UiT
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OF NORWAY

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Department of Electrical Engineering

Energy storage technologies from a power system point of view

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Raymond Klippenvåg Wang

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Executive summary

This thesis presents energy storage technologies, as well as their most applicable ways of integration into the power system. The storage technologies provided are relevant in regards to ancillary services, peak shaving, energy arbitrage and not least integration in combination with intermittent renewable production.

A grid analysis was performed to determine the obvious differences between different placements of the storage system ranging from behind the meter to feeding transformer of the radial. The analyses are static of nature and is included to exhibit power flow, voltage stability and load percentage of the transformers. Dynamic analyses are not included due to time constraints.

The grid simulations were performed in the software NetBas. The results of the simulation concur with most previous studies in the field that behind the meter placement is the most optimal. In addition to placing the storage as far downstream the power system as possible, it is important that local consumption plays a deciding factor concerning the placement of the ESS. The economic feasibility of energy storage integration is outside the scope of the thesis project, but it is suggested that it will increase as battery prices decrease.

Considerations are also made on the future smart grids. Smart grids will increase distributed energy generation with wind and residential solar power. A possible solution to this is presented throughout the thesis as distributed energy storage. This has the potential to assist the existing ancillary services as well as allow further increase the penetration of distributed energy generation.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ESS - Energy Storage System

TSO - Transmission System Owner

DSO - Distribution System Owner

KILE - Societal costs of unreliability

AMS - Advanced Metering System

kW - Kilowatt

kWh - Kilowatt hours

MW - Megawatt

MWh - Megawatt hours

EV - Electric Vehicle

PV - Photo Voltaic

NVE - The Norwegian Water Resources and Energy Directorate

DSO - Distribution Grid Owner

DC - Direct Current

HVDC - High Voltage Direct Current

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10th June 2019</td></tr>
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Chapter 1

Background

Technical progress and a rapid decrease in costs of batteries have made energy storage an increasingly attractive field of study. While some storage technologies are mature and have been in use for many years, others are still at a theoretical and untested stage. This thesis will provide an overview of the most interesting of such technologies, the mature as well as the immature.

The Norwegian power system is in particular need of energy storage, in one form or another. In addition to not having a strong central grid running through this elongated country, there are many small districts spread out over a great distance, making the radials supplying electricity weaker as they increase in length. A sudden increase in consumption near the end of such radials is almost certain to end in expensive grid reinforcements of either lines/cables or transformers. Energy storage have seen a positive development both technically end economically which allows a relatively cheap and somewhat long term solution to this problem.

1.1 Aim

Based on a specific transformer circuit using historical consumption data as basis, this thesis aims to provide background theory on storage technologies as well as give an insight of the implementation of, specifically, batteries in the power system. The aim of this report is also to assess and compare the placement of batteries in the distribution grid - behind the meter placement will be compared to placement in the distribution grid used as peak shaving and energy arbitrage. Without reviewing the economic aspects in detail, the goal is to determine the best solution for battery placement and sizing in order to postpone or neglect traditional grid reinforcements.

1.2 Problem description

The purpose of this thesis is to determine a strategy of battery implementation in the Norwegian power system with the purpose of increasing the grid utilization and thus eliminating the need for grid reinforcements.

1.3 Main objectives

In order to provide an adequate solution, the objects of this thesis are:

1. Give an overview of energy storage technologies.
2. Provide solutions of how to integrate energy storage technologies in a power system.
3. With focus on batteries:
    - How to dimension, place and operate.
    - Estimate the system benefits.
4. Validate the above-mentioned strategies by building and running simulations using a data from Nordkraft in NetBas.

1.3.1 Limitations

In order to finish the thesis within the deadline, the following subjects will not be addressed:

- Dynamic analyses will not be performed as NetBas is the chosen analysis-software. The time a dynamic analysis might demand will reflect poorly on the result of the rest of the thesis.
- Specific components needed to realize the implementation as well as regulatory framework and guidelines in NEK400 will not be taken into consideration.
- In depth investigation of possible legislative issues is not wasted any time on as this is partly a feasibility study.
- Control systems and measurement requirements included in energy management systems and battery management systems is not going to be a part of this thesis.
- Detailed description of protection and possible selectivity issues.
- The effects of temperature on batteries.
- The simulations will focus on one specific transformer circuit. The transfer value of such an analysis is considered to be great enough to limit the simulations to the radial in question.

1.4 Outline

- Chapter 2 introduces the basic concepts of the report.
- Chapter 3 describes the methodology of the case study.
- Chapter 4 introduces the energy storage technologies and provides solutions of how to implement them in the power system.
- Chapter 5 gives an overview of the simulation model and presents the relevant results of the analysis.
- Chapter 6 presents conclusions and ideas for further work
- Appendix A contains an automated report of the NetBas simulation model developed for this thesis.

Chapter 2

Introduction

2.1 Energy storage in the power system

"Power is an extremely perishable product because it must be used at the same time as it is generated. Therefore, it is important that there is a balance between production and consumption at all times. This is called instantaneous balance. Every time you charge your mobile phone, the amount of power required by the charger must be produced at the same time at a power plant, so that there is always a balance between how much is produced and how much is consumed in the power system." (Statnett, 2018) [1]

Electricity is defined as a perishable product, which means that it has to be consumed at the time of production. This introduces a problem in power systems where more and more intermittent, unregulated power production is being implemented. As all other perishable products, conservation of some level is possible. Energy storage systems (ESS) present themselves as possible solutions.

Energy storage is going to play a central role in the future smart grids. Not only because it is more attractive for a consumer to participate with the possibility of storing excess energy produced during low price hours, but because the relative amount of wind- and solar power is growing both nationally and globally. Together with increased participation from end users in the form of prosumers, this introduces a large amount of intermittent power production. This creates a need for flexibility across the power system; for producers, distributors as well as consumers. This is not solved inertly by implementing energy storage systems, but it is a vital step in the right direction. Energy storage will not only help with the intermittency. It also provides a range of grid supporting services.

2.1.1 Energy storage services

The grid services that energy storage systems are able to provide, can be divided into three categories: Customer services, utility services and TSO services. There are three distinct levels each service in each category can fall beneath: Transmission, distribution and consumption (behind the meter). Figure 1.1 shows a detailed representation of the grid services.

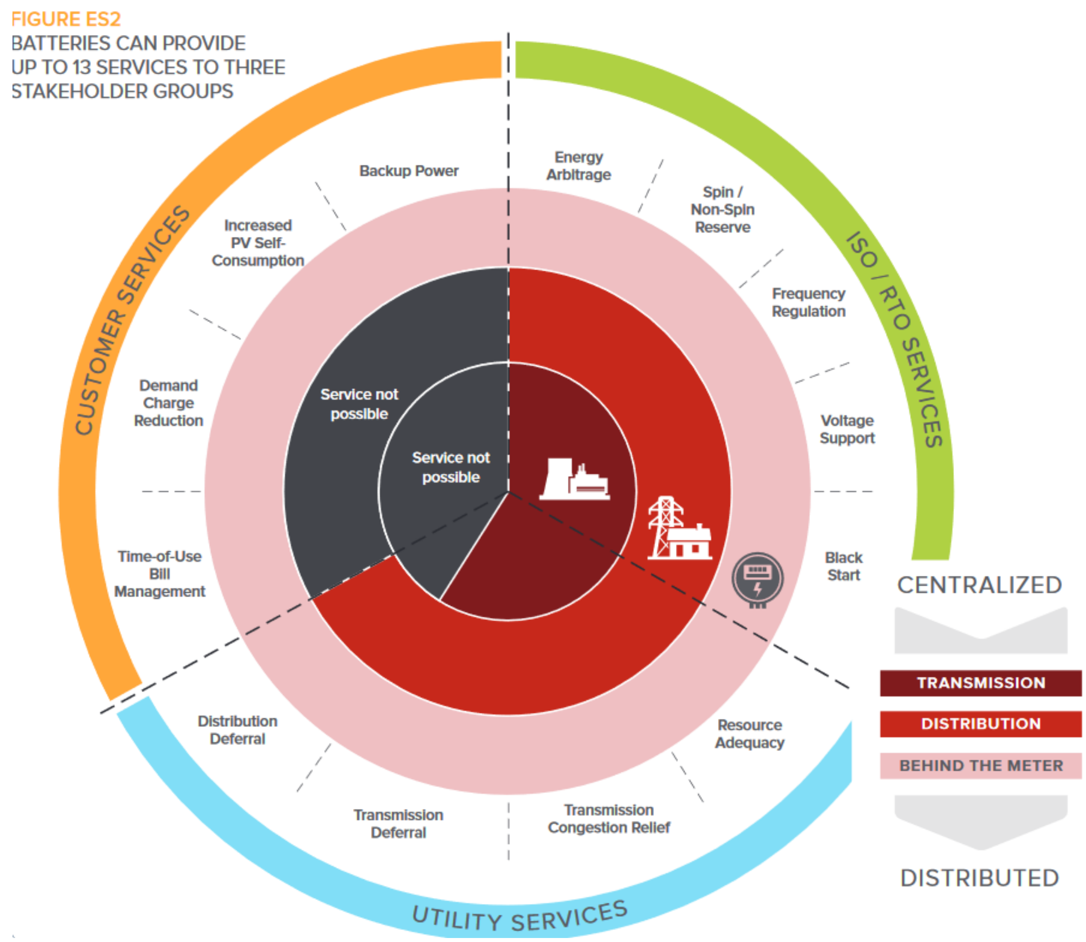

Figure 2.1: Energy storage services [2]

As a part of this thesis project, the system benefits that ESSs are able to provide through the grid services listed in tables 2.1, 2.2 and 2.3 will be investigated.

Table 2.1: Customer services

SERVICE NAME	DEFINITION
Time-of-use bill management	Minimization of purchase of electricity during high price hours.
Increased PV self-consumption	Combining energy storage and PV solar production allows storage instead of export thus maximizing the financial benefit.
Demand charge reduction	Using a local form of peak shaving to reduce peak loads at the end user. In the case of power based tariff, this will effectively reduce the customer bill.
Backup power	Backup power made available for purchase by end user. Grid owner may purchase this stored energy following a blackout.

Table 2.2: Utility services

SERVICE NAME	DEFINITION
Resource adequacy	To ensure sufficient available resources to supply the electric demand.
Distribution deferral	Postponing, minimizing or completely avoiding the need for grid reinforcements in the distribution system.
Transmission congestion relief	Relieving or completely avoiding congestions in any part of the transmission system.
Transmission deferral	Postponing, minimizing or completely avoiding the need for grid reinforcements in the transmission system.

Table 2.3: TSO/DSO services

SERVICE NAME	DEFINITION
Energy arbitrage	Utilizing the fluctuating nature of the electricity price to purchase energy at low prices and selling energy back to the grid at high prices.
Frequency regulation	The automated response that change production or consumption in response to a deviation from the normal 50.00 Hz system frequency.
Spin/non-spin reserves	Spinning reserve is grid connected capacity that immediately can serve the grid in case of unexpected events. Non-spin reserve is capacity that can serve the grid within a short period.
Voltage support	The support to keep grid voltage within acceptable limits. This is valid for all parts of the grid.
Black start	In the event of a partly or total blackout of the grid, black start assets are required to bring the grid back online and restore full operation.

The further downstream the system the storage is located, the higher the amount of system services is available. All 13 services are available with behind the meter placement of energy storage, but some services require either large consumers or numerous smaller ones to be able to provide the service properly. As location of the storage system is centralized, the fewer services are available. Even though the availability decrease as we move upstream the system, the services are still needed in the power system. Table 2.2 shows that all the individual services listed are indeed essential for an optimal operation of the power system. The only innovation being that instead of the conventional ways of providing these services, it is intended to use energy storage systems to provide them.

Societal costs of unreliability (KILE) [3] is also worth investigating as a part of the energy storage services, because using energy storage as a backup in cases of loss of supply can save the grid owners a lot of money. The cost of a single outage for residential end users is the product of a so-called KILE-rate and the interrupted power:

$$K = k(r) \times P \tag{2.1}$$

Where K is the KILE-cost measured in NOK, k(r) is the KILE-rate measured in NOK per kilowatt and P is the interrupted power measured in kilowatts. For residental consumers the KILE-rate used in equation 2.1 is calculated as follows, using costs from 2006:

$$k(r) = 8.8 \times r + 1 \tag{2.2}$$

Where r is the duration of the interrupted supply measured in hours.

2.1.2 Peak shaving services

Peak shaving by energy storage is equal to load shedding from a power system point of view. On a macro level though, peak shaving by energy storage is more versatile in its use. The energy storage system can be installed to relieve congested areas in the system as well as shaving the peaks in hours of high load. Load shedding will achieve the same result of reducing peak load, but is limited in the sense that the load is directly affected and must be reduced or completely shut down. A third option is also possible to perform peak shaving; activating a local power generation system. However, this can be expensive and would in most cases take several seconds to activate.

Figure 2.2 shows how the overall consumption is reduced, unlike *load shifting* where loads are shifted in time to occur at periods of lower total consumption. By shaving the peaks in consumption, the traditional reinforcement methods of upgrading parts of the grid will render useless. Traditional reinforcement of the grid is already a sub optimal solution of dealing with congestions, as periods of high load occur for only small windows and the upgraded grid would end up underutilized.

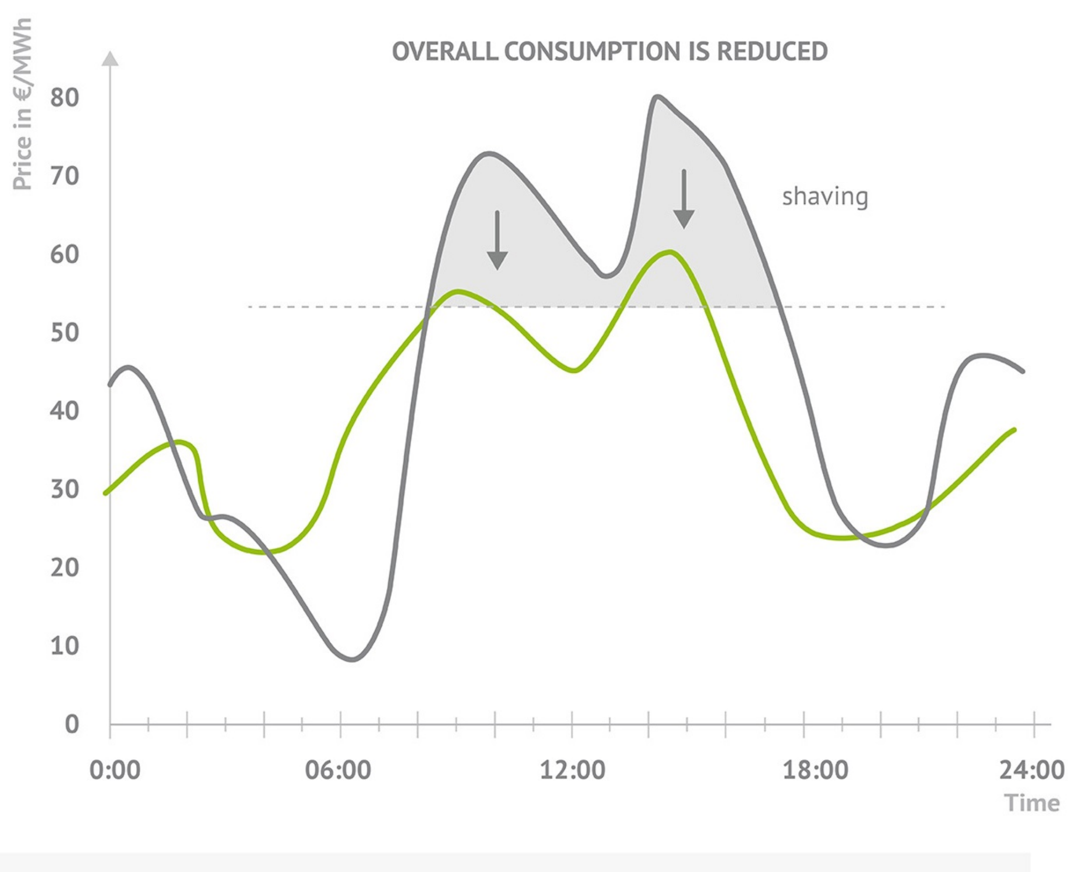

Figure 2.2: Peak shaving [4]

One of the perks of using energy storage as a means of peak shaving is illustrated in Figure 2.3 - where the variations of consumption can be made more or less constant seen from the grid by charging a battery in times of low load, and discharging in times of high load.

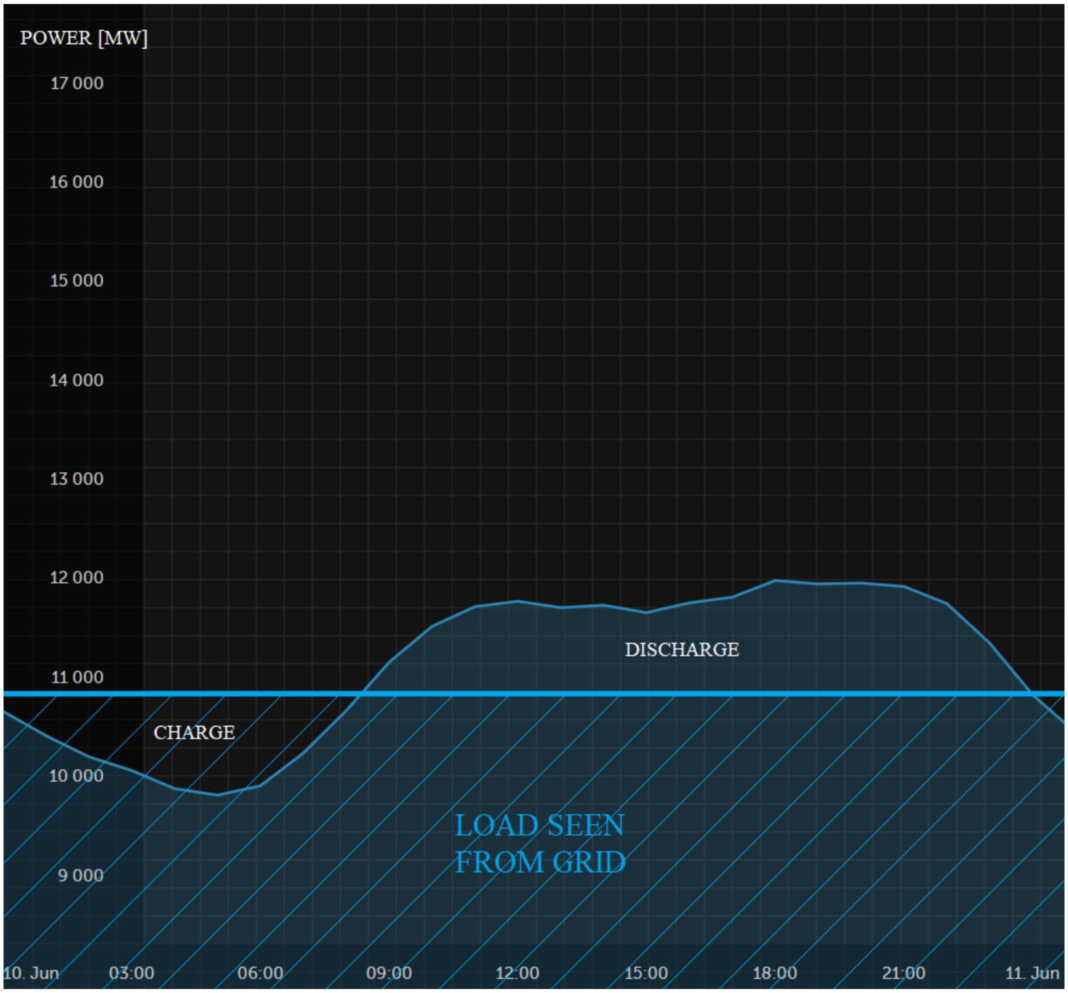

Figure 2.3: Peak shaving on a typical summer day in Norway [5]

2.1.3 Storage placement

Referring back to section 2.1.1, it is clear that the further downstream the system the storage is placed, the higher the amount of system services is available. The hierarchy is such that what is called centralized storage services, are services placed in the transmission grid. Distributed storage services are the services that can be utilized when the storage is placed behind the meter. The distribution grid is an intermediary of these two and storage services placed here can be characterized as both centralized and distributed.

It is only in later years the focus of studies and research has shifted towards grid connected storage systems in the distribution grid. The focus has largely been on behind the meter storage because that is where the storage will fulfill most of its potential and there has also been focus on large storage systems in the transmission system, mostly due to the maturity of the pumped hydropower plants that are defined as energy storage. The focus of this thesis will mainly be on comparing the placement of energy storage, namely batteries, in a transformer circuit. Assumptions and hypotheticals will be drawn because this is still an immature field of study.

2.1.4 Legislations of storage systems

With every change in the power system, there are regulations and legislative issues that the changes must comply with. Although this is not going to be of focus in the thesis, a short debrief is included to clarify the current status of legislative issues connected to energy storage in the distribution grid.

The problem arises when the distribution grid owner (DSO) make the energy storage a part of their infrastructure. The process of storing and releasing energy from any energy storage technology that is a part of their infrastructure would mimic energy arbitrage. There are clear regulations stating that this will in turn violate regulations stating that a DSO are to distribute energy, but not to engage in the electricity market.

2.2 Smart grids, an introduction

Smart grids are the grids of the future. Being able to efficiently integrate actions and behaviors of the online end users with the goal of achieving a sustainable power system with minimized losses and maximizing the security and reliability of supply, all the while staying as economically efficient as possible [6].

There are many definitions that precisely describe the smart grid concept: The inevitable merge of information technology and the power system to form the systems of tomorrow is the most fitting. Not only will this make it easier to control new and existing power systems, it will also form an easy stream of information between all actors connected to the grid. This opens up possibilities of bidirectional power flow not only between utility and consumer, but it will also allow the consumer to play a more active role both in the system and the market. This means less stress on transformers and lines/cables that are overloaded during peak load, and a chance for consumer to go towards balance in their energy accounting or even become a prosumer.

A prosumer is a customer on the consuming end of the power system that, in addition to consuming energy, is able to produce power and send it back to the grid. The concept of prosumers is even more attractive with the possibility of energy storage. This is because the consumer, with the technology available today, is able to produce/release capacity in one of three ways: wind power, solar power or from plug-in electric or hybrid vehicles by reversing the charging process to discharge the batteries through advanced power electronics. With the possibility of energy storage the excess energy produced (not used to cover self-consumption) can either be sent directly back to the grid or stored to be used at a later occasion with little own production and high electricity prices or to be sold and sent to the grid in a high price situation.

The Norwegian distribution grid is being prepared for the power system of the future with the most recent upgrade towards this being a nation-wide implementation of smart AMS-meters.

Chapter 3

Method

Electricity is categorized as an extremely perishable product. Each watt hour that is instantaneously in use needs to be produced somewhere in the power system at the same instance. The instantaneous power varies throughout the day - so much so that the AMS rollout (due 01.01.2019) is a result of wanting even finer resolution of energy consumption; hour by hour, and eventually 15 minutes resolution. It is possible to shift the need for energy in time to compensate for load fluctuations, but generally each type of load has a characteristic profile that the instantaneous power will follow.

It is important that there is a distinction of the different types of variation in energy demand. The energy demand is defined within a specific time interval and is calculated as the interval of the instantaneous power. The distinctions are time specific and are divided into annual and daily variation. Annual variation is a direct effect of seasonal change, both in temperature and weather. The Norwegian consumption is approximated to consist of 64 % heating and 15 % water heating [7], thus there is a natural increase in load during the winter months. The daily variation is a direct effect of consumer behaviour. The load is naturally higher during the day and lower during the night.

It is desirable to control the load profile in order to attain a as stable as possible consumption of energy from a power system point of view. This is achieved either through peak shaving or by shifting peak consumption to hours of lower consumption. Due to fluctuations in consumption, the energy must be previously stored locally in order for the ESS to properly and effectively reduce the peak load. The simulation method chosen for this thesis does not consider consumer variation, but the production and consumption is rather a fixed value at normal operation. A form of peak shaving will however be implemented in the example circuit although it does not appear in the results. The battery packs installed will nevertheless lead to less strain on the distribution system as a whole, and will try to cover some of the local consumption.

Chapter 4

Storage technologies

In the modern global economy, energy storage plays a central role, but storage of electrical energy is still relatively rare. The most vital part of Norwegian economy is oil and gas, which is regularly stored and is most commonly used at the smaller scale for fuel in vehicles. Residential storage of energy through hot water is standard in modern homes. Yet when it comes to storage of electrical energy, anything but small scale storage in batteries, is still unusual.

Although storage of electricity is versatile in the way that there are many technologies able to achieve it, it is far from straightforward. The electricity needs to be converted into some other form of energy before it is at all able to be stored. I.e. in a flywheel the electrical energy is turned into rotational energy, while in a battery it is converted into chemical energy. The conversion process makes energy storage both complex and frequently less efficient. This contributes to making ESSs costly.

The goal of grid operators is to make supply equal to demand in the operating hour. When unexpected events create an unbalance between these two, the traditional way to deal with it is to increase production from the fastest responding and already spinning power plants in the system. Energy storage systems can, in theory, acquire the same result in a cleaner fashion and much faster. As aforementioned, ESS could also reduce the need for grid reinforcements, depending on the placement.

ESS also plays an important role in making intermittent renewable generation more efficient. Renewables such as wind, solar and tidal are completely unable to supply continuous electrical power. If combined with some form of energy storage system will not only reduce uncertainty of the supply but also increase the value of the energy generated. The intermittent nature of these renewables often result in unused energy in cases of low demand and high (renewable) production. This results in shedding of excess power when in reality it can be stored for use at a time where demand is ready and the transmission system can cope with it.

Ever since electricity first came around, human kind has been trying to obtain effective energy storage methods to enable use on demand. The last century has shown an immense evolution of the energy storage industry. Continuous adaptation and development has resulted in great advances in energy storage technology.

4.1 Electrochemical energy storage - Batteries

Solid state batteries is a form of electrochemical energy storage. Active materials contained within the battery are converted into electricity. The recognizable attribute of solid state batteries is that both the electrodes and the electrolytes are solid as opposed to liquid or polymer.

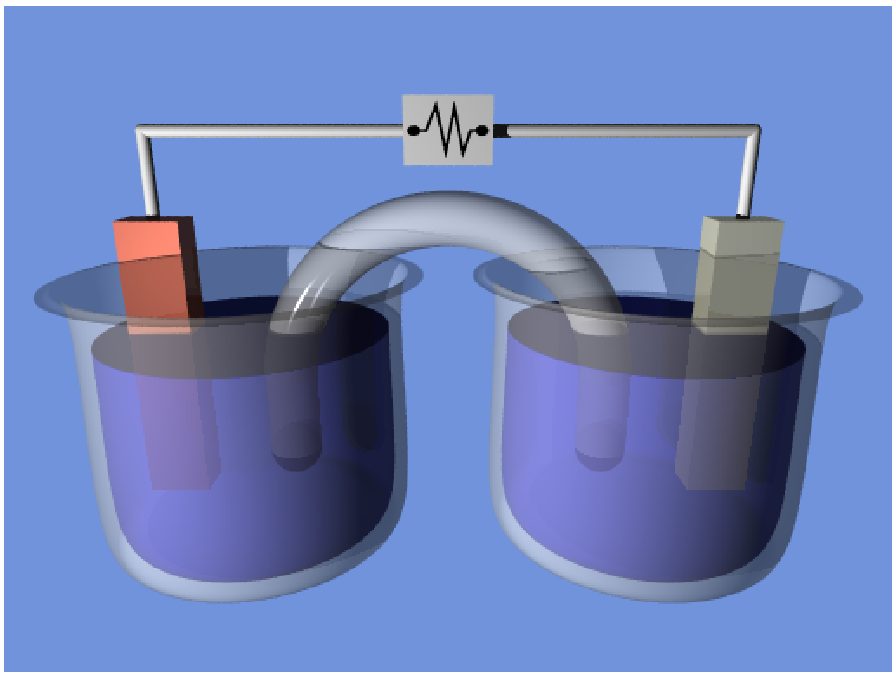

Figure 4.1: Principle of the standard electrochemical battery [8]

Figure 4.1 shows a standard electrochemical cell - also called a battery.
Solid state batteries are batteries that utilize both solid electrolytes and solid electrodes. The greatest advantage of solid electrolytes are safety and high energy density. The safety aspect comes from removing the flammable organic solvents in the more conventional liquid electrolyte batteries (flow batteries). This section will focus on large-scale solid state batteries. Batteries convert chemical energy into electrical energy and consist of a positive and a negative electrode separated by an electrolyte.

4.1.1 Electrochemical capacitors

The electrochemical capacitor, also referred to as the supercapacitor, is a double-layered capacitor with capacitance values much higher than regular capacitors (but lower voltage limits). Supercapacitors will commonly be 10 to 100 times more energy dense than electrolytic capacitors and will react, regarding charge, much faster than most batteries, and it will also tolerate more charge and discharge cycles than any rechargeable battery. This energy storage technology is however immature and of a smaller scale than what is in the scope of this thesis.

4.1.2 Lithium ion batteries (Li-ion)

Presently, most of the commercial batteries are based on Li-ion conducting polymer electrolytes. Lithium is the lightest of all metals, and can be used as the anode in contact with Li+-salt electrolytes, and will provide a wider electropositive potential. Hence, the Li/Li+-salt batteries can facilitate a high energy density.

The lithium ion battery has been around since the early 90's. It has developed from small-scale use in consumer products into larger-format cells for use in electrical vehicles and pure energy storage. It is also expected a significant synergy between batteries of this type and power systems with the emergence of electric vehicles powered by Li-ion batteries. The deployment of lithium ion batteries in energy storage applications has hit a wide range. Everything from energy-type batteries of a few kilowatt hours in combination with residential rooftop photovoltaic solar (PV) arrays, to multi-megawatt hour containerized batteries used as grid ancillary services.

4.1.3 Nickel cadmium batteries (Ni-Cd)

Cadmium is a toxic heavy metal and therefore requires special care during battery disposal. The European Union has banned the sale of Ni-Cd batteries except for medical use, alarm systems, emergency lighting and potable power tools (banned since 2016) [9].

4.1.4 Nickel metal hybrid batteries (Ni-MH)

A nickel metal hybrid battery is another type of rechargeable battery. The charge and discharge is a chemical reaction between nickel oxide hydroxide (NiOOH) as cathode (positive electrode), and the anode (negative electrode) uses a hydrogen-absorbing alloy. The Ni-MH battery can have two to three times the capacity of an equivalent sized Ni-Cd battery, and the energy density of this type of battery can even approach that of a Li-ion battery.

4.1.5 Sodium sulphur batteries (Na-S)

Na-S batteries operate at a temperature of 300 °C to 350 °C, which can be an operational problem for intermittent operation. Significant installations for energy storage to facilitate distribution line construction deferral. The battery must be kept hot - >300 °C - to facilitate the charging process, for which independent heaters can be used as a part of the battery system. Na-S batteries have a long lifetime compared to other solid state batteries; 15 years or 4500 charge cycles, but is limited in its use because of the high temperature of operation.

The largest sodium sulphur battery installation is a 108 MW, 648 MWh unit for wind stabilization in Northern Japan. The demand for Na-S batteries as an effective means of stabilizing renewable energy output and providing ancillary services is expanding. This is an area of use applicable for most of the large scale energy storage technologies introduced in this thesis but not in focus.

4.2 Redox flow batteries

The redox flow battery stores chemical energy in two external liquid electrolyte tanks. The tanks contain soluble redox couples which can be pumped into a cell stack. The cell stack is made up of two electrolyte flow compartments which are separated by ion selective membranes. The process of generating electricity from chemical energy, and thus the name of these batteries, derives from the reduction-oxidation or redox operation that is performed. During a charge cycle, one of the electrolytes is oxidized at the anode, while another electrolyte is being reduced at the cathode. The electrical energy, which is provided through an external circuit, is converted to the electrolyte chemical energy and can be stored for later use. This process is reversed to perform a discharge cycle.

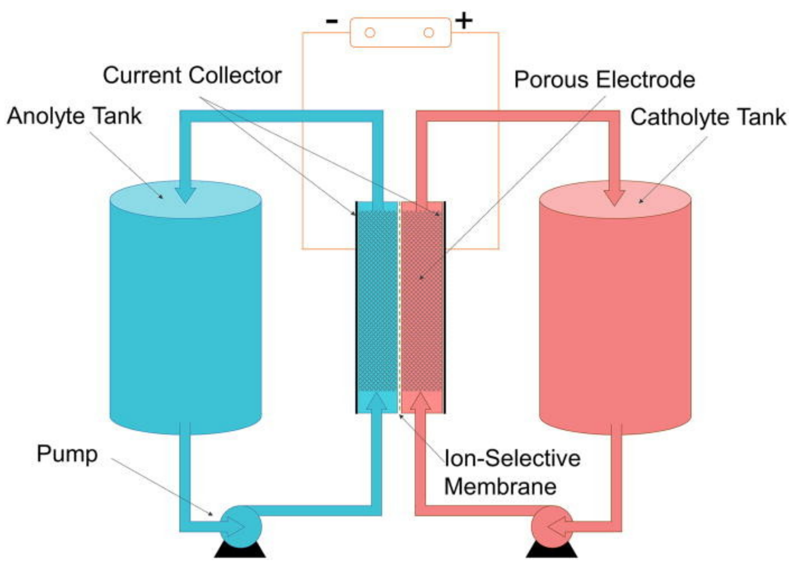

Figure 4.2: Principle of the redox flow battery [10]

The capacity of flow batteries is only dependent on the size of the electrolyte tanks. Thus, this particular energy storage can effortlessly switch from being in the kilowatt hours range to tens and hundreds of megawatt hours. The power and energy ratings of true redox flow batteries are independent of each other. This allows for further optimization of each battery for each application. Three specific redox flow batteries are listed and briefly explained in the following sections [11].

4.2.1 Iron-Chromium redox flow batteries (ICB)

Iron-Chromium flow batteries utilize the redox couples Fe2+ and Fe3+ as well as Cr2+ and Cr3+. These are soluble and stored in separate electrolyte tanks. The theoretical efficiency of ICBs is 70-80 %. ICBs are still immature but are projected to be safe, reliable and cost-effective for use as distributed energy storage in the future.

4.2.2 Zinc-Bromine flow batteries (Zn-Br)

Zinc-Bromine batteries are not true flow batteries, but rather a hybrid flow battery. Zinc is plated onto the anode as a solid during each charge cycle. During discharge, the zinc is oxidized to Zn2+. The other redox couple employed is Br2 and Br-. Zn-Br batteries have a modest efficiency of 65-75 %. The system also requires a full discharge every few days because of the hybrid nature of the zinc.

4.2.3 Vanadium redox flow batteries (VRB)

Vanadium flow batteries utilize the redox couples V2+ and V3+ in addition to V4+ and V5+. VRBs are the most tested and used of the introduced flow batteries. This has resulted in a reported efficiency of around 85 %, and response times faster than 1 ms. The proclaimed lifetime of vanadium flow batteries is somewhere between 10 000 to 17 000 charge cycles and is very dependent on the application of the battery as V5+ is highly oxidative [12].

4.3 Electric vehicles

Electric vehicles have grown dramatically in popularity the last years, nationally as well as internationally. The large quantity of vehicles makes much battery capacity available when many are charging simultaneously. If there is charged capacity on the battery, the correct technology implemented in the charger can reverse the energy flow to make the battery deliver power to the grid. This will of course demand changes in the residential circuitry - and with today's market structure making them prosumers.

Charging electric vehicles can also be used as peak shavers. Allowing control of the charger to TSO or another third party to disconnect charger in peak consumption hours. This can be done either by disconnecting charging vehicles or using the aforementioned technology to reverse the energy flow from the vehicles battery.

It is not only electric vehicles that will help the energy business. Reversely, the implementation of batteries in the power system will boost the development of new and existing battery technologies. Which in turn will result in better batteries or even completely new energy storage technologies to use in electric vehicles.

4.4 Flywheels

A flywheel is a rotating mechanical unit which can be used to store rotational energy [13]. Flywheel energy storage works by accelerating a rotor (flywheel) to an immensely high velocity and maintaining the energy as rotational energy. The energy can be extracted from the system by braking the rotational velocity of the flywheel - according to the principle of conservation of energy [14].

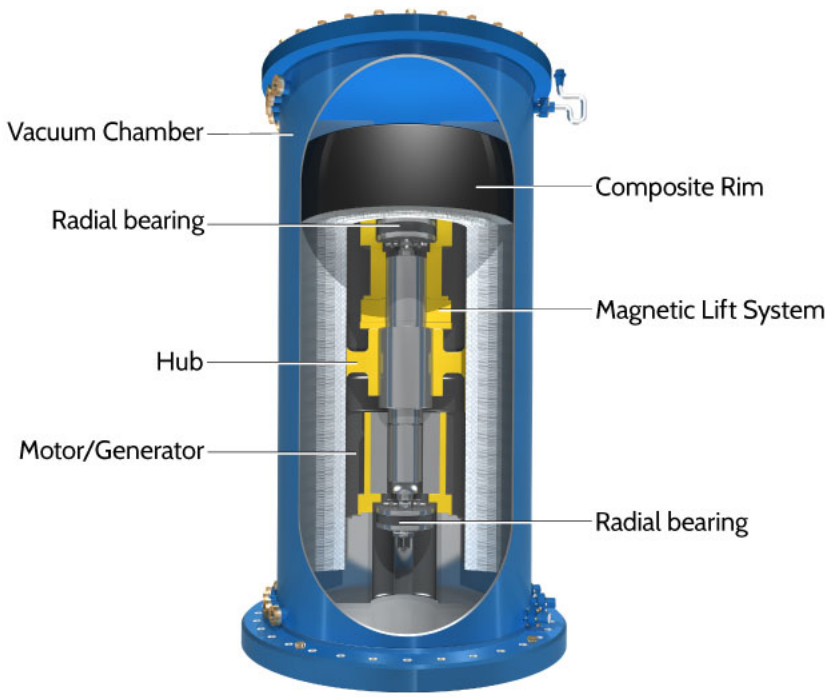

Figure 4.3: Principle of a carbon fiber flywheel (design by Beacon Power, LLC). [15]

Conventional steel bearings are limited to a few thousand revolutions per minute (RPM). Magnetic bearings with composite carbon fiber, can enable 60 000 RPM.

The flywheel technology has many advantageous properties that can improve the existing power system. Flywheels can capture energy from intermittent sources, such as solar and wind power over time and deliver a continuous supply of power to the system. Flywheels can also react on signal from the system to deliver frequency regulation and improved quality of electricity.

In addition to working as an energy reserve if needed, the flywheel can also act as a spinning reserve. Meaning it will contribute with rotational energy to the system. Because in fault situations, the total amount of inertia (i.e. from spinning reserves, rotating turbines in hydro-power plants etc.) present in the power system is crucial in a way that it will moderate the total dip in frequency.

4.5 Compressed air energy storage (CAES)

Compressing air into high pressure tanks allows the use of energy at low-cost to increase the amount of energy stored per unit of volume. The energy can be released to meet higher demand periods. Large scale applications must conserve the heat energy associated with compressing the air in order to keep the efficiency of the storage system to an acceptable level. CAES is alike pumped-hydro plants in terms of storage capacity and their applications.

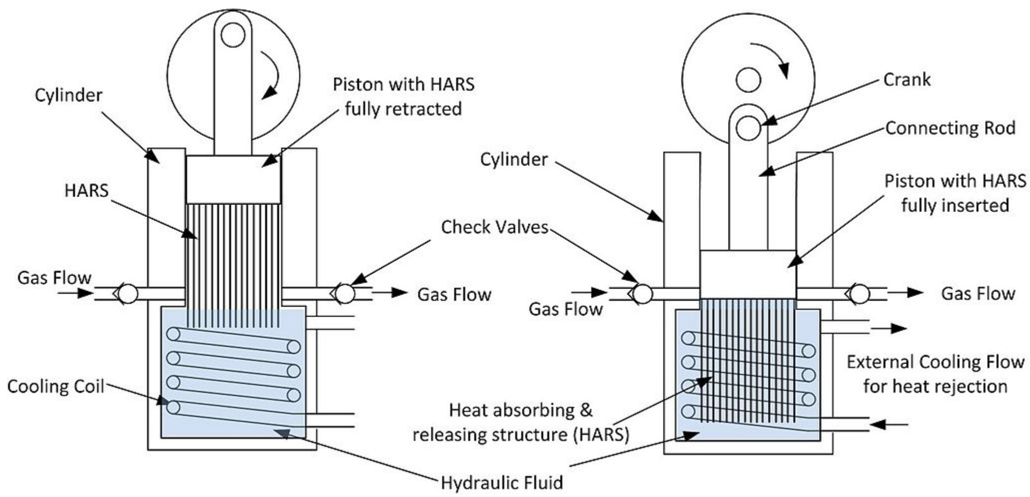

Figure 4.4: Principle of isothermal compression and expansion. [16]

Figure 3.4 shows the schematics of a near isothermal (true isothermal CAES does not exist) energy storage system. The leftmost figure shows the system as it is ready to start storage. A motor will drive the piston downwards, from its fully retracted position, as air flows in and is compressed inside the heat absorbing and releasing structure (HARS). During peak hours this compressed air is released by retracting the piston and reheating the air. The air is sent through multiple turbines at various pressures and temperatures to generate electricity.

Since it is not possible to process and store compressed air at the very high temperatures reached during compression, the heat must be removed prior to storage. Traditional CAES essentially dumps the heat into the atmosphere, therefore requiring a second injection of heat prior to re-expansion. Advanced adiabatic CAES aims to remove the heat and store it separately, then re-inject at the expansion stage. This has potential to dramatically increase the round-trip efficiency of the process.

Advanced adiabatic compressed air energy storage (AA-CAES) is still an immature and untested technology of energy storage. AA-CAES is an upgrade from traditional CAES in the sense that the efficiency is elevated and that the advanced adiabatic process is supposedly a zero-carbon process. The adiabatic storage manages to fulfill this by storing the heat created during compression of air parallel to the actual compressed air storage. The heat is then returned and used to reheat the air as it is expanded. AA-CAES is still under development and the theoretical efficiency of AA-CAES is close to 100 % with the perfect insulation. In practice the round trip efficiency is expected to be around 70 %.

Means of storing heat:

- Stored in a solid such as concrete or stone
- Stored in a fluid such as oil
- Stored in an inflatable bag of water
- Stored in molted salt solutions

4.6 Thermal energy storage

”Thermal energy of a certain gathering of particles is the overall energy of the particles at a certain temperature.” (Bjørn Pedersen, UiO) [17]

The simplest form of thermal energy storage is in conjunction with coal and gas being extracted and stored for later use in a turbine. Thermal storage is also used with CAES as described above to increase the efficiency of an otherwise inefficient system.

Thermal energy storage can be categorized into two different types of systems; sealed systems and pumped heat energy storage. The sealed systems stores heat in mediums like molten salt or ice-slush. If converted into steam, this stored heat can be used to power conventional steam turbines. Pumped heat energy storage exploits the temperature difference between two heat stores. A heat engine drives a generator to recover the energy.

4.7 Hydropower

A reservoir hydropower plant is the simplest form of energy storage in hydropower. The water, and thus the potential energy, is stored in a dam to be harnessed whenever the plant owner sees fit (water value can be calculated using parameters like electricity price, head height and reservoir size etc. to decide when to produce).

4.7.1 Pumped hydroelectric energy storage

Pumped hydroelectric energy storage is principally the same as a regular reservoir hydropower plant. An extra, lower reservoir is however needed to temporarily store the discharge from the upper reservoir. The water in the lower reservoir is pumped back up to the upper reservoir. The most efficient way to run a pumped hydroelecric energy storage is to use excess capacity as power to pump water from lower to upper reservoir.

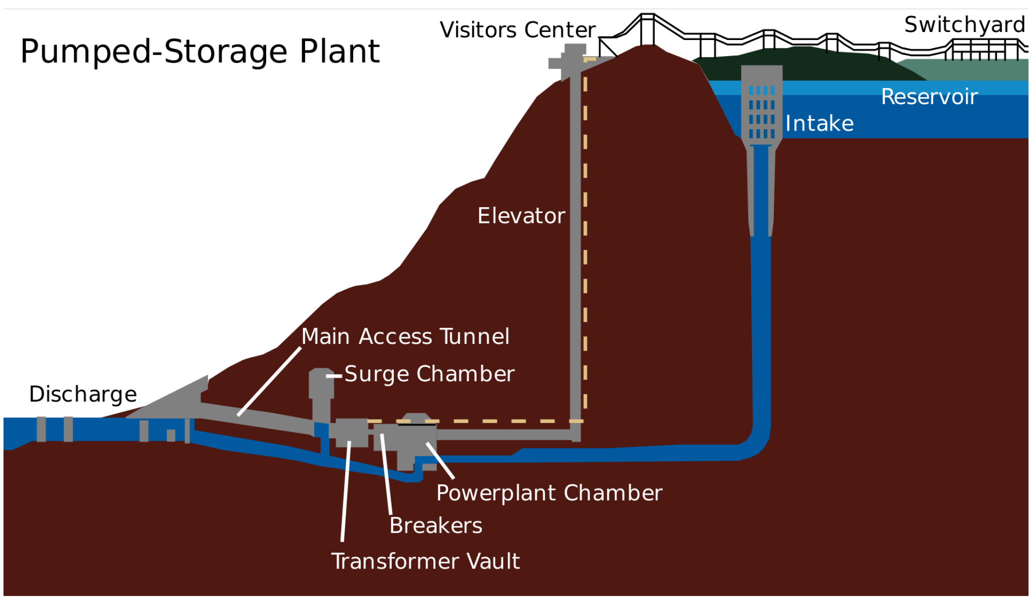

Figure 4.5: Principle of pumped hydroelectric energy storage [18]

Pumped hydroelectric energy storage can be divided into two subsections: sub-surface and surface reservoir - where surface reservoirs are dominating. For sub-surface systems, both the upper and the lower reservoir is below the surface. Although this is only theoretical, this solution of pumped hydroelectric energy storage is promising and possibly very valuable as the environmental and visual impact is minor (man-made, existing structures such as abandoned mines are good locations for sub-surface hydroelectric energy storage). Surface reservoirs, as shown in Figure 4.5 account for all existing pumped hydroelectric storage systems. These systems can again be divided into two categories: closed-loop and open-loop systems. Closed-loop systems are defined as systems not continuously connected to a natural flow of water, whereas open-loop systems are continuously connected.

A further improvement of this storage technology is the use of variable-speed machines. Frequency regulation is not possible while the regular pumped-storage plant is in pump mode. Additionally, the unit in turbine mode cannot operate at peak efficiency when partially loaded. Variable-speed machines enable the power consumed in pumping mode to be varied over a range of outputs. Modifying the speed also allows the turbine to operate at peak efficiency over a larger portion of its operating band.

4.8 Superconducting magnetic energy

Superconducting magnetic energy storage (SMES) store its energy in the magnetic field created by the flow of current in a superconducting coil [19]. The coil is so-called superconducting because it has been cryogenically cooled down to a temperature below its critical temperature. The typical SMES system consists of these three parts: superconducting coil, power conditioning system and a cryogenically cooled refrigerator.

One of the largest advantages of SMES is that once the coil is charged, the current will not decay and the magnetic energy can be stored infinitely (as long as the temperature is kept below superconducting limit).

To release the energy into the grid, the coil is simply discharged. The power conditioning system uses a converter to invert and rectify the current. It is estimated that current conversion accounts for 2-3 % each direction. SMES systems are extremely efficient. The high costs of SMES and its technical challenges are the primary limitations of commercial and practical use of systems such as these.

4.9 Integration of energy storage systems

- **Integration combined with renewables**
  Energy storage used in combination with renewable energy production is something that has been a point of interest lately. To counteract the highly intermittent nature of renewable generation, ESS may be used to smooth, firm and time-shift the output. Integration costs on a system level is also avoided.

- **Energy storage services**
  Ancillary services are vital to security and stability of the grid. Services like spinning reserves, reliability control and frequency control, to name a few, must be present in the system to ensure safe and reliable operation. The grid services can be supplied without the use of ESS but with the increasing amount of renewables in the system and coal and gas turbines being phased out, new alternatives are needed. The most applicable ancillary services that ESSs are able to provide are investigated in 2.1.1.

- **Peak shaving**
  Behind the meter storage allows smoothing of the load curve by charging ESS during off-peak periods and discharging during peak demand. See 2.1.2 for a detailed description of peak shaving.

- **Energy arbitrage**
  Exploiting the fluctuations in the electricity price to purchase and store energy during low price periods and sell back the stored energy during high price periods.

Chapter 5

Case

The simulations are divided into different scenarios with different placement of the batteries to show the changing power flow of charging and discharging batteries in the circuit. The simulations will be performed in NetBas and because of time constraints the simulations are performed on a static system. The software used will perform quick load-flow analyses based on an iterative process. NetBas is not able to perform dynamic simulations, so each scenario is based on the static analyses that NetBas is able to provide. The intention is to investigate the changes in load-flow and compare the load level of mainly the transformers in the circuit, as the placement and size of the batteries are changed. Each scenario will be investigated both during charge and discharge of the batteries.

5.1 Grid analyses

The transformer circuit that will be analyzed is a typical residential radial with some industrial loads connected to one or two of the nodes. An additional PQ-point is placed at the end of one radial branch - a small power plant. See figure 4.1 for the configuration of the grid, batteries included (designed as one load and one generator to *mimic* a battery bank). The generator part of the battery is set as a PQ-point to keep the voltage as stable as possible.

The analyzed radial is fed from transformer FA33-T2 and the high voltage circuit in question is operated at 22 kV. Simulations are performed on this grid at 22 kV (which is a live grid operated by network owned Nordkraft Nett AS).

5.1.1 Parameters of simulation

As mentioned in the sub-chapter of sizing batteries, using batteries with relatively high energy capacity makes the most sense in a transformer circuit as this one. The power capacity is dependent on where the batteries are placed. Behind-the-meter battery banks will naturally be much smaller in capacity than battery banks placed in the feeding transformer of the radial. The idea is to use the battery banks as time-shift or peak shaving, thus, charging during low load hours and discharging during peak hours. In the current power market this will be equivalent to charging during low price hours and discharging during high price hours. This means that the potential for energy storage to save grid owner from expensive maintenance costs and possible reinforcement costs can be just as attractive as the potential to use the storage system to mimic a power plant which can trade capacity in the power market.

The model is a small section of the distribution grid owned by Nordkraft [20]. In addition to the existing grid, battery banks will be placed; on the low voltage side of feeding transformer, behind the meter in the radials with the most heavily loaded transformers, and behind the meter in the two radials furthest away from the feeding transformer. The simulation will be run based on historical data from 2010 and 2016. For an overview of the most important data see figure 4.1. The grid analyses will be run as different scenarios: Scenario 1 - Energy storage in feeding transformer, Scenario 2 - Energy storage in over loaded branches, and Scenario 3 - Energy storage in the extremities. Each scenario will be run twice, once for charging energy storage and once for discharging energy storage.

The radial is fed with capacity corresponding to the historical consumption in 2010, which is 2.357 MW. The size of the battery banks will firstly be chosen based on this feeding capacity. The second thing to consider is how heavily the transformer is loaded prior to installing the storage system (transformers are usually more loaded than both lines and cables in residential radials such as this). The goal is to show how the placement of the storage systems affects the power flow during charge and discharge of the batteries.

The load characteristics in this radial is mostly residential with some industry. The power consumption is therefore mostly active, but there is a low consumption of reactive power as well. The parameters of the grid are provided by Nordkraft Nett. Feeding node FA33 is used as swing bus for all scenarios of this simulation (parameters provided by Nordkraft Nett).

The storage technology applied in the simulation is batteries. Deciding the specific technology is irrelevant for the analyses and is henceforth called battery packs. A sizing strategy is in this case not needed, as brute force trial and error is more effective.

5.2 The model

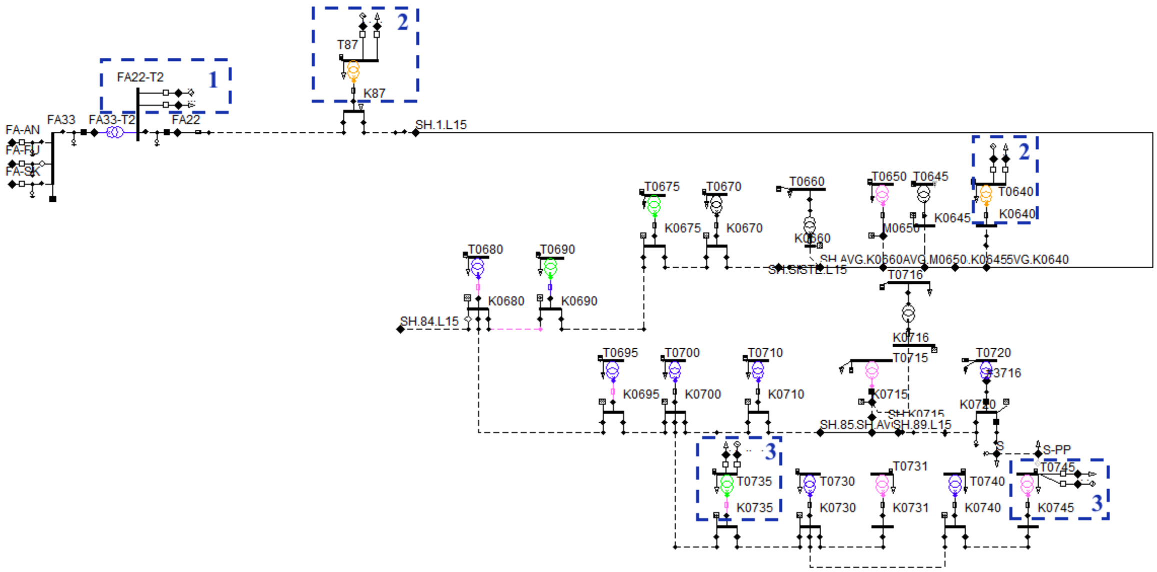

Figure 5.1: The transformer circuit

The radial is, as aforementioned, fed from transformer FA33-T2. The following results represent the grid as is today and each scenario with battery banks placed throughout the radial. For in depth results, see appendix A. In certain situations the transformer circuit is able to deliver power back to the grid. These situations can be seen in the following tables in the value of PRODUCTION of node FA33. Negative value means that there is a surplus of capacity on the low voltage side of the transformer, and a positive value means that there is a deficit. Each placement of the energy storage is marked according to scenario number 1, 2 and 3.

5.3 Current situation

This section will present the current situation of the grid and provide a brief explanation of why each scenario is desired to investigate.

Table 5.1: Voltages, power flow and load percentage in the current grid.

NODE	VOLTAGE [kV]	LOAD [kW]	PRODUCTION [MW]	LOAD PERCENTAGE, TRANSFORMER [%]
FA33	34,700	0	2,357	N/A
FA22-T2	22,022	N/A	0	48
K87/T87	21,985	313,287	0	105
K0640/T0640	21,961	99,496	0	103
K0645/T0645	21,907	0,03	0	0
M0650/T0650	N/A	12,609	0	26
K0660/T0660	21,812	15,169	0	16
K0670/T0670	21,765	11,447	0	12
K0675/T0675	21,752	68,716	0	72
K0690/T0690	21,727	371,962	0	77
K0680/T0680	21,714	230,327	0	48
K0695/T0695	21,701	228,518	0	47
K0700/T0700	21,685	171,338	0	59
K0710/T0710	21,679	54,906	0	57
K0715/T0715	N/A	76,012	0	25
K0716/K0716	21,675	31,000	0	10
K0720/T0720	21,674	166,584	0	56
S-PP	21,674	N/A	N/A	N/A
K0735/T0735	21,677	128,156	0	68
K0730/T0730	21,674	129,178	0	42
K0731/T0731	21,673	76,320	0	26
K0740/T0740	21,673	53,994	0	56
K0745/T0745	21,672	63,436	0	32

Running the simulations in the current grid shows that the radial is supplied with 2.357 MW. Feeding transformer FA33-T2 is at a load percentage of 48 %, which means that the potential for energy storage at this point is not towards distribution deferral but rather energy arbitrage. There are also two distribution transformers that are overloaded; T87 and T0640 loaded at 105 % and 103 % respectively. This gives reason to investigate in behind the meter energy storage in these two branches. Transformers T0745 and T0735 are loaded at 68 % and 32 % respectively and are placed a great distance away from the feeding point of the radial. This gives reason to investigate in behind the meter energy storage in these two branches as well. Values marked with N/A either means that results are unavailable or not applicable for the simulation results.

The highest voltage drop is at 1.98 % which is within acceptable limits. Voltage drops will not be a point of focus in each of the scenarios as the distribution transformers are over loaded before reaching unacceptable levels of voltage drop. Placing batteries in an existing radial such as this can introduce abnormalities in short circuit currents and can change the direction of the power flow. This is something that the protection systems need to be designed to handle. Further analysis of this will not be a topic in this thesis, but it is suggested to investigate if this solution proves viable.

Note that this is a static analysis. The loads and production displayed in table will therefore not change as desired when charging and discharging the batteries. In cases of charging, the optimal state of the grid is much higher production than consumption. And in cases of discharging, the optimal state of the grid is reversed: Higher consumption than production. As this radial is part of a larger city wide grid, the ”production” in the feeding node is decided by the total consumption and the sum of losses in the radial. Thus, a static analysis in NetBas is the best way to illustrate the change in load flow in the given time frame. It is also worth noticing that the NODES are sorted by configuration, see figure 4.1.

5.4 Scenario 1 - Feeding storage

This section will present the results of scenario 1 where the battery is placed on the low voltage bus of the feeding transformer.

Table 5.2: Voltages, power flow and load percentage - Scenario 1 with charging batteries.

NODE	VOLTAGE, CHARGING [kV]	LOAD, CHARGING [kW]	PRODUCTION, CHARGING [MW]	LOAD PERCENTAGE, TRANSFORMER, CHARGING [%]
FA33	34,700	0	4,731	N/A
FA22-T2	21,939	2357,000	0	95
K87/T87	21,902	317,414	0	106
K0640/T0640	21,878	101,532	0	103
K0645/T0645	21,824	0,000	0	0
M0650/T0650	N/A	12,854	0	26
K0660/T0660	21,728	15,400	0	16
K0670/T0670	21,681	11,447	0	12
K0675/T0675	21,667	68,716	0	73
K0690/T0690	21,643	375,607	0	77
K0680/T0680	21,630	232,357	0	48
K0695/T0695	21,617	230,198	0	47
K0700/T0700	21,600	173,015	0	59
K0710/T0710	21,595	55,587	0	57
K0715/T0715	N/A	76,216	0	25
K0716/K0716	21,591	31,136	0	10
K0720/T0720	21,590	168,157	0	56
S-PP	21,590	N/A	N/A	N/A
K0735/T0735	21,592	129,508	0	68
K0730/T0730	21,589	130,157	0	42
K0731/T0731	21,588	77,157	0	26
K0740/T0740	21,588	54,663	0	56
K0745/T0745	21,587	63,943	0	32

Table 5.3: Voltages, power flow and load percentage - Scenario 1 with discharging batteries.

NODE	VOLTAGE, DISCHARGING [kV]	LOAD, DISCHARGING [kW]	PRODUCTION, DISCHARGING [MW]	LOAD PERCENTAGE, TRANSFORMER, DISCHARGING [%]
FA33	34,700	0	-0,006	N/A
FA22-T2	22,085	0,006	2,357	8
K87/T87	22,048	317,376	0	105
K0640/T0640	22,024	101,512	0	103
K0645/T0645	21,970	0,000	0	0
M0650/T0650	N/A	12,855	0	26
K0660/T0660	21,875	15,403	0	16
K0670/T0670	21,828	11,447	0	12
K0675/T0675	21,815	68,716	0	72
K0690/T0690	21,791	375,582	0	77
K0680/T0680	21,778	232,356	0	47
K0695/T0695	21,765	230,199	0	47
K0700/T0700	21,748	173,012	0	59
K0710/T0710	21,743	55,585	0	57
K0715/T0715	N/A	76,213	0	25
K0716/K0716	21,739	31,136	0	10
K0720/T0720	21,738	168,152	0	56
S-PP	21,738	N/A	N/A	N/A
K0735/T0735	21,740	129,503	0	68
K0730/T0730	21,674	130,391	0	41
K0731/T0731	21,736	77,163	0	25
K0740/T0740	21,736	54,661	0	56
K0745/T0745	21,735	63,950	0	32

In scenario 1, the battery is placed on the low voltage side of the feeding transformer. The battery is designed to add 2.357 MW to the already existing capacity of 2.357 MW. This constitutes in more than a doubling of the capacity fed to the radial when the battery is loading and thus acting as a load (not an exact doubling because of added losses). When discharging, the large capacity of the battery is able to be the sole supplier of the radial (excluding power plant S-PP), and even feeding 6 kW back to the grid.

According to the parameters of the swing bus, the high voltage side of FA33-T2 is locked at 34.700 kV. As seen in table 4.2 and table 4.3 the voltages are not to affected by the battery. This is due to the fact that the battery is installed as a PQ-point to try and maintain a stable as possible voltage. The load flow in the radial, other than in nodes FA33 and FA22, is not affected by an installment of a battery at this location.

The main thing to notice in tables 4.2 and 4.3 is the load percentage of transformer FA22-T2. Referring back to the current situation - table 4.1, this transformer is today loaded at 48 %. But with a battery of this size placed on the low voltage bus of the transformer, the load percentage changes to 95 % when charging and 8 % when discharging. Battery storage is not so much power storage as it is energy storage with the current state of battery technology and power electronics. Thus, the battery of 2.357 MW can be designed to have a charge/discharge time of i.e. 3 hours (to cover the highest peaks of a residential/industrial radial) bringing the energy capacity of the battery to 7.071 MWh according to equation 5.1.

$$E = P \times t \tag{5.1}$$

Where E is energy measured in watt-hours, P is power measured in watts and t is time measured in hours. This means that the battery needs to be provided with 2.357 MW for three hours to achieve its full energy potential, and it takes three full hours to empty the energy storage completely. Choosing the appropriate power to energy ratio of a battery for use in a radial such as this can be very hard due to extremely varying power curves in Norway.

5.5 Scenario 2 - Loaded branch storage

This section will present the results of scenario 2 where the batteries are placed in the two branches with the heaviest loaded distribution transformers.

Table 5.4: Voltages, power flow and load percentage - Scenario 2 with charging batteries.

NODE	VOLTAGE, CHARGING [kV]	LOAD, CHARGING [kW]	PRODUCTION, CHARGING [MW]	LOAD PERCENTAGE, TRANSFORMER, CHARGING [%]
FA33	34,700	0	2,713	N/A
FA22-T2	21,998	0	0	55
K87/T87	21,956	600,969	0	196
K0640/T0640	21,930	170,562	0	171
K0645/T0645	21,877	0,000	0	0
M0650/T0650	N/A	12,854	0	26
K0660/T0660	21,781	15,401	0	16
K0670/T0670	21,734	11,447	0	12
K0675/T0675	21,721	68,716	0	72
K0690/T0690	21,696	375,598	0	77
K0680/T0680	21,683	232,357	0	48
K0695/T0695	21,670	230,199	0	47
K0700/T0700	21,654	173,014	0	59
K0710/T0710	21,648	55,587	0	57
K0715/T0715	N/A	76,215	0	25
K0716/K0716	21,644	31,136	0	10
K0720/T0720	21,643	168,155	0	56
S-PP	21,643	N/A	N/A	N/A
K0735/T0735	21,646	129,506	0	68
K0730/T0730	21,642	130,390	0	42
K0731/T0731	21,642	77,159	0	26
K0740/T0740	21,641	54,662	0	56
K0745/T0745	21,641	63,946	0	32

Table 5.5: Voltages, power flow and load percentage - Scenario 2 with discharging batteries.

NODE	VOLTAGE, DISCHARGING [kV]	LOAD, DISCHARGING [kW]	PRODUCTION, DISCHARGING [MW]	LOAD PERCENTAGE, TRANSFORMER, DISCHARGING [%]
FA33	34,700	0	2,009	N/A
FA22-T2	22,038	0	0	41
K87/T87	22,006	39,361	0,275	28
K0640/T0640	21,983	34,065	0,660	26
K0645/T0645	21,929	0,000	0	0
M0650/T0650	N/A	12,855	0	26
K0660/T0660	21,834	15,402	0	16
K0670/T0670	21,787	11,447	0	12
K0675/T0675	21,773	68,716	0	72
K0690/T0690	21,749	375,589	0	77
K0680/T0680	21,736	232,356	0	47
K0695/T0695	21,723	230,199	0	47
K0700/T0700	21,707	173,013	0	59
K0710/T0710	21,701	55,586	0	57
K0715/T0715	N/A	76,214	0	25
K0716/K0716	21,697	31,136	0	10
K0720/T0720	21,696	168,153	0	56
S-PP	21,696	N/A	N/A	N/A
K0735/T0735	21,699	129,505	0	68
K0730/T0730	21,695	130,391	0	41
K0731/T0731	21,695	77,161	0	26
K0740/T0740	21,694	54,661	0	56
K0745/T0745	21,693	63,948	0	32

In scenario 2, smaller batteries are placed on the low voltage side of T87 and T0640. Since the consumers in this radial are inserted in the model as one summed load object, the batteries are placed here. The actual placement of this battery would be distributed behind the meter of each or some of the consumers. Behind the meter storage makes more sense than placing it on the distribution transformer bus both because of legislative issues with ownership and control of batteries in the transformer stations. And because of the opportunities of prosumers and smart grid design that arise when placing the storage behind each consumers meter. Another argument for placing the storage behind the meter is that the amount of grid services that present themselves increase the further downstream the radial the battery is placed.

The sizes of the batteries in this scenario are 66 kW on the low voltage side of K87, and 275 kW on the low voltage side of K0640. Looking at the voltages we see that also in this scenario installing generators (and an extra load) as a PQ-point does not notably affect the voltages in the radial. Charging the batteries does not affect the the radial other that up to the point of node K0640. The capacity provided to the radial is increased by the size of the batteries plus extra losses. During discharge on the other hand, feeding transformer and the two previously over loaded transformers are relieved of their stress. This works better in practice than it does in a static analysis such as this.

Nodes K87/T87 and K0640/T0640 in table 4.5 seem better. Adding production to the branches with over loaded transformers seem to relieve them of close to all of their stress. Transformers are at a load percentages 28 % and 26 % respectively, and the transformers which previously provided power in the 100s mega-watts range, are both down to thirty something mega-watts. However, looking at table 4.4 we see on of the major problems with this method of grid analysis. Already over loaded transformers T87 at 105 % and T0640 at 103 % are, with charging batteries, at load percentages 196 % and 171% respectively. In reality the charging process would not have been initiated in this specific grid state. For the charging to initiate the consumption in both branches must be lower.

The optimal solution in this specific scenario is behind the meter placement of the batteries of each prosumer. That way the added load which is a charging battery does not have to be provided through the distribution transformer, but rather by own production through i.e. residential solar power. The batteries can still be charged from the grid if the grid state allows it on each customers bill. The previously mentioned energy arbitration, then preformed by grid owned, is available for the end user in a smaller scale. There are no regulations or issues with doing this in the current market but as prosumers are rising in numbers some regulations are expected.

5.6 Scenario 3 - Branched storage

This section will present the results of scenario 3 where the batteries are placed far away form the feeding point of the radial.

Table 5.6: Voltages, power flow and load percentage - Scenario 3 with charging batteries.

NODE	VOLTAGE, CHARGING [kV]	LOAD, CHARGING [kW]	PRODUCTION, CHARGING [MW]	LOAD PERCENTAGE, TRANSFORMER, CHARGING [%]
FA33	34,700	0	2,568	N/A
FA22-T2	22,010	0	0	52
K87/T87	21,970	317,396	0	105
K0640/T0640	21,944	101,523	0	103
K0645/T0645	21,885	0,000	0	0
M0650/T0650	N/A	12,854	0	26
K0660/T0660	21,780	15,401	0	16
K0670/T0670	21,728	11,447	0	12
K0675/T0675	21,713	68,716	0	72
K0690/T0690	21,686	375,599	0	77
K0680/T0680	21,671	232,357	0	48
K0695/T0695	21,656	230,199	0	47
K0700/T0700	21,636	173,012	0	59
K0710/T0710	21,630	55,587	0	57
K0715/T0715	N/A	76,216	0	25
K0716/K0716	21,626	31,136	0	10
K0720/T0720	21,625	168,156	0	56
S-PP	21,625	N/A	N/A	N/A
K0735/T0735	21,624	192,474	0	100
K0730/T0730	21,620	130,390	0	42
K0731/T0731	21,619	77,158	0	26
K0740/T0740	21,618	54,662	0	56
K0745/T0745	21,615	203,662	0	100

Table 5.7: Voltages, power flow and load percentage - Scenario 3 with discharging batteries.

NODE	VOLTAGE, DISCHARGING [kV]	LOAD, DISCHARGING [kW]	PRODUCTION, DISCHARGING [MW]	LOAD PERCENTAGE, TRANSFORMER, DISCHARGING [%]
FA33	34,700	0	2,148	N/A
FA22-T2	22,031	0	0	43
K87/T87	21,997	317,390	0	105
K0640/T0640	21,975	101,518	0	103
K0645/T0645	21,926	0,000	0	0
M0650/T0650	N/A	12,855	0	26
K0660/T0660	21,840	15,402	0	16
K0670/T0670	21,797	11,447	0	12
K0675/T0675	21,785	68,716	0	72
K0690/T0690	21,764	375,586	0	77
K0680/T0680	21,752	232,356	0	47
K0695/T0695	21,742	230,199	0	47
K0700/T0700	21,728	173,012	0	59
K0710/T0710	21,723	55,585	0	57
K0715/T0715	N/A	76,214	0	25
K0716/K0716	21,719	31,136	0	10
K0720/T0720	21,718	168,152	0	56
S-PP	21,718	N/A	N/A	N/A
K0735/T0735	21,724	66,936	0,062	38
K0730/T0730	21,722	130,391	0	41
K0731/T0731	21,721	77,163	0	25
K0740/T0740	21,722	54,661	0	56
K0745/T0745	21,723	76,532	0,140	32

In scenario 3, smaller batteries are placed on the low voltage side of transformers T0735 and T0745. The problem with the model being the high voltage circuit of the radial maintains also in this scenario where the battery is seemingly placed in the distribution transformer station, when in reality they are placed behind the meter of the end users.

The batteries placed in this scenario are of sizes 62 kW in K0735 and 140 kW in K0745 which are chosen because it brings the load percentage of both transformers in question up to 100 % in a charging state. The total storage capacity is lower than previous scenarios which becomes clear when looking at the load percentage of FA22-T2 in tables 4.6 and 4.7. The load percentage does not fluctuate more than 5 %.

Table 5.8: Voltages and reactive power flow - scenario 3 with discharging batteries

NODE	VOLTAGE, DISCHARGING [kV]	LOAD, DISCHARGING [kVAr]	PRODUCTION, DISCHARGING [MVAr]
K0635/T0635	21,677	33,247	0
K0645/T0645	21,672	0	15,931

If we compare the nodes K0735 and K0745 in table 4.7 and table 4.8 we see that the reactive capacity of the battery placed in node K0745 is able to produce reactive power. This causes a jump in voltage in the branch in question, bringing the voltage closer to its optimal level of 22 kV.

5.7 Conclusion of grid analysis

The technical results of the analysis show that energy storage is not essential for this specific radial. However, charging electric vehicles and other power demanding equipment is becoming more common in Norwegian homes. The transformers and even lines that were installed to handle the typical Norwegian power curve shown in figure 1.3, might not be able to handle the high peaks that arise when many electric vehicles are being charged at the same time as induction cooktops are being used in many homes. To postpone or completely defer having to perform expensive grid reinforcements can be done by installing energy storage in some of the branches looked at in this analysis.

Using NetBas to investigate the benefits and the feasibility of implementing energy storage in an existing radial is far from optimal. The consumption data is static and there is no way to install an actual storage system in the existing grid. In this case it is solved by emulating a battery through one load and one generator (PQ-point) with the same active capacity. Due to the static nature of the analysis the reactive part of the battery is mostly ignored. It is however worth mentioning that it is the reactive part of the battery (consumption or generation) that is regulating the voltage by striving to keep the grid at a power factor of 1.0.

Both from a theoretical and a technical perspective, placing the batteries behind the meter of end users is the optimal solution.

For full simulation result, see Appendix A.

Chapter 6

Conclusion and further work

6.1 Conclusions

Based on the presented theory and the data analysis, the future smart grid and the development of prices of batteries combine perfectly to enable implementation of behind the meter storage at each end user. This especially applies with prosumers and in long radial grids. To delay or defer expensive grid reinforcements, Li-ion batteries can be installed behind the meter of some or all consumers in a given radial.

The placement of batteries in a radial like this has been the topic in many studies before this one. Currently, the legislative issues are decisive in the way that grid owners are not allowed to own energy grid connected storage systems. Fortunately, both other studies and the theoretical as well as the technical analysis of this thesis conclude that behind the meter placement of ESS is the optimal solution. This is naturally a modified truth as the use of the ESS play a role in the placement of it.

In chapter 5, the results of the analysis show that the batteries can be used to keep the voltage in a stretched radial stable also in the extremities. What an analysis like this does not show, is that energy storage contributes in strengthening the reliability of the power supply. According to NVE, the national reliability of supply is at 99.988 % [21]. With 116.6 TWh of supplied energy, the remaining 0.012 % constitutes 13 992 kWh. Equations 2.1 and 2.2 shows that this will accumulate a considerable amount of money. This however, requires the ownership of the storage system to be in the hands of the grid owners to function properly.

6.2 Further work

This thesis can hopefully help in the planning phase and in the transition from the current grid to the future smart grid. Further data analysis is required to see how the grid reacts in a dynamic situation which was not possible to present in this thesis. Further thesis projects can build on the foundation that has been completed in this report. A dynamic simulation of how the system responds to implementation of energy storage is recommended. Another possibility also includes a dynamic simulation in addition to consider the end users as prosumers instead of regular consumers. An optimal sizing strategy to determine the size of the batteries is recommended.

Building further to this thesis, the most interesting change would be to place batteries in nodes K0680 and K0695. The transformers have a large amount of free capacity before they are overloaded and although these branches are not located in the extremities, the potential of installing battery packs of approximately 230 MW in each of the branches would surely help keep the voltage more stable than the current situation. Another interesting thing to investigate in this particular radial would be to distribute all 2.357 MW of scenario 1 into each branch - or behind the meter of each end user to be more precise.

The ongoing discussion of export and import of power is also something that energy storage systems, in a larger scale than the one in this thesis, can help settle. One side of the discussion is the perception that the overseas HVDC-cables connecting the Nordics and Continental Europe is operated purely with EU's economic intentions; export of cheap, clean power during the day and import of expensive, dirty power during the night. Instead of exporting, large scale storage systems can store the surplus of energy. When the large hydro power plants regulate down for the night, the storage systems can release the energy and thus decrease or defer the need for import.

An interesting thesis project idea, that might be a little off topic from this one, is a feasibility study of using direct current (DC) in the main grid and as the main way of transporting electricity from one point to another. Electronic equipment and considerable amounts of today's power electronics uses DC in one way or another. The increasing use of batteries as ESS contributes the interest in such a feasibility study containg prosumers with behind the meter battery storage.

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Appendices

Appendix A

Full tables of results - grid analyses

Complete table of results are attached with the report.

Appendix B

Simulation files

All simulation files are attached with the report.