OULUN YLIOPISTO

TEKNILLINEN TIEDEKUNTA

The use of batteries as a frequency containment reserve in the power system

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PROCESS ENGINEERING

Bachelor’s thesis

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Tiivistelmä

Maailma on siirtymässä jatkuvasti enemmän uusiutuvien energianlähteiden käyttöön sähköntuotannossa. Monet uusiutuvista energianlähteistä ovat luonteeltaan arvaamattomia, mikä voi aiheuttaa ongelmia sähköjärjestelmässä. Yksi ongelmista on epävakaampi sähköjärjestelmä, joka johtuu jatkuvasti vaihtelevasta sähköntuotannosta. Ongelman ratkaisemiseksi tarvitaan sähkönvarastointitekniikoita, joiden energiantuotanantoa voidaan lisätä tai vähentää nopeasti sähköjärjestelmän vakauttamiseksi.

Tämä opinnäytetyö tutkii mahdollisuutta käyttää akkuja sähköverkon taajuusohjaukseen ja häiriöreserviksi. Tässä kirjallisuuskatsauksessa tarkastellaan vain sähköenergian varastointimenetelmiä. Tämän opinnäytetyön yhtenä tavoitteena on vertailla akkuja ja pumppuvoimalaitoksia. Pumppuvoimalaitokset ovat vanhaa teknologiaa ja todistettavasti tehokas ratkaisu sähköenergian varastointiin mutta niillä on paljon negatiivisia ympäristövaikutuksia ja ne ovat tilaa vieviä. Suurin osa nykyisistä sähköenergian varastointi ratkaisuista on pumppuvoimalaitoksia ja niitä voidaan käyttää taajuusohjaukseen veden virtausnopeutta säätämällä voimalaitoksissa. Akkujen vasteaika on kuitenkin millisekuntteja, minkä takia ne olisivat ideaalisia taajuusohjaukseen sähköjärjestelmässä.

Akkuja voitaisiin integroida sähköjärjestelmään kahdella eri tapaa. Hajautetusti kulutuksen puolella sähköjärjestelmää tai keskitetysti sähkötuotannon puolella. Hajauttujen akkujärjestelmien etuja olisi sähköjärjestelmän kuorman vähentäminen ja joustavuus. Hajautetut akkurjärjestelmät ovat kuitenkin monimutkaisempia ja hintavampia kuin keskitetyt akkujärjestelmät. Keskitetyissä akkujärjestelmissä voidaan kuitenkin käyttää paljon erilaisia akkuja hajautettuihin akkujärjestelmiin verrattuna. Hajautetut akkujärjestelmät sopisivat enemmän taajuusohjaukseen, kun taas keskitetyt akkujärjestestelmät kuormituksen tasapainottamiseen.

Muita tietoja

ABSTRACT
FOR THESIS

University of Oulu Faculty of Technology

Degree Programme (Bachelor's Thesis, Master's Thesis) Process Engineering	Major Subject (Licentiate Thesis)
Author Pörhö Henri Vilhelm	Thesis Supervisor Prof. Pongrácz E, TkT

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Abstract

The world is constantly shifting towards increasing the amount of renewable energy use for electricity generation. Many of the renewable energy sources have an unpredictable nature, which can cause issues in the power system. One of the issues with increased renewable energy penetration is more unstable power system due to constantly fluctuating power generation. For this purpose, energy storage systems with fast ramp up and down times are required to stabilize the power system.

This thesis is exploring the possibility to use batteries as a containment reserve in the power system. Only electrical energy storage methods are reviewed in this literature review. One of the aims of this thesis was to compare batteries and pumped hydro storage. Pumped hydro electric facilities are old and provenly efficient technologies, but they have a high environmental and land use impact. Majority of the current electric energy storage systems are pumped hydro facilities and they can be used for frequency control by changing the water flow rate. Ramp up time of the most batteries can be measured in milliseconds, which is why they would be ideal for controlling the frequency in the power system.

Batteries could be implemented two main ways in the power system. Decentralized way on the load side of the power system or centralized way on the power generation side. The advantages of decentralized battery system are in effectiveness, flexibility and ability to reduce traffic in the electricity grid. However, decentralized battery systems would be more complex and costly. Centralized energy systems on the generation side can utilize wider range of batteries compared to decentralized battery systems. Decentralized battery systems would suit especially for frequency control where as centralized systems would be good for load levelling purposes.

Additional Information

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1 INTRODUCTION

In the future, the share of renewable energy sources is most likely increasing, especially the amounts of wind and wood sources in the finnish energy mix (Fingrid 2019). One of the driving forces for adding more renewable energy to the energy mix is the climate change and the depletion of fossil fuels. With increased amounts of, for example wind power penetration, difficulties in power grid balancing might occur due to weather conditions being unpredictable. Energy storage can be utilized in the wind power generation to stabilize the power output. When the amount of wind power penetration increases, more storage is needed to stabilize the power system, which is why research and development for better energy storage methods is important for the stability of the power system in the future. It is also believed that a lot wind power is going to waste especially during the nights when demand for electricity is low. Therefore, energy storage is crucial in maximizing the wind power potential in the energy mix. Energy storage for wind farms could potentially be used as both frequency control and load levelling unit. Aside from adding storage being necessary for the power system to work in the future, the energy transition might create new business opportunities for example, in the power balancing business.

The power system itself is pretty unpredictable because the consumption is constantly varying based on how consumers use electricity. Weather conditions also have an effect on the consumption of electricity. For example in Finland, where the climate can be very cold during winter times, a lot of electricity goes into heating. Apart from the demand side unpredicability, electricity generation itself can create imbalances, like maintentances of baseload or load following power plants. The state of the power system depends on all of the loads and production capacities connected to it. (Fingrid 2019)

These imbalances could be more effectively negated by adding more electric energy storage to the power system. Battery energy storage would suit for this purpose because most battery systems can be turned on and off practically instantly and they are quite energy efficient. Battery energy storage units would serve as both, a frequency control unit and load leveling unit. Battery systems are well suited for frequency control because of the ability to be quickly turned on and off. During the nights when there is little need for electricity compared to peak times, the cheap electricicity could be stored to battery energy systems, to be used during day time. This would be beneficial not only economically but environmentally as well, as this would reduce the need of using peaker power plants. Especially for wind energy, where the production capacity is constantly varying, storing the electricity is nearly required for efficient utilization. However, pumped hydro energy storage has been the mainstream method for storing bulk amounts of electricity in the past. Why shift into using more battery electric energy storage if the hydro energy storage methods have been working reasonably well to this date? What are the advantages of using batteries compared to pumped hydro storage?

Battery systems do seem like a great addition to the power system because of the swift response time but there are a few things that need to be taken into consideration when deciding do we really need them. Firstly, the prices of the batteries tend to be quite high on capital costs, and they require mantentance as well. Also, it should be taken into account that each battery has different traits which affects the system size as well as the characteristics. For example, it is believed that some of the battery types are unfeasible for smaller scale applications where as other battery types might have too big of an environmental impact for larger scale battery applications.

Attention should be paid on how the batteries are built. Battery systems could be built two different ways. One of the ways is centralized storage on the power generation side, which means building large battery facilities next to power generation. Typically these kinds of systems are built next to wind- or solar parks. Another way of building a battery system is decentralized way, where several small scale batteries would be built on the load side. These smaller scale units would then work as a distributed source of energy but the overall capacity would still equal that of a larger scale battery system. Both of these are valid way of building a battery energy storage but would decentralized or centralized energy storage method be more effective in the power system? This thesis reviews some of the possible battery energy storage methods that could be integrated to the power system. Only electrical energy storage methods are reviewed.

2 POWER SYSTEM

The power system is one of the core features in the modern society. Electricity is vital part of many businesses in Finland. For example, our industry and transportation via train are completely dependend on constant electricity feed. In 2017, the Finnish industry used 40 TWh worth of electricity. This corresponds to 47.2% of Finlands total consumption in that year. (Energia 2018) It is essential that our power system can adapt to the upcoming energy transition.

2.1 Basics of the power system

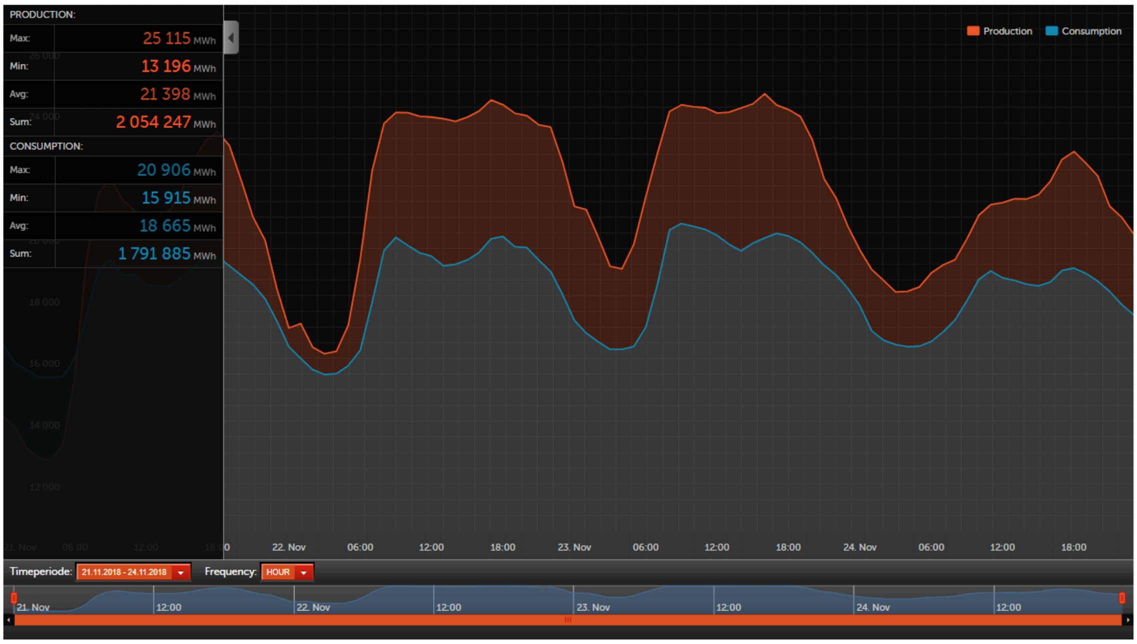
The main function of the power system is to provide customers with electricity. The power system is a complex system which main parts include power plants, high and low voltage distribution networks, substations and of course, the customers. The Finnish transmission grid, or the high voltage electricity grid, is owned by Fingrid Oyj. The high-voltage electricity grid's purpose is to connect all the different parts of the power system together. According to Fingrid, the transmission grid is around 14600 kilometres in length with approximately 120 substations. (Fingrid 2019) Fingrid is also part of ENTSO-E, which is an organization of transmission operators. ENTSO-E's main objective is to completely liberalize the energy market and increase the amount of renewable energy in the power system on European level. (ENTSOE 2019) Being the responsible transmission operator in Finland, Fingrid Oyj has the responsibility of maintaining, balancing and developing the electricity grid. In general, Fingrid Oyj's responsibility is to enable smooth trading between producers and consumers. (Fingrid 2019)

The power system can be divided roughly into three different areas; production, transmission and distribution. In the first step, primary energy is converted into electricity by power plants. Primary energy means crude energy source from nature that has not been transformed into refined form. The power plants can be "traditional" thermal power plants that use for example peat, coal or uranium to heat water into steam which is led into turbines for electricity generation. Alternatively, some primary energy sources can be used straight for electricity generation like wind, hydro or solar power. Once the electricity is produced, the electricity travels through a substation where the electricity is transformed into more suitable form for the transmission grid. In Finland, there are three different voltage transmission networks that are maintained by Fingrid Oyj: 400kV, 220kV and 110kV networks. (Fingrid 2019) Transmission voltage has important role in the electricity transmission because transmitting the electricity at higher voltages leads to lesser electricity losses when compared to transmission with lower voltages. (Fingrid 2019) Therefore, if the distance that electricity needs to travel is long or there is just much traffic on the powerlines on the area it is beneficial to transform it to higher voltage for transmission. Once the electricity is transmitted to target area it is transformed back to lower voltage for the distribution network where it is distributed for customers.

Power plants can be divided roughly into three categories. The baseload power plants which, like the name states, produce the base amount of electricity that the power system needs. These power plants usually take a long time ramp up and down and they usually operate at constant output. Then we have load following power plants. Load following power plants are used mainly for frequency control along with peaker power plants. Usage of load following power plants depends on the current demand of electricity and they are used in order of efficiency and costs. Load following power plants are usually relatively easy to start up and shut down. Peaker power plants are used only if it is necessary as a back up, as they are heavy for the environment and are usually inefficient compared to the other power plant types.

2.2 Frequency control

Frequency control is important aspect in the power system for environmental and economic reasons as well as stability of the electricity grid. As electricity consumption is constantly varying, the production rate must be adjusted to match consumption in order to minimize overproduction and possibility of a power outage. Adjusting of the production rate is usually done by ramping up or down the flexible load following power or peaker power plants. Usually hydropower plants or gas turbines are used because they have faster response time compared to thermal power plants. (Bright Hub Engineering 2019)


PRODUCTION:
Max: 25 115 MWh
Min: 13 196 MWh
Avg: 21 398 MWh
Sum: 2 054 247 MWh
CONSUMPTION:
Max: 20 906 MWh
Min: 15 915 MWh
Avg: 18 665 MWh
Sum: 1 791 885 MWh

Timeperiode: 21.11.2018 - 24.11.2018
Frequency: HOUR

Figure 1. Baltic sea area power system state 21.11.2018-24.11.2018 (Statnett, 2019)

The ratio between consumption and production is directly linked into frequency of the electricity grid. In Finland and most other EU countries use frequency of 50hz in their electricity grids. (Bright Hub Engineering 2019) The electricity grids frequency indicates how much load there currently is on the grid. For example, if the load on the grid suddenly increases, the speed of turbines is lowering because the generators must do more work in order to keep up with the increased power demand, hence lowering the frequency because the turbines run more slowly. In practice, this means that during high load the frequency tends to be slower while during lower loads the frequency tends to be faster. Typically, transmission system operators try to keep the frequency between 49.9 hz and 50.1 hz. (Fingrid 2019)

2.3 Electricity mix in finland

In Finland, baseload energy is generated by nuclear power and combined heat and power plants. Nuclear power plants are difficult to ramp up and down, and since they produce little to no carbon dioxide emissions when operating, they make ideal baseload power plants. A lot of combined heat and power production is also required in Finland because of the cold climate. The share of nuclear energy and combined heat and power productions have been staying quite the same from the 2000 levels. The share of condensing power is constantly decreasing while share of wind power increases. This trend is most likely to continue in the following years. Another possibility is that the amount of nuclear power increases in the future. Fennovoima is aiming to get construction permit for a new nuclear power plant in Pyhäjoki. According to Fennovoima the power plant would produce approximately 10% of the total electricity consumption in Finland. (Fennovoima 2019)

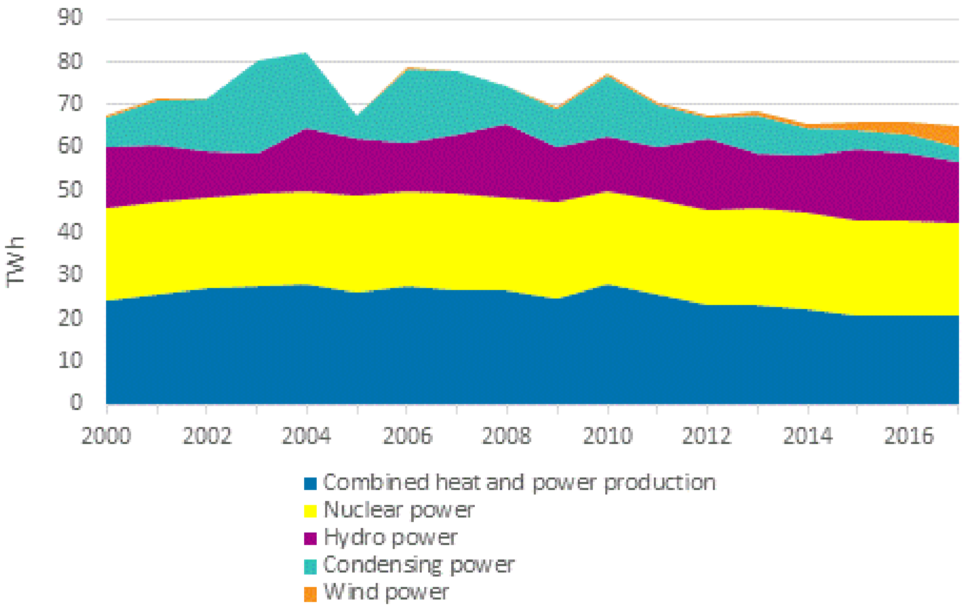


Figure 2. Electricity generation in Finland from 2000 to 2017. (Statistics Finland, 2018)

2.4 Legislations regarding energy transmission

The Finnish Energy Authority has appointed Fingrid Oyj as the responsible transmission system operator for the Finnish transmission grid. Fingrid Oyj is therefore responsible for the upkeeping of the power system by matching the production and consumption, by handling the disturbances quickly and by using the power system so its system security stays intact and at agreed level. (Fingrid 2019)

3 ELECTRICITY STORAGE OPTIONS

Electrical energy storages work by converting electrical energy into an intermediate that can be stored and then utilized at will. There are many intermediates that electrical energy can be converted to, like gravitational potential, kinetic energy in form a flywheel, or chemical energy. In batteries, electricity is converted into electrochemical form. Batteries tend to have pretty good efficiencies, they are reliable, and they can be switched on and off nearly instantly. However, general problems with batteries are the maintenance costs and hazardous materials that they utilize. A battery energy storage is typically composed of a series of electrochemical cells. (Luo et al. 2015, p. 516) The number of electrochemical cells and how they are connected on each other depends on features of the battery storage. By increasing the number of electrochemical cells in series you can increase the voltage to the desired volume.

3.1 Battery storage

Batteries can be built from many kinds of materials. The materials which are used in the batteries usually determine the characteristics of the battery in question. The characteristics that each battery has then plays an important role when choosing optimal battery type for different situations. The typical factors used to determine characteristics of batteries are usually:

- Capacity, which means how much electricity energy the battery can store.
- Efficiency, which means how much electricity is used to charge the battery and how much electricity can be attained at later time.
- Peak power, which means the maximum output that the battery may have.
- Self discharge rate, which states how much of the electricity is lost in the battery at a given time.
- Cell voltage, which means the amount voltage each cell has.
- Energy density, which means the amount of electricity that can be stored to the battery per weight unit.
- Costs of the battery.
- Temperature in which the battery operates.

- Life cycle, which indicates how many times the battery can typically be recharged and discharged before having to replace the battery. (Texas instruments 2011)

3.1.1 Lithium-ion battery

Lithium-ion batteries are arguably one of the most known battery types because it is one of the most common battery type in portable devices such as mobile phones. It has good properties compared to other battery types such as high energy density (150+ Wh/kg), low self-discharge rate, long life cycle and it can operate in various kinds of temperatures. Also, being able to reach over 80% energy efficiency would make it a good candidate for mass energy storage. (Lu 2017, p. 2-10) However, the reason why there aren’t any large-scale lithium-ion battery systems is because the price of lithium-ion battery systems is high. (Du and Lu 2015, p. 13). The prices of lithium have been rising a lot because of increased demand of high-power batteries. Cobalt, which is used as cathode material in lithium-ion batteries, is even more costly than lithium. (Meg Dailey 2017) The lithium reserves are also a matter of interest. According to the US. Geological survey, the known lithium reserves are estimately 16 million tonnes. (National Minerals Information Center 2019) Also, lithium-ion batteries’ safety is a concern, since they can potentially cause fires or explosions. Lithium-ions battery safety can be increased by using electrode coatings or by improving cell design. (Santhanagopalan et al. 2015, p. 14) Currently, the largest operating lithium-ion battery system is Tesla’s 100 MW/129 MWh battery located in Australia. (Electrek 2017)

3.1.2 Lead-acid battery

Lead-acid batteries are an old invention and they are still one of the most used batteries out there. Lead-acid batteries are quite popular in solar energy systems. (Du and Lu 2015, p. 8) Lead-acid battery consists of PbO_2 cathode and Pb anode with sulfuric acid acting as electrolyte. (Luo et al. 2015, p. 516) They are reliable and cheap batteries. Lead acid batteries have the ability to give pulse like power. (Nikolaidis and Poullikkas 2018, p. 48) Just like most other battery types, the lead acid battery has fast response time. However, sulfuric acid is very corrosive, hence some problems with corrosion might occur. This can be observed as low life cycle of 500 to 1000 cycles which is low compared to other battery types. The other downsides of the lead acid battery are, that during charging hydrogen and oxygen are released which might cause them to react and explode or start fires. Lead-acid batteries performance is also highly dependend on the temperature. Also, their energy density is poor. (Santhanagopalan et al. 2015, p. 4) Lead-acid batteries low life cycle combined with poor energy density makes them an unfeasible choice for building a larger storage system from.

3.1.3 Nickel batteries

One of the most commonly known and oldest nickel-based battery is the nickel-cadmium battery. However, nickel-cadmium batteries are banned in EU countries due to being toxic to the environment. Only emergency appliances that have nickel-cadmium batteries are allowed. (European parliament 2013)

Since nickel-cadmium batteries are banned, nickel metal hydride batteries or NiMH batteries have taken its place. Nickel metal hydride batteries are based on absorption and desorption of hydrogen in the battery cells. Compared to the nickel-cadmium battery, the nickel metal hydride battery is more environmentally friendly, because the toxic cadmium is replaced with hydrogen absorbing alloys. (Han et al. 2017, p. 1) The energy density of nickel metal hydride batteries is quite good, around 60-120 WH/kg. They make a great option especially for small scale applications in the future, like batteries for hybrid electric cars. Another benefit of the nickel metal hydride batteries is their price. For load levelling purposes, a nickel metal hybride battery costs from 300 to 600 dollars per kWh. The life cycle of nickel metal hydride batteries is also high. (Battery University 2017) However, nickel metal hydride batteries have high self-discharge rates because of parasitic reactions. Nickel metal hydride batteries may also cause fires if the battery starts leaking.

3.1.4 Sodium-sulfur battery

Sodium-sulfur batteries differ a little bit from the design of traditional batteries because in sodium-sulfur batteries, both the anode and cathode are in liquid form during the operation. The anode and cathode are separated by a beta-alumina solid electrolyte. (Santhanagopalan et al. 2015, p. 6) Beta-alumina is a ceramic membrane that has the ability to conduct sodium ions efficiently. (The journal of The Minerals, Metals & Materials Society 2010) However, this only works when the temperature of beta-alumina is high. The typical operation temperature of sodium sulfur batteries is around

300-350 degrees. (Du and Lu 2015, p. 12) The high temperature causes a few problems like melting of the sulfur, which is quite corrosive. Also, high temperatures decrease the working life of the beta-alumina solid electrolyte. (Song et al 2016) Apart from the high temperature requirement, the sodium-sulfur battery seems like a solid option for mass electricity storage, especially for load levelling purposes. Even with the high temperature, they have high life cycle of 2500 without significant losses in performance and can still work relatively well around 5000 charges in. (Santhanagopalan et al. 2015, p. 7) Well built sodium-sulfur battery can have high energy density and high efficiency rates, on top of that 99% of the sodium-sulfur battery is recyclable. (Du and Lu 2015, p. 12) Significant threat to the sodium-sulfur battery is the possibility that the beta-alumina could degrade to a point where the two liquids can mix, causing a battery failure and an explosion in the process. (Song et al. 2016)

3.2 Flow batteries

Flow batteries can be divided into two categories, traditional redox flow batteries and hybrid redox flow batteries. Redox flow battery is a hybrid of a rechargeable battery and a fuel cell. They have long life spans compared to their battery counterparts. They are also relatively cheap and require little maintenance. Redox flow batteries work a bit differently from the traditional batteries because the electrochemical reactions occur between two electrolytes that are pumped into the core of the battery, where they react with each other through a membrane that allows only certain ions to pass. The electrons, which form during the electrochemical reactions, move through a circuit creating current in the process. Redox flow batteries can also be reloaded instantly, just like fuel cells, by changing the liquids inside the two chambers. Typical problem in redox flow batteries is their low energy density. (Ya-ching Tseng 2011, p. 11) Flow batteries are a little bit different when comparing them to traditional batteries, since their output power can be changed by adjusting the flowrate. The capacity of flow batteries is determined by the amount of electrolyte in the chambers. (Cunha et al. 2015, p. 10) Hybrid redox flow battery is a redox flow battery where at least one of the electrolytes is replaced with a reactant that does not dissolve into the electrolyte. (Energy Storage Association, 2019)

3.2.1 Vanadium Redox flow battery

Vanadium redox flow battery is a flow battery that utilizes vanadium's different oxidation states to create a rechargeable battery system. They are good candidates for mass electric energy storage because they have high efficiencies and have long life cycles. A vanadium redox flow battery can reach life cycles of 10000-16000 (Ya-ching Tseng 2011, p. 14). Depending on the usage of the battery system, it is expected that a properly build vanadium redox battery system would be able to work nearly two decades without significant degradation. They also have fast response times which makes them optimal for load balancing. However, they are quite costly. The main problem within vanadium redox flow batteries is that they have low energy density because the vanadium must be dissolved into the water. Because they are low in energy density, they are usually used in small and medium sized systems. (Du and Lu. 2015, p. 14) However, there are some large-scale facilities planned. Rongke Power is planning on building a 200MW/800MWh system to China. (Weaver 2017) Currently, the largest system installed is in Japan with power output of 15 MW and capacity of 60 MWh. (Greentechmedia 2016)

3.2.2 Zinc bromine flow battery

Zinc bromine flow battery is considered to be a hybrid flow battery because of the energy stored in solid zinc metal. Like most flow batteries, the zinc bromine flow battery has low self discharge rate, decent energy density (34 to 54 Wh/kg) and have fast response times. (Drazga 2012, p. 53) However, the efficiency of zinc bromine flow battery is bad compared to the alternatives, only 65 to 75%. The conditions inside the battery are quite rough because of the bromine which is highly reactive. Due to the high reactivity of bromine, the battery suffers from low life cycle of only 2000 cycles. However, the zinc bromine flow battery offers high cell voltage which might be useful in some applications. Although most of the zinc bromine batteries' characteristics seem unattractive, they make valid option for small or decentralized energy storage. They are one of the most economical energy storage methods out there. (Du and Lu. 2015, p. 13)

3.3 Supercapacitors as energy storage

In theory, supercapacitors could be used for reserve power. Supercapacitor works by storing the positive and negative charges to the electric field. They are traditionally used in application where there is a need for surge like power. Supercapacitors have very high life cycle and efficiency. The problem with supercapacitors is that they have high dissipation rates and low energy density, hence they are usually used for short term electricity storage. (Du and Lu 2015, p. 18)

3.4 Other energy storage methods

Battery energy storage is not the mainstream method for storing electric energy on the larger scale. The batteries are still quite new technology for larger scale applications when comparing them to the older, proven technologies: Pumped hydro energy storage and compressed air energy storage. Majority of the bulk electricity storage is pumped hydro energy because it is relatively simple and effective method of storing energy. Compressed air energy storage methods have been available for a long time as well and it can have similar types of traits as pumped hydro storage, but it is usually considered to be more technologically challenging. The possibility of storing electricity into hydrogen is also interesting technology for the future, because it enables effective and long-term bulk energy storage method.

3.4.1 Compressed air energy storage

Compressed air energy storage systems use electricity to run compressors that pressurize the air into vessels to be used later in electricity generators. Usually different types of underground reservoirs are used. (Drazga 2012, p. 64) The compressed air energy storage technology is one of the two traditional bulk energy storage methods, the other one being pumped hydro energy storage. The compressed air energy storage and pumped hydro energy storage suffer from same kinds of problems and advantages, such as they can not be built anywhere and their ramp up time is generally quite high. (Du and Lu 2015, p. 6) Compressed air energy storage units can be built to for example old mines that are no longer in use or other unused air tight locations. According to study made by Lazard, compressed air energy storage seems to be more economical from these solutions. (Lazard 2016)

3.4.2 Pumped hydro energy storage

Pumped hydro storage transforms the electrical energy into potential energy. Surplus electricity is used to pump water from the lower reservoir into higher reservoir separated by a dam. (Schlögl 2013, p. 40) The water reservoir can then be transformed back into electricity by water turbines. Pumped hydro power is the biggest capacity energy storage out there to the date and it is very similar to the compressed air energy storage systems in terms of characteristics. Pumped hydro energy storages are typically built on the rivers in order to maximize the renewable energy potential. Similarly to compressed air energy storage, its advantage lies in the ability to have very high stored capacity.

3.4.3 Hydrogen energy storage

Hydrogen energy storage refers to technology where water is broken down into hydrogen and oxygen through hydrolysis. The energy in this case is not converted into other type of energy but into a medium. The hydrogen can be pressurized into a vessel or alternatively it could be stored into metal hydrides. (Rosen 2012, p. 11) Storing the hydrogen into metal hydrides could potentially increase the safety of the storage method. The hydrogen in the metal hydrides can be released later by heating the storage material. Hydrogen can then be used in for example fuel cells to generate electricity and heat. Manufacturing hydrogen safely through electrolysis requires complex safety measures as the hydrogen can react with the oxygen in the atmosphere if a leak were to occur, although hydrogen reacting with the air in explosive manner is unlikely because the gas is so light. (Da Rosa 2013) Hydrogen storage would be good candidate for even bigger scale electricity storage if the electrolysis process wouldn’t be so expensive and complex. However, it is believed that hydrogen energy storage methods may be one of the leading technologies in the future especially for long term electricity storage.

4 DISCUSSION

Batteries as energy storage medium could be implemented multiple ways to the power system. Taking everything into account, multiple scenarios should be considered, because the way they are implemented to the power system defines how much and how the batteries affect to the existing power system. The objective of this work was to compare in particular centralized and decentralized solutions, as well as compare batteries to the existing energy storage methods, such as pumped hydro.

4.1 Batteries vs pumped hydro storage

Looking at the current prices of both batteries and pumped hydro storage, the pumped hydro storage is cheaper in terms of both capital and operating costs. (Lazard 2016) The costs might be a subject to change in the following years because the batteries are getting cheaper every year, with the exception of lithium ion batteries. However, there are some disadvantages in pumped hydro energy storage, such as construction times of water reservoirs and environmental impact assessments that must be made before the construction can start. Building a hydro power station can take years, whereas Tesla managed to build a 100 MW/129MWh battery system in just under 100 days. Another disadvantage of pumped hydro energy storage compared to battery energy storage systems is the switchability. Battery systems can be ramped up and down fast when needed, usually in seconds whereas response times of pumped hydro stations might be anywhere from few seconds to 15 minutes depending on the state of the power plant. (Pérez-diaz et al. 2012 p.159) In extreme conditions, the difference might be enough to save the power system from a power outage. Aswell, battery energy systems can be built practically anywhere regardless of terrain. The battery energy systems can even be mobilized when needed elsewhere, the batteries could be moved to another location.

The environmental impact of pumped hydro stations is also significant, because a lot of concrete and energy is going into building them. Globaly, production of concrete is responsible for sizeable amounts of carbon dioxide emissions (~4%). (Andrew 2018) During the operation of pumped hydro energy storage facility, some greenhouse gases are also emitted such as methane and carbon dioxide. This is because the organic matter in the reservois degrade into smaller components. (Räsänen et al. 2018) On the other hand, a well-built pumped hydro power storage unit can be operational for over 20 years without significant degradation. (Lazard 2016, p. 20) While mechanical parts from the hydro power station would have to be replaced after 25-40 years, the large concrete buildings like dams and artificial lakes can technically have lifetime of 80 to 150 years. (Flury and Frischknecht 2012, p. 14) However, it should be considered that battery storage systems require maintenance every few years and can have lifetimes of 5-10 years after which the batteries would need to be replaced. Also, battery aging and losing energy density is an issue.

Pumped hydro storage facilities have a lot larger capacity when compared to battery systems. Around 95% of the known energy storage facilities capacity is pumped hydro storage. The world's largest energy storage facility by power rating is the Bath County pumped hydro plant is, which has a maximum generation capacity of 3003 MW. (Luo et al. 2015, p. 313) In comparison, the scale of electrochemical energy storage is significantly lower both in terms of capacity and power; the storage capacity's share was ~1% in 2016 (Hydro World 2018), and the largest battery system built by Tesla currently operating in Australia has a power output of 100 MW.

Both, hydro and battery energy storage possibilities are likely needed in the future. The strengths of pumped hydro storage are in their cost to store electricity and their huge capacity possibilities. Batteries are useful because of their fast response times and their ability to be built nearly anywhere.

4.2 Centralized vs decentralized storage

The next issues to consider is whether we should build larger scale storage systems on the generation side or smaller scale storage systems on the customer side? Centralized energy storage methods refer to large-scale battery systems that have high capacities and are typically located near electricity generation. The systems that are currently installed are used mainly for load levelling purposes. The largest battery systems currently have capacities of over 100 MW. The main advantage of large-scale battery systems compared to the smaller ones is that "industrial" type batteries, such as sodium-sulfur batteries can be used. For example, sodium sulfur battery, which is not feasible for small-scale battery systems because of the high operation temperatures but would be more environmentally and economically viable than, for example lithium ion batteries. Sodium sulfur battery systems have already been used for load levelling purposes.

(Santhanagopalan et al 2015, p. 6) Building a large-scale system is cheaper compared to many small-scale units because the operation is happening at a single place. The maintenance costs of the large-scalestorage system should be cheaper as well. Also, for small-scale technologies one needs the batteries to work together in order to be used for frequency control, therefore each separate battery would have to be connected to a controller unit. This means that a lot of extra effort would have to go into building separate battery systems.

Decentralized battery energy storage units generally refer to distributed small-scale batteries on the load side which, in an ideal situation, would form a network and hierarchically work together to control the frequency. (Omid Palizban 2016, p. 20) The batteries would be located near or in the residential buildings where they would supply electricity to a single or multiple house depending on the size of the battery and the electricity consumption of the buildings. The batteries would serve as a large capacity system, just distributed to the load side. The advantages of having the capacity integrated next to the residential buildings is that if a power outage was to occur, a battery system that is integrated to the buildings can provide the building with backup power, whereas large systems located on the generation side can not transmit the electricity because the electricity grid is down. As well, if the battery systems were installed on the load side, they could possibly be used to ease the load in the electricity grid by feeding the building with electricity if the grid has traffic. Storage systems on the load side can also utilize the surplus electricity of the grid, which is formed because the generation should always be a bit higher than the consumption. Energy storage integrated into buildings work well with possible solar panel additions as well, since the solar power systems usually require some sort of energy storage to be effective.

There is also the problem of energy density. Currently the only battery types that can have high enough energy density for small-scale energy storage are the lithim-ion and nickel-metal hydride battery types. Lithium is not sustainable for batteries that would be needed to establish a small-scale battery system, since manufacturing of the batteries would produce massive amounts of CO_2 emissions. The problem with nickel metal hydride is the high discharge rate. A lot of electricity would go to waste if the electricity isn’t used briefly. In principle, nickel-metal hydride batteries could be used in small-scale applications for load shifting, where the electricity would not have to be stored for longer than few hours. However, nickel is quite toxic for the environment.

Vanadium as a substance, is not toxic for the environment or for humans. Although some harmful effects might occur in case of chronic exposures. (Lenntech 2018) The vanadium redox flow battery has incredibly high life cycle of 10 000-16 000 cycles. (Ya-Ching Tseng 2011, p. 14) However, the energy density is quite low, which is why the feasibility for smaller scale applications must be considered. For example, locating a vanadium flow battery system into residential areas might become a problem because the battery size may be too big for the houses. In general, the vanadium redox flow batteries would work in medium- to large-scale energy storage facilities. One of the most important traits that the flow batteries have is that the energy output is defined by the flow rate inside the battery. This is a trait for frequency control in mind, as you can match the generation and consumption close to each other by just adjusting the power of pumps that dictate the flow rate. Vanadium redox flow batteries would suit well for decentralized energy storage.

Costs of the battery system is a major issue of small-scale batteries because consumers have little economic incentive. The benefit that a consumer would get by installing a battery system are minimal compared to the costs of a battery system, since the difference in price of electricity during the night and day are measured in cents. The consumer would probably never get their money back, as the capital and maintenance costs for the batteries would be too high. According to the Institute for Energy Research (2016), Tesla's 7 kWh lithium-ion battery system called Powerwall would have payback time of 38 years if the system would only be used for load levelling purposes. Residential battery systems would make more economic sense in case the consumer had the possibility to generate electricity that they would store in the battery system for example, solar panels on their roofs. Even then, it should be considered if it was more beneficial for the consumer to sell the electricity straight to the electricity grid. This is because majority of the electricity produced by the solar panels is happening during the day time when the electricity price is already quite high compared to the night time electricity.

In addition to the batteries themselves being expensive, a network of small-scale batteries working as decentralized energy storage would require them to be controlled in order to reach maximum efficiency for frequency control. This would mean building a specific control centre or control system around the batteries. Each battery would need to have controllers and meters installed. Data would also have to be transmitted to the control system, preferably wirelessly because it is cheaper to organize due to not having to wire each of the devices. Data would have to be transmitted and processed in the control system briefly because the power systems state might change fast. As well, a lot of data would have to be processed for example, traffic patterns, data correlations and energy data itself. This means that battery system controllers would have to have good computational capacity as well. (Ho et al 2014, p. 53) Centralized energy storage facility would be cheaper to organize when compared to decentralized because less data communications are required between the components.

It is not feasible for each household to have their own electricity storage because it would be too expensive and nonsustainable. However, mediumsized battery systems on the load side could be considered. It has been speculated that one or two battery systems per microgrid could be suitable. This would give the same benefits as having several small batteries, such as being able to use the batteries as a back up reserve in case power outages were to occur, but it would not be too heavy investment for the consumer. Large energy companies might take the load levelling business as an opportunity in the future, as there is high chance of peak electricity costs rising in the future. Utilizing batteries as a load levelling method might be profitable for the energy companies for multiple reasons. Firstly, they might get away with only using battery electricity storage during the peak times instead of having to use peaker power plants. Using peaker power plants is more expensive to use. Secondly, they might make profit from load balancing because it is happening on a larger scale and power companies have they own methods of producing electricity. As the batteries would be located near the residential buildings but still be separate from them, different types of batteries could be used. Vanadium redox batteries and molten salt batteries both have remarkable characteristics for electric energy storage but can not be used in small-scale applications as vanadium redox batteries have quite small energy density and molten salt batteries have too high temperature requirements.

4.3 Further considerations

Battery storage is a great addition to the battery system regardless in which part of the power system they would locate. However, there are some issues with batteries that are related to their nature. It should be remembered that battery technology is still relatively new, which means that there is still a lot of development potential. For example, optimization of the negative electrodes chemical composition has a signficant impact on the properties of nickel metal hydride batteries. (Han et al. 2017)

At the end of their life, the batteries will end up as hazardous waste. Therefore the recyclability of batteries is one of the major concerns regarding battery energy storage systems. Especially in case of lithium-ion batteries because the electrolytes used in them are flammable. Some of the recycling processes are quite energy consuming as well, such as the pyrometallurgical process for recycling lithium-ion batteries, which requires temperatures of 300 degrees for the lithium parts to avoid explosions, and 700 degrees for the plastics. The alternative hydrometallurgical process is less energy intensive but requires expensive extractans to work. (Huang B et al. 2018) It is believed that, currently, there is little economic sense in the hydrometallurgical process.

Another issue with lithium-ion batteries is the carbon dioxide emissions produced during manufacturing. Manufacturing of lithium-ion batteries releases approximately 150-200 kg of CO_2 per kWh during its life cycle. (Romare and Dahllöf 2017, p. 39-42) Using lithium-ion batteries for frequency control and load shifting would reduce the emissions by a large margin, but the benefits gained from load levelling would be countered by the emissions produced in the manufacturing stage. However, lithium-ion batteries are not the only battery type with this problem: Production of nickel metal hydride batteries also produce a lot of carbon dioxide. According to the European Comission, production of nickel metal hydride batteries consumes approximately 90 megajoules of energy per kg produced, which is nearly equivalent to the energy required in the production of lithium-ion batteries. (European Comission 2012)

Resource depletion is another problem that impact future strategies on expanding the battery infra. As stated earlier, lithium reserves are limited which leads to higher price of battery systems year by year. According to the U.S. Geological survey, the current lithium reserves are around 16 million tonnes. There are few other battery materials aside from lithium that are at supply risk. Cobalt, vanadium and natural graphite are all classified to be critical raw materials by the European Commission. (European Comission 2017) Cobalt is used in lithium-ion - and nickel metal hydride batteries. (Cobalt Institute 2019) Graphite can be used in electrode materials in batteries. (U.S. Geological Survey 2018)

Sodium sulfur batteries on the other hand are made from almost purely from recyclable materials. As they are quite cheap and have long life cycles, they would make a valid option for mass energy storage if they did not have the high temperature requirement. The sodium sulfur batteries need to be kept at the 300-350 degrees for the battery to work, which might be a problem from economic point of view, as a lot of energy goes into heating of these batteries on the larger scale. High temperatures also increase the risk of fires, which is why they are usually considered to be a bad energy storage option for residential areas. The sodium sulfur batteries could be a valid option for industrial conditions. (Nikolaidis and Poullikkas 2018, p. 48)

5 CONCLUSIONS

Considering that pumped hydro storage systems have been around for a long time and they are proven to be effective for frequency control and load levelling purposes, why should one utilize batteries for frequency control and load levelling? Batteries have much faster response time when comparing to hydro storage systems. In general, the response time of batteries can be measured in milliseconds in most cases. The response time is going to be an important factor, assuming that the amount of wind power penetration is increasing in the power system. It is important that the energy storage medium has fast response times because fluctuations in the power system are happening on much faster rate with higher renewable energy penetration than without. Slower responding energy storage methods might have problems keeping up with the fluctuations of renewable power generation.

Other advantages that batteries have over pumped hydro storage systems is that they could be considered to have lower environmental impact. Batteries do not produce emissions when they are operating, unlike pumped hydro storage. The pumped hydro storage facilities are usually built next to water streams in order to maximize renewable energy potential. Building a pumped hydro storage facility might cause some resistance from the locals because it is believed that people see pumped hydro storage facilities as a nuisance since they take a lot of space and occupy local rivers.

Both, decentralized and centralized energy storage possibilities have their own advantages. One of the research questions was, which one would be the optimal way of storing electricity? Decentralized electric energy storage on the load side has few benefits over centralized large-scale battery units. One of the largest advantages that decentralized battery units have compared to centralized battery units is that decentralized battery units can reduce traffic on the grid. This can be useful in emergency situations or if maintenances must be made to the grid. As well, batteries can utilize the surplus electricity from the grid and use it for recharging. However, the cons of decentralized energy storage are that several small-scale facilities would be needed for the system to be effective. Additionally, building many independent battery systems is costly. Battery system maintenances are going to be much harder to organize in decentralized systems as well. Centralized battery units are cheaper and industrial type of batteries like molten salt batteries can be used in them. However, a decentralized system with several batteries is usually considered to have more benefits, because the system is more versatile. Decentralized battery systems would be able to supply electricity straight to the area where it is needed, which is not possible in larger scale systems. As the batteries in decentralized systems are not part of the bigger system, some of the batteries could stay in recharge mode while others would supply the consumers with electricity. Decentralized battery systems would be better especially for frequency control whereas centralized battery systems could be used for load levelling. Larger battery systems would not be so flexible in this regard, because recharging of a battery and discharging is not possible at the same time. However, this problem in larger scale systems could be countered by dividing the system in parts, so it would consist of several small parts. In conclusion, the decentralized energy storage options seem more effective but more costly as well, when compared to centralized energy storage.

Whilst batteries will most likely play a part in the future power systems, they have their own downsides as well. In most cases, batteries will become hazardous waste at the end of their life. Some also contain critical raw materials, which means that recycling of the batteries would have to be more mandatory for batteries in the future. Production of the batteries is an energy intensive process and produce a lot of carbon dioxide emissions. A well-built battery energy storage system would however significantly reduce the carbon dioxide emissions from the other sectors in the power system.

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