transmission [83]. The decreased costs in system components related to the use of DSR is though considerably larger than the increased cost of transmission that this could cause, and can thereby still be seen as economically profitable [83].

2.4.1 EVs as demand response

One way of flattening out the demand profile by shifting loads to off-peak hours is to plan the use of some loads, like EVs, to off-peak hours [84]. EVs has great potential for DR, since they are parked for a large duration of the day, has relatively low consumption of energy in comparison to the high battery power and energy levels, as well as their intrinsic potential to store energy [85].

As of today, there are some barriers for private owners of EVs to participate in demand-side integration (DSI) programs, which includes both DR and demand side management (DSM) [86]. Since they have to make a relatively large investment for the needed infrastructure, the willingness for owners to participate in these programs is to an extent limited [86]. Due to this it becomes even more important that the participants of such programs become economically compensated in some way [86].

With a growing integration of EVs, it can be expected that EVs will become a large load in the future. If the charging of these EVs would be uncontrolled, it could lead to the creation of new demand peaks, or an increase of the already existing demand peaks (depending on when the charging takes place) [85], [86]. This could cause significant risks to the security of the power system [86].

One method to solve this problem could be to schedule the charging, and optimize the charging for cost minimization based on the day-ahead or intraday market pricing [87]. By doing so, consumers could schedule their charging of EVs to time intervals when the electricity price is low, usually during the night. This could however lead to that all EVs in the same area are charged during the same time, which would lead to a creation of new demand peaks [87]. Another scheduling method could be to optimize the charging based on active power loss minimization in the power system. With this method, the charging of EVs would be distributed between the off-peak hours, and the demand peak would remain unaffected [87]. When using scheduling methods such as these, it is however usually desired that the EVs are fully charged at the time when they are expected to start the next trip [87].

3
Method and modelling

The main objective of this thesis is to evaluate during which circumstances reinforcement of the grid is more profitable made with batteries or cables, considering both economic aspects as well as other benefits. The work-flow of this thesis has been summarized and can be seen in Figure 3.1, which starts with a literature pre-study and is followed by three different steps.

The pre-study consists of literature regarding reinforcements in general, as well as information gathering about cables and batteries, which is further explained in section 3.1. Step 1 consists of data gathering and is further explained in section 3.2, step 2 consists of simulations and is further explained in section 3.3. Step 3 consists of an explanation of how the different results will be evaluated as well as the expected results and can be found in section 3.4. A description of the GAMS model development can be seen in section 3.5.

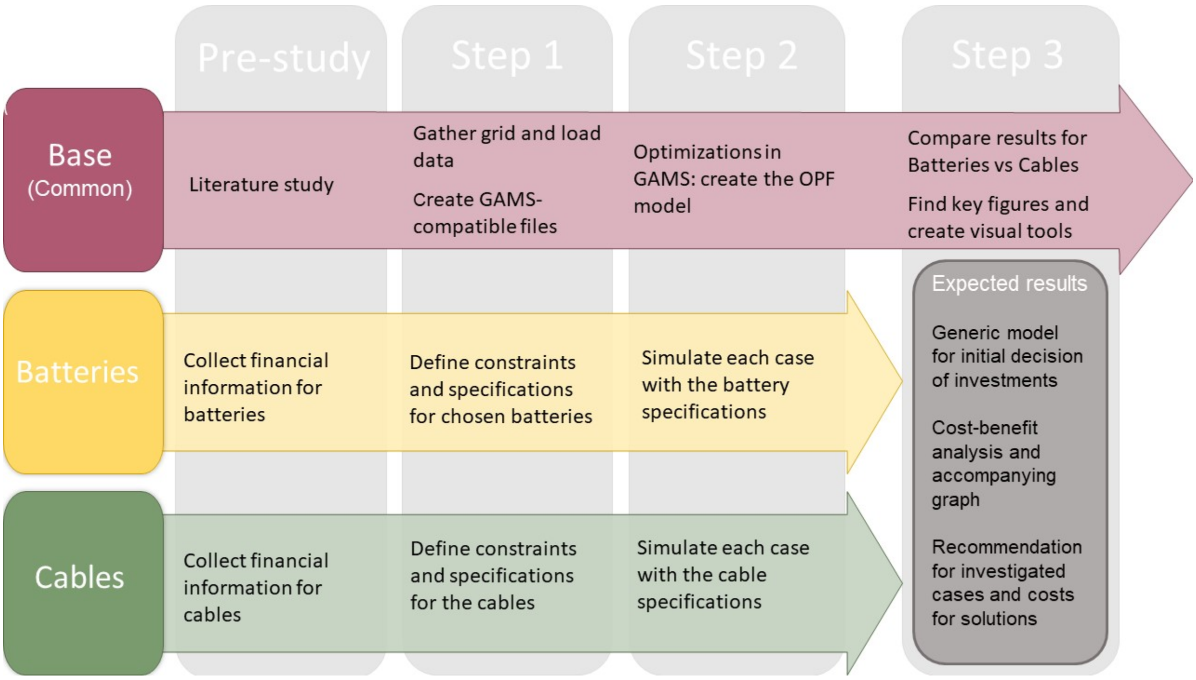

Figure 3.1: Flowchart of the working procedure showing the different steps.

3.1 Pre-study

To start off this thesis, a pre-study on how reinforcements are carried out today was conducted in order to understand the laws and constraints that lies around the subject. This was done by researching information and making contact with knowledgeable people in the field, both within academia and the industry. Further, to evaluate the financial side of the project, data regarding the cost of installations dependent on the equipment was in this step of the study retrieved. The data was then later used in the comparison stage of the thesis, see step 3.

For the battery reinforcement solutions more research was needed as the cases where this type of reinforcement are used, are and have not been used to the same extent as cables. Additionally, most cases are only theoretical once based on simulations. Reinforcement by cables was studied by looking at previous work and theory for cable reinforcement while the equipment selection and cost information for new investments was collected from the EBR-catalogue. The EBR-catalog is a tool created by the Swedish trade organization Energiföretagen Sverige and is used by Swedish grid owners and authorities for estimations of reinforcement costs and production time estimations.

3.2 Step 1

In the first step, data for the grid at the different locations was gathered, such as cable and transformer data as well as load profiles. Data for suitable batteries was in this step also collected. The data for the grid consists of capacity limits of the different networks, buses and lines of the different locations, and the load data consists of average consumed active power for the previous hour. Gävle and Kalmar Energi were the main providers of the data used in the simulations for grid, load and cables for the different cases.

The battery-data consists of applicable battery specifications needed to match with the two main cases, as well as simulation results from previous work useful for step 2. Data for EV implementation in the EV case was provided by David Steen, Post Doc at Chalmers in the area of Electrical engineering. From the simulation results, useful constraints were defined and used in step 2. For the cables, the data used consists of line lengths, resistance, reactance, line charge and maximum current limit. For the batteries, the data used consists of power and energy level, as well as SOC, charge and discharge limits. The data used for EVs consists of energy consumed and hours for when drivers arrive at home and leave, as well as average driving distance, charging time and energy consumed.

3.3 Step 2

In the second step, an OPF model was created in the software GAMS, which was run two times with different objectives. The first being to minimize the current, and from those results find suiting cable and battery sizes. The sizes were then implemented and the program was run again with the objective to minimize the total system losses. To achieve this, the OPF model evaluated total power losses and contained all relevant equations and constraints regarding the cables and batteries. The development of the model is further explained in section 3.5.

The simulations were run for four different days, specifically chosen to represent different situations in the grid and the whole year. This was done to see how the solutions withhold, how the batteries were utilized and the differences in power flow between the cable and battery solutions with resulting losses. The simulations for cables and batteries were done separately and then compared during step 3.

From the results of running the first objective the maximum current in the system was obtained, which was used to find suitable cable dimensions. To find cable sizes available on the market and their corresponding current limits Draka's, a cable manufacturer, product catalogue was used [15].

To find suiting sizes of batteries, a 15-day period with the initial grid configuration was simulated in GAMS, where the most demanding day was placed in the middle (as the eighth day). By using the objective to minimize the current, the number of times the capacity of the critical line was exceeded and with how much power was extracted. The initial size of the battery was then calculated as the highest sum of energy needed to cover consecutive hours, or an addition of multiple periods of consecutive hours when there was a short time period in between with levels close to 100% of the current limit. This battery size was then put into the GAMS model. If the estimated size was insufficient when running the simulations for the 15 days, energy was added in steps of 1 kWh until the battery was large enough to accommodate the power needed during these 15 days.

3.4 Step 3

In the third step, the results from the different cases were evaluated, and a comparison whether batteries or cables were more beneficial was made. The relevant results were then processed to suite Matlab and Excel, where visual aids, such as figures, were created.

From the loss calculations and specifications needed for each solution found in step 2 the costs were calculated. As simulations during one entire year was not possible to be performed, estimations of losses and cost of losses during one entire year was done by choosing four days for the different cases, which were added together accordingly to be able represent one year.

The annualized cost of the investment was calculated by using the CRF, which can be expressed according to

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}, \tag{3.1}$$

where i is the present-worth interest rate, where a value of 5% was used, and n is the depreciation period. The annualized investment cost was then calculated as

$$C_{annualized} = C_i \times CRF, \tag{3.2}$$

where C_i is the total investment cost. The two different batteries had different recommended lifetimes, where the lifetime for the Li-ion battery used was 10 years, and the lifetime used for the NiMH battery was 20 years. To be able to compare the different battery solutions with the cable solution in the aspect of lifetime, the needed amount of re-investments of both batteries was accounted for in the total investment cost. However, the same depreciation time was used for all solution, which was 40 years and which equals a CRF value of 0.0583.

As the lifetime of batteries is dependent on how frequent the cycles are performed, and simulations over one entire year was not possible to perform, a sensitivity analysis was done with lifetimes of 8, 10, 13.33 and 20 years to evaluate the impact the lifetime had on the annualized investment cost, and also to compare the different battery solutions. To investigate the impact that the interest rate had on the annualized investment cost, a sensitivity analysis of the interest rate with values of 3%, 5% and 7% was performed as well.

The results consists of a cost-benefit analysis, presented in tables and graphically in figures as a comparison of the different solutions, for the two different cases. These results were then used to give recommendations if batteries or cables are more economically beneficial for the different cases. The results also consist of the additional sub-cases, which was used to be able to provide more general recommendations based on the size of the load and the grid configuration. The final results present the impact that an increased integration of EVs has on the grid, considering uncontrolled and scheduled charging, for both cable and battery solutions.

3.5 Model development

The development of the model used in GAMS can be seen in Figure 3.2, which displays a flowcharts of the model. In this figure, the input data used, equality and inequality constraints, equations and objective function can be seen, as well as the outputs of the model.

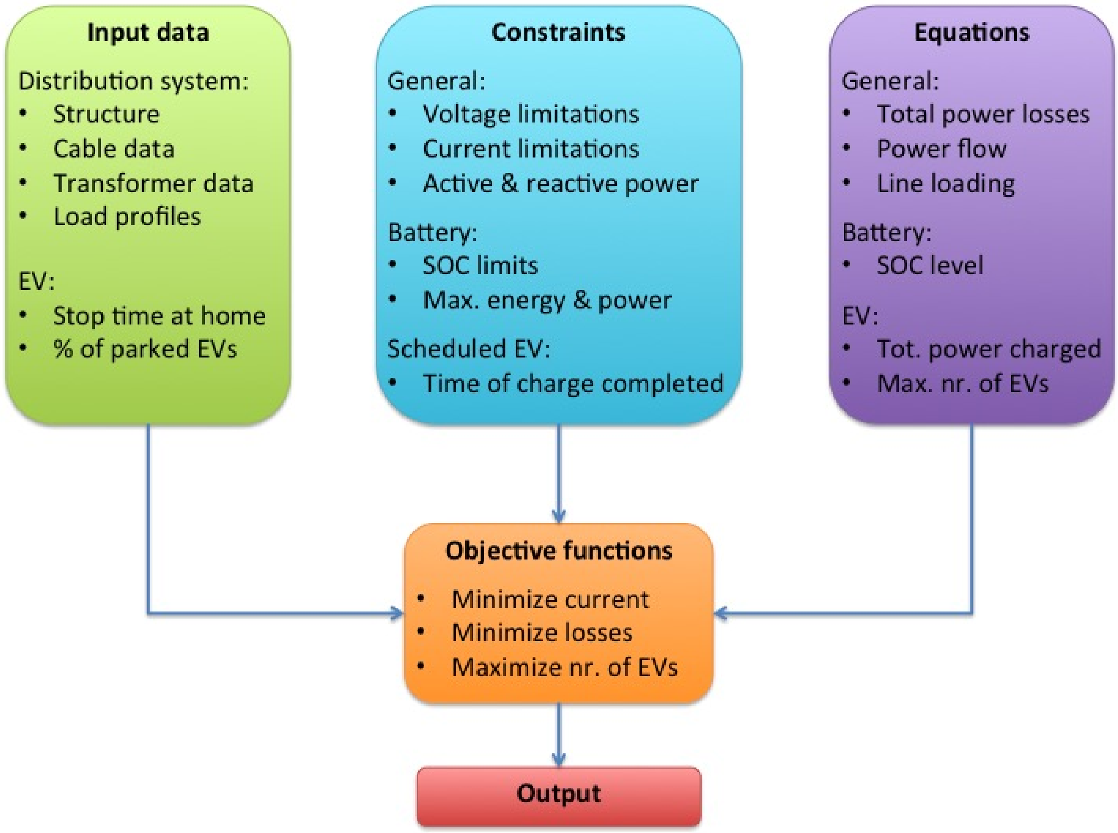

Figure 3.2: Flowchart of the model development in GAMS.

The objective to minimize the total power transmission losses in the system was calculated as

$$\min\ P_{loss} = 0.5 \sum_{l=1}^{N_L} \sum_{h=1}^{N_H} G_{i,j} \Big(V_{i,h}^2 + V_{j,h}^2 - 2V_{i,h}V_{j,h}cos(\delta_{i,h} - \delta_{j,h}) \Big), \tag{3.3}$$

where N_L is the total number of lines in the system and N_H is the number of hours. $G_{i,j}$ is the conductance of the line between bus i and j at hour h [21]. The cost of power losses was thereby calculated as

$$C_{loss} = 0.5 \sum_{l=1}^{N_L} \sum_{h=1}^{N_H} \Big(G_{i,j} \Big(V_{i,h}^2 + V_{j,h}^2 - 2V_{i,h}V_{j,h}cos(\delta_{i,h} - \delta_{j,h}) \Big) C_{spot\ price} \Big), \tag{3.4}$$

where $C_{spot\ price}$ is the electricity spot price.

The equality power flow constraints used in the model can be expressed as

$$P_{G_{i,h}} - P_{D_{i,h}} = \sum_{j=1}^{N_B} V_{i,h}V_{j,h}Y_{i,j}cos(\theta_{i,j} - \delta_{i,h} + \delta_{j,h}), \quad \forall\ h \tag{3.5}$$

$$Q_{G_{i,h}} - Q_{D_{i,h}} = -\sum_{j=1}^{N_B} V_{i,h}V_{j,h}Y_{i,j}sin(\theta_{i,j} - \delta_{i,h} + \delta_{j,h}), \quad \forall\ h \tag{3.6}$$

where $P_{Gi,h}$ and $P_{Di,h}$ is the active power generation and demand at bus i, $Q_{Gi,h}$ and $Q_{Di,h}$ is the reactive power generation and demand at bus i and N_B is the total number of buses in the system. $V_{i,h}$ and $V_{i,h}$ are the voltage magnitudes at buses i and j, $Y_{i,j}$ is the magnitude of the admittance bus element, $\theta_{i,j}$ is the angle of the admittance bus element and $\delta_{i,h}$ and $\delta_{j,h}$ is the voltage angle at bus i and j for hour h [21]. From equation 3.28 it can be seen that the reactive power losses are negative in the system, which is due to the fact that the shunt capacitance feeds the system with reactive power [7].

The inequality constraints can be expressed as

$$V_i^{min} \leq V_{i,h} \leq V_j^{max} \tag{3.7}$$

$$P_i^{min} \leq P_{i,h} \leq P_j^{max} \tag{3.8}$$

$$Q_i^{min} \leq Q_{i,h} \leq Q_j^{max}, \tag{3.9}$$

where V_i^{min} is equal to 0.95 $p.u.$ and V_j^{max} is equal to 1.05$p.u.$, and P_j^{max} and Q_j^{max} at the bus representing the grid is equal to infinity.

The constraints for line loading can be expressed as

$$Re\{I_{i,j,h}\} = V_{j,h}Y_{i,j}cos(\theta_{i,j} + \delta_{j,h}) - V_{i,h}Y_{i,j}cos(\theta_{i,j} + \delta_{i,h}) + V_{i,h}C_{i,j}sin(\delta_{i,h}) \tag{3.10}$$

$$Im\{I_{i,j,h}\} = V_{j,h}Y_{i,j}sin(\theta_{i,j} + \delta_{j,h}) - V_{i,h}Y_{i,j}sin(\theta_{i,j} + \delta_{i,h}) + V_{i,h}C_{i,j}cos(\delta_{i,h}) \tag{3.11}$$

$$\left|I_{i,j,h}\right| = \sqrt{Re\{I_{i,j,h}\}^2 + Im\{I_{i,j,h}\}^2}, \tag{3.12}$$

where $Re\{I_{i,j,h}\}$ and $Im\{I_{i,j,h}\}$ are the real and imaginary parts of the current $I_{i,j,h}$ respectively, and $C_{i,j}$ is the capacitance of the line. The current limit can be expressed as

$$I_{i,j}^{min} \leq I_{i,j,h} \leq I_{i,j}^{max}, \tag{3.13}$$

where $I_{i,j}^{min}$ and $I_{i,j}^{max}$ is the lower and upper current limits.

3.5.1 Implemented constraints for batteries

Charge and discharge of a battery can not be performed at the same time, which can be expressed as

$$P_{ec_{i,h}} \times P_{ed_{i,h}} = 0, \tag{3.14}$$

where $P_{ec_{i,h}}$ is the amount of power charging the battery and $P_{ed_{i,h}}$ is the amount of power discharged from the battery. Since the C-rate of both the NiMH and the Li-ion battery was above $1C$, and the simulations are only performed with an hourly resolution, the charging and discharging of the batteries was not limited further.

The state of charge (SOC) of a NiMH battery has a charge limit between 0-100% according to

$$0 \leq SOC \leq 1, \tag{3.15}$$

whereas the Li-ion battery has a SOC limit between 2-98% according to

$$0.02 \leq SOC \leq 0.98. \tag{3.16}$$

The change in SOC of the battery can be expressed as

$$SOC_{1_{i,h}} = SOC_{i,h-1} + \frac{\eta_{ec} \times P_{ec_{i,h-1}}}{E_{max}} - \frac{\eta_{ed} \times P_{ed_{i,h-1}}}{E_{max}}, \tag{3.17}$$

where η_{ec} is the charging efficiency of the battery, and η_{ed} is the discharging efficiency of the battery. The amount of power discharged from the batteries can be expressed as

$$P_{ed_{i,h}} = \frac{SOC_{i,h} - SOC_{lo_{i,h}}}{E_{max}}, \tag{3.18}$$

where $SOC_{lo_{i,h}}$ is the lower limit of the SOC for the batteries.

With batteries implemented in the model, the power flow equations changes as well according to

$$P_{G_{i,h}} + P_{ed_{i,h}} - P_{ec_{i,h}} - P_{D_{i,h}} = \sum_{j=1}^{N_B} V_{i,h}V_{j,h}Y_{i,j}cos(\theta_{i,j} - \delta_{i,h} + \delta_{j,h}) \tag{3.19}$$

$$Q_{G_{i,h}} + Q_{batt_{i,h}} - Q_{D_{i,h}} = -\sum_{j=1}^{N_B} V_{i,h}V_{j,h}Y_{i,j}sin(\theta_{i,j} - \delta_{i,h} + \delta_{j,h}), \tag{3.20}$$

where $Q_{batt_{i,h}}$ is the reactive compensation from the battery.

3.5.2 Implemented constraints for EVs

When EV load curves were added into GAMS, both uncontrolled and scheduled charging was investigated for the cable and battery solution respectively. Uncontrolled charging is based on that the driver starts charging immediately when arriving home which results in a peak in the system. Scheduled charging is based on that the grid itself decides when charging is best suited, distributing the charging over several hours. Both charging methods are described in chapter 2.4.

The amount of power charging each EV was calculated as

$$CP_{EV} = \frac{l_{drive}\ E_{EV}}{CT_{EV}\ \eta_{ch+bat}}, \tag{3.21}$$

where l_{drive} is the length of distance driven, E_{EV} is the energy consumed, CT_{EV} is the charging time and η_{ch+bat} is the efficiency of the charger and battery together of the EV assumed to be 95%.

The number of EVs connected to each bus in the system was distributed as the same percentage as the load is on each bus of the total load. This was done as

$$EV_{pos_{i,h}} = EV_{stop_h} EV_{share_i}, \tag{3.22}$$

where EV_{stop_h} is the percentage of EVs stopping at home at hour h and EV_{share_i} is the percentage share at each bus.

The objective function was also changed to maximize the number of EVs possible to charge according to

$$EV^{max} = EV_{stop_h} increase, \tag{3.23}$$

where *increase* is the penetration level of EVs.

The power flow equations also needed some modification. In the cable solution, the power injected to the EVs was put into the active power flow equation according to

$$P_{G_{i,h}} - P_{D_{i,h}} - P_{EV_{i,h}} = \sum_{j=1}^{N_B} V_{i,h} V_{j,h} Y_{i,j} cos(\theta_{i,j} - \delta_{i,h} + \delta_{j,h}), \tag{3.24}$$

where $P_{EV_{i,h}}$ is the active power charging the EVs, and the reactive power flow equation according to

$$Q_{G_{i,h}} - Q_{D_{i,h}} - Q_{EV_{i,h}} = -\sum_{j=1}^{N_B} V_{i,h} V_{j,h} Y_{i,j} sin(\theta_{i,j} - \delta_{i,h} + \delta_{j,h}), \tag{3.25}$$

where $Q_{EV_{i,h}}$ is the reactive power consumed by the EVs calculated as

$$Q_{EV_{i,h}} = P_{EV_{i,h}} tan\varphi, \tag{3.26}$$

where φ is the power factor angle of the EV charger.

In the battery solution, the power flow equations were expressed as

$$P_{G_{i,h}} + P_{ed_{i,h}} - P_{ec_{i,h}} - P_{D_{i,h}} - P_{EV_{i,h}} = \sum_{j=1}^{N_B} V_{i,h} V_{j,h} Y_{i,j} cos(\theta_{i,j} - \delta_{i,h} + \delta_{j,h}) \tag{3.27}$$

$$Q_{G_{i,h}} + Q_{batt_{i,h}} - Q_{D_{i,h}} - Q_{EV_{i,h}} = -\sum_{j=1}^{N_B} V_{i,h} V_{j,h} Y_{i,j} sin(\theta_{i,j} - \delta_{i,h} + \delta_{j,h}). \tag{3.28}$$

3.5.2.1 Uncontrolled charging

For uncontrolled charging, the total power drawn from the grid to the EVs can be expressed as

$$P_{EV_{i,h}} = (EV_{pos_{i,h}} + EV_{pos_{i,h-1}})\ increase\ CP_{EV} CT_{EV}. \tag{3.29}$$

3.5.2.2 Scheduled charging

When simulating the scheduled charging, the total power charging the EVs is limited by the number of EVs that are parked. The EVs parked was distributed between the buses in the same way according to

$$EV_{parked_{i,h}} = EV_{home_h} EV_{share_i}, \tag{3.30}$$

where EV_{home_h} is the percentage of EVs parked at home at hour h. The power charging the EVs was then expressed as

$$P_{EV_{i,h}} \leq EV_{parked_{i,h}}\ increase\ CP_{EV}. \tag{3.31}$$

The charging of the EVs was also limited to only charging between the first hour when the EVs arrives at home, hour 14, until hour 6, according to

$$P_{EV_{i,h}} = 0 \quad \text{for} \begin{cases} h < 14 \\ h > 6 \end{cases}, \tag{3.32}$$

and further set equal to

$$\sum_{h=0}^{24} P_{EV_{i,h}} = \sum_{h=0}^{24} EV_{pos_{i,h}}\ increase\ CP_{EV} CT_{EV}. \tag{3.33}$$

4

Description of investigated cases and assumptions

In this chapter a general description of the three different cases that were evaluated and the additional sub-cases is presented. The assumptions and data alterations made, as well as which days that were used for the simulations can also be found. A summarised description of each case can be found in table 4.1, which includes what each case consists of, where batteries were placed as well as which types of batteries that were investigated.

In section 4.1 the case in Furuvik is explained and in section 4.2 the case at Kalmar Airport is explained, where there is a planned load increase in both cases which results in a need for reinforcement of the grid. In section 4.3 a future scenario with an increased integration of EVs is explained, where charging EV were integrated in the Furuvik case. In section 4.4 the chosen days to simulate for each case is presented, and in section 4.5 an explanation of how the two main cases were used to create additional sub-cases can be found. A summation of all the assumptions made in this thesis can be found in section 4.6.

Table 4.1: General description of the three investigated cases.

Case	**Contains**	**Battery placement**	**Battery type**
Case 1 Furuvik	- Residential area - 9 network stations - 50% load increase	- Centralized	- NiMH - Li-ion
Case 2 Kalmar	- 2-bus system - 40% load increase	- Close to customer	- NiMH - Li-ion
Case 3 Future EV	- Furuvik settings - Uncontrolled/scheduled charging	- Centralized	- NiMH - Li-ion

4.1 Case 1: Furuvik

The location consists of residential areas and has a planned demand increase of 50%. To the location, power is today radially fed via an 4.2 km long overhead-line with a fuse limit of 170 A from the larger city Gävle, but as the line is incapable of accommodating the increased demand, reinforcements are therefore needed. Gävle Energi's current plan is to tear down the overhead-line and replace it with a cable, large enough to accommodate the increased demand. However, cable replacements are costly and as a possible reinforcement solution could be batteries in this type of grid, Gävle Energi is interested in investigating the possibility.

The grid configuration can be seen in Figure 4.1 (for values see table A.1 in Appendix A.1.1), where the overhead line going into Furuvik that is planned to be replaced can be seen (displayed in red). As the current limit on the other lines was not provided, and there is no other source of electricity import or generation, the same current limit of 170 A was used on all lines.

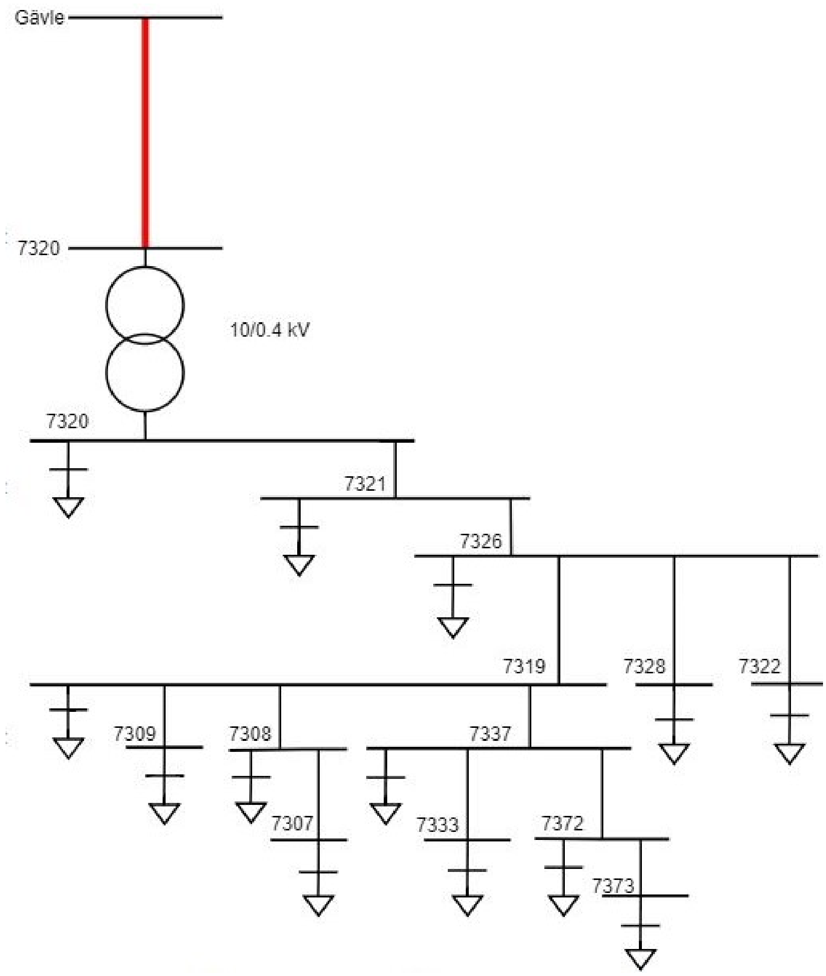

Figure 4.1: Configuration of the grid in Furuvik. The red line represents the overhead line which needs reinforcement in order to provide the demanded power to Furuvik.

4.1.1 Input load data and alterations made

Alterations to the data from Gävle Energi for the Furuvik-case was needed due to that measuring errors had occurred in one of their meter stations, where zero-values and values around 10^6 kW had been recorded, while the maximum values for remaining hours had been 295.68 kW at that station. To solve this in a reasonable and uncomplicated way, the consumption from the same hour 7 days before and after was averaged and used as a new estimate value for the faulty hour. The result of this adjustment takes the season and weekday variance into account. However, it is not a fully adequate method for estimating consumption from the faulty hours in terms of load forecasting, but as load forecasting is not the objective of this thesis a simpler method taking some factors into account is reasonable. In table 4.2 the affected days and values from the data given by Gävle Energi and the values that they were replaced with are shown.

Table 4.2: Alterations made to the load data from Gävle Energi.

		Consumption, kW			
Date	**Hour**	**Original**	**7 days before**	**7 days after**	**Estimated**
2018-02-01	15:00	1000062.92	61.67	84.26	72.96
2018-02-01	16:00	0	66.96	86.76	76.86
2018-02-01	17:00	0	79.72	96.17	87.94
2018-02-01	18:00	0	75.02	94.72	84.87
2018-02-01	19:00	999972.94	75.56	94.57	85.07
2017-09-05	11:00	1000036.61	32.17	27.57	29.87
2017-09-05	12:00	999997.37	22.73	28.05	25.39
2017-03-26	04:00	0	69.76	46.64	58.20

As simulations are performed on days spanned over one year, 365 days, and data received from Gävle Energi's 9 out of 10 meters in Furuvik only have hourly recorded data between 2017-07-01-03:00 and 2018-02-14-24:00, data to fit the period 2017-02-15-00:00 - 2017-07-01-02:00 needed to be formed. This was done by using the data from meter station 7321, which had saved hourly consumption previous to 2017-07-01-03:00, and putting that data in relation to the data from meters which only have data from 2017-07-01-03:00. The relation was acquired from the period where both meters have recorded data. This was done in this way as Gävle Energi did not have data from the meters on that period, but ensured that relations for all meters would be approximately the same for the missing period.

The relation for recorded consumption between the meters which do not have data previous to 2017-07-01-03:00 and the one which does is displayed in table 4.3. The total consumption of the period is compared as the percentage of the consumption recorded by the meter with data from 2017-02-15-00:00, and the resulting total load curve can be seen in Figure 4.2. The days with the maximum and minimum average consumption from this year are displayed in Figure 4.3 and 4.4 respectively.

Table 4.3: Relations between meter station 7321 for consumption between 2017-07-01-03:00 and 2018-02-14-24:00 to all other 9 meters.

Meter	7308	7337	7328	7320	7333	7322	7319	7326	7372
Relation, [%]	178.0	40.92	80.55	142.3	0.4934	71.61	124.7	143.2	63.75

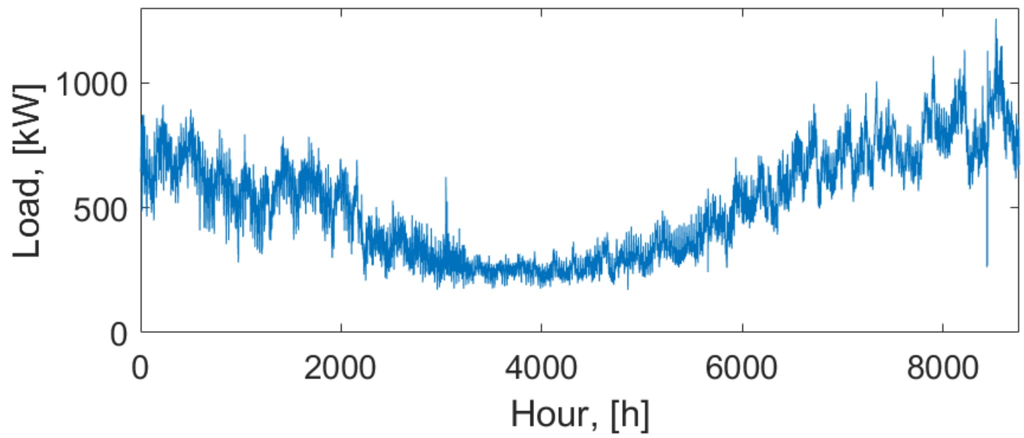

Figure 4.2: Total load demand curve in Furuvik over 365 days, starting on 2017-02-15 01:00 and ending on 2018-02-14 00:00.

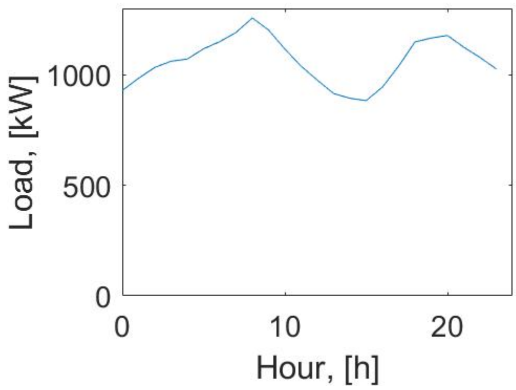

Figure 4.3: Total load demand in Furuvik during the day with maximum average consumption.

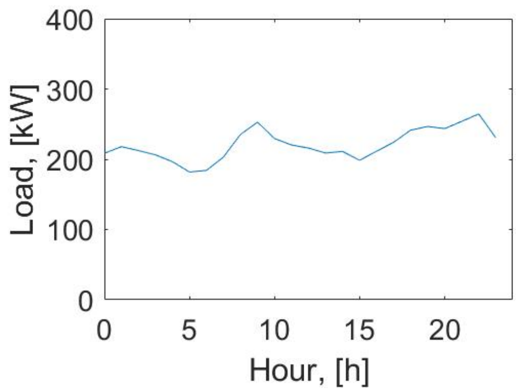

Figure 4.4: Total load demand in Furuvik during the day with minimum average consumption.

4.2 Case 2: Kalmar

Located at Kalmar-Öland Airport is an operation consisting of education and a smaller workshop, with a building area of 1200 m^2 where the heating is done by heat pump. At this business today the maximum power consumption is close to their current limit, and there is a need for a load increase of about 40% which is not possible as of today due to a fuse limit of 25 A. The cable used is an underground cable, AKKJ 4x150/41, 1.01 km long with a current limit of 290 A at 70°C, which other customers are connected to as well and can be seen in Figure 4.5 (displayed in red), which shows the grid configuration at Kalmar Airport (for values see table A.2 in Appendix A.1.2). The reinforcement and replacement of this cable is supposed to meet the annual increase in load.

At present there is a network station where a new cable is supposed to be connected, but there has to be an investment made into a new satellite station as well with a transformer of 100 kVA at the end point of the new cable. The total cable length between the two stations is estimated to be 1400 m, which is supposed to be installed in an excavation through a farmland, alternatively beside a country road where the speed limit is 70 km/h. The cable that is to be used is a 10 kV cable with a cross-section area of 150 mm^2, PEX isolated. Additionally, a Cu-line of 50 mm^2 will also be placed between the two network stations. In this case, additionally to the costs regarding investment and instalment of the cable and battery storage, the costs concerning the new satellite station had to be accounted for as well, which includes labour and materials.

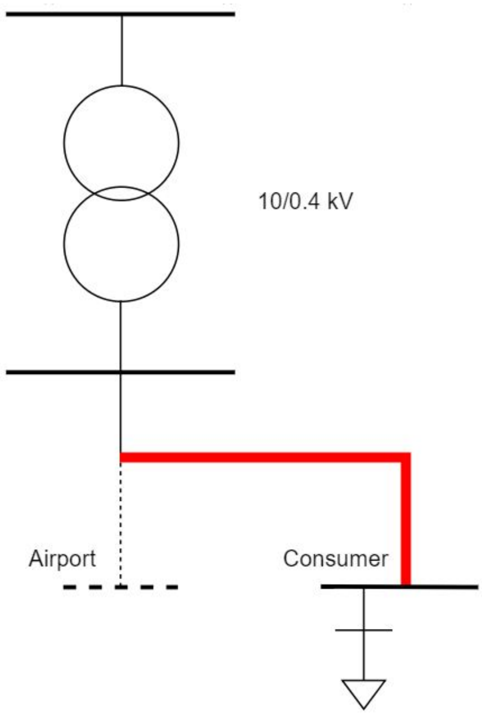

Figure 4.5: Configuration of the grid at Kalmar-Öland Airport. The red line represents the cable which needs reinforcement in order to provide the demanded power to the customer.

4.2.1 Input load data and alterations made

The case in Kalmar where there is a need for reinforcement is located at Kalmar-Öland Airport. This makes it one of the exceptions from the requirement for network concession, i.e. a non-concessionary network. Kalmar Energi does therefore not have any data from the actually proposed load, since it is not a customer to them. Instead Kalmar Energi provided load data from an equivalent customer, and this load data is used for the Kalmar case in this thesis. The data used from Kalmar Energi is on the span of 356 days starting at 2016-08-17-15:00 and ending at 2017-08-17-14:00, which can be seen in Figure 4.6, and the days with the maximum and minimum average consumption from this year are displayed in Figure 4.7 and 4.8 respectively. The values of this data however was too high to fit the fuse limit during the simulations, so 27% of the amount of the load data was used for all days to be able to fit the fuse limit of 25 A. When looking at Figure 4.6 a pattern of weekdays and weekend days in combination with high and low demand seasons can be seen, where weekend days have a significant lower consumption than weekdays.

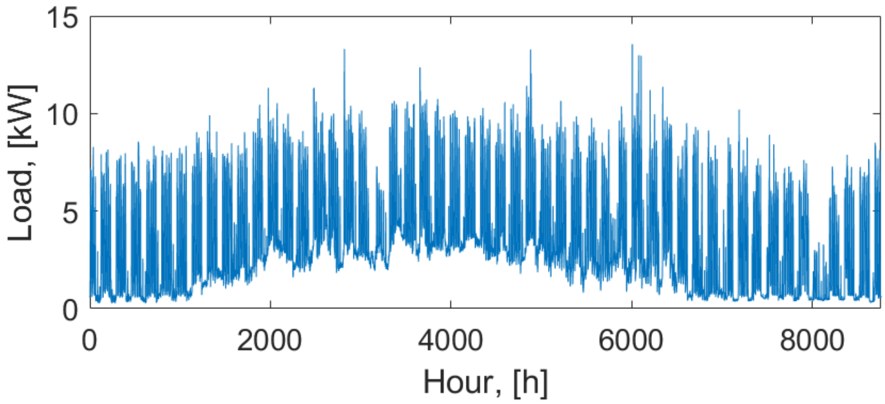

Figure 4.6: Total load demand curve from Kalmar Energi over 365 days, starting on 2016-08-17 00:00 and ending on 2017-08-16 23:00.

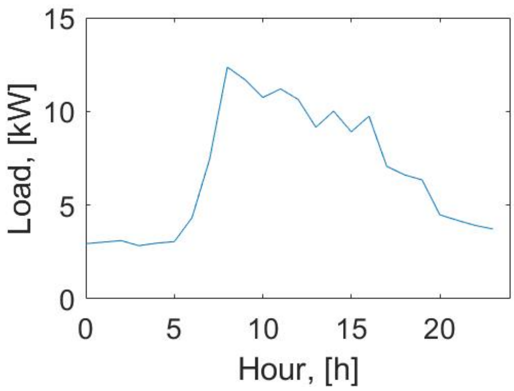

Figure 4.7: Total load demand in Kalmar during the day with maximum average consumption.

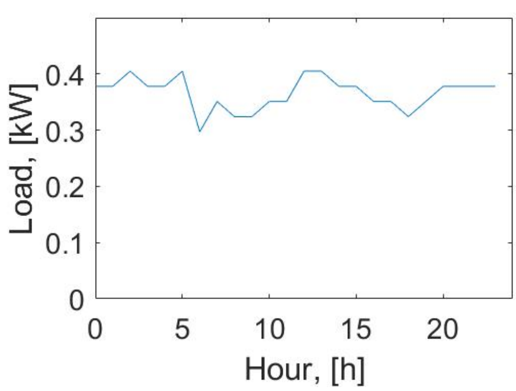

Figure 4.8: Total load demand in Kalmar during the day with minimum average consumption.

At the present the cable connected to the customer is a AKKJ 4x150/41 cable, 1.01 km long, which in the other end is connected to a 200 kVA, 10/0.4 kV transformer. The current limit, resistance, inductance and capacitance of this cable was not known by the customer. Instead, these values were provided by the technical support at the company Draka Kabel Sverige AB. The values used for the AKKJ 4x150/41 cable in the simulations of the initial circumstances are a current limit of 290 A at 70°C when placed underground, a resistance value of 0.206 Ω/km, inductance value of 0.22 mH/km and a capacitance value of 0.58 $\mu F/km$ [88], while considering the fuse limit of 25 A.

4.3 Case 3: Future EV

This case was aimed to investigate the consequences that an increased use of EVs can have on parts of the grid where grid reinforcement solutions such as cable and BESS implementation has been performed. The aim was also to investigate the impact of DR. As a base for this case the Furuvik case was chosen and EVs were integrated in all correlated sub-cases for both cable and battery solutions, as Furuvik, in contrary to Kalmar airport, is largely residential and at-home charging was the primary interest. To evaluate the impact of EVs and DR on both solutions, the number of EVs in all sub-cases were maximised.

To include EVs, loads represented by an average need of energy related to the average driving distance each day and energy demand of an EV was used in combination with movement patterns for residential areas. Values about energy charged and average distance driven was gathered from [89], [90]. According to [89], the average distance a vehicle has driven during one day in Gävleborgs län and Sweden in total is approximately 33 km. The corresponding energy the EV consumes is 6.6 kWh/day, which is calculated from that the demand is approximated to be 20 $kWh/100\ km$ [90]. To calculate the needed power equation 3.21 was used and a charging time of 2 hours was assumed [91].

These values were used together with driving patterns and EV equations gathered from [91] to simulate an EV case in GAMS. In this case both uncontrolled and scheduled charging were simulated to see the effect of controlled charging and thereby DR. The uncontrolled charging stipulates that charging of the EVs takes place directly after arrival at home, whereas the scheduled charging can take place from the hour of arrival until 06:00, where vehicles according to the data started to leave home, seen in Figure 4.9. The information of movement was gathered from David Steen which he used in [91]. In Figure 4.9, the percentage of all existing cars in a residential area which are parked for each hour of the day is presented along with how the data was altered to demand all cars to be charged at 06:00.

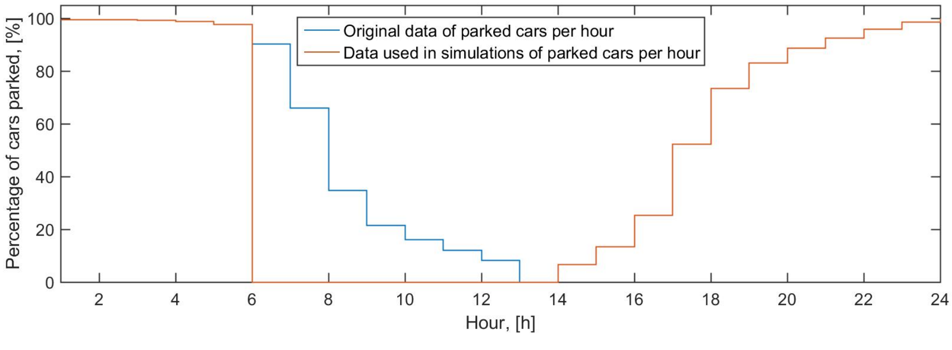

Figure 4.9: Number of EVs in percentage parked at home during the different hours of a day, as is was given and as it was manipulated for.

4.4 Data for simulated days

As described in scope, chapter 1.4, six days were simulated for both the Furuvik and Kalmar case to give an indication to the type of equipment needed for reinforcements. These days were selected on the base of minimum and maximum average consumption of one day (24h), and minimum valley and maximum peak consumption of the year. Additionally, to these four selected days, two days from the year which could act as average days were selected. In table 4.4 the dates for the simulated days are shown. The selected days for Furuvik represents one day during the fall and one during the spring, and the selected days for Kalmar were chosen to represent one weekday during low demand and one weekend day during high demand. In table 4.4 the day simulated in the EV case can also be seen, which is only the day with maximum average demand in the Furuvik case, as this represent a worst case scenario.

Table 4.4: Dates of the days used for the three different cases.

Case	**Min. average**	**Max. average**	**Min. point**	**Max. point**	**Selected 1**	**Selected 2**
Furuvik	17-07-02	18-02-06	17-08-06	18-02-06	17-05-10	17-11-12
Kalmar	17-08-13	17-01-16	16-08-22	17-04-24	16-09-10	17-02-07
EV	-	18-02-06	-	-	-	

4.5 Additional sub-cases

Even though the planned demand increase at the specific sites is set by Gävle and Kalmar Energi, the data received from both could be used to accommodate different type of scenarios. By increasing the range of demand, a wider grasp on how the benefits and costs vary dependent on different circumstances could be compared and was done for all cases.

Sub-cases for evaluation of the optimal solution, dependent on the demand, were first and foremost done at the consumption level required by Gävle and Kalmar Energi for the day with the maximum average demand. When those and the maximum level of possible increase in the existing solution were found, additional levels were tested. The levels ranged up to an additional 100% of the initial load, where tests were run with a 10% interval. This range of levels were also applied to the EV case in order to see how the numbers of EVs changed over the different levels and solutions.

4.6 Assumptions

To perform the simulations and calculations needed in this thesis, a lot of assumptions had to be made, both general and case specific. The general assumptions made that was used for all cases are:

- Simulations only performed during steady-state conditions
- Sizing and characteristics
  - Cables: Draka's product catalogue [15]
  - NiMH battery: Sufficient energy level to accommodate the 15 consecutive days with the highest average demand, SOC limit of $0 - 100\%$ [92]
  - Li-ion battery: Sufficient energy level to accommodate the 15 consecutive days with the highest average demand, SOC limit of $2 - 98\%$ [93]
- Investment costs
  - Cables and transformers: Gathered from EBR-catalogue of 2012
  - NiMH battery: $1.05 * (5000[SEK/kWh] * E[kWh] + 2000[SEK/kW] * P[kW])$, where E is the energy capacity and determines the cost of batterypacks, BMS and housing, P is the power level and determines the cost of inverter, transformer and power cabling, and 1.05 represents the installation cost [92]. Out of the lump sum of 5000 SEK/kWh, the batterypacks stand for 4000 SEK/kWh.
  - Li-ion battery: 250 EUR/kWh wich stands for 43% of the total investment cost which includes battery pack, balance of system, PCS/inverter, energy management system, transformer and engineering, procurement and construction [93], used conversion rate 1 EUR : 10.21 SEK (gathered 2018-05-21)
- Lifetime and depreciation time
  - Cables: 40 years
  - NiMH battery: 20 years (calendrical lifetime) [92]
  - Li-ion battery: 10 years (guaranteed lifetime) [93]
- Interest rate: 5%
- Electricity price: 301.3 SEK/MWh [14], average of SE1-SE4 for year 2017
- Transformer losses: inductance value of 5% of the rated power, resistance losses neglected

4.6.1 Case 1: Furuvik

The assumptions made in the Furuvik case were:

- Yearly losses: four days chosen to represent an entire year, 91 days for each chosen day plus one day calculated as the average of the four
  - Max average, (2018-02-06)
  - Min average, (2017-07-02)

    - Selected 1, (2017-05-10)
    - Selected 2, (2017-11-02)
- Current limit: 170 A for all lines
- Load demand on buses for missing hours: same percentage share of meter station 10 as other hours

4.6.2 Case 2: Kalmar

The assumptions made in the Kalmar case were:

- Yearly losses: four days chosen to represent an entire year represented by 253 number of weekdays and 112 number of weekend days and bank-holidays
    - Max average, 2017-01-16 (high demand weekday)
    - Min average, 2017-08-13 (low demand weekend)
    - Selected 1, 2016-09-10 (low demand weekday)
    - Selected 2, 2016-10-29 (high demand weekend)
- Load demand curve: 27% of the given load data (to fit fuse limit of 25 A)

4.6.3 Case 3: EV

The assumptions made in the EV case were:

- Distance driven: 33 km
- Energy consumed: 6.6 kWh/day
- Charging time: 2 h

5

Case results

In this chapter the different results from the cases investigated can be found. In section 5.1, the results from the Furuvik case can be found and in section 5.2 the results from the Kalmar case can be found, which for both sections shows results from the cable solutions, battery solutions as well as additional sub-cases for the two cases. In section 5.4 the results from the EV case can be found.

5.1 Case 1: Furuvik

When simulating the current grid configuration in the Furuvik case in GAMS for the day with the highest average and peak consumption (which was the same day), it could be seen that the load from the initial value could be increased with 27.33% with the overhead line used right now, with a current and fuse limit of 170 A. From this it could be understood that for a load demand increase of 50%, the overhead line currently used can not accommodate that increased demand for days with high consumption, and some type of reinforcement has to be made. For the second step, with an optimization to minimize the current with the increased load demand of 50%, the result from GAMS during the day with the highest average and peak consumption was that the maximum current needed was 205.3 A, which is 35.27 A more than the current limit of 170 A.

The relationship between maximum and minimum power demand during the day with the maximum average demand, which can be seen in Figure 4.3, was also investigated. It could be seen that the relationship, the maximum variation of the load curve, expressed as

$$\frac{P_{max} - P_{min}}{P_{max}} \tag{5.1}$$

was 0.2976.

5.1.1 Cable results

Since the maximum current needed was 205.3 A with an increased load demand of 50%, the cable chosen from the EBR-catalogue to accommodate this load is an underground cable for countryside usage. This cable has a conductor area of $3 \times 150\ mm^2$ and a maximum current limit of 260 A at a conductor temperature of 65°C when placed underground. The cable length needs to be 4.2 km. The characteristics of the cable is a resistance value of 0.206 Ω/km, inductance value of 0.28 mH/km and a capacitance value of 0.38 $\mu F/km$.

The total investment cost of the chosen cable is 360 000 SEK/km, which equals a cost of 1 512 000 SEK for the length of 4.2 km and an annualized total investment cost of 88 120 SEK. The yearly total energy losses in the system were estimated to be 117.9 MWh. With an electricity spot price of 301.3 SEK/MWh, the cost of the yearly losses were estimated to be 35 520 SEK.

The largest voltage deviation could be seen during the day with maximum peak and average consumption, at a value of 0.02563 $p.u.$ The largest current was also seen during the maximum peak and average consumption day, which was 78.07% of the current limit on the cable. The peak generated power during this day was 1.930 MW.

5.1.2 Battery results

As the Furuvik case does not have line data between the meter stations and the customers, only a centralized battery placement was considered. The placement of the battery was chosen to be as close to the incoming overhead line as possible, placed after the transformer at bus 7320, which is placed between the overhead line and the connecting cable into Furuvik. According to the method explained in section 3.3, the battery sizes for the NiMH and the Li-ion batteries were chosen.

The simulations resulted in a needed energy level of at least 2 230 kWh. From the simulations it was also seen that the maximum power needed during one hour was 1953.8209 kW, which is 353.8209 kW higher than the maximum power allowed with a current limit of 170 A. This resulted in a minimum battery power level of 354 kW.

The NiMH battery chosen for the centralized battery solution was a 354 kW, 2230 kWh battery. A larger Li-ion battery was needed due to the more constrained SOC limitation levels, and the Li-ion battery chosen was a 354 kW, 3400 kWh battery.

The total investment cost for the Li-ion battery was calculated to be 80 730 000 SEK, which equals an annualized cost of 4 705 000 SEK. The yearly total energy losses were estimated to be 164.9 MWh, with a cost of 49 670 SEK. The largest voltage deviation could be seen during the day with maximum peak and average consumption, for the Li-ion battery with the value of 0.03179 $p.u.$ The largest current could also be seen during the day with the maximum peak consumption, where the current was 99.80% of the overhead-line fuse limit for the Li-ion battery. The peak generated power was the highest during this day, at a value of 1.621 MW.

The total investment cost for the NiMH battery was calculated as 24 901 800 SEK, which equals an annualized cost of 1 451 231 SEK. The yearly total energy losses were estimated to be 167.1 MWh, with a cost of 50 330 SEK. The largest voltage deviation could for the NiMH battery also be seen during the day with maximum peak and average consumption, with a value of 0.03182 $p.u.$ The largest current could also be seen during the day with the maximum peak consumption, where the current was 100% of the overhead-line fuse limit for the NiMH battery. The peak generated power was the highest during this day, at a value of 1.647 MW.

For both battery solutions, the amount of peak load shaving the batteries could perform was investigated, by simulating the 15 days with the highest average and peak consumption in GAMS. In Figure 5.1 and 5.2 the resulting curves can be seen for the Li-ion and NiMH battery solutions respectively. In both of these figures it can be seen that the batteries shaves the peak demand, where the demand, electricity imported and maximum power transmitted, as well as SOC level, energy charged and discharged from the respective batteries is shown. It can also be seen that during these days, both batteries are completely cycled only once, and that the demand during these days is quite high during most hours with small variations.

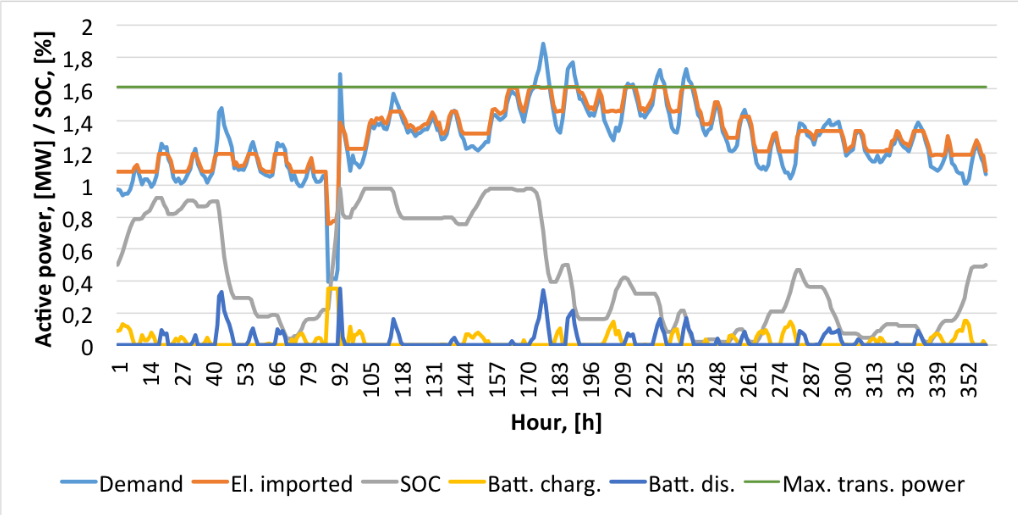

Figure 5.1: Performance of the Li-ion battery during the 15 days with highest peak and average demand.

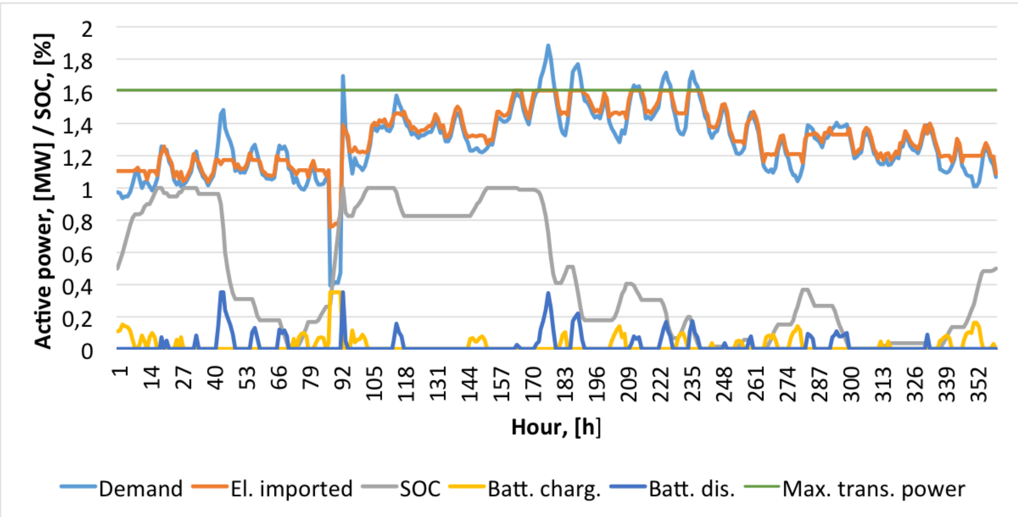

Figure 5.2: Performance of the NiMH battery during the 15 days with highest peak and average demand.

5.1.3 Comparison of solutions

In table 5.1 a comparison between the three solutions is made for the planned demand increase of 50%, which shows the different benefits and their respective value. In the table it can be seen that the cable solution outperforms the batteries for all benefits except in the aspect of peak power imported, as the cable is not able to perform peak load shaving. When comparing the battery solutions against each other the main difference is the investment cost where the NiMH is cheaper than the Li-ion. On the other benefits they are shown to be very similar.

Table 5.1: Comparison of benefits from cable and battery reinforcement solutions.

	Type of reinforcement		
Benefits	**Cable**	**Li-ion battery**	**NiMH battery**
Total investment cost, [SEK]	1 512 000	80 730 000	24 901 800
Annualized cost, [SEK/40 years]	88 120	4 705 000	1 451 231
Yearly energy losses, [MWh]	117.9	164.9	167.1
Cost of yearly energy losses, [SEK]	35 520	49 670	50 330
Max. voltage drop, [p.u.]	0.02563	0.03179	0.03182
Max. current, [%]	78.07	99.80	100
Peak power imported [MW]	1.930	1.621	1.647

5.1.4 Additional sub-cases of Furuvik

Additional to the Furuvik case, other possible scenarios were created which shows a load demand in the range of 100 − 200%, where cables and battery solutions respectively was selected in the same manner as the Furuvik case (values used for cables can be seen in table A.3 and for batteries in table A.4 in Appendix A.2.1). For these additional sub-cases, total investment cost, annualized investment cost as well as annual cost of losses were evaluated.

In the Furuvik case with the battery solutions, a load increase above 50% with the initial grid settings was not possible. This due to congestion on the line between the battery and the next bus in Furuvik, in contrary to the limiting factor for the other levels where it has been the overhead line going to the transformer where the battery is placed that has been limiting.

This was solved by increasing the current limit on the line between the battery and the next bus in Furuvik. When simulating for a load demand higher than the needed 150% with the objective to minimize the current, it was seen that for 160% demand and the corresponding battery implemented a maximum current of 181.3 A was needed, and the current limit on that line was thereby selected to 182 A. For 170% load demand and the corresponding battery implemented a maximum current of 192.3 A was needed, and the current limit on that line was thereby selected to 193 A. Between a load demand of 180 − 200% the power flow equations was not able to solve feasible solutions for all hours and all buses, and therefore no results for these hours are displayed.

In Figure 5.3 the annualized investment costs for the battery and cable solutions are shown, and in Figure 5.4 the annualized investment costs for the cable solutions are shown separately (for exact values see table A.5 in Appendix A.2.1). As can be seen in the figures the cost differs largely between the different solutions. When comparing the Li-ion battery with the NiMH battery it can be seen that the annualized cost for NiMH is lower on all levels, which is reasonable since only two NiMH batteries were needed compared to the Li-ion solution where four batteries were needed. Comparing both battery solutions to the cable solutions it can be seen that the both battery solutions are more expensive than the cable solution for demand levels of 140% and larger, but for the 130% demand level, where the annualized investment cost are similar for all solutions, the cheapest solution is the NiMH battery. The investment cost of the batteries is not linear since the increased size of the batteries at the different demand levels is not linear. The increase in cable investment cost at 150% and 190% represent at which demand level an investment for a larger cable is needed.

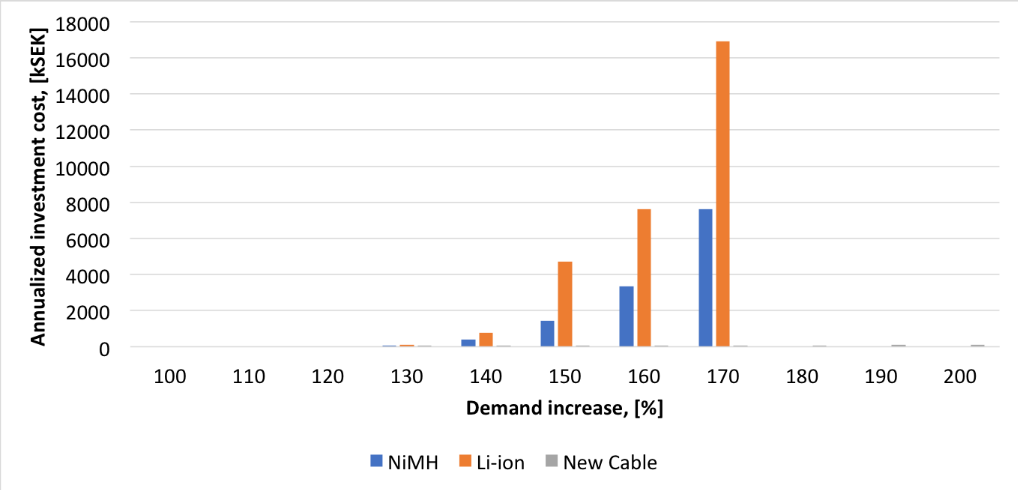

Figure 5.3: The annualized investment costs in SEK for all solutions and the levels of increased demand. The 100% represents a peak demand of 1257 kW.

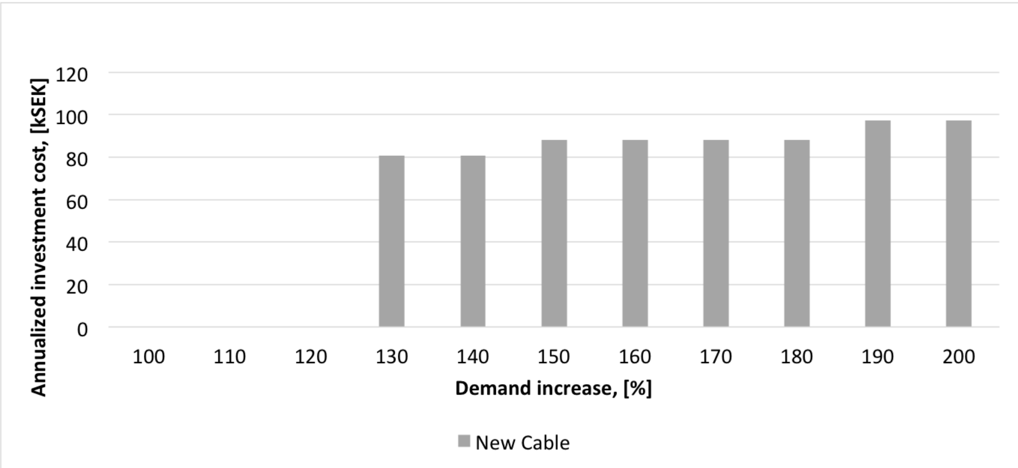

Figure 5.4: The annualized investment costs in SEK for the cable solutions and the levels of increased demand. The 100% represents a peak demand of 1257 kW.

In order for the batteries to have the same annualized investment cost as the cable solutions at each level a cost for the battery packs was calculated. The resulting costs for the battery pack to decrease in order to reach the cables is presented in table 5.2, in both actual $price/kWh$ and % decrease from the price today. As a reference, the price of a Li-ion battery pack is 250 EUR/kWh which corresponds to 2553 SEK/kWh and the price of a NiMH battery pack is 4000 SEK/kWh.

Table 5.2: Needed price of batteries and the corresponding price decrease for each demand level in order to reach the investment cost of cables.

	Li-ion		**NiMH**	
Demand level, [%]	**Battery pack price,** [SEK/kWh]	**Price decrease,** [%]	**Battery pack price,** [SEK/kWh]	**Price decrease,** [%]
130	1752	31.33	4767	-19.16
140	261.4	89.76	73.26	114.8
150	47.81	98.13	-1083	124.9
160	29.55	98.84	-1086	126.2
170	13.29	99.48	-1059	126.1

In the table it can be seen that the prices for NiMH do not need to decrease in order for the solutions to become profitable at 130% but that for demand levels from 150% the price for NiMH batteries should be negative in order to become profitable. If the NiMH battery solutions should be at the same level as a cable investment from 140% the cost for equipment need to decrease as well. For 170% the needed decrease is lower than at 160%, which is due to that the energy needed increases non-linearly and drastically between 160% and 170%, whereas the power increases linearly.

To see if and when Li-ion batteries would be profitable a report by MOBI Research Group was consulted where forecasts of EV battery prices were looked at [16]. From their investigation they could see how companies have been predicting the price and from that made their own based on procurement, manufacturing and sales. In their forecast, made year 2017, they believe the price of Li-ion batteries will be at 195 $\$/kWh$ 2020 while Tesla's prediction the same year said their batteries would be 131 $\$/kWh$. Hence, if either companies' predictions are right Li-ion will be more profitable than the cable solution by 2020 for the 130% level. Predictions made between 2010-2016 have made predictions for 2020 to be between $210-300$ $\$/kWh$ where predictions closer to 2017 have displayed lower prices. For Li-ion batteries to become profitable above 130%, several years has to pass as it is not until somewhere between 2025 and 2030 that the price will go below 100 $\$/kWh$ according to [16].

In Figure 5.5 the cost of losses over one year is displayed (for exact values see table A.6 in Appendix A.2.1). In the figure it can be seen that the losses for cables is non-linear, as with every drop in losses a new cable has been installed and hence resulting in lower losses than for the previous demand level. It can also be seen that for all demand levels the losses are higher for the battery solutions than for the cable solution.

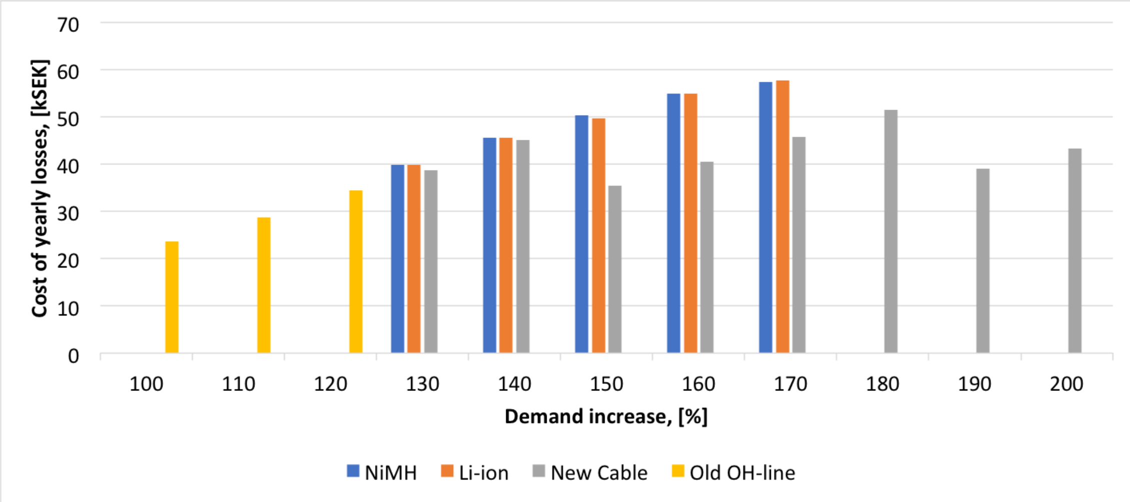

Figure 5.5: The yearly cost of losses in SEK for each solution and the levels of increased demand. The 100% represents a peak demand of 1257 kW.

The sum of the annualized investment cost and the cost of the yearly losses for all solutions can be seen in Figure 5.6, and for the cable solutions in Figure 5.7 (for exact values see table A.7 in Appendix A.2.1). When comparing the total cost of the different battery solutions it can be seen that the NiMH battery still is the cheapest battery for all demand levels. When comparing the total yearly cost of batteries with the cable costs it can be seen that the total yearly costs of the cable solutions is much lower for all demand levels on and above 140%.

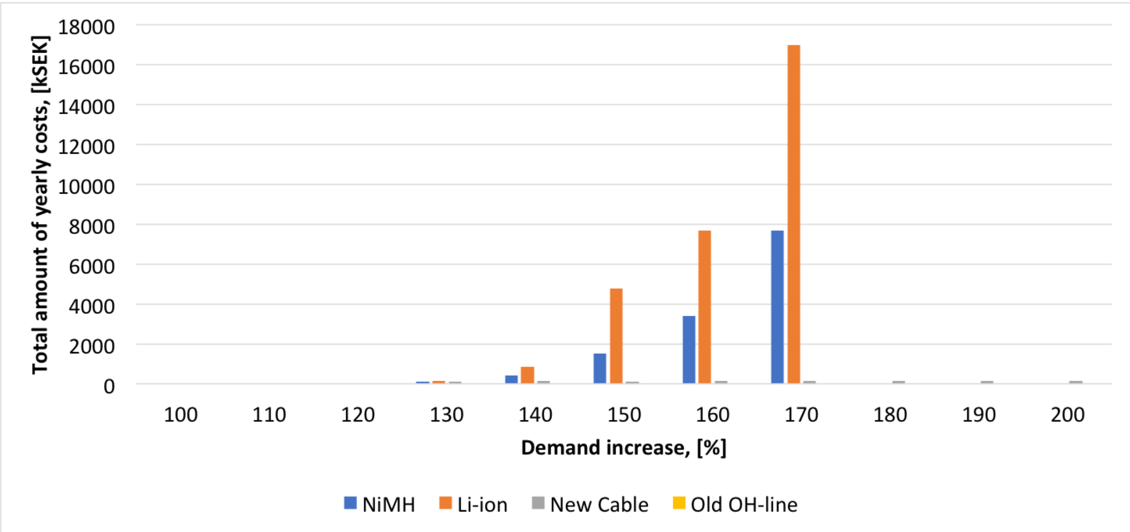

Figure 5.6: The total yearly costs for all solutions in SEK and the levels of demanded increase. In the total costs losses and investment costs are included. The 100% represents a peak demand of 1257 kW.

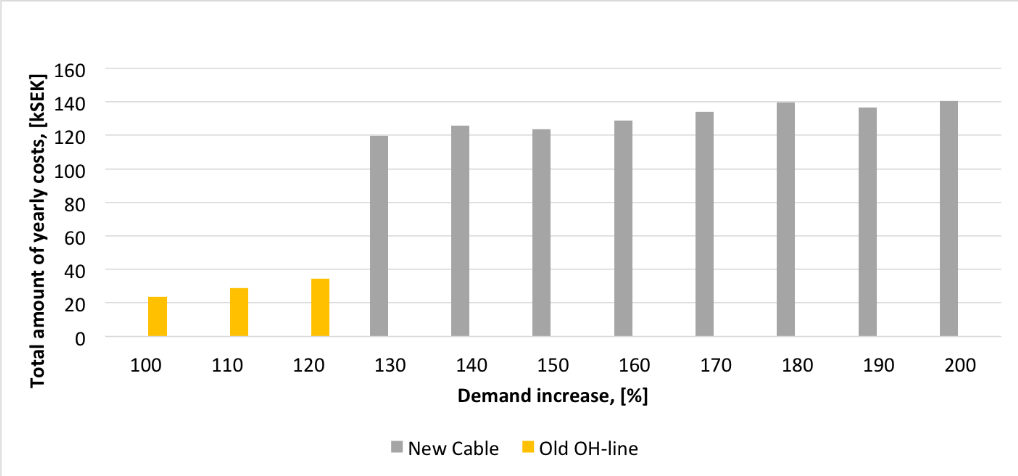

Figure 5.7: The total yearly costs (investment and losses) for the current solution and possible new cables in SEK and the levels of demanded increase. The 100% represents a peak demand of 1256.9 kW.

5.2 Case 2: Kalmar Airport

When simulating the current grid configuration for the Kalmar case in GAMS for the day with the highest peak consumption, it could be seen that the load from the initial value could be increased with 7.881% with the cable connected right now and with a fuse limit of 25 A. From this it could be understood that for a load increase of 40%, the cable and fuse currently used can not accommodate that increased load for days with high load, and some type of reinforcement has to be made. For the second step, with an optimization to minimize the current with the increased load of 40%, the result from GAMS during the day with the highest peak consumption was that the maximum current needed was 32.90 A, which is 7.900 A more than the fuse limit of 25 A.

The relationship between maximum and minimum power demand during the day with the maximum average demand, which can be seen in Figure 4.7, was also investigated. It could be seen that the relationship, the maximum variation of the load curve, expressed as

$$\frac{P_{max} - P_{min}}{P_{max}} \tag{5.2}$$

was 0.7707.

5.2.1 Cable results

The cable chosen from the EBR-catalogue to accommodate the increased load demand was as desired an PEX-isolated underground cable for countryside usage, with a conductor area of 3×150 mm^2 and a maximum current limit of 260 A at a conductor temperature of 65°C when placed underground. The cable length needs to be 1.4 km.

As the cable solution consists of both a new cable, a copper ground line and also a new satellite station with a transformer, the total investment cost equals the sum of the cable, ground line, satellite station and transformer cost. The transformer chosen is a 12/0.4 kV 100 kVA transformer, and the satellite station chosen is on the 12/0.4 kV voltage level.

The total investment cost of the chosen cable is 360 000 SEK/km, which equals a cost of 504 000 SEK for the length of 1.4 km. The characteristics of the cable is a resistance value of 0.206 Ω/km, inductance value of 0.28 mH/km and a capacitance value of 0.38 $\mu F/km$. As the current limit of the cable is 260 A, the new fuse limit was selected to be 63 A to allow at least the demand increase of 40%.

Information about cost of a ground line could not be found in the EBR-catalogue. This information was instead provided by Nexans, which was an estimated cost of 35 SEK/m for ground lines [94]. With a cable length of 1.4 km, the cost of the ground line equals 49 000 SEK. According to the EBR-catalogue, the cost of a 12/0.4 kV satellite station is 75 600 SEK, and the cost of a 12/0.4 kV 100 kVA transformer including coil is 110 000 SEK. This equals a total investment cost of 738 600 SEK. With a depreciation period of 40 years and a CRF of 0.0583, the annualized total investment cost becomes 43 040 SEK. The yearly total energy losses in the system was estimated to be 0.5868 MWh. With an electricity spot price of 301.3 SEK/MWh, the cost of the yearly losses were estimated to be 176.8 SEK.

The largest voltage deviation could be seen during the day with maximum peak consumption with the value of 0.04577 $p.u.$ The largest current could also be see during the day with maximum peak consumption, with a current of 28.26% of the new cable current limit. The peak power imported during this day was 19.77 kW.

5.2.2 Battery results

As the Kalmar case is only considering one customer, the placement of the battery was chosen to be as close to the customer as possible, which was at the bus in the end of the cable. According to the method explained in section 3.3, the battery sizes for the NiMH and the Li-ion batteries were chosen.

The simulations resulted in a needed energy level of at least 9 kWh. From the simulations it was also seen that the maximum power needed during one hour was 17.77 kW, which is 2.968 kW higher than the maximum power allowed with a current and fuse limit of 25 A. This resulted in the selection of a battery power level of 4.73 kW. Both the NiMH and the Li-ion batteries was selected to have the same capacity. The power level was selected to be 4.73 kW, and the energy level was selected as 9 kWh for both batteries.

The total investment cost for the Li-ion battery was calculated to be 213 700 SEK, which equals an annualized cost of 12 450 SEK. The yearly total energy losses were estimated to be 0.5274 MWh, with a cost of 258.9 SEK. The largest voltage deviation could be seen during the day with maximum peak consumption, for the Li-ion battery with the value of 0.02164 $p.u.$ The largest current could also be seen during the day with the maximum peak consumption, where the current was 99.18% of the fuse current limit for the Li-ion battery. The peak generated power was the highest during this day, at a value of 14.80 kW.

The total investment cost for the NiMH battery was calculated to be 127 000, which equals an annualized cost of 7 399 SEK. The yearly total energy losses were estimated to be 0.5263 MWh, with a cost of 158.6 SEK. The largest voltage deviation could for the NiMH battery also be seen during the day with maximum peak consumption, with the same value of 0.02164 $p.u.$ The largest current could also be seen during the day with the maximum peak consumption, where the current had the same value of 99.18% of the cable current limit for the NiMH battery. The peak generated power was the highest during this day, at the same value of 14.80 kW.

For the different battery solutions, the amount of peak load shaving the batteries could perform was also investigated. This was done by simulating the 15 days with the highest average and peak consumption in GAMS. In Figure 5.8 and 5.9 the resulting curves can be seen for the Li-ion and NiMH battery solutions respectively. In both of these figures it can be seen that the batteries shaves the peak demand, where the demand, electricity imported and maximum power transmitted, as well as SOC level, energy charged and discharged from the respective batteries is shown. It can also be seen that during these days, both batteries are completely cycled almost daily and that the load demand varies throughout the days with a higher demand during daytime and a lower demand during night-time and weekends.

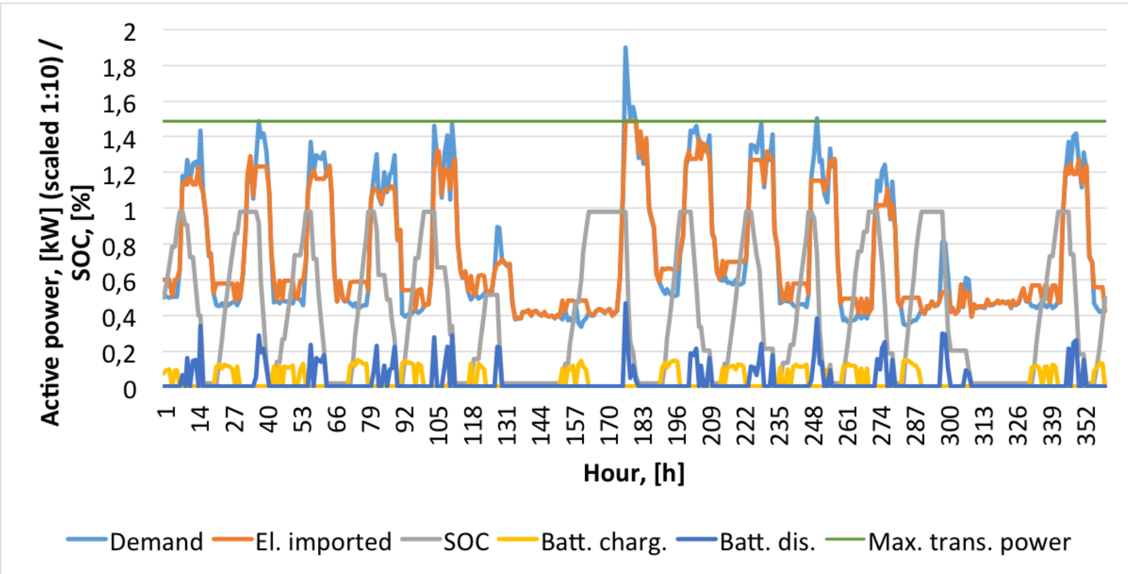

Figure 5.8: Performance of the Li-ion battery during the 15 days with highest average and peak demand.

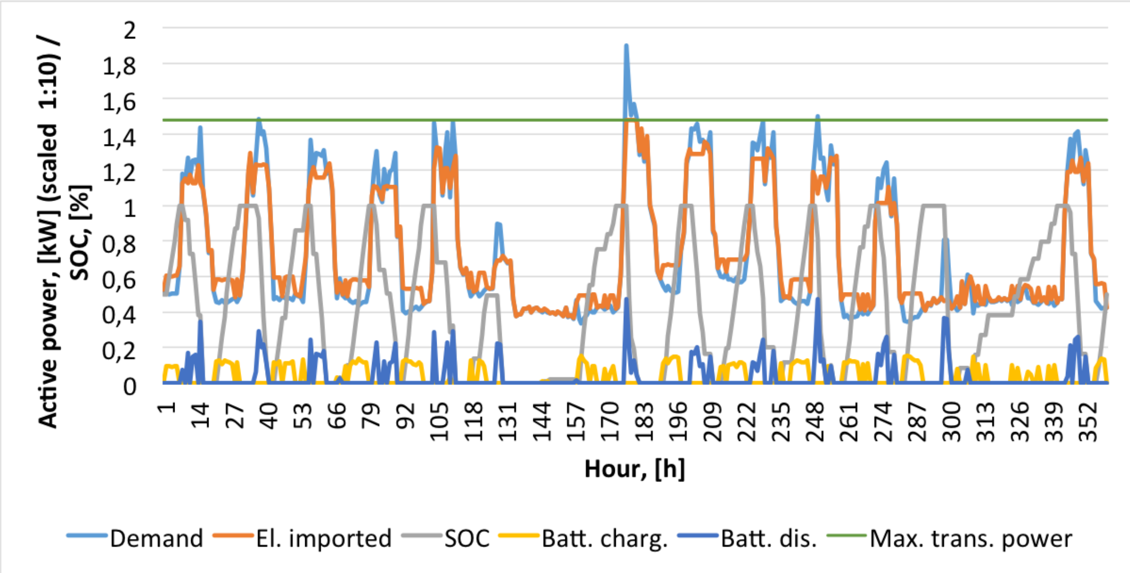

Figure 5.9: Performance of the NiMH battery during the 15 days with highest average and peak demand.

5.2.3 Comparison of solutions

In table 5.3 a comparison between the three solutions is made for the planned demand increase of 40%, which shows the different benefits and their respective value. In the table is can be seen that both battery solutions outperform the cable solution in all aspects. When comparing the two battery solutions it can also be seen that the NiMH battery is the cheapest solution, but when considering the other benefits the Li-ion and NiMH batteries show the same results as the same battery size was used.

Table 5.3: Comparison of benefits from cable and battery reinforcement solutions.

	Type of reinforcement		
Benefits	**Cable**	**Li-ion battery**	**NiMH battery**
Total investment cost, [SEK]	738 600	213 700	127 000
Annualized cost, [SEK/40 years]	43 040	12 450	7 399
Yearly energy losses, [MWh]	0.5868	0.5274	0.5263
Yearly cost of energy losses, [SEK]	176.8	158.9	158.6
Max. voltage variation, [p.u.]	0.04577	0.02164	0.02164
Max. current, [%]	28.26	99.18	99.18
Peak power imported, [kW]	19.77	14.80	14.80

5.2.4 Additional sub-cases of Kalmar

Additional to the Kalmar case, other possible scenarios were created which shows a load demand in the range of $100 - 200\%$, where cables and battery solutions respectively was selected in the same manner as the Kalmar case (values used for cables can be seen in table A.8 and for batteries in table A.9 in Appendix A.2.2). For these additional sub-cases, total investment cost, annualized investment cost as well as annual cost of yearly losses were evaluated.

When simulating the Kalmar case for the cable solution with a load demand between $170 - 200\%$, it could be seen that the voltage drop was too big, which means that no feasible solution could be found in this load range. This means that the cable solution for sub-cases in the $170 - 200\%$ load range does not have any results.

In Figure 5.10 the annualized investment costs for the different battery and cable solutions are shown (for exact values see table A.10 in Appendix A.2.2). In this figure it can be seen that the cable solution has the same cost over the whole demand spectra, since no larger cable is needed, and that it is the most expensive solution up for all demand levels where the cable solution was feasible. Between the two battery solutions the NiMH battery is the cheapest.

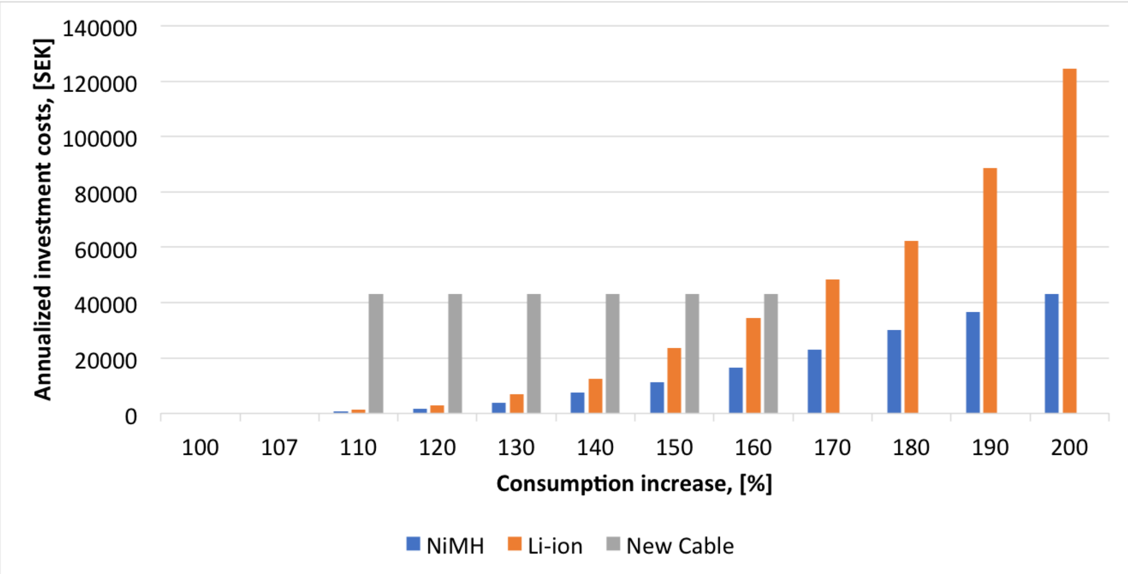

Figure 5.10: The annualized investment cost in SEK for each solution and the levels of demanded increase. The 100% represents a peak demand of 13.6 kW.

In Figure 5.11 the cost of the yearly energy losses can be seen (for exact values see table A.11 in Appendix A.2.2). The drop seen in cost of losses in the cable solution is due to that above 160% load demand, the simulations showed a too large voltage drop and the cable solutions was therefore deemed to be insufficient. The cable solution in the Kalmar case display a higher cost of losses than both NiMH and Li-ion batteries for all demand levels except 110%, where they display the exact same losses over the whole spectra.

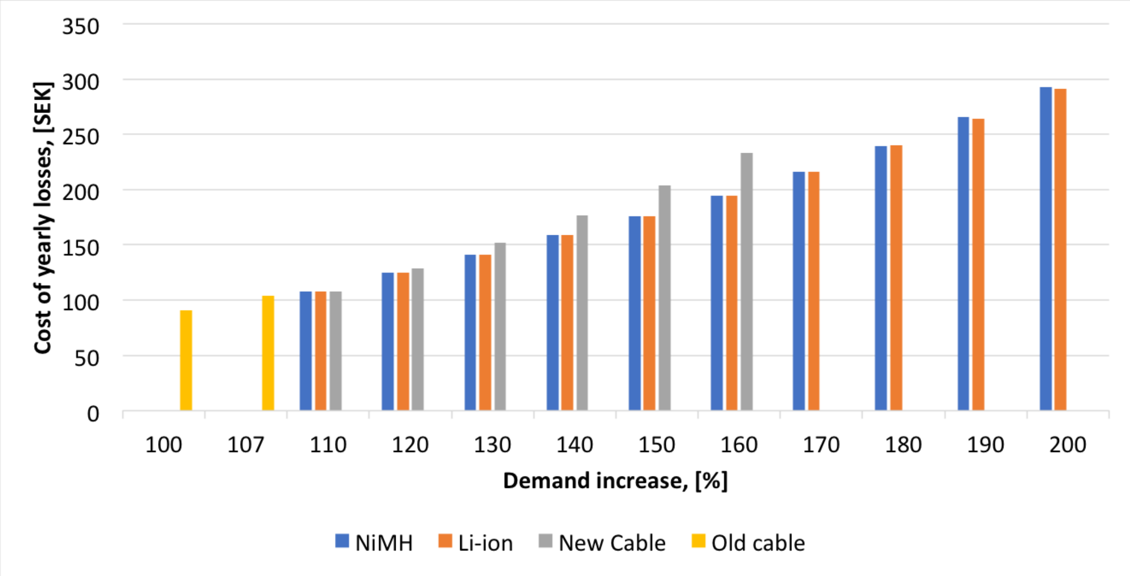

Figure 5.11: The yearly cost of losses in SEK for each solution and the levels of demanded increase. The 100% represents a peak demand of 13.6 kW.

When comparing all 3 possible solutions, shown in Figure 5.12, it is clear that both battery solutions are more profitable for all demand levels which has a cable solution, and the least expensive of the two types is the NiMH battery (for exact values see table A.12 in Appendix A.2.2). What should be remembered is that the cable solution is no longer feasible after 160%, and if the demand should be higher the NiMH battery is shown to be the most optimal solution.

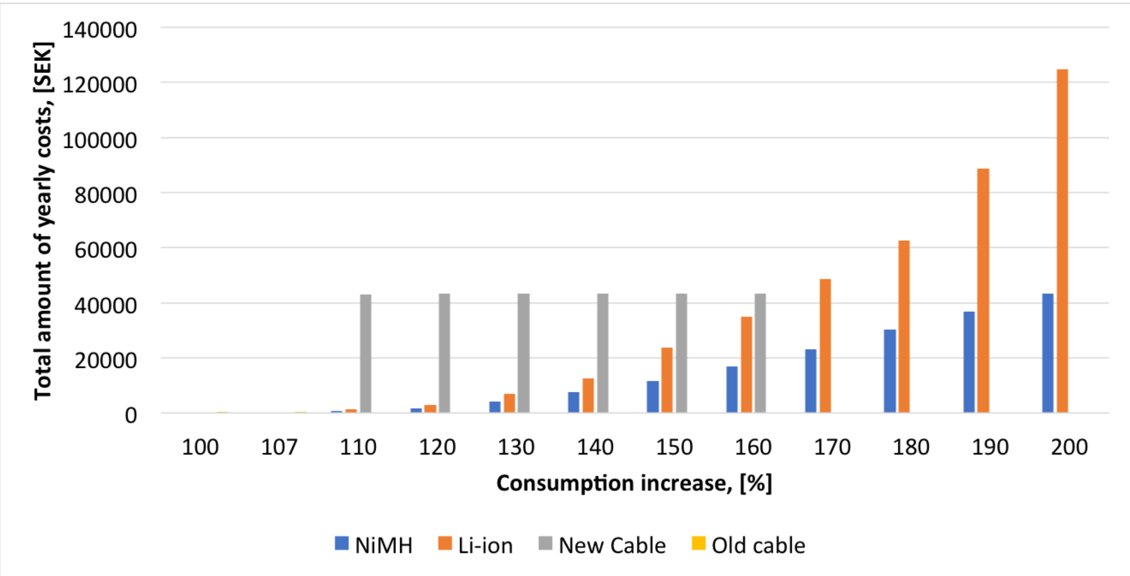

Figure 5.12: The total yearly cost (investment and losses) in SEK for each solution and the levels of demanded increase. The 100% represents a peak demand of 13.6 kW.

5.3 Comparison of cases and sensitivity analysis

From comparing the results presented for the cases Furuvik and Kalmar, it can be seen that batteries are more profitable when the load is smaller, as this results in a lower investment cost, but also varies throughout the day. There can also be seen a certain break-even point for all cases where the large initial investment cost but marginally different cost for increased dimensions of cables becomes more profitable than batteries. When comparing the placement of the batteries in these cases it can also be seen that the batteries can perform more benefits when placed close to the end customer, as the batteries in the Kalmar case delivered more benefits than the batteries in the Furuvik case.

In Figure 5.13, 5.14 and 5.15 a sensitivity analysis for how the battery's lifetime affects the annualized cost is shown in the Furuvik case with an interest rate of 3%, 5% and 7% respectively, where all figures shows lifetimes of 8, 10, 13.33 and 20 years. When comparing the Li-ion and NiMH batteries with different lifetimes it can be seen that it is highly relevant when estimating costs. As the lifetime is dependent on the numbers of cycles, as stated in section 3.4, the number of re-investments during 40 years depends on the demanded activity of the battery.

It can also be seen that at an interest rate of 3% and 5%, the Li-ion battery is the most expensive one at demand levels of 140% and more for all lifetimes. With an interest rate of 7%, the Li-ion battery is the most expensive one for all lifetimes and a demand level of 140% and more. At all interest rates the Li-ion battery does however have the lowest annualized cost for all lifetimes at a demand level of 130%. When comparing the impact that the lifetime and interest rate has on the annualized investment cost, it can be seen that the interest rate and the lifetime has almost the same impact on the annualized investment cost, and that the annualized investment cost differs a lot depending on the lifetime and interest rate used.

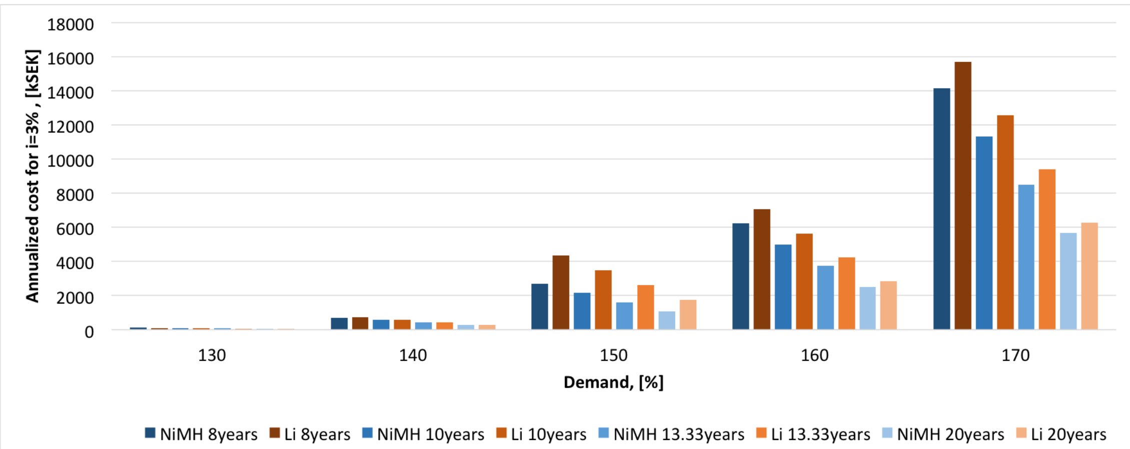

Figure 5.13: Sensitivity analysis for battery costs in Furuvik with different lifetimes, i=3%, over the demanded levels where battery solutions were applicable.

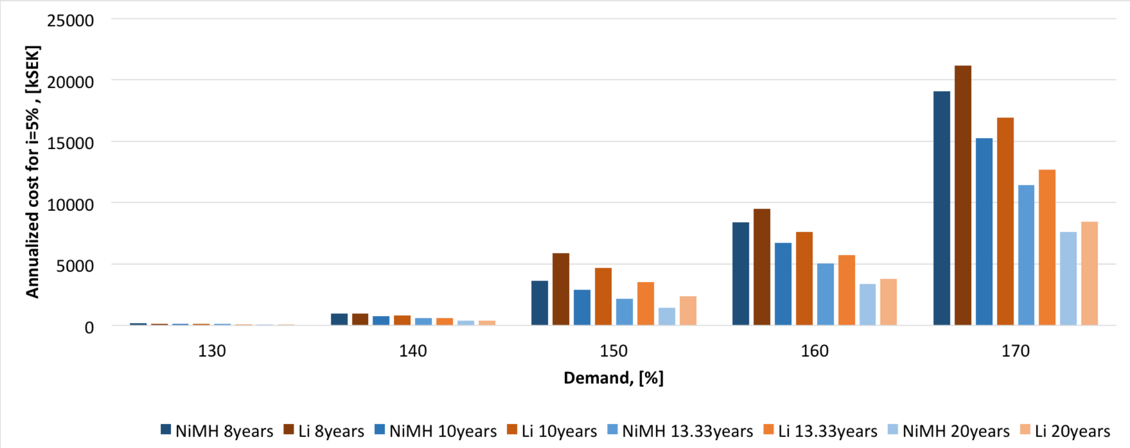

Figure 5.14: Sensitivity analysis for battery costs in Furuvik with different lifetimes, i=5%, over the demanded levels where battery solutions were applicable.

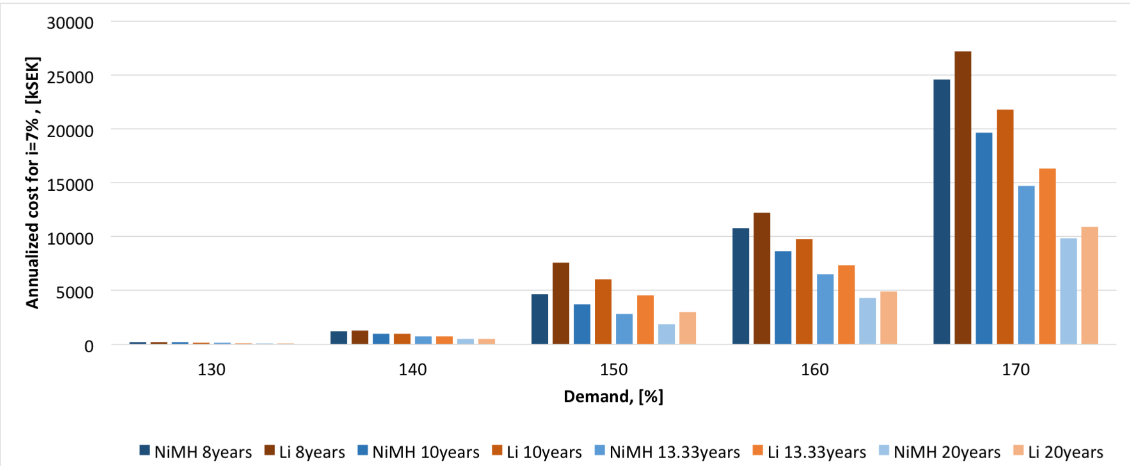

Figure 5.15: Sensitivity analysis for battery costs in Furuvik with different lifetimes, i=7%, over the demanded levels where battery solutions were applicable.

In Figure 5.16, 5.17 and 5.18 a sensitivity analysis for how the battery's lifetime affects the annualized cost is shown in the Kalmar case with an interest rate of 3%, 5% and 7% respectively, where all figures shows lifetimes of 8, 10, 13.33 and 20 years. In these figures it can be seen that with the same lifetime, the Li-ion battery is the cheapest one for all interest rates up to a demand level of 150%, where the NiMH battery becomes cheaper. When comparing the impact that the interest rate and the lifetime has on the annualized investment cost, the same thing can be said as in the Furuvik case, that both the interest rate and the lifetime has a large impact on the annualized investment cost.

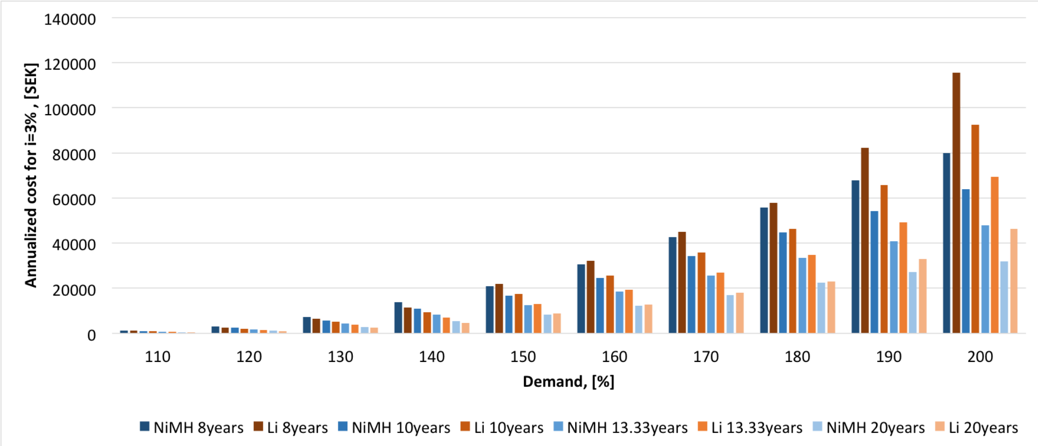

Figure 5.16: Sensitivity analysis for battery costs in Kalmar with different lifetimes, i=3%, over the demanded levels where battery solutions were applicable.

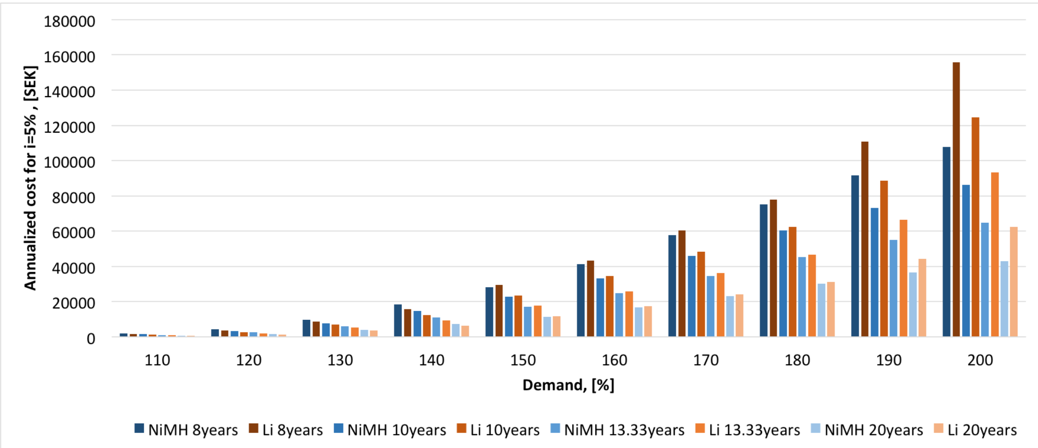

Figure 5.17: Sensitivity analysis for battery costs in Kalmar with different lifetimes, i=5%, over the demanded levels where battery solutions were applicable.

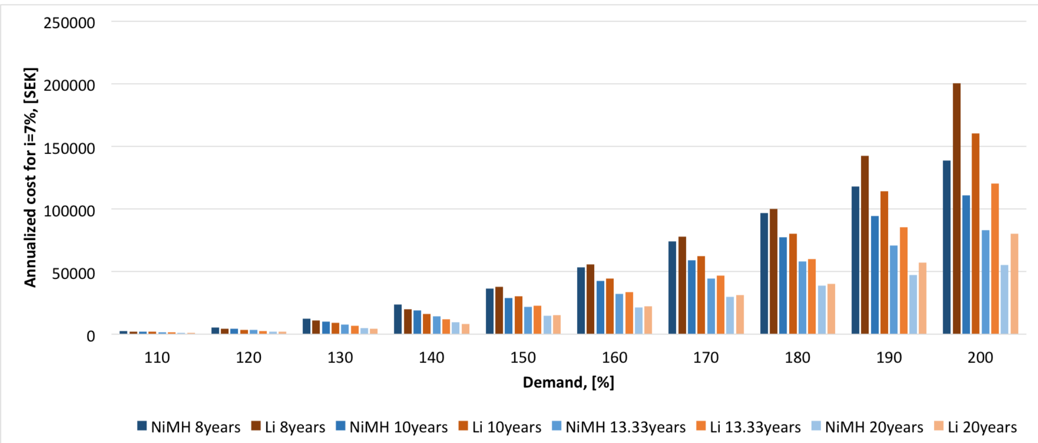

Figure 5.18: Sensitivity analysis for battery costs in Kalmar with different lifetimes, i=7%, over the demanded levels where battery solutions were applicable.

When comparing the figures from both cases it is seen that Li-ion batteries have a lower cost on smaller batteries in comparison to NiMH. Additionally, both cases show a strong lifetime dependence on the annualized cost.

5.3.1 Indicators for selecting reinforcement solution

When comparing the two cases, some indicators were found for during which circumstances a reinforcement done by cables or batteries were more beneficial. These indicators were the amount of the average demand level and variations between maximum and minimum power in the load profile. These indicators together with the most beneficial reinforcement solution choice when considering these indicators can be found in table 5.4. The batteries are presented as a single solution in the table as they should be selected for the same circumstances. When demand levels are low batteries should be selected, but for these low levels it is a difference in the type of battery which should be selected. Li-ion are to be selected at low levels of low demand and NiMH at high levels of low demand.

Table 5.4: The indicators found, showing when it is more beneficial to invest in cables or batteries respectively for reinforcement. Demand is the average consumption and variation stands for the difference between maximum and minimum demand.

	Demand level		**Variations**	
Reinforcement type	**Low**	**High**	**Low**	**High**
Cable	-	✓	✓	-
Battery	✓	-	-	✓

5.4 Case 3: Future EV

The results for uncontrolled charging of EVs in the additional sub-cases of Furuvik can be seen in table 5.5, where the maximum number of EVs possible to be integrated in each solution for all demand levels can be found. For the battery solutions, both fixed and variable SOC is displayed, where fixed SOC represent a SOC of 50% at hour 1 and 24, and variable SOC represent SOC levels decided by GAMS for all hours, which means that the battery SOC level might be high at the start of the day and low at the end of the day. In this table it can be seen that the number of EVs possible to integrate in the cable solution is about twice as many as for the battery solutions. It can also be seen that the number of EVs integrated decreases with increasing demand level in the cable solutions until a new cable is installed, in comparison to the battery solutions where the number of EVs integrated (mostly) increases with an increased demand level with a variable SOC.

Table 5.5: Comparison of maximum number of EVs for the different solutions for uncontrolled charging.

Demand, [%]	**Old OH-line**	**Cable**	**Li-ion** (fx. SOC)	**Li-ion** (var. SOC)	**NiMH** (fx. SOC)	**NiMH** (var. SOC)
100	9.636					
110	7.752					
120	5.466					
130		9.694	4.131	4.131	4.159	4.159
140		7.81	4.849	4.849	2.523	3.89
150		15.245	-	5.179	0.025	5.179
160		13.361	-	5.56	-	5.56
170		11.478	-	5.939	-	5.939
180		9.438				
190		21.224				
200		19.341				

The results for scheduled charging of EVs in the additional sub-cases of Furuvik can be seen in table 5.6, where the maximum number of EVs possible to be integrated in each solution for all demand levels can be found in the same manner as for uncontrolled charging. In this table it can be seen that the number of EVs possible to integrate in the cable solution is still larger than for the battery solutions. It can also be seen that the number of EVs integrated decreases with increasing demand level in the cable solutions until a new cable is installed as before, but for the battery solutions the number of EVs vary. The highest number of EVs can be found on the 170% demand level for both batteries.

Table 5.6: Comparison of maximum number of EVs for the different solutions for scheduled charging.

Demand, [%]	**Old OH-line**	**Cable**	**Li-ion** (fx. SOC)	**Li-ion** (var. SOC)	**NiMH** (fx. SOC)	**NiMH** (var. SOC)
100	37.737					
110	30.079					
120	22.42					
130		37.679	15.669	16.007	15.683	16.036
140		30.021	8.46	11.198	8.408	11.099
150		59.771	-	12.693	-	8.754
160		52.113	-	10.395	-	10.471
170		44.445	-	24.683	-	25.946
180		36.797				
190		83.383				
200		78.726				

When comparing the two tables, it can be seen that the results of scheduled charging can integrate about four times more EVs in comparison to uncontrolled charging, for both the cable and battery solutions.

6

Discussion

In this chapter discussion on the method used, the results from this thesis and possible improvements can be found, but also discussion about sustainability and ethical issues. In section 6.1 the impact that the assumptions and simplifications made has on the end result is discussed. In section 6.2 a discussion and comparison of the results can be found, and in section 6.3 the problem about implementing BESS in the energy system is analysed. Finally in section 6.4 a discussion about sustainability and ethical issues can be found.

6.1 Assumptions and simplifications made in the method

Some of the generalizations made in this thesis, for both cables and batteries, may have had significant impacts on the solutions chosen and the conclusions drawn from the results. Some of these generalizations are:

- Assumed yearly losses in the system
- Disregarding an estimate yearly load increase
- Electricity spot price used
- Weather conditions and extreme points
- Resolution of data
- Short circuit currents
- No margins on the solutions
- The EBR-catalogue

The amount of total yearly power losses in the system, for all cases, is only an estimate. This means that the real amount of losses during a year is not found. Even if they were it would only be the losses for that specific year's data which the results were based on. The sensitivities of the amount of losses is dependent on the amount of power transmitted and the state of the equipment. Energimyndigheten predicts an annual load increase of about 0.15% between $2014-2035$, but depending on how the future energy system will look like, the annual load increase until year 2050 can vary and is estimated to be between -0.16% and 0.79% [95], which equals an average annual increase of 0.315%.

Even if there is a degradation of the equipment and there is an estimated load increase of 0.315% each year, it is in this thesis assumed to be a constant load during the 40 years and no degradation. These two disregarded factors would play a significant role in the solution selected as an annual load increase of 0.315% over 40 years is equal to a load difference from the start value of more than 13%. When adding degradation of the equipment an additional increase of transmitted power is needed to adjust for the loss. Hence, the solutions presented in this thesis do not adjust for future changes and may therefore not present accurate solutions if a load increase of a certain percentage is not supposed to be viewed as the total expected increase after 40 years. Using the data given can however give an estimate of what the solutions would cost a couple years in the future. This could be an advantage for battery solutions however as the equipment needs to be replaced and new assumptions and costs can be considered. The first investment can thereby be fitted to suit the need during the 40 years better.

Just as the load and losses were assumed to be constant over the 40 years, the electricity spot price was assumed to be constant as well. This is also a simplification as the price is predicted to increase in the future, which will lead to a higher cost from losses over the years. Hence, the results and conclusions on amount of losses and their costs is only valid for the period which is represented by the data provided.

Going back to the demand and resulting load, the solution presented is only valid for years with similar load profiles like the once used in the simulations, or years with lesser demand. However, as the solutions are made to suite the simulated days they are not capable of handling peaks much larger than the ones in the provided data, especially for batteries, which makes the solutions only suite the year simulated. This is a problem as the demand fluctuates with weather conditions. To solve this, data of several years could be used to find maximum peaks and high base demands, in order to accommodate for extreme weather and unexpected peaks in the solutions.

Limitations in the data is that the highest resolution is one measurement per hour. Data with this resolution removes the possibility to find the actual peaks as the measurements are the average consumption during the previous hour. Adding to this is the simplification of not calculating short circuit currents, which also result in large peaks. As the solutions are somewhat or completely based on the peak power needed to be delivered, the true size of the cables and batteries are not the same as selected in this thesis. By only having this type of data and disregarding short circuits, a solution with higher quality regarding the acceptable peaks is not achievable. However, if only the maximum peak would have been known a margin could have been made which could have been used to re-size the solutions.

The estimation of the investment cost is only initial and rough. This as only the planning section in the EBR-catalogue was used and the costs represent the average cost of similar projects performed during 2011. As the cost of projects later than 2011 is not known and the prices only give an average of the project performed, nothing of the circumstances during that year is known and to base prices of investments during 2018/2019 on that may result in an unjust representation of investment costs.

6.1.1 Batteries

For the battery solutions there are some additional simplifications which could result in wrongful conclusions. Amongst these are:

- Non-optimized battery size
- Non-optimized battery placement
- Interval where the battery is tested
- Lifetime expectancy
- Degradation
- No possible incomes like trading on NordPool spot market, ancillary services and tariffs

Due to time constraints an optimized size for the batteries were not found in GAMS for any of the cases or levels of demand. This means that the conclusions in this thesis can contribute to incorrect conclusions and wrongful assumptions for the reader. As the batteries are not optimized, results regarding for example the cost of instalment and losses may be wrong as too large batteries might have been recommended. On the other hand, since the load only has hourly resolution, it can be expected that the real demand peaks are higher than seen in the load data, which means that a larger battery might actually be needed.

In contrary to cable instalments, the cost for batteries is highly dependent on the size needed and a solution with an excessively large battery would give an unnecessary large investment cost. However, as the battery size increases the total system losses should decrease, if the same theory as for the cable solution holds. Tests on this and how the costs may compare have not been done but it would be an interesting subject to develop. Additionally, with the dimensioning of the battery size, not selecting the most optimum size but rather with a margin, although unknown, can benefit the system in terms of congestion and unexpected peaks, as discussed in earlier sections.

Similarly, the placement of the batteries was neither optimized in GAMS, but selected to be on the bus with the receiving end of the existing overhead line/cable due to time constraints. This has put limits on the benefits which could possibly be considered, in the aspect of distributed batteries, as well as may have given another result on sizes needed for the batteries.

To size the batteries the method described in section 3.3 was used, where a period of 15 days with the most demanding day was placed as the 8th day. This was done in order to see how many times during that period the battery would be needed and if the estimated battery size would be able to handle the demand when implemented. If so, it was decided to hold for all circumstances over the whole year and deemed to be a fitting size. When assuming this, longer periods than this with high base demand and peaks can cause the size not to be enough, and result in congestion on the lines and affect customers which are given less power than wanted.

From the information provided by Christian at Nilar and Manuel at GE the lifetime of the batteries have been very roughly estimated as the number of cycles of the batteries have not been investigated. The number of years that each battery pack and its accessories can live is therefore a large sensitivity in the cost results for the solutions. For Li-ion the estimated life expectancy was selected to be the lowest number of years GE guarantee function for, to perform a worst-case cost. This however may have resulted in that batteries may be viewed as a non-competitive solution to cables for the larger capacity instalments. Although this can be argued, the fact that no degradation of the batteries is included in the results, the instalment cost could be reasonable as the cost for power losses and loss of benefits during the end of the lifetime could be guarded for when selecting the lowest number of guarantied functioning years.

Another aspect which gives the battery solutions an unfair disadvantage is the simplification of not taking into account possible sources of incomes for BESS, like trading on NordPool spot market, ancillary services and different types of tariffs. As these incomes would depend on who the owner is, and are complicated to calculate, they were neglected. The owner of the BESS would however receive at least some of these possible sources of income, which would result in that the annualized cost of the battery solutions would be decreased.

6.2 Comparison of results

The difference in benefits received from the battery solutions in the Furuvik and Kalmar case can be explained by the selected placement of the batteries and the profile of the load demand curve. As the batteries in the Kalmar case is placed as close to the customer as possible, where BESS can achieve the greatest benefits, this case was expected to receive benefits considering voltage deviation and peak power, and the power losses were decreased as well. In comparison to the Furuvik case, where the battery placement was centralized, the batteries could not perform these benefits. The load demand curve in the Kalmar case also had larger variations, where the relationship between maximum and minimum power demand during the day with the maximum average demand was 77.07%, in contrary to the Furuvik case where this relationship only was 29.76% due to smaller load variations. With larger load variations, batteries will have more time to charge and does therefore not need to be oversized to the same extent as for a load profile with only small load variations.

As the cost of battery solutions greatly depend on lifetime, and lifetimes for both required solutions were based on recommendations from General Electric and Nilar, the lifetimes selected do not represent the actual lifetime each battery pack would have in a real case and therefore the final cost could vary a lot. Included in lifetime is both calendrical and cyclic lifetime and as the number of cycles each battery would need during a year is unknown, due to that a whole year could not be simulated and that it is not known until the year has passed, the actual lifetime could not be found. This results in a high volatility in the final total cost of the instalment for the investor. By looking at the sensitivity analysis performed where multiple cases of lifetimes were investigated an estimate of what a battery solution could cost is shown in the thesis, if the lifetime estimations made in section 3.4 were to be wrong.

When comparing the variation of lifetime and interest rate in the sensitivity analysis, it could be seen that both the lifetime of batteries and the interest rate had a large impact on the annualized investment cost. This means that both of these aspects should be taken into consideration when investing in BESS, and use as accurate values as possible to get a reasonable annualized investment cost. From comparing both cases it could also be seen that Li-ion batteries have a lower cost on smaller batteries in comparison to NiMH.

In the EV case the importance of DR became evident, as the scheduled charging could integrate about four times as many EVs as the uncontrolled charging, even with the constraint of completed charging at 06:00. For all demand levels though, the cable solutions could integrate more EVs than the battery solutions. This is however not unexpected, as both battery solutions for all demand levels was sized to fit the load demand increase, and not an increased load due to EVs. That these solutions still could accommodate charging of some EVs with a variable SOC limit, and be increased about four times with scheduled charging still makes BESS a solution to an increased integration of EVs. The fact that all battery solutions could not accommodate the integration of EVs at demand levels above 140% does though show the importance of correct sizing of the BESS.

6.3 BESS implementation

As have been presented in the chapters about BESS in this thesis and their possibilities, found in section 2.3, BESS can be an essential part for stabilizing the grid as more intermittent energy generation enters the system. With current law regulations it is however problematic, and in some aspects impossible for the system to take part of all the possible benefits and services that BESS can provide. The resulting solutions for each case with batteries presented show not to be beneficially today in all sizes, which may be a result of that all services they could provide cannot be accounted for.

Described in [10] are areas of usage and how they can be combined in order to fully make use of a battery's potential. From [10] it is clear that combining service application areas is crucial, and regulations prohibiting DSO's from acting needs to be lifted if batteries are supposed to be used at their full potential as a BESS. With the move on removing the double taxation on batteries solutions including them may become more profitable. As increasingly more grid solutions include BESS, examples presented in section 2.3.3, the technology is pushing forward and the need for new regulations are growing.

With the growing need developers may help to push the boundaries and influence or raise the subject of outdated regulations to suit the coming technologies. A possible place where the changes could start is inside companies. As they try to increase profits they are able to seek other solutions than traditional ones, while at the same time having more capital than private individuals. As DSO's have an obligation to deliver electricity, they may be more resilient towards investing in new solutions than companies who can continue to be connected to the grid and rely on the DSO to provide for their demand.

6.3.1 BESS placement and ownership

To implement batteries laws and regulations need to be applied differently dependent on the owner and as all of these parameters are unknown or limited in this thesis and in real life it implies further difficulties if aiming for BESS to become a conventionally used technology. Further challenges arise on the aspect of ownership if batteries were to be stationed at different levels in the system. Placement of batteries and the owners of them should be discussed as the services they can offer and the way they could interact with other equipment and services in the system is highly dependent on them.

When discussing having batteries at high voltage levels in the distributions system or in the transmission system questions arise around if batteries actually should be seen as possible solutions, as the price is so much higher than for installing new cables. As batteries are good at short on/off periods due to low ramp up/down times and costs the further away from the customer the battery is placed this behaviour is needed less as fluctuations become more and more smoothened. Cases where there is a lack of energy battery-solutions seem to be less economically profitable and less beneficial to the total system. Hence, a battery's main purpose in a solution should be to act as a power-source and not an energy-source. Therefore, from the results in this thesis and the literature studied batteries should not be placed in the transmission system if the main purpose is to strengthen the system by peak load shaving. If batteries were to be placed on these voltage levels it is possible that the best use for them would be to ease stress on equipment, such as transformers, as they there could use their behaviour as and advantage and thereby lengthen the lifetime of equipment. If this was the altered purpose of the equipment the owners of the equipment would be suitable owners of the batteries as they would be placed adjacent and the behaviour of the equipment would be known.

Where it is seen that batteries have the most beneficial impact is as close to the end user as possible. Placement should therefore be on the lower voltage levels in the distribution system and most profitable behind-the-meter. Here ownership becomes more tricky as several options and business models could be applied. Owners could be the grid owner, an municipality owned company, the customer, the electricity supplier for each customer or an independent company. The independent company could however also be the owner of BESS on all voltage levels of the grid. An easy option of the ownership, irregardless if the battery is placed behind-the-meter or on one or two levels higher, could be the grid owner. If the placement was behind-the-meter the service and cost of instalment could be seen as a part of the network cost paid to the grid owner by all customers. A possible problem with the customer having access to the battery could be hazards related to handling the battery and general mistreatment but as several other services supplied to the same type of customer are on the market systems of dealing with these problems should be applicable for even this service. Some of the services aimed at could be water supply and waste removal services, where the customer is expected to not mistreat the appliances and for example flush down large items in the pipes causing damage, damage the waste receptacle or wrongfully sort the waste.

If the BESS owner would be the electricity customer some type of incentives might be needed in order to help people make the decision of installing a battery behind-the-meter. Even though investing in BESS for home-usage as a societal and environmental contribution could be enough for some it might not be for all, in the same way as homeowner to this day rely on fossil fuels to heat their homes incentives to change behaviour and encourage investments might be needed.

6.4 Sustainability and ethical issues

The usage of both cables and batteries in the energy system bring up a lot of sustainability and ethical issues, although very different. In the two following sections, these issues regarding cables and batteries respectively are discussed.

6.4.1 Cables

The materials used for cables are not scarce, and the installation as well as the extraction of cables are very expensive, which means that from an economic point of view it might be better not to recycle old cables that are no longer being used. From a material resource point of view however this is very unsustainable, as according to [20] cable materials worth billions of SEK lies beneath the ground. Many of the underground cables used today are very old, and at the time of installation, recycling possibilities of these cables might not have been a concern, which could be the reason to why the extraction cost is still too high to be profitable.

With an electricity system that has a quite unsure future with a lot of new techniques on the horizon, the usable lifetime of a new cable installation might not be the same as it has been in the past. From this perspective, as well as a life cycle and material point of view, installation of new cables should be done in a way that simplifies and reduces the costs for extraction and recycling of cables that will no longer be used.

A drawback with installing new cables from an innovation and technical development point of view is that they have a long life time. At present, cable installations have been regarded to have a lifetime of 40 years, but cables installed in the early 1900 are still providing power in Sweden [18]. These long lifetimes can result in inflexibility and hesitations to invest in new technology that has a shorter lifetime. As written in the report by Power Circle [3], to invest in new technology demands interested and engaged people at the companies, a situation which not is a reality at every company in the energy sector. To invest in batteries even if the financial incentives are not there could be interesting and a way of leading the development of a new type of power system.

6.4.2 Batteries

With the rising penetration of EVs and increased intermittent generation, battery's building blocks and afterlife have been the targets of different investigations, and rightfully so. To consider batteries as rightful contenders in a stride for a sustainable future, a change in the material industry and the afterlife needs to happen. When the mining industry causes severe health and environmental problems, presented in 2.2.4.2 and 2.2.4.1, in order to produce the materials needed for batteries other options are still needed.

With that said, batteries are still one of the technologies that can be used for the world to keep on consuming energy as before, but to only consider one type of technology and only one technology in general as the solution can be argued against. To implement the right type of battery for every different situation is important in order to not exhaust resources and to obtain the best solutions. With the increased usage and variation of sizes more technologies can be incorporated in the solutions. It is also important to consider the whole system and how batteries can be used in multiple applications during one lifetime, by regarding EVs as rolling battery storage they can be used for DR and as their lifetime in an EV is up the "spent" car batteries can be used as energy storage behind-the-meters. To also regard what type of system the batteries are put in and what their main purpose in that system is is important as it may vary between already existing constructions and new-builds.

For distribution system deferral, BESS could possibly be used in order to investigate if predictions of load usage in an area are correct and hence postpone investments, and later make more educated and optimized investments as the actual load demand curve has been established. The batteries could then be moved on to another site to perform the same task. However, the space for such solutions would possibly be seen as redundant as for a new cable investment to be made, it is not the cable itself which gives the highest cost, but the installation.

If a cable solution after installation was shown to be of insufficient size to meet the demand, a reinvestment would be needed and hence a high total cost would have been invested. If the insufficient sized cable was to result in a lower cost for a battery reinforcement than a cable, a combination of the two solutions could be used. The cost of a faulty cable investment like this speaks for testing the actual demand at a new site with batteries before investing in a traditional long-term solution such as cables. By planing investments like this, optimization of cable reinforcements could be done and material usage could be minimized as the batteries could be used elsewhere after. This uncertainty in load prediction and the high investment costs of cables results in grid owners today overdimensioning their cable investments and hence not optimizing solutions and using more materials than necessary.

In this thesis no tariffs or subsidies have been accounted for which shows that batteries have a place when reinforcements are required even without them. When and if including these, the results may have shown batteries to be profitable over a larger span of demand, and therefore show to be a larger competitor to cables than shown here.

7
Conclusion and future work

This chapter contains the conclusions made in this thesis and suggestions of interesting areas for future work. In section 7.1 the conclusions made can be found, both case-specific and more general, and in section 7.2 the suggestions for work are presented.

7.1 Conclusion

The main aim of this thesis was to evaluate the two cases Furuvik and Kalmar. The conclusion from these cases was that in the Furuvik case, an investment into a new cable would be the most economically beneficial choice, when considering both economic and other benefits. In the Kalmar case however, an investment is more economically beneficial when made into a BESS, where the NiMH battery was the cheapest choice. In this case, where the battery was placed as close to the customer as possible, the BESS could deliver more benefits as well such as reducing the losses, and is thereby providing both an economic benefit as well as other benefits.

From the generalized results it could be concluded that the main aspects to consider when planning an investment is the amount of energy needed and the profile of the demand curve. For a battery to be used in an efficient way and not be oversized, the demand curve needs to have some variation in order to have more time to be charged, and not oversized to the extent that the investment cost becomes larger than the investment cost for the corresponding cable. From the results and equation 5.1, a variation of at least 77.07% between maximum and minimum power during one day was needed, as a variation of 29.76% was not large enough. It could also be seen that for both cases, due to the high initial investment cost of cables which thereafter only increases slightly, there will come a break-even point in all cases where the investment cost for cables is cheaper than the investment cost of BESS. From the results of the EV case, the importance of DR when integrating EVs in a grid became obvious, as the maximum number of EVs possible to integrate for scheduled charging was about four times larger than for uncontrolled charging.

Another conclusion is that there is not one solution for all possible situations, but that the best solution varies for different circumstances. In order to select the best solution, interest rate and lifetime of the battery on the site, both in regards to cyclical and calendrical lifetime, need to be evaluated during the process so that the right type of solution, and the right type of battery is selected.

7.2 Future work

Due to the assumptions and simplifications made in this thesis, there is a lot of areas which could have been investigated but were not, and leaves many areas of improvement and suggestions for future work. Some of the areas that are of extra interest to conduct future work in are:

- *Load data resolution and time period:* When the exact maximum peak demand and demand profile is known, the BESS can be minimized for this load. This is important since the BESS would thereby not be oversized, contributing to an unnecessary large investment cost. Another aspect is that the power electronics needed is dependent on the size of the peaks and how fast they appear, which can stand for a large part of the total investment cost.
- *Optimized placement of BESS:* With an optimized placement of the BESS, the size of the BESS might be able to be minimized further, and also be able to offer more benefits. Within this area, investigations of how placements of batteries behind-the-meter should be handled in the aspects of risk assessment would be interesting to include in future work.
- *Income opportunities for BESS:* As BESS can deliver more economic benefits than considered in this thesis, an investigation of the economic value of these benefits would increase the economic benefits of these BESS, and thereby giving them a more fair and reasonable annualized cost.
- *Demand response:* The impact of DR in grids with and without BESS would be interesting to investigate further. This in order to evaluate how BESS handles DR during different circumstances, and if it does this more efficiently than a conventional grid, only consisting of overhead lines and cables.

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A

Appendix 1

A.1 Initial settings

A.1.1 Furuvik

Table A.1: Used characteristics of the lines in Furuvik.

Buses	I **lim.**, [A]	R, [Ω/km]	L, [mH/km]	C, [μF/km]
7307 - 7308	170	0.206	0.32	-
7308 - 7309	170	0.206	0.32	-
7308 - 7319	170	0.32	0.32	-
7319 - 7337	170	0.32	0.32	-
7337 - 7333	170	0.32	0.32	-
7337 - 7372	170	0.641	0.38	-
7372 - 7373	170	0.641	0.38	-
7319 - 7322	170	0.32	0.32	-
7322 - 7326	170	0.32	0.32	-
7326 - 7328	170	0.32	0.32	-
7326 - 7321	170	0.32	0.32	-
7321 - 7320	170	0.32	0.32	-
OH-line - 7320	170	0.336	-	-

A.1.2 Kalmar

Table A.2: Used characteristics of the lines in Kalmar.

Buses	I **lim.**, [A]	R, [Ω/km]	L, [mH/km]	C, [μF/km]
Trafo - Customer	25	0.206	0.22	0.58

A.2 Results

A.2.1 Furuvik

Table A.3: Characteristics of the cables used for the different demand levels.

Demand level, [%]	I **lim.,** [A]	R**,** [Ω/km]	L**,** [mH/km]	C**,** [μF/km]
130	205	0.32	0.3	0.32
140	205	0.32	0.3	0.32
150	260	0.206	0.28	0.38
160	260	0.206	0.28	0.38
170	260	0.206	0.28	0.38
180	260	0.206	0.28	0.38
190	340	0.125	0.26	0.46
200	340	0.125	0.26	0.46

Table A.4: Battery sizes used for the different demand levels.

	NiMH battery		**Li-ion battery**	
Demand level, [%]	**Energy,** [kWh]	**Power,** [kW]	**Energy,** [kWh]	**Power,** [kW]
130	85	84.92	85	84.92
140	537	220	570	220
150	2230	352	3400	354
160	5300	490	5500	490
170	12 227	626	12 227	626
180	26 319	763	26 319	763
190	37 084	901	37 084	901
200	65 017	1 039	65 017	1 039

Table A.5: Annualized investment cost.

Demand level, [%]	**New cable,** [kSEK]	**Li-ion,** [kSEK]	**NiMH,** [kSEK]
100	-	-	-
110	-	-	-
120	-	-	-
130	80.77353	117.6202	72.79898
140	80.77353	788.7475	382.4504
150	88.11658	4 704.81	1 451.231
160	88.11658	7 610.721	3 363.116
170	88.11658	16 919.33	7 635.179
180	88.11658	-	-
190	97.41777	-	-
200	97.41777	-	-

Table A.6: Cost of annual losses.

Demand level, [%]	**Old OH-line,** [kSEK]	**New cable,** [kSEK]	**Li-ion,** [kSEK]	**NiMH,** [kSEK]
100	23.72218	-	-	-
110	28.79624	-	-	-
120	34.34088	-	-	-
130	-	38.74784	39.89181	39.89029
140	-	45.07943	45.5407	45.54151
150	-	35.5182	49.67216	50.33283
160	-	40.50102	55.00181	54.98753
170	-	45.82317	57.65274	57.34376
180	-	51.48699	-	-
190	-	38.9722	-	-
200	-	43.2505	-	-

Table A.7: Annual total costs.

Demand level, [%]	**Old OH-line,** [kSEK]	**New cable,** [kSEK]	**Li-ion,** [kSEK]	**NiMH,** [kSEK]
100	23.72218	-	-	-
110	28.79624	-	-	-
120	34.34088	-	-	-
130	-	119.5214	157.512	112.6893
140	-	125.853	834.2882	427.9919
150	-	123.6348	4 754.482	1 501.564
160	-	128.6176	7 665.723	3 418.104
170	-	133.9398	16 976.98	7 692.523
180	-	139.6036	-	-
190	-	136.39	-	-
200	-	140.6683	-	-

A.2.2 Kalmar

Table A.8: Characteristics of the cables used for the different demand levels.

Demand level, [%]	I **lim.,** [A]	R**,** [Ω/km]	L**,** [mH/km]	C**,** [μF/km]
110-200	260	0.206	0.28	0.38

Table A.9: Battery sizes used for the different demand levels.

	NiMH battery		**Li-ion battery**	
Demand level, [%]	**Energy,** [kWh]	**Power,** [kW]	**Energy,** [kWh]	**Power,** [kW]
110	1	0.44	1	0.44
120	2	1.87	2	1.87
130	5	3.29	5	3.29
140	9	4.73	9	4.73
150	16	6.16	17	16.6
160	24	7.61	25	7.61
170	34	9.06	35	9.06
180	45	10.52	45	10.52
190	55	12	64	12
200	65	13.46	90	13.46

Table A.10: Annualized investment cost.

Demand level, [%]	**New cable,** [SEK]	**Li-ion,** [SEK]	**NiMH,** [SEK]
100	-	-	-
107	-	-	-
110	43 044.25	1 383.768	719.6187
120	43 044.25	2 767.535	1 681.558
130	43 044.25	6 918.838	3 864.891
140	43 044.25	12 453.91	7 399.345
150	43 044.25	23 524.05	11 298.5
160	43 044.25	34 594.19	16 548.78
170	43 044.25	48 431.86	23 022.9
180	43 044.25	62 269.54	30 111.39
190	43 044.25	88 561.12	36 592.86
200	43 044.25	124 539.1	43 069.43

Table A.11: Cost of annual losses.

Demand level, [%]	**Old cable,** [SEK]	**New cable,** [SEK]	**Li-ion,** [SEK]	**NiMH,** [SEK]
100	90.86993	-	-	-
107	104.2276	-	-	-
110	-	107.6741	108.0673	108.0398
120	-	128.7184	124.6992	124.6167
130	-	151.7421	141.3038	141.1387
140	-	176.7865	158.8981	158.5682
150	-	203.8734	175.5301	175.75
160	-	233.0358	194.8012	194.8012
170	-	-	215.942	215.832
180	-	-	239.859	239.5566
190	-	-	264.4087	265.2607
200	-	-	291.13	292.9991

Table A.12: Annual total costs.

Demand level, [%]	**Old cable,** [SEK]	**New cable,** [SEK]	**Li-ion,** [SEK]	**NiMH,** [SEK]
100	90.86993	-	-	-
107	104.2276	-	-	-
110	-	43 151.92	1 491.835	827.6586
120	-	43 172.97	2 892.234	1 806.175
130	-	43 195.99	7 060.141	4 006.03
140	-	43 221.04	12 612.81	7 557.913
150	-	43 248.12	23 699.58	11 474.25
160	-	43 277.29	34 788.99	16 743.58
170	-	-	48 647.8	23 238.74
180	-	-	62 509.4	30 350.95
190	-	-	88 825.53	36 858.12
200	-	-	124 830.2	43 362.43