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THE ADDED VALUE OF A BATTERY ENERGY STORAGE SYSTEM FOR ENERGY COMPANY

School of Technology and Innovations
Master's Thesis in Smart Energy
Master of Science in Technology

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PREFACE

First of all, I want to thank Lahti Energia Oy and Mikko Rajala for giving me this opportunity to write my Master's thesis on such an exciting topic. Additionally, I want to thank my supervisor from the University of Vaasa, Hannu Laaksonen. Both of you supported and guided me during this time-consuming project. Also, I would like to mention Otto Tuomala and Laura Suomalainen who helped and advised me during the scientific writing process.

I want to take this moment to thank everyone I have met during these years in Vaasa. Each one of you have played a part along this road. We have had a wonderful time and I hope we can continue this journey for years to come. Special thanks to our guild Tutti Ry for all of the unforgettable memories and experiences gained from the events and the Tuttis.

Lastly, I want to thank my family for helping me pursue my goals in every aspect of my studies from the first year of kindergarten to this day. Thank you for your support and love. I could not have accomplished this without your support.

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Mika Laakso

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TIIVISTELMÄ:

Suomen valtio on päättänyt luopua kivihiilen käytöstä sähkön- ja energiantuotannossa toukokuuhun 2029 mennessä. Samaan aikaan liikenteen sähköistyessä sähkönkulutus Suomessa kasvaa, joten korvaavia tuotantomuotoja on lisättävä takaamaan sähkön riittävyys. Uusiutuva energia on ympäristöystävällinen vaihtoehto fossiilisilla polttoaineilla tuotetun energian korvaamiseksi. Suomen valtio on viime vuosina tukenut uusiutuvia energialähteitä, joka on edesauttanut uusiutuvien energialähteiden määrän kasvua maassamme. Sääolosuhteista riippuvan tuulivoiman ja aurinkoenergian kasvu on kuitenkin tuonut mukanaan tuotannon vaihtelevuuteen ja ennustettavuuteen liittyviä haasteita, joita ei aiemmin ole ilmennyt. Sähköjärjestelmään kytkettyjen uusiutuvien energialähteiden tuotanto ei ole tasaista, kuten perinteisten voimalaitosten. Jotta sähkön saanti voidaan turvata tulevaisuudessa, on oltava vaihtoehtoja, joilla tasata sähköntuotantoa tulevaisuudessa. Tällä hetkellä toteuttamiskelpoisin markkinoilla oleva ratkaisu uusiutuvan energian lyhyen aikavälin vaihtelun hallintaan on litiumioniakku.

Tämän tutkimuksen tarkoitus on selvittää litiumioniakkupohjaisen energiavaraston tuoma lisäarvo, silloin kun se on liitetty uusiutuvan energialähteen rinnalle. Tutkimuksessa tarkastellaan sekä taloudellisia, että teknisiä hyötyjä, joita litiumioniakku tuo mukanaan. Koska tutkimus on suoritettu Lahti Energian toimeksiantona, on mahdollisen investoinnin oltava taloudellisesti kannattava. Tutkimuksen aineistona on hyödynnetty tieteellisiä artikkeleita energianvarastoinnin nykytilasta sekä jo olemassa olevista energiavarastoista saatuja tietoja ja tuloksia. Kappaleessa seitsemän on toteutettu case-tutkimus litiumioniakkupohjaisen energiavaraston kannattavuudesta.

Työn tulokset osoittavat litiumioniakkuvaraston olevan todella potentiaalinen joustava energiaresurssi energiayhtiön tarpeisiin. Kannattavuuslaskelmien perusteella akkuvarasto on taloudellisesti kannattamaton, mikäli energiavarastolla on vain yksi käyttötarkoitus ja tulonlähde. Litiumioniakun monipuolisuus kuitenkin mahdollistaa energiavaraston hyödyntämisen useaan eri käyttötarkoitukseen. Tämä akkuvaraston monikäyttö mahdollistaa akkuvaraston kannattavan hyödyntämisen ja tällöin mahdollisen investoinnin tuoma lisäarvo yritykselle on kiistaton.

AVAINSANAT: Litiumioniakut, kiinteä energiavarasto, energiamarkkinat, lisäarvo

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ABSTRACT:

The Finnish government has decided to renounce the use of coal power plants to electricity production starting May 2029. At the same time, consumption of electricity increases when transportation becomes electrified in Finland. To ensure the supply of electricity, compensatory production methods must be increased. Renewable energy is an environmentally friendly option to replace fossil fuel-based electricity production. In recent years, the State of Finland has supported renewable energy sources which has helped with increasing renewable energy in our country. However, the growth of weather dependent wind power and solar power has caused challenges related to production variability and predictability, which did not exist earlier. Electricity production of grid-connected renewables is not constant, like the production of traditional power plants. In order to ensure electricity in the future, there must be entities which are capable of production equalization. Currently, the most feasible solution for the integration of renewable energy is the lithium-ion battery.

The purpose of this research is to clarify the surplus value of lithium-ion based energy storage when it is connected to a renewable energy source. Research involves both technical and economic benefits that the lithium-ion battery involves. Because this study is commissioned by Lahti Energia, the potential investment must be economically feasible. Research material in this thesis is based on results and information of already existing energy storages and scientific articles about the present situation of energy storages. Chapter seven examines a case study about the cost-effectiveness of a lithium-ion based energy storage system.

The results present the lithium-ion battery's high potential as a flexible energy resource to the energy company. Calculations proved the unprofitability of the lithium-ion battery if the energy storage has only one source of income and one purpose of use. However, the versatility of the lithium-ion battery enables the use of energy storage to multiple applications. This multi-use of BESS enables profitable operation. When BESS is in multi-use, the surplus value to company that the potential investment brings along is undoubted.

KEYWORDS: Lithium-ion batteries, stationary energy storage, energy market, surplus value

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ACRONYMS

AC/DC	Alternating current-direct current
ADB	Asian Development Bank
aFRR	Automatic Frequency Restoration Reserve
BESS	Battery energy storage system
C&I	Commercial and industrial
CHP	Combined heat and power plant
DoD	Depth of discharge
DOE	United States Department of Energy
EC	European Communities
EMEA	Europe, the Middle East and Africa
EPC	Engineering, procurement, and construction
EU	European Union
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve for Normal Operation
FFR	Fast Frequency Reserve
HVDC	High voltage direct current
IRENA	International Renewable Energy Agency
IRR	Internal rate of return
ISO	International Organization for Standardization
IT	Information technology
KOY	joint-stock property company
LCO	Lithium cobalt oxide battery
LCOS	Levelized cost of storage
LFP	Lithium iron phosphate battery
LMO	Lithium manganese oxide battery
LTO	Lithium titanate battery
mFRR	Manual Frequency Restoration Reserve
NaS	Sodium sulphur battery
NCA	Lithium nickel cobalt aluminium battery
NiMH	Nickel-metal hybrid battery
NMC	Lithium nickel manganese cobalt oxide battery
NPV	Net present value
Oy	limited company
PCS	Power conversion system
PV-BESS	Residential photovoltaic battery storage system
ROI	Return on investment
SMES	Superconductive magnetic energy storage
SoH	State of health
UNFCCC	United Nations Framework Convention on Climate Change
UPS	Uninterrupted power supply

1 INTRODUCTION

This Master's thesis is done by order of Lahti Energia Oy (later Lahti Energia). The study was conducted to determine the performance of energy storage in the changing power generation industry. The increased number of battery energy storages in Finland attracted the attention of Lahti Energia to the benefits of these storage solutions. The aim of the study is to clarify the current feasibility of large-scale stationary battery energy storage in a rapidly developing energy storage sector.

> *The Paris Agreement central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius.* (UNFCCC, 2018)

It may not be appropriate to claim that climate change has created a market area for battery energy storages. In the other words, the replacement of fossil fuels with renewable energy has transformed the energy production system in an unprecedented way. The rate of change has brought new problems to the energy sector, but versatile batteries are an environmentally friendly choice for most of these problems. (Castillo & Gayme, 2014) Later in this thesis, research shows that lithium-ion batteries are also an economically viable solution for these problems.

1.1 Literature review

Currently, energy storages draw a lot of research. At the head of research are electric vehicle batteries which expedite the whole battery energy storage industry. (Schmidt, Melchior, Hawkes, & Stafell, 2019) For one reason or another, large-scale stationary batteries have not received as much research as some other energy storage topics. Certainly, compared to many other Master's theses topics, stationary batteries and the surplus value of storage have been extensively studied.

Rufer (2018) splits energy storages to pieces and writes about the strengths and weaknesses of every technology. Aneke and Wang (2016), Argyrou, Christodoulides and Kalogirou (2018) and Luo, Wang, Dooner and Clarke (2015) create a wide comparison between storage types and possible applications. IRENA (2017), ADB (2018) and Lebedeva, Di Persio and Broon-Brett (2016) compare the current and the future lithium-ion technologies. Hesse, Schimpe, Kucevic and Jossen (2017) present everything you need to know about stationary lithium-ion batteries. Particularly, they discuss applications and the surplus value of lithium-ion battery energy storages. Leisen, Steffen and Weber (2019) examine business models and risk analysis.

For lithium-ion storages, Fingrid is the main partners who enable, rule, and manage markets. Another mentionable partner is Nord Pool. Kuivaniemi and Uimonen (2019) and Karttunen et al. (2020) clarify Fingrid's balancing markets. Salokoski (2017) estimates the future of Finnish energy production and the possibilities of energy storages. Finnish Government (2019), UNFCCC (2018), and The European Parliament and the Council of the European Union (2006) set policies and regulations that energy storage must fulfill now and in the future.

The complex economic analysis of energy storage investments is introduced by Belderbos, Delarue, Kessels and D'haeseleer (2017), Bradbury, Pratson and Patiño-Echeverri (2014) and DOE (2019). Pawel (2014) has presented detailed economical efficiency calculations for several energy storages. Schmidt, Melchior, Hawkes and Stafell (2019) have divided levelized cost of storage into pieces.

1.2 Scope of the thesis

The scope of the thesis covers lithium-ion battery utilization possibilities and cost-efficiency aspects. Investment must add value to its owners and be as versatile as possible. A time of great change creates uncertainty about the future in which case variables need to be considered with great accuracy. At the end of this paper, the study comes to discussing the basic purpose of business activities: is the investment profitable during the estimated service life? The profitability is analysed with several use cases.

1.3 Structure of the thesis

As Figure 1 presents, the battery energy storage investment has been examined from several different viewpoints. After the introduction, energy storage technologies are examined. A couple of different storage types are compared against lithium-ion batteries. Comparison includes multiple variables, such as costs, time variables, and maturity.

After the survey has proved that lithium-ion battery is currently the most attractive energy storage solution, the different lithium-ion battery types are presented. The same chapter introduces the future prospects of lithium-ion batteries. The fourth chapter presents applications for lithium-ion batteries.

When the technology decision is made and the applications are known, it is time to consider the economical aspect of this thesis. At first, the markets are presented from the fastest responses to power reserves. Competitive technologies, battery suitability to the markets and business models are examined.

The sixth chapter considers the rationality of the investment. Other batteries in Finland are examined and a risk evaluation is conducted. The Case study is presented in chapter seven. It includes the most common energy investment calculations. The last chapter summarizes the entire thesis with a critical point of view.

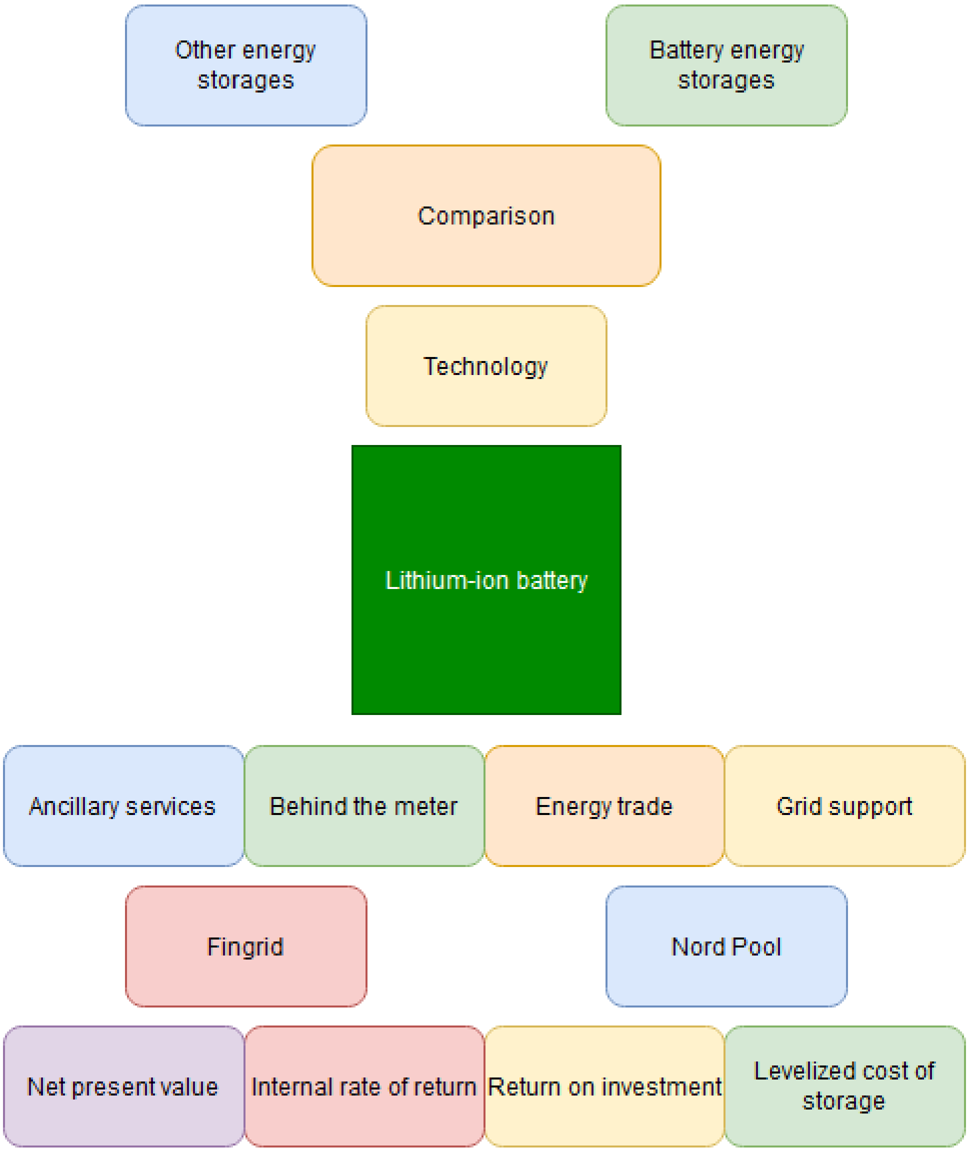

Figure 1. The structure of the thesis.

1.4 Case company

Lahti Energia is a subsidiary of the city of Lahti. Their main products are electricity and district heating. District heating is produced in gasification power plant Kymijärvi 2 and in biopower plant Kymijärvi 3. Electricity is produced in Kymijärvi 2, and company has partial ownership in several companies which produce and develop renewable electricity in Finland. In addition to these, small-scale power plants and reserve power stations are used as a secondary source and during peak-hours to ensure the supply of district heating. In a normal situation, auxiliary power is needed only during the coldest days of winter. (Lahti Energia, 2019a)

The company provides district heating through the network area in Lahti, Hollola and Asikkala. In addition to Lahti and Hollola, their electricity distribution network extends partly to the municipalities of Iitti and Asikkala. LE-Sähköverkko Oy, a subsidiary of Lahti Energia, takes care of the distribution system. (Lahti Energia, 2019a)

Figure 2. Kymijärvi power station area in Lahti, Finland. The highest construction is disused coal power plant Kymijärvi 1. On the left side of Kymijärvi 1 is gasification power plant Kymijärvi 2 which has generated electricity and district heating since 2012. In the foreground of the picture is biopower plant Kymijärvi 3 which has produced district heating since 2019. (Lahti Energia, 2020)

In the years 1975 to 2019, combined heat and power (CHP) plant Kymijärvi 1 produced electricity and district heating to its customers. Kymijärvi 1 was a coal power plant, and it produced 150 MW of electricity and 190 MW of district heating. When this old power plant was coming to the end of its lifetime, Lahti Energia decided to replace it with two renewable powerplants Kymijärvi 2 and 3. When Lahti Energia mothballed Kymijärvi 1 at the end of March 2019, the company became a coal free energy producer. Lahti Energia was one of the first energy companies in Finland who renounced the use of coal. As

Figure 2 presents, Kymijärvi 1, 2 and 3 are in the same power station area, and Lahti Energia owns all three power plants.

In 2015, Helen purchased the first megawatt size stationary lithium-ion energy storage in Finland. At the time, it was expensive and partly for research purposes. (Karppinen, 2017) A couple of years later, other energy companies purchased their own batteries, but the purpose of use has changed. Now, revenue comes from Fingrid's reserve markets. During recent years, stationary battery energy storages have been assembled next to wind farms or microgrids, and even inside a mall. The curiosity for energy storing among the energy industry has increased after these investments.

2 ENERGY STORAGE SYSTEMS

Energy storages are now widely developed and researched, which has led to several different storage solutions. When energy storage solutions are compared, it is necessary to rule out solutions which are not realistic to our case company. This chapter outlines competitors for lithium-ion batteries and illustrates that lithium-ion batteries are currently the only viable solution. Storage solutions which are not for one reason or another reasonable to compare have been excluded in section 2.1 and 2.2. Comparison between lithium-ion batteries and other possible energy storage solutions is explored in section 2.3.

2.1 Battery energy storage types

Batteries are electrochemical energy storages which can store electricity. These rechargeable batteries can be charged and discharged multiple times. Batteries can be allocated into two main categories: flow batteries and batteries. (Luo, Wang, Dooner, & Clarke, 2015) The most used grid-scale battery energy storage technology is lithium-ion battery energy storage systems. In Finland, lithium-ion batteries are the only solution to store megawatts of electricity. This chapter presents several commercialized battery energy storage types. Flow batteries are explored in chapter 2.2 and lithium-ion batteries in chapter 3.

Lead-acid batteries are one of the oldest battery technologies and are still in use. A typical lead-acid battery has metallic lead as an anode material and lead dioxide as a cathode material. Figure 3 describes the simplified operating principle of a lead-acid battery, where sulfuric acid is an electrolyte material between the negative anode and positive cathode. (Argyrou, Christodoulides, & Kalogirou, 2018) The most advanced lead-acid battery technologies are valve-regulated lead-acid batteries and flooded lead-acid batteries. (IRENA, 2017)

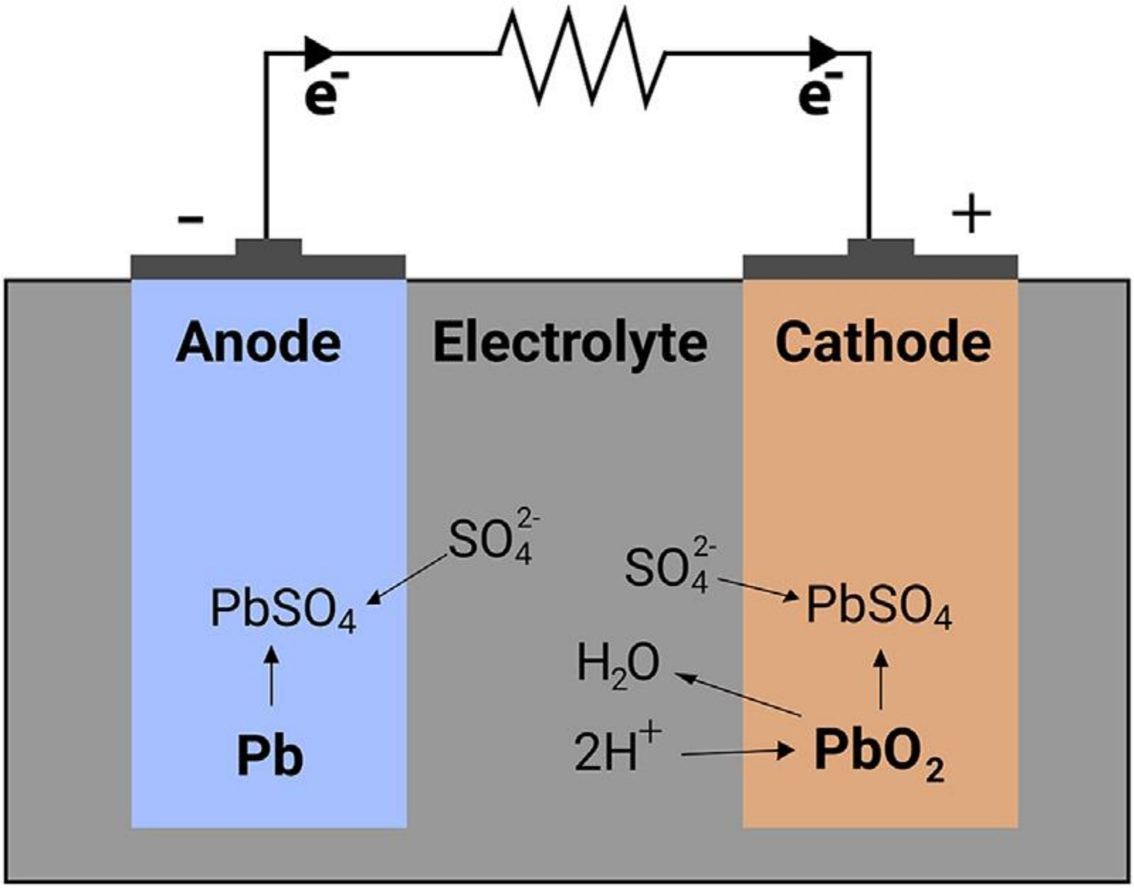

Figure 3. Lead-acid battery. (Argyrou, Christodoulides, & Kalogirou, 2018)

One reliable group of batteries is nickel-based batteries. The very first nickel battery was commercialised in 1915. The nickel cadmium battery is perhaps the most advanced nickel battery. It has cadmium as an anode material and nickel hydroxide as a cathode material. (Argyrou, Christodoulides, & Kalogirou, 2018) The nickel-iron battery and nickel-metal hybrid battery (NiMH) are also mentionable solutions which have drawn a lot of research in recent years. (IRENA, 2017) NiMH is compared to lithium-ion batteries in section 2.3.

Sodium sulphur batteries (NaS) can be large-scale energy storage solutions. As the name says, the anode material is sodium and the cathode material is sulphur. (Argyrou, Christodoulides, & Kalogirou, 2018) When compared to other storage solutions, high operational temperatures from 300 °C to 350 °C are the most problematic aspect for NaS.

Another mentionable high temperature battery type is the sodium nickel chloride battery. (IRENA, 2017) NaS is compared to lithium-ion batteries in section 2.3.

2.2 Other energy storage types

This chapter examines energy storage technologies which are not sensible for our case company. Reasons for examining are e.g. topography, energy efficiency and dependency on fossil fuels.

Pumped-storage hydroelectricity is the most used and probably the best solution for large-scale energy storing. The problem is that topography in Finland is not suitable for pumped-storage hydroelectricity. This gravity-based storage system needs extensive higher and lower reservoirs which can be seen in a Figure 4**.** Reservoirs could be lakes, rivers or man-made lakes. High population density, especially close to water, prevents high changes of water-levels. (Argyrou, Christodoulides, & Kalogirou, 2018)

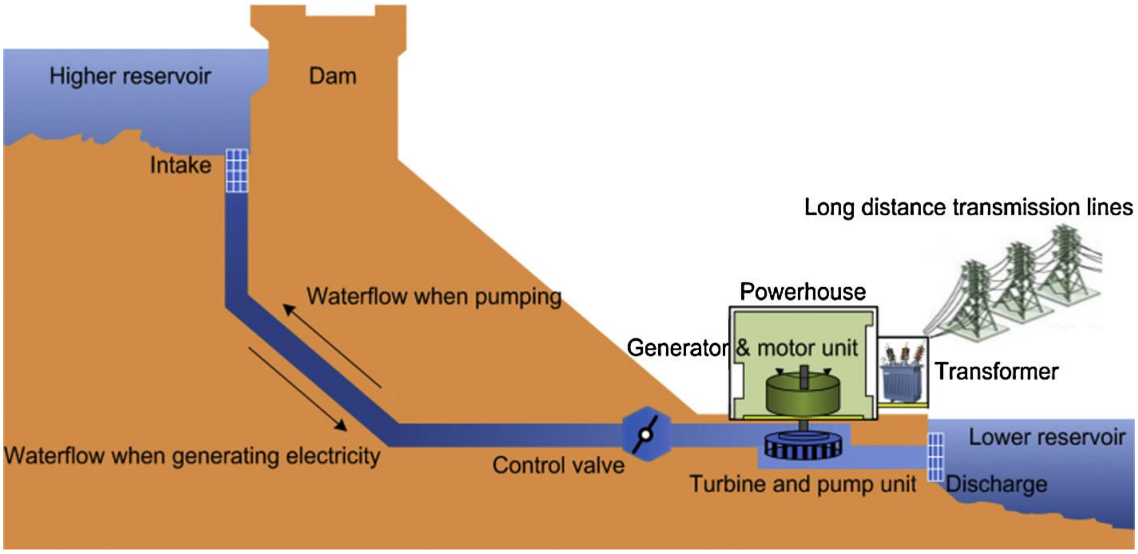

Figure 4. Simplified layout of pumped-storage hydroelectricity. (Luo, Wang, Dooner, & Clarke, 2015)

Pumped-storage hydroelectricity system’s efficiency is dependent on hydraulic-head. In practice, hydraulic-head is the difference of water-levels in higher and lower reservoirs.

The ratio between vertical separation and efficiency can be described as the more the better. (Argyrou, Christodoulides, & Kalogirou, 2018) Hydraulic-head has to be at least 300 metres for profitable operation. (Poullikkas, 2013)

Thermal energy storages include several different storage solutions. Currently, Lahti Energia has one sensible thermal energy storage in use. Tank thermal energy storage is located next to the Teivaanmäki power plant to store district heating water. This 10 000 m^3 tank enables the optimization of electricity and district heating generation in the Kymijärvi 2 CHP plant.

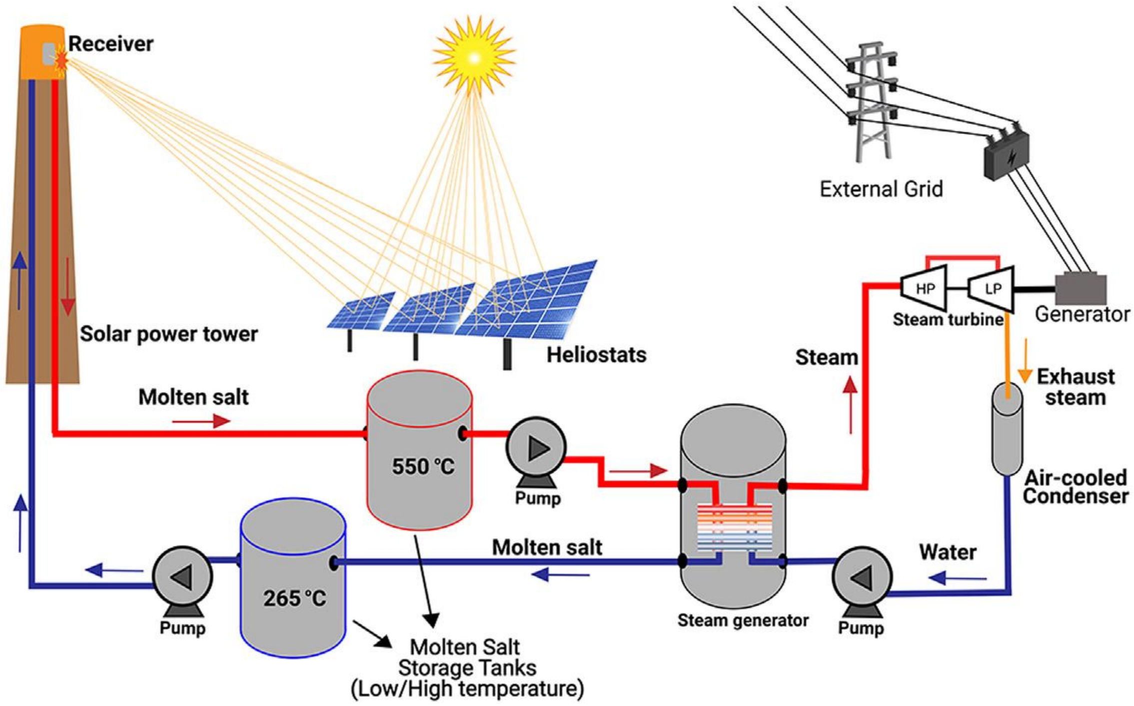

Figure 5. Molten salt storage tanks alongside concentrated solar power. (Argyrou, Christodoulides, & Kalogirou, 2018)

Currently, most of the thermal energy storages are not for large-scale electricity storage purposes. The only considerable solution is molten salt which is a high temperature thermal energy storage. As Figure 5 presents, molten salt is a large-scale energy storage solution which is mainly used alongside concentrated solar power. The biggest issue of molten salt is its solidification temperature. Depending on the source, the solidification point is between 100 °C and 265 °C. The efficiency of molten salt next to concentrated solar power is between 30% and 60%. (Argyrou, Christodoulides, & Kalogirou, 2018) (Aneke & Wang, 2016)

In addition to pumped-storage hydroelectricity, another large-scale storage solution is compressed air energy storage. There are currently two large-scale compressed air energy storages in use: a 290 MW power plant in Huntorf, Germany and a 110 MW power plant in McIntosh, USA. In the year 2020, two new compressed air energy storages started to operate in the USA. Compressed air energy storage is not yet an independent system, so it needs a gas turbine to operate. (Argyrou, Christodoulides, & Kalogirou, 2018) Research and development of environmentally friendly compressed air energy storages is extensive. From Lahti Energia's point of view, fully renewable compressed air energy storage is in the developing stage and the company is looking for a mature solution. (Argyrou, Christodoulides, & Kalogirou, 2018)

Large-scale companies have openly stated that hydrogen might be the solution for energy storing. Currently, companies have invested in and researched the hydrogen fuel cell, which is a promising new technology. It has the highest energy density of all storages from 800 to 10 000 Wh/kg, but the round-trip efficiency is poor. (Aneke & Wang, 2016) One fuel-cell is expected to be part of the microgrid in the Lemene-project at Lempäälä, Finland. (Siemens, 2019a)

Flow batteries have taken big steps ahead and some large-scale batteries are under construction (UniEnergy Technologies, 2016). Even though large-scale stationary flow batteries are under construction, it is still a relatively new technology which has its own issues. Flow battery efficiency varies between 60% and 85%, but capital costs are approximately the same as lithium-ion batteries. Other drawbacks are low performance results, an even more complicated structure than traditional batteries and issues with reactant mass movements. The most advanced flow battery types are the vanadium redox flow battery and zinc-bromine flow battery. (Argyrou, Christodoulides, & Kalogirou, 2018) (Luo, Wang, Dooner, & Clarke, 2015)

2.3 Comparison between seven storage technologies

Section 2.2 clarified the storage solutions which are not sensible solutions for our case company. This chapter compares six different energy storage technologies to the lithium-ion battery. These technologies are lead-acid, NiMH, NaS, superconductive magnetic energy storage, flywheel and supercapacitor. All these energy storage solutions compete in the same market area which requires a fast and irregular response. These competitive solutions are compared to lithium-ion batteries in the following chapters. Before the comparison, storage solutions which are not introduced yet are introduced shortly.

The superconductive magnetic energy storage (SMES) is electrical energy storage where the coil is below superconducting temperature. The coil must be a superconductive material, such as vanadium or niobium-titanium. Superconductive temperature is dependent on the coil's material and each material has a unique superconductive temperature. Normal operational temperatures for SMES varies between 5 K and 70 K. Superconductive temperature removes resistance, which enables energy storing almost without losses. Figure 6 presents components of SMES which are superconductive coil, a power quality system, a refrigerator system and a vacuum-insulated vessel. (Luo, Wang, Dooner, & Clarke, 2015)

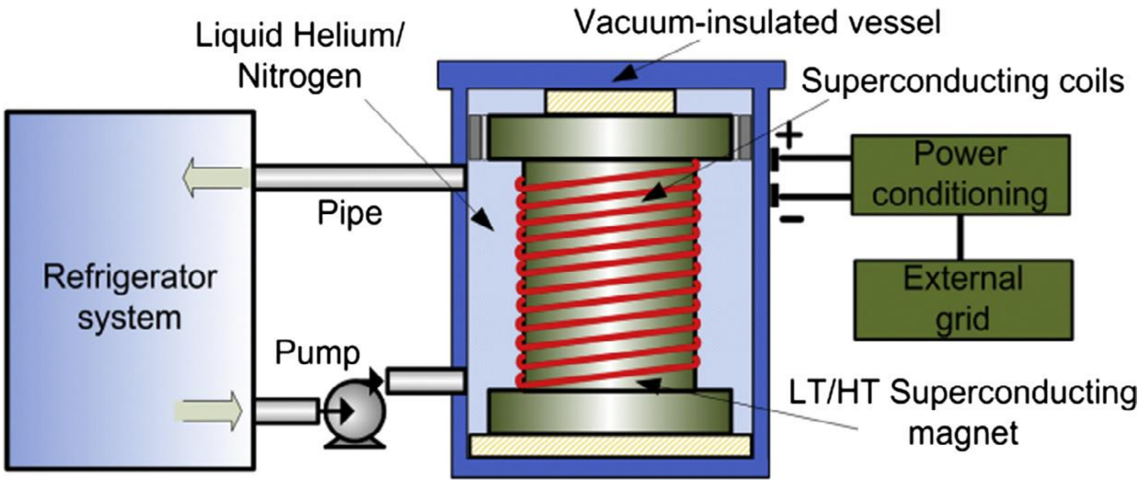

Figure 6. Typical layout of SMES. (Luo, Wang, Dooner, & Clarke, 2015)

Kinetic energy can be stored by using flywheel. A rotating mass of steel rotors resist the changes of electricity. When the flywheel is charged, it can be compared to the motor which consumes energy. Charging increases the speed of steel rotors. When discharging, the load is connected to the system and the flywheel operates like a generator. The energy of the flywheel is directly proportional to the speed of steel rotors, so during discharging the speed of the flywheel decreases. The rotational energy of the flywheel can be easily calculated as

$$E = \frac{1}{2} J \omega^2,$$

where J is the moment of inertia and ω is the angular velocity. (Argyrou, Christodoulides, & Kalogirou, 2018)

As aforementioned SMES, the supercapacitor is a relatively new innovation which has drawn a lot of research in recent years. Researchers started to develop supercapacitors, because they wanted fast energy storage with a long service life. The supercapacitors' operating principle is the same as a capacitor. The surface of electrodes in supercapacitors is larger, which enables higher energy density and increased capacity. Other names for supercapacitors are electric double layer capacitor, electrochemical capacitor, and ultra-capacitor. (Aneke & Wang, 2016)

2.3.1 Densities and costs

The power density is measured as output power per mass of storage or output power per storage volume. While power density uses watt per kilogram or litre, the energy density unit is watt-hour per kilogram or litre (energy per mass or volume of storage). If power density is high, it usually refers to solutions which are capable for fast response, high discharge current and high power excellence.

Batteries other than lithium-ion have power density between 150 and 240 W/kg. (Argyrou, Christodoulides, & Kalogirou, 2018) The rest of the compared storage system has quite equal power density, between 500 and 2 000 W/kg. NaS's and lithium-ion batteries' energy density is hundreds of watthours per kilograms. NiMH is the third with energy density between 70 and 80 Wh/kg. Other solution's energy density is less than 50 Wh/kg. (Aneke & Wang, 2016) Power density and energy density are not the highest priority reference values, because Lahti Energia's aim is to have stationary battery alongside a renewable energy source.

Even though power and energy densities were not the most relevant characteristics, these two reflect the costs of energy storages. SMES, supercapacitor, and flywheel have significantly lower power capital costs than modern battery solutions. The only competitive battery solution is lead-acid, which power capital costs are only between 300 and 600 €/kW. (Argyrou, Christodoulides, & Kalogirou, 2018) In this category, lithium-ion has obvious weakness. Supercapacitor's power capital costs are roughly ten times lower than lithium-ions. Of course, we must take into consideration the purpose of use for each of these energy storage solutions. SMES, supercapacitor and flywheel are designed for rapid power input and output, but not for long-term energy output. (Aneke & Wang, 2016)

Energy capital costs illustrate aforementioned claims. Battery solutions have lower energy capital costs than other solutions. The only exception is lithium-ion’s and supercapacitor’s energy capital costs, which are in the same scale. Mature lead-acid has the lowest energy capital costs while SMES has the highest energy capital costs. (Argyrou, Christodoulides, & Kalogirou, 2018)

2.3.2 Time variables

When investment decisions are made, service life has a significant role. Too short of a service life can make even the greatest solutions unprofitable. (Aneke & Wang, 2016) Service life of batteries is shorter compared to the other three solutions. SMES’s service life is 20 years or more while lead-acid battery is useable for only 3 to 12 years. Lithium-ion battery service life is between 5 and 15 years. (Argyrou, Christodoulides, & Kalogirou, 2018)

An even more descriptive difference is cycle life. Cycle life is the sum of full charge and discharge cycles until the battery comes to the end of its service life. Figure 7 shows how DoD affects cycle life. SMESs, supercapacitors and flywheels have the greatest cycle lives of all storage solutions.

The cycle life of these three competitors varies between 20 000 and 100 000+ cycles, while typically batteries’ cycle life is approximately couple of thousand cycles. (Argyrou, Christodoulides, & Kalogirou, 2018)

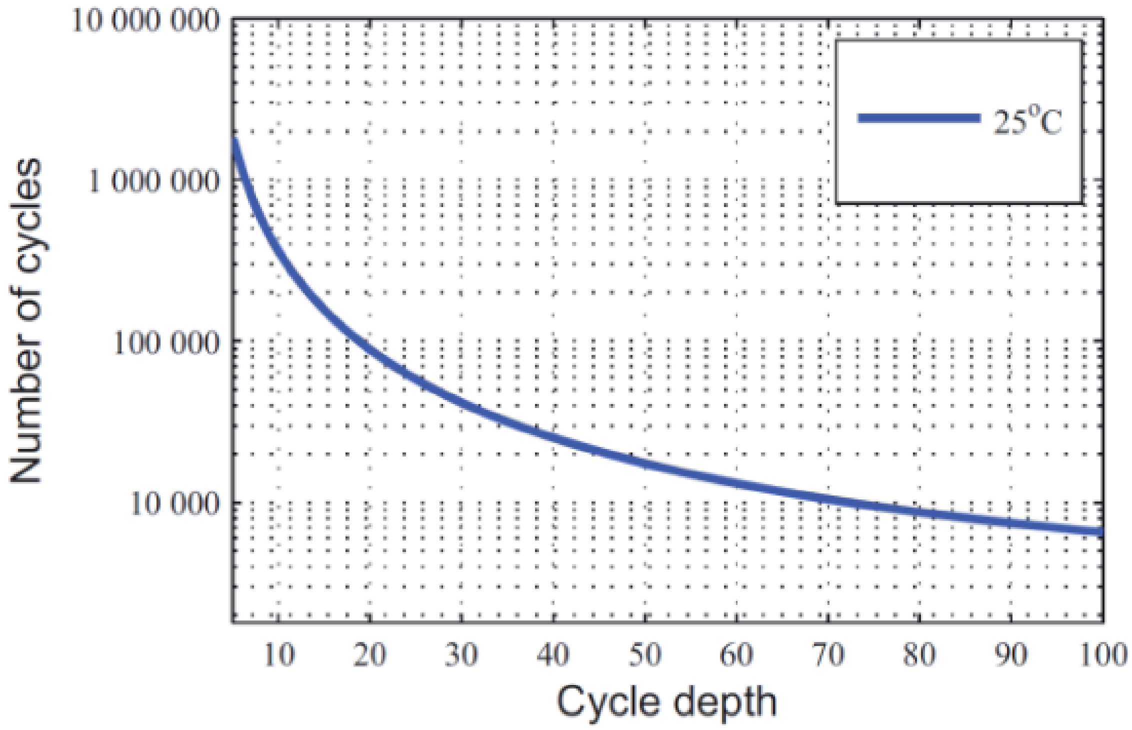

Figure 7. Lithium iron phosphate battery has higher cyclic life than other lithium-ion batteries. Even so, if DoD is 100%, lithium iron phosphate battery's cycle life is only a couple of thousand cycles. (Swierczynski, 2012)

As Figure 7 presents, some lithium-ion batteries have a higher cycle life than others. For example, lithium iron phosphate and lithium titanate batteries can operate 15 000 - 20 000 cycles before deterioration. (IRENA, 2017, p. 67) (Swierczynski, 2012) A more realistic average cycle life for other lithium-ion batteries is approximately 4 500 cycles. (Argyrou, Christodoulides, & Kalogirou, 2018) When cycle life of lithium-ion batteries varies between sources, it brings out the differences between lithium-ion types. Lithium-ion types are examined in chapter 3.

Storage duration is the time difference between charging and discharging the energy storage. Each solution has its own optimal storage duration. This means that the efficiency of energy storage is dependent on duration time. Flywheels are competitive when storage duration is only seconds to minutes. Optimal duration time for supercapacitors and SMES is usually less than an hour, but a few hours if needed. The reason for such short duration times is a rapid self-discharge. Batteries have longer duration time from minutes to days. (Luo, Wang, Dooner, & Clarke, 2015)

Batteries dominate self-discharge percent, while the three other competitors have a high self-discharge percent within 24 hours. NaS has the lowest percent and lithium-ion batteries self-discharge rate is only 0,1 – 0,3 percent per day. Flywheel's self-discharge rate is 100% per day, so basically it stops during a 24-hour period. (Argyrou, Christodoulides, & Kalogirou, 2018)

The storage solution must have a fast response time to satisfy Lahti Energia's and Fingrid's prerequisites. If response time is 0,7 seconds or more, energy storage is not able to operate in some of the reserve markets which are examined in chapter 5. (Aneke & Wang, 2016) SMES's, batteries' and supercapacitor's response times are five milliseconds or less. The response time for flywheels is seconds. (Argyrou, Christodoulides, & Kalogirou, 2018) The flywheel is the only mechanical energy storage in this comparison, while other solutions are electromechanical or electrical. Other mechanical energy storages, such as pumped-storage hydroelectricity and compressed air energy storages, cannot compete in markets which demand fast response time. (IRENA, 2017)

2.3.3 Round-trip efficiency

While electricity is stored, some percent of energy is lost between charging and discharging. The percentage difference of input and output is called round-trip efficiency. The variables of efficiency are charging, discharging and self-discharge during storing. The round-trip efficiency can be calculated as

$$\eta_{cnt} = (\eta_{ch} - \eta_0)\eta_d,$$

where η_{cnt} is the real normal round-trip efficiency, η_{ch} is the instantaneous power efficiencies during charging, η_0 is the self-discharge energy factor and η_d is the instantaneous power efficiencies during charging. (Rufer, 2018, pp. 9 - 13)

NiMH and lead-acid batteries have poor round-trip efficiencies. (Argyrou, Christodoulides, & Kalogirou, 2018) Others round-trip efficiencies vary between different studies and sources. For example, research results give 75 – 99% round-trip efficiency to lithium-ion batteries and 84 – 98 % efficiency to supercapacitors. Common to all of these studies is multiple results which are more than 90 %. For this reason, it can be stated that all the other competitors have a round-trip efficiency higher than 90 %.The differences between the round-trip efficiency of NaS, lithium-ion, SMES, flywheel, and supercapacitor is irrelevant to their comparison. (Aneke & Wang, 2016) (Argyrou, Christodoulides, & Kalogirou, 2018) (Luo, Wang, Dooner, & Clarke, 2015)

2.3.4 Maturity

Technological maturity needs to be concerned to minimize the risks. Lahti Energia does not want to be a test bed for prospective storage solutions. The company’s aim is to have a storage system that has already been proven a reliable solution in northern Europe.

SMES and supercapacitors are developing technologies which have their own issues before large-scale commercialisation. Lithium-ion, NiMH, NaS and flywheel are commercialized solutions, as Figure 8 shows. Still, these four technologies have obstacles to solve when competition between technologies accelerates. Even though Figure 8 does not include the lead-acid battery, it is the only mature solution. The history of lead-acid batteries goes back to the 19th century. (Ibrahim & Ilinca, 2013) Lithium-ion batteries are being built all over the Nordic countries and several projects are underway. Section 6.3 presents lithium-ion storage projects in Finland.

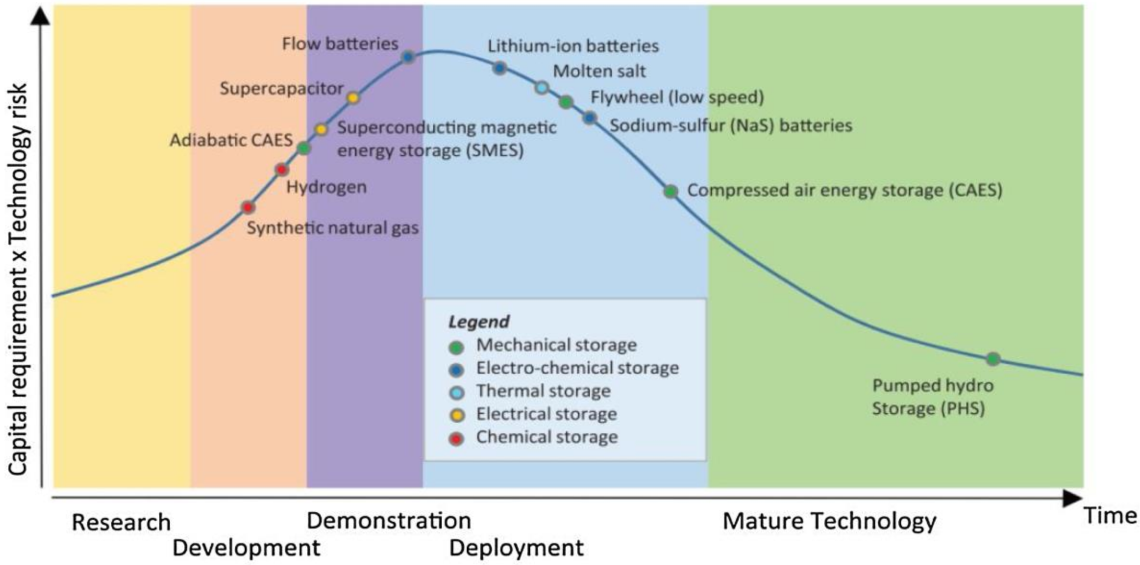

Figure 8. Maturity of energy storages. (Michiorri, et al., 2015)

2.3.5 Conclusion

In this chapter, lithium-ion batteries were compared to six different energy storage technologies. Alternative energy storage technologies were NiMH, NaS, lead-acid, SMES, supercapacitor, and flywheel. TTable 1 summarizes the technical and economical characteristics of these seven technologies.

When electric vehicles draw a lot of research and development interest, batteries which are suitable for electric vehicles also draw more attention than the others. Therefore, lithium-ion batteries are expected to develop more than other batteries in the future. When observing power capital costs and energy capital costs from Table 1, lithium-ion is an expensive solution. Especially the power capital costs are high. Costs are weak point of lithium-ion batteries.

Other issues of lithium-ion batteries are service life and cycle life. When initial investment is high, the payback period might be hard to fit between the limits of service life and cycle life. SMESs, supercapacitors and flywheels clearly perform better than lithium-ion batteries in this regard. Lithium-ion batteries have the longest service life and the highest cycle life of compared battery solutions.

The response time of lithium-ion batteries is significantly faster than any application's or market's demand. Meanwhile, the flywheel's response time is too long for some markets and applications. Other solutions have no problems with response times. Another cross of for applications and markets is duration. SMESs, supercapacitors and flywheels have short duration time, which means high self-discharge. Therefore, these competitors are suitable only for short-term storing. Variation in lithium-ion battery types in duration and self-discharge is so small, that it does not change the situation to one way or the other.

Round-trip efficiency excludes other battery solutions than lithium-ion. Other batteries are cheaper than lithium-ion batteries, but all the other aforementioned characteristics are almost equal. Efficiencies for other solutions than batteries are 90% or more. As mentioned earlier, round-trip efficiency of lithium-ion batteries can be stated to be as good as SMESs, flywheels and supercapacitors.

Even though the lead-acid battery is the most mature solution in this comparison, lithium-ion batteries outperform lead-acid in other characteristics. The lithium-ion battery is the most commercialized and mature solution for our case company. At the same time, lithium-ion batteries have been found to be functional and sensible solutions in Nordic countries. Even though competitors outperform lithium-ion batteries by some meters, it is easy to say that the lithium-ion battery is the only suitable solution for our case company. The lithium-ion battery is suitable for several energy storage solutions, while competitors are suitable only for some. Comparison pointed out expected outcomes.

Table 1. Compared technical and economical characteristics. (Aneke & Wang, 2016) (Argyrou, Christodoulides, & Kalogirou, 2018) (Luo, Wang, Dooner, & Clarke, 2015)

	Lithium-ion	**SMES**	**Superca-pacitor**	**Flywheel**	**NaS**	**NiMH**	**Lead-acid**
Power density (W/kg)	500 – 2 000	500 – 2 000	500 – 5 000	400 – 1 500	150 – 240	175	180 – 200
Power capital cost (€/kW)	1 200 – 4 000	200 – 300	100 – 300	250 – 350	1 000 – 3 000	600 – 1 800	300 – 600
Energy density (Wh/kg)	75 – 200	0,5 – 5	2,5 – 15	10 – 30	150 – 240	70 – 80	25 – 45
Energy capital cost (€/kWh)	600 – 2 500	1 000 – 10 000	300 – 2 000	1 000 – 5 000	300 – 500	200 – 1 800	150 – 500
Service life (years)	5 – 15	20+	10 – 20	15	10 – 15	15	3 – 12
Cycle life	1 000 – 10 000	100 000+	100 000+	20 000+	2 500 – 4 500	500 – 1 800	200 – 1 800
Storage duration	minutes to days	minutes to hours	seconds to hours	seconds to minutes	seconds to hours	minutes to days	minutes to days
Self-discharge (%/day)	0,1 – 0,3	10 – 15	5	100	0,05	0,4 – 1,2	0,1 – 0,3
Response time (ms)	< 5	5	< 5	1 000+	< 5	< 5	< 5
Round-trip efficiency (%)	75 – 99	90 – 98	84 – 98	85 – 95	75 – 90	65 – 70	63 – 90
Maturity	Commer-cialized	Developing	Developing	Commer-cialized	Commer-cialized	Commer-cialized	Mature

3 LITHIUM-ION BATTERY ENERGY STORAGES

3.1 Lithium-ion battery energy storage technology

A stationary battery energy storage includes more components than just a battery. These components can be classified in multiple ways. The classification below begins from the smallest cell to the grid connected transformer.

A battery cell is a component where electricity is stored. A cell has two electrodes: the negative electrode known as the anode and the positive electrode known as the cathode. Between the anode and cathode is electrolyte. Electrolyte can be in solid, liquid, or ropy state. During charging, electrons move from cathode to anode along an external circuit. When a battery is discharged, the opposite reaction happens. (Luo, Wang, Dooner, & Clarke, 2015) Three typical packaging designs of battery cells are cylindrical, prismatic and pouch. (Maiser, 2014)

When two or more battery cells are connected to each other, it is called a battery module. In a module, cells can be connected in parallel, in series or in parallel and in series. The cells are placed in modules for easier control of a single cell. One battery can contain thousands of cells. (Maiser, 2014)

The last battery component is the battery pack. Packs include modules, a battery management system, a thermal management system and electronic components. The purpose of a battery management system is to protect the modules and cells against harmful changes in current, voltage and temperature. The thermal management system keeps temperature between safety limits. In large-scale stationary energy storages, the aforementioned components are in the battery racks instead of the packs. (ADB, 2018, p. 7)

After the battery itself, the components that take care of system operation are needed. System operation components are the energy management system, the supervisory control and data acquisition system and the system’s thermal management system. The task of these three is to guarantee reliable performance of the system. The energy management system is responsible for energy flows and distribution. The supervisory control and data acquisition system manages monitoring, IT, alarm systems and fire protection. The system's thermal management system has the same responsibilities as it has in a battery pack. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

Power electronics are needed to convert electricity between battery and network. A two way AC/DC converter or inverter enables the batteries to be connected to the grid. Like other parts of the system, power electronics also have a control and management system and a thermal management system. The last component, the transformer, is needed if the battery is connected to medium or high voltage grid. (Hesse, Schimpe, Kucevic, & Jossen, 2017) All of the aforementioned components together form the battery energy storage system (BESS), which is also illustrated in Figure 9**.** Aforementioned components are normally placed inside a construction or into one or multiple containers.

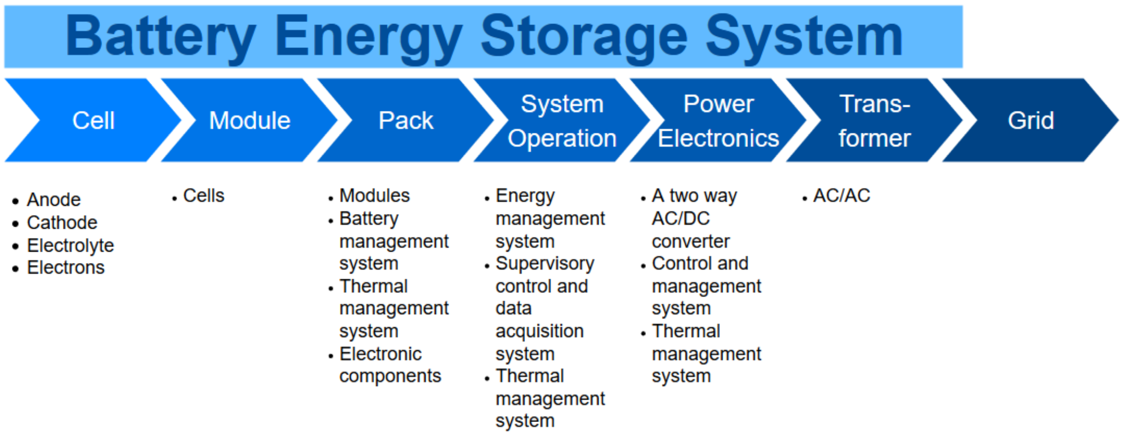

Figure 9. Basic components of BESS. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

The depth of discharge (DoD) is one of the most vital variables in battery technology. DoD presents the percent of usable energy of a battery. Some research studies claim 100% DoD for lithium-ion batteries, but reality is somewhere around 90%. (IRENA, 2017) If a battery is discharged to almost empty, the DoD is high and calendar aging of battery increases. Calendar aging affects a battery's service life negatively. DoD must be taken into account when the selection of the lithium-ion battery type is made. Different battery types react variously when charge level is low. The opposite of DoD is state of charge. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

One way to present the aging of a battery is the state of health (SoH). When SoH is 100%, a battery behaves just as the manufacturer promised. During operation, SoH decreases, because of degradation. Degradation means higher internal resistance and capacity losses. (Hesse, Schimpe, Kucevic, & Jossen, 2017) Battery manufacturers announce their batteries SoH in the control and management system. In reality, large-scale stationary batteries include hundreds of battery cells, so it is impossible to a define single battery cell's SoH.

Power conversion system (PCS) is a group of components which enables connection between battery and grid. These components are, for example, the inverter, transformer and physical lines. PCS enables the battery's output signal to be fed into to the grid. (Killer, Farrokhseresht, & Paterakis, 2020) Costs of PCS are partially dependent on voltage. If power is constant, high voltage enables a smaller current which leads to smaller losses and components. Currently, DC voltages in PCS are less than 1 000 V, but in the future DC voltage is expected to be 1 500 V. (Mongird, et al., 2019)

3.2 Types

Lithium-ion batteries are a group of different lithium-ion battery types. Common to all these batteries is lithium-ions which move between the anode and cathode. Most of the types have carbon graphite as an anode material, but there are some exceptions. Figure 10 presents estimated development of installation costs and round-trip efficiency between 2016 and 2030. Lithium-ion batteries are ahead of other battery types. (IRENA, 2017)

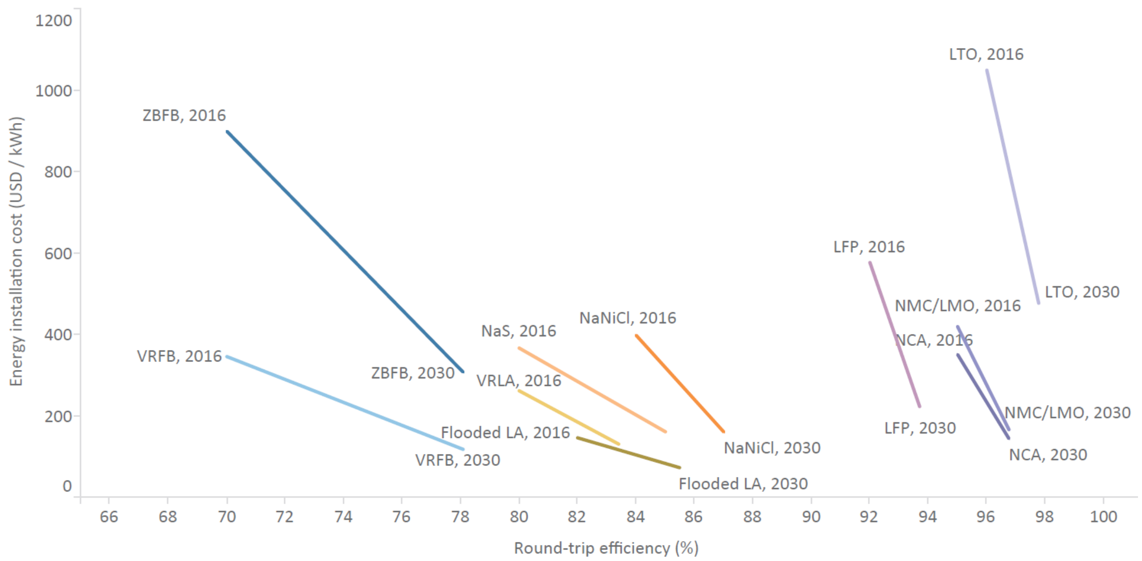

Figure 10. Estimated installation costs and round-trip efficiency of battery energy storage technologies between 2016 and 2030. On the left side of the picture are flow batteries and other battery technologies while lithium-ion batteries are on the right side of the picture. (IRENA, 2017)

3.2.1 Lithium cobalt oxide

In a lithium cobalt oxide ($LiCoO_2$ or LCO) battery, the cathode is made of cobalt oxide and the structure of the cathode is layered. The anode material is carbon graphite. Currently, LCO batteries have more disadvantages than advantages. It has shorter service life and lower load capability than the other lithium-ion battery types. Thermal instability makes it also less interesting. (ADB, 2018, p. 12)

3.2.2 Lithium manganese oxide

In 1983, a new lithium-ion battery was presented in the Materials Research Bulletin. This new battery type was a lithium manganese oxide ($LiMn_2O_4$ or LMO) battery. The structure of the battery cells in a lithium manganese oxide battery is three-dimensional spinel. (ADB, 2018, p. 12) This crystal structure enables better ion flow between the anode and cathode. A better flow means less internal resistance and higher current during discharge. (IRENA, 2017, pp. 65 - 66)

Other advantages compared to other types are a higher safety factor and better thermal stability. From an economical point of view, the LMO battery is cheaper and less susceptible to changes in manufacturing costs, because the cathode does not include cobalt. (IRENA, 2017, pp. 65 - 66) After the increased demand of lithium-ion batteries, the price of cobalt has been sensitive to economic fluctuations. (National Emergency Supply Agency, 2017)

The disadvantages of LMO batteries are cycle life and service life. Other types also have higher energy performances. Low energy performance, relatively short service life and moderate cycle life makes LMO less attractive in stationary solutions. It also has carbon graphite as an anode material. (IRENA, 2017, pp. 65 - 66)

3.2.3 Lithium nickel manganese cobalt oxide

As a stationary battery solution, a lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$ or NMC) battery has increased its market share. Large manufacturers, such as Samsung SDI in Figure 11, currently develop NMC batteries. (Hesse, Schimpe, Kucevic, & Jossen, 2017) The NMC battery has been developed from the LCO battery. Researchers wanted to have the same structural stability, but a cheaper metal to replace cobalt. A structure of battery cells is layered crystal where there commonly is an equal amount of nickel, cobalt, and manganese. Other volume ratios are 5/3/2 and 4/4/1. Tailored ratios enable the customer to choose a high energy or high power battery. The NMC battery has better thermal stability than LCO. Thermal stability is directly proportional to the percentage of cobalt. (IRENA, 2017, p. 66)

Figure 11. Samsung SDI’s NMC batteries. (Samsung SDI, 2016)

3.2.4 Lithium nickel cobalt aluminium

The lithium nickel cobalt aluminium ($LiNiCoAlO_2$ or NCA) battery is another cheaper development version of the lithium cobalt oxide battery. At the beginning of the development process, lithium nickel oxide batteries reached low costs and better energy densities, but at the same time suffered unstable thermal performance. The solution for thermal performance was aluminium. Aluminium also improved other strengths. NCA batteries’ cathode material can be nickel, cobalt or aluminium. (IRENA, 2017, pp. 65-66)

NCA batteries have very high energy and power density thanks to aluminium. High densities, high cycle life and long service life has made lithium nickel cobalt aluminium batteries a suitable solution for electric vehicles. Especially electric vehicle and battery manufacturer Tesla has developed this battery type a lot. High operational voltage creates degradation of electrolytes, which is the biggest issue of NCA. Currently, NCA also has some safety and temperature dependent issues. (IRENA, 2017, pp. 65 - 66)

3.2.5 Lithium iron phosphate

In 1996, The University of Texas discovered that iron phosphate is a considerable cathode material. Cathode is made of nanoscale phosphates. The lithium iron phosphate ($LiFePO_4$

or LFP) battery has a low resistance, high cycle life and good performance metrics. (ADB, 2018, p. 12) Unlike other types, the LFP battery has a non-toxic cathode material. A non-toxic cathode is more secure than toxic cathode materials. Aforementioned benefits have made the LFP battery an attractive option for stationary battery solutions. (IRENA, 2017, p. 66)

The LFP battery has relatively low cell voltage, low energy capacity and some material issues. It also has proportionably low round-trip efficiency. A lot of research and development work is done to reduce these issues. Currently, scientists are trying to create smaller and smaller nanoparticles to maximize power density per volume. The addition of titanium or vanadium may solve low cell voltage problems. (IRENA, 2017, pp. 67 - 68)

3.2.6 Lithium titanate

In every aforementioned lithium-ion battery type, the negative electrode, anode, is made of carbon graphite. Lithium as an anode material is quite common in non-rechargeable batteries. The lithium titanate ($Li_4Ti_5O_{12}$ or LTO) battery is the only large-scale chargeable lithium-ion battery where lithium is an anode material. An anode has a spinel structure. (IRENA, 2017, p. 67) Carbon graphite as an anode material enables >3 V nominal cell voltage while the LTO's nominal cell voltage is 2,4 V. LTO battery types include multiple different cathode materials. Common cathode materials are lithium nickel manganese cobalt oxide and lithium manganese oxide. (ADB, 2018, p. 12)

The advantages of LTO are fast charging, higher power ratings and stable chemical conditions. Chemical stability creates thermal stability and reduces the risk of thermal runaway. High thermal stability means fewer aging issues and decomposition of materials. In reality, thermal stability results in a longer service life and better cycle life. Other type's cycle life varies between zero and couple of thousands of cycles. The only exception is LFP which has a cycle life from 100 to 10 000 cycles. Cycle life between 5 000 to 20 000 cycles lifts the LTO to its own class. The LTO also has the best round-trip efficiency. (IRENA, 2017, pp. 67 - 68) Low temperatures do not affect LTO batteries as much as low temperatures affect other types. When operation temperature is –30 °C, the LTO battery is able to use 80 % of its full capacity. (ADB, 2018, p. 12)

Lower nominal cell voltage also means lower energy density. In addition to these two, the lithium titanate batteries are more expensive than other types. The reason for high prices is expensive titanium. LTO batteries are roughly twice as expensive as other types. (IRENA, 2017, pp. 65, 67)

3.3 Future solutions

3.3.1 Lithium metal batteries

Anodes in lithium metal batteries have ten times bigger capacity than in traditional lithium-ion batteries. Currently, there are some issues of stabilizing the anode and the electrodeposition is still unstable. To become a commercial solution, lithium metal battery stability needs to be improved. In some scenarios, the 3D printing of lithium metal batteries can be seen as revolutionary invention. 3D printing and other cheap forms of production draw researchers’ interest. Currently, the lithium metal battery is in the middle stage of development. (Lebedeva, Di Persio, & Broon-Brett, 2016, pp. 21-22)

3.3.2 Solid-state lithium batteries

The solid-state battery is expected to be the next big breakthrough in the battery industry. The technology is a potential solution to electric cars, BESS, and computers. This new technology is expected to be a long-lived solution, lightweight and capable of up to 23 000 cycles. (European Comission, 2018) (Braga, Subramaniyam, Murchison, & Goodenough, 2018)

As the name suggests, the electrolyte is solid instead of liquid. Solid-state batteries’ self-discharge is lower than lithium-ion batteries’ self-discharge. The reason for low self-discharge is solid electrolyte’s minor electronic conductivity. Only ions move when the electrolyte is solid. (Lebedeva, Di Persio, & Broon-Brett, 2016, p. 22) Solid electrolyte is a considerably less flammable solution than liquid electrolyte, where even a small overheat can create a thermal runaway. The most common solid electrolytes are the organic polymer and the inorganic ceramic. The solid electrolyte enables multiple anode and cathode materials such as lithium metal. (European Comission, 2018)

Solid-state batteries are not mature solutions. It is expected to take a decade before we have the first commercial solid-state battery. This environmentally friendlier and cheaper battery type gives a competitive advantage in power performance. The problem occurs with the movement of the electrodes inside the electrolyte. (European Comission, 2018)

3.3.3 Lithium sulphur batteries

The biggest benefit of lithium sulphur batteries, and perhaps the reason why it is the focus of a lot of research, is its energy density. The energy density of 400 Wh/kg is roughly twice as good as NMC batteries' energy density. Lithium sulphur batteries are also safer than commercial types. The chemical compound makes lithium sulphur batteries safer. This battery type is still far away from commercialization. The cycle life of the lithium sulphur battery is less than one hundred, so there is a lot of work to be done. This battery type also has high self-discharge per day and conductivity issues. (IRENA, 2017, p. 75)

3.3.4 Lithium air batteries

The highest estimated power and energy density of all BESSs belongs to the lithium air battery. (IRENA, 2017, p. 75) The theoretical energy density for this type is 3 500 Wh/kg. The barrier for this type is the lack of understanding of its electrochemical and chemical behaviour. To reach the aforementioned density, lithium metal electrodes' full-cycle efficiency must be improved. Lithium air batteries also have stability issues. The management of air flow and cleanness should be concerned, because the purity of air has a direct effect on the battery's performance. (Lebedeva, Di Persio, & Broon-Brett, 2016, pp. 23 - 24) As Figure 12 presents, the cathode materials are oxygen and porous carbon. (Argyrou, Christodoulides, & Kalogirou, 2018)

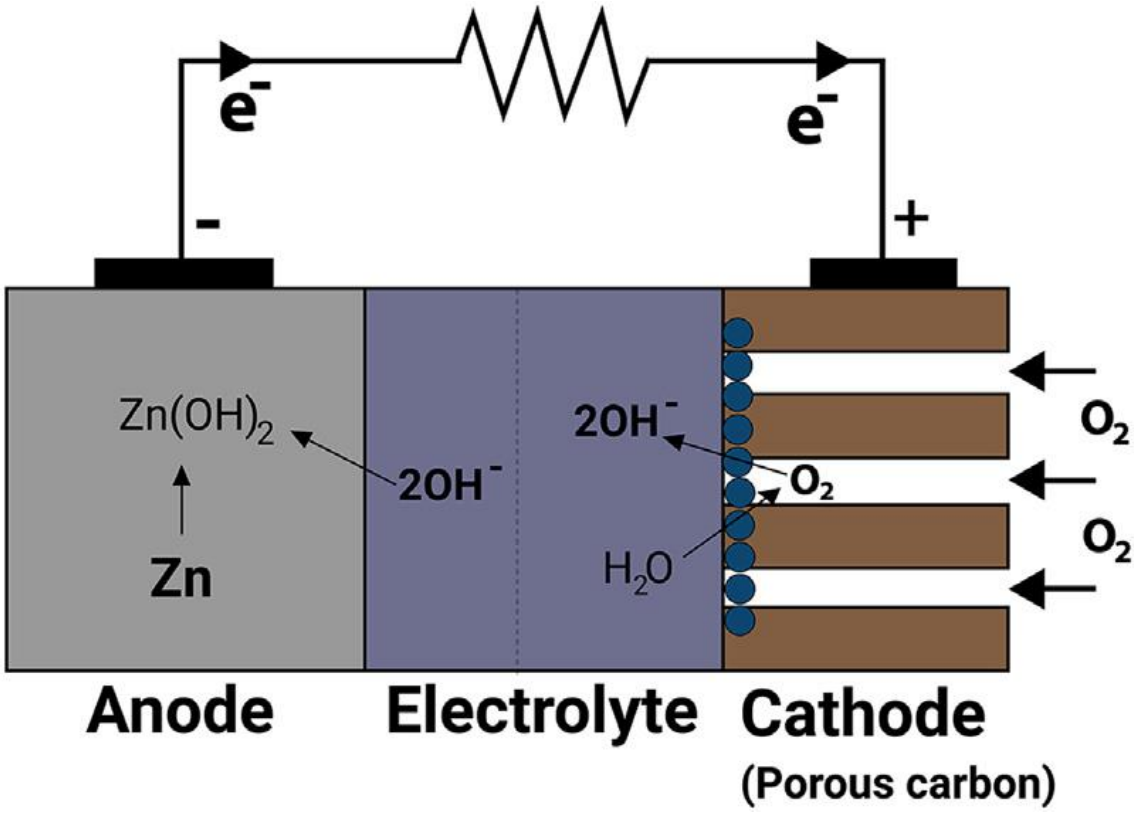

Figure 12. Layout of lithium-air battery. (Argyrou, Christodoulides, & Kalogirou, 2018)

4 LITHIUM-ION BATTERY STORAGE APPLICATIONS AND USE CASES

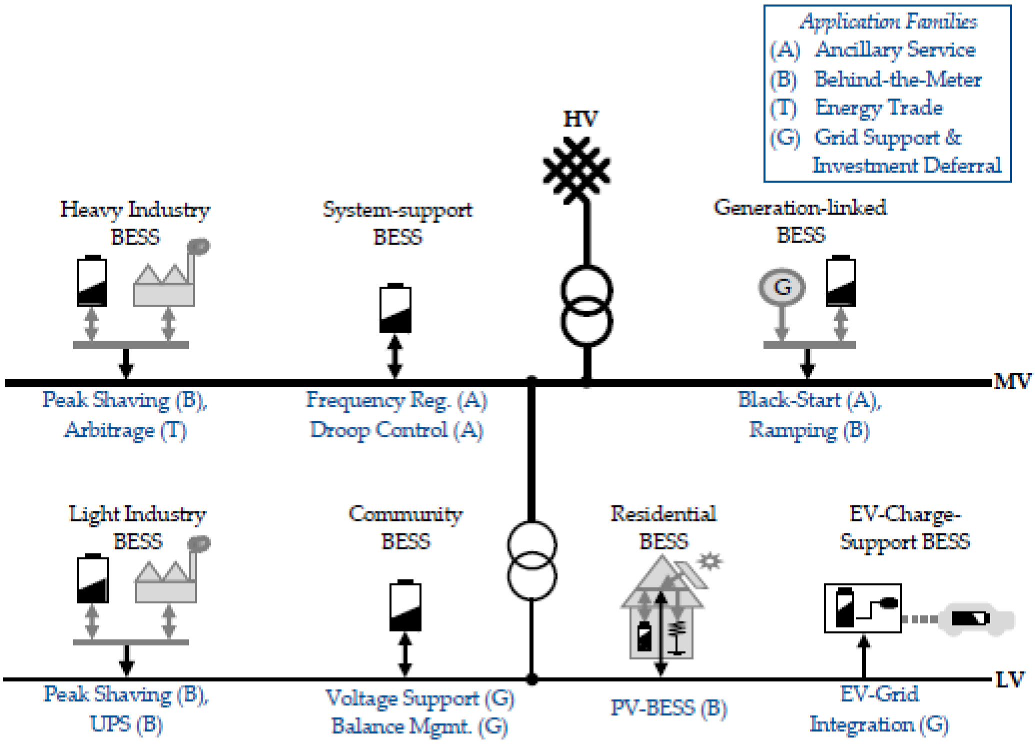

Figure 13. Various BESS applications connected to medium and low voltage network. Some of the applications are not taken into consideration in this chapter. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

Lithium-ion batteries are able to support the electricity network in many ways. This chapter presents those applications which are realistic for BESS alongside a power plant. For this reason, the residential photovoltaic battery storage system (PV-BESS), which is mentioned in Figure 13, is not considered in this chapter. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

4.1 Ancillary services

As mentioned in Figure 13, BESS's primary ancillary services are, for example, frequency regulation, black-start and voltage droop control. From a system point of view, it is essential to keep the supply and demand of electricity in balance. BESS's reaction time to supply and demand changes varies between milliseconds and seconds based on battery type. Recent studies note that battery storages are the best solutions for variations which last a few seconds or less. In a cases like these where short variations exist, BESS is a mature solution and it has higher profitability than other solutions. (Hesse, Schimpe, Kucevic, & Jossen, 2017) Transmission system operators manage frequency regulation in several market areas. Here in Finland, this public sale is provided by Fingrid.

In frequency control applications, BESS begins to feed active power to the network when frequency is below 50 Hz and the transmission system operator cannot fix frequency fluctuation by itself. The battery can also absorb active power from the grid if frequency is more than 50 Hz. Simplified, absorb is charging the battery and supply is discharging. (Datta, Kalam, & Shi, 2019)

Black-start is a situation where a power system outage must be fixed by using other grids or auxiliary power. Usually, only a small part of the power system collapses. For example, a power outage in low voltage network can be fixed by using a high voltage grid. The whole power system rarely collapses, but during a nationwide power outage, there must be auxiliary power to normalize the situation. In general, power suppliers and system operators use other solutions, such as hydroelectric units, diesel generators or gas turbines during black-start. (Feltes & Grande-Moran, 2008)

Currently, BESS can take care most of the black-start cases. The lithium-ion battery is a good choice for black-start situations, because it has a low self-discharge and high nominal output. Black-start capability is an important backup application, not just for a distribution system operator or power supplier, but also for a transmission system operator. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

Other ancillary services are, for example, voltage droop control, time shifting, standing reserve and spinning reserve. (Luo, Wang, Dooner, & Clarke, 2015) Voltage droop control can manage the voltage decrease when a large-scale energy consumer, such as a big industrial engine, is synchronized to network. (Hesse, Schimpe, Kucevic, & Jossen, 2017) Fingrid has several frequency reserve markets which are designed for seconds-to-hours control. These reserves are thoroughly explored in section 5.1.2. (Kuivaniemi & Uimonen, 2019)

4.2 Behind-the-meter

As the title suggests, this group of applications is designed for demand side control. These applications are not essentials for transmission and distribution system operators. Behind-the-meter applications are of interest for small-scale producers, energy companies and industrial customers. As mentioned in the beginning of this chapter, all of the behind-the-meter solutions cannot be directly utilized by BESS next to a renewable energy source. This section presents the possibilities of BESS in behind-the-meter solutions.

Uninterrupted power supply (UPS) is important for both suppliers and customers. Especially hospitals, telecommunication companies, and server centres must have UPS. Currently, several hospitals have gas engines to ensure power supply. BESS's have captured a share of the market, because lithium-ion batteries are reliable and maintenance costs are low over their long service life. New BESSs, which are primary developed to UPS, are constantly capturing market share. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

Sometimes demand for electricity changes quickly. These changes are called ramping. If power demand increases, ramping up is needed. When power demand decreases, it is known as ramping down. Base load power stations, such as nuclear power, are not suitable for ramping because output power is mainly constant. (Grey Cells Energy Ltd., 2019) BESS is a suitable solution for ramping up or down and currently there is no market for ramping. If BESS is used to level off the output power, it is just an auxiliary service for a renewable energy supplier. All in all, every behind-the-meter application requires a special system design for lithium-ion batteries. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

On the 6th of April, 2017, the California Self Generation Incentive Program promised compensations for those energy customers who purchase new environmentally friendly energy technologies. These specified technologies were e.g. wind turbines, internal combustion engines, fuel cells, and energy storage systems. One of the terms for compensation insisted that new technology should cover the customers' on-site electricity demand either partially or entirely. (Orion & Florez, 2017)

The compensations were a great success for behind-the-meter energy storages. Even though the list included dozens of technologies, renewable energy generation technologies gathered only 15% of compensations. The program used compensations to support medium and large-scale energy storages. In order for compensations to be paid, at least 90% of the energy storages had to be bigger than 10 kW. Terms did not define maximum capacity for each energy storage. The total value of BESS compensations were 176 million euros. (Orion & Florez, 2017)

The electricity transmission company Elenia has bought *battery-as-a-service* from Fortum. This pilot project is designed to decrease power outages in a rural area in Kuru, Finland. More about *battery-as-a-service* is examined in section 5.2.2. (Alaperä, 2019a)

4.3 Energy trade

Variation in supply and demand causes fluctuations in wholesale prices. BESS can be charged and discharged during these variations. In the past, non-adaptive generation and base load generation created a profitable market for pumped-storage hydroelectricity. For cost-effective use of pumped-storage hydroelectricity, the power-to-energy ratio must be approximately 1:8. Currently, variations in daily wholesale prices are not as high as they used to be. Reasons for smaller fluctuations are, for example, development of demand-side management. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

Increasing the amount of solar and wind power enable new markets for BESS. The playfully named California duck curve is a good example of the increased amount of solar power and the problems it might cause. When the California duck curve appears, traditional electricity production must be disconnected between 9 am and 1 pm. In this case, traditional electricity production means other forms of production than wind and solar power. To avoid excess generation, traditional production must be decoupled. In the California duck curve case, solar power covered 45% of the total electricity demand between 1 pm and 2 pm. (Denholm, O'Connell, Brinkman, & Jorgenson, 2015, p. 3) Figure 14 visualizes the Californian duck curve.

A bigger issue appears when the sun goes down and solar power does not produce electricity anymore. This ramp up is usually between 5 pm and 8 pm. The demand for an increase in electricity production could be as high as 13 000 MW within three hours. (Denholm, O'Connell, Brinkman, & Jorgenson, 2015, p. 3)

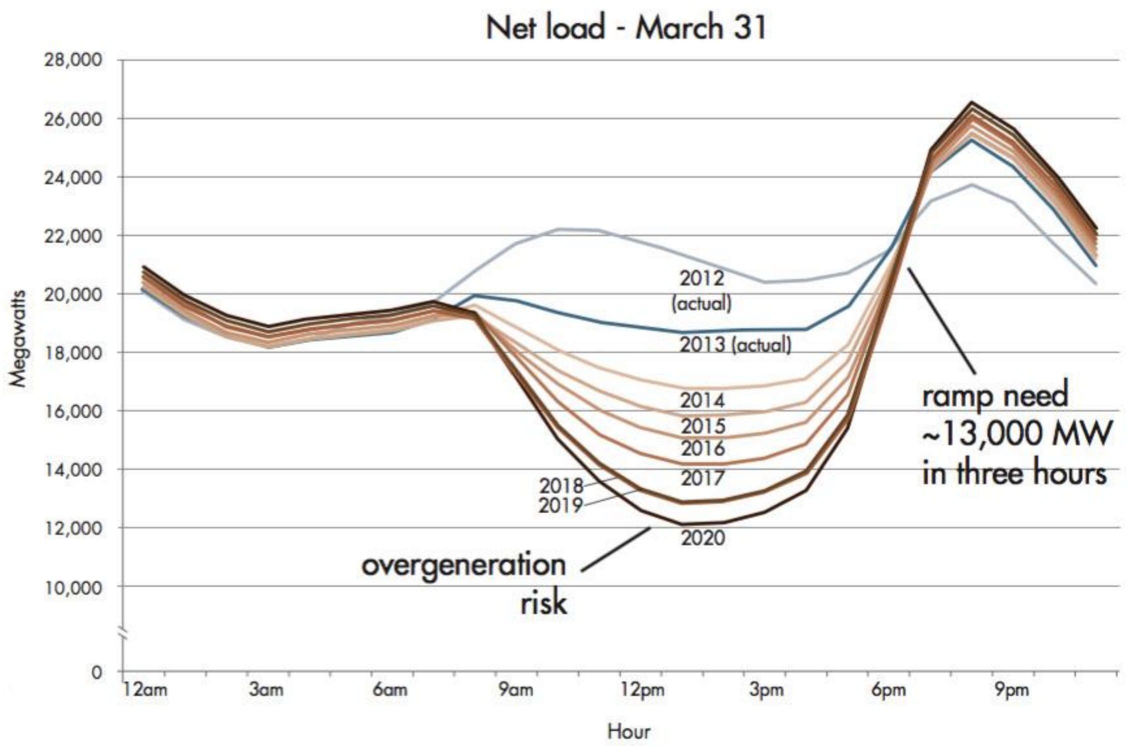

Figure 14. Average and estimated California duck curve between 2012 and 2020 in California Independent System Operator’s network. (Denholm, O'Connell, Brinkman, & Jorgenson, 2015)

When large changes, such as the California duck curve, become popular, BESS becomes more profitable. Of course, BESS cannot ramp up 13 000 MW, but it can be used for peak shaving, give balance during changes, or limit the actual rate of change. In cases like these, quick response time is a benefit for BESS. New studies have proved that lithium-ion batteries are economically viable in situations like the California duck curve. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

It is vital to remember the market saturation which appears in cases like the California duck curve. Too much solar power decreases photovoltaic companies' market revenues. In the evening, other energy sources make profit when solar power production decreases. If markets reach this point, even arbitrage may become profitable. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

4.4 Grid support and capacity deferral

BESS can support the grid in many ways. For example, it can manage demand and supply fluctuations in power grids. It may also provide another option for grid reinforcements, or at least postpone grid reforms. For example, transformers are always designed for peak loads, and BESS can reduce these peak loads. A smaller peak load enables smaller transformers. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

Renewable energy sources and variations in residential and industrial loads create voltage changes. A well-designed BESS is able to control voltage variations by charging and discharging itself. When BESS is used in voltage support, the issue is the lack of compensation. In practice, companies do not make revenue directly from voltage support, but BESS can save money indirectly. The implementation of electricity storage might be a useful product for a distribution system operator, whose duty is to control and stabilize the distribution network. (Hesse, Schimpe, Kucevic, & Jossen, 2017) One of these companies is LE-Sähköverkko.

Globally, the increasing number of electric vehicles and expansive charging infrastructure are driving distribution system operators to be prepared for major voltage fluctuations. The increasing peak power of fast charging solutions requires grid reinforcements at all levels. The charging of electric busses and vehicles by using BESSs have been studied as an alternative solution. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

4.5 Multi-use of BESS

In addition to those aforementioned applications, there are several multi-use applications for BESSs. These multi-use applications, which are also known as multi-purpose and value stacking, are highly studied and researched topics. The reason for such high interest is BESS's is their long inactive time in single-use cases. Often in the single-use cases, the turnover of the investment is far from optimum cash flow. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

The multi-use of BESSs might be challenging in some situations, but well-designed multi-use enables larger profit. It is vital to take into account negative characteristics of lithium-ion batteries, such as the finite number of cycles, DoD, and degradation. Other parties in electricity markets, especially those who set terms for regulatory markets, may not allow multi-use. (Hesse, Schimpe, Kucevic, & Jossen, 2017) For example, Fingrid has specific regulatory constraints for each reserve market. (Kuivaniemi & Uimonen, 2019) It may be difficult to fulfil two regulatory market terms at the same time.

Microgrid and island mode are applications where multi-use of BESS is required. BESS and a well-designed automation system are able to manage concurrent frequency control, voltage control, and power control during fluctuations of supply and demand. Often in microgrids and island mode, BESS can decrease fuel costs when demand for combustion engines and reserve power decreases. Reduction in fuel consumption decreases greenhouse gas emissions in the area. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

One feasible multi-use scenario for Lahti Energia would be a combination of Fingrid's balancing markets and ancillary grid services in the distribution system. Because BESS has a finite number of cycles, high compensation prices are needed for profitable operation in the regulation market. Usually, compensation prices are profitable only a couple of hours per day or less. (Fingrid, 2020a)

During the inactive time, BESS can be used for other services, such as voltage regulation and control, ramping, load levelling, or peak shaving. When reserve market prices are unprofitable, grid services are valuable for the distribution system even though the BESS operator does not receive financial compensation. In addition to regulation markets and grid services, tertiary applications such as black start, capability to island operation, and standing reserve are part of the surplus value of BESS. (Luo, Wang, Dooner, & Clarke, 2015)

In the future, grid services at the distribution system level might become economically viable if a new flexibility market is established to balance the distribution network. Currently, smart local flexibility markets are being investigated in a couple of countries. (de Heer & van de Reek, 2018) (Alaperä, 2019b, pp. 14 - 15) Finland is a pioneering country in flexible market resources due to the remote reading of electricity meters and competitive know-how. (Salokoski, 2017) The University of Vaasa and Technical Research Centre of Finland (VTT) has an ongoing pilot project, Fleximar, where flexible resources at the distribution system operator level are explored in association with Finnish electrical engineering companies. (VTT, 2019)

5 MARKETS AND BUSINESS MODELS FOR BATTERY ENERGY STORAGES

Batteries are not yet the most common players in electricity markets. In Finland, nuclear, CHP, and coal power are the base load power stations. Batteries should not be compared to those, because batteries are not a primary source of energy. After the base load, there are multiple medium and small-size loads following power plants. Over the past decade, renewable energy has gained ground in this part of electricity markets. (Staffell & Rustomji, 2016)

As is well known, electricity generation of renewables is hard to estimate accurately in the long run, because renewable energy is strongly weather dependent. Biopower is an exception, and it can be compared to traditional CHP or coal power plants. The fluctuations of renewables open the markets for balancing, management, and auxiliary services. Capacitors, gas turbines, and diesel motors have been common solutions for these applications. Currently, versatile BESSs are displacing these slow and polluting systems. (Staffell & Rustomji, 2016)

5.1 Structure of Finnish electricity markets

Since 1998, all users in the Finnish electricity market could tender their electricity supplier. The gradual opening of the electricity market began in 1995. Before the competition in the electricity markets started, local electricity retailers had exclusive marketing rights in their own market area. Currently, there are approximately 75 retail dealers in the Finnish electricity market. (Ministry of Economic Affair and Employment of Finland, 2019)

5.1.1 Nord Pool

The history of Nord Pool began in 1991 when the Norwegian parliament decided to open an electricity trading market. In the beginning, the name of the company was Statnett

Marked AS, and it operated only in Norway. After couple of years, operation expanded when Sweden, Denmark and Finland joined the markets. During the 21st century, Nord Pool has expanded, and currently there are 21 countries from Central, Northern and Western Europe. The biggest owner of Nord Pool is Euronext. (Nord Pool, 2020)

5.1.1.1 Day-ahead market

Nord Pool's Day-ahead market is an electricity market where participants can buy or sell electricity. The Day-ahead market includes 21 bidding zones in 14 countries. Every bidding zone has their own hourly prices. Currently, there are over 3 000 participants in the market, and they place more than 2 000 orders daily. Approximately, 500 TWh of electricity is traded through Day-ahead market. (Nord Pool, 2019a)

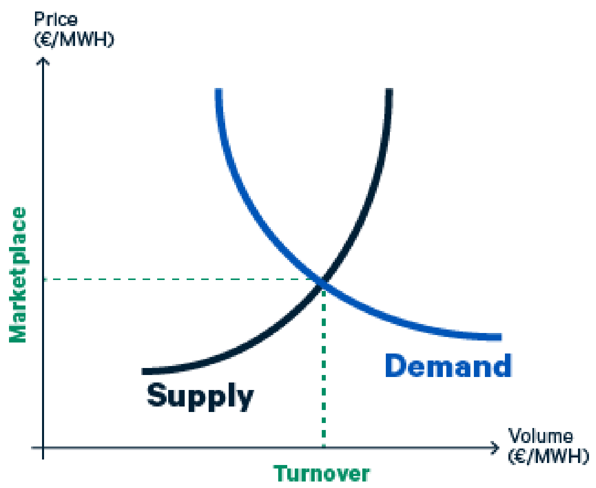

Figure 15. The algorithm-based preliminary estimation of Nord Pool's Day-ahead market price where supply and demand of electricity come across. This figure is an illustration and does not visualize real-life cases. (Nord Pool, 2019a)

The timeline of the Day-ahead market begins at 11 am on the previous day when network capacities are published. Participants have to submit their bids until 1 pm on the previous day. After bids have been submitted, the algorithm calculates the point where expected supply and demand cross each other as in Figure 15. The algorithm uses multiple variables to forecast tomorrow's energy demand in every market zone. This is how hourly prices for every bid zone are formed. (Nord Pool, 2019a)

5.1.1.2 Intraday market

The primary task of the Day-ahead market is to create a valid estimation of supply and demand. In reality, electricity demand changes constantly. When algorithm of Day-ahead market cannot properly forecast electricity demand for each hour in every bidding zone, Nord Pool's Intraday market secure the balance of supply and demand. Weather dependent renewable energy sources increase fluctuations and uncertainty of the power requirements. Balance of power system is vital for many reasons, but from the market perspective, it is important to avoid the use of power reserves. (Nord Pool, 2019b)

Intraday is also vital if hazards appear in Nordic power system. Latest large-scale hazard in Finnish power system occurred 2018 when a fire broke out at Fingrid's 400 kV Olkiluoto substation. As a result of the fire, nuclear power plants Olkiluoto 1 and 2 had to be disconnected from the national grid. (TVO, 2018)

Intraday is a 24/7 market where bids are left one hour before use. The supplier who set the best price is used first. In Finland, the capacities of Intraday are provided by Fingrid and determined after Day-ahead market's flow results. Timing of capacities is based on agreements and operational procedures. Demand for Intraday market capacities are automated, depending on the direction and volumes of trades. Intraday offers 15-, 30- and 60-minute products and block product to ensure the flexibility of market areas. (Nord Pool, 2019b)

5.1.2 Fingrid's balancing markets

In the mid-90s, Finnish transmission network was controlled and owned by several transmission system operators. In November 1996, Fingrid Oyj (later Fingrid) was established to unify Finnish high voltage grid. On the last day of August in 1997, Imatran Voima Oy, Pohjolan Voima Oy and Finnish Government signed the contract to centralize the transmission grid business and management into one company. Since that day, Fingrid has managed the national grid of Finland. Currently, Fingrid's main tasks are maintenance of national grid and securing the availability of electricity throughout the country. To ensure the availability of electricity throughout the country, Fingrid has opened several balancing markets and power reserve markets for energy companies and other energy producers. (Tähtinen, 2017)

Fingrid has decided to keep frequency between 50,1 Hz and 49,9 Hz in the Finnish national grid. As Figure 16 presents, Fingrid has several markets to reach that goal. (Fingrid, 2019b) Currently, Fingrid's balancing markets are undergoing great changes. When energy production turns from fossils to green, markets must adapt simultaneously. Changes to frequency-controlled reserves' technical requirements can be assumed in the coming years. (Frantti, 2020) The following is an overview of Fingrid's balancing markets and requirements.

	FFR	FCR-D	FCR-N	aFRR	mFRR
	Fast Frequency reserve, Finland 20 %, In Nordics, total 0-300 MW (estimate)	**Frequency Containment Reserve for Disturbances,** Finland 290 MW, Nordics total 1450 MW	**Frequency Containment Reserve for Normal Operation,** Finland 120 MW, Nordics total 600 MW	**Automatic Frequency Restoration Reserve,** Finland 60-80 MW, Nordics total 300-400 MW	**Manual Frequency Restoration Reserve** Reference incident + imbalances of balance responsible parties
Activated	In big frequency deviations, In low inertia situations	In big frequency deviations	Used all the time	Used in certain hours	Activated if necessary
Activation speed	In a second	In seconds	In a couple of minutes	In five minutes	In fifteen minutes

Figure 16. An overview of Fingrid's frequency balancing market places. (Karttunen, et al., 2020)

5.1.2.1 Fast Frequency Reserve

Fingrid presented a new Fast Frequency Reserve (FFR) during Reserves day on the 8th of May, 2019. The FFR is a recent product, the idea of which came out in summer 2018. The reason to create a new reserve market was the lack of inertia. (Kuivaniemi & Uimonen, 2019) Inertia means the rotational kinetic energy which resists the change of speed. When a grid has a low level of inertia, it is more fragile to changes in energy production or consumption. These changes create frequency fluctuations. If frequency fluctuations get out of hand, the power grid may collapse partly or entirely. The decreasing number of condensing power plants and the rising number of renewable energy sources, such as photovoltaics and wind power, have reduced inertia globally. Before FFR, Nordic transmission system operators limited the power of the biggest power plant, the Oskarshamn 3 nuclear power plant, to avoid inertia. (Laasonen, 2018)

The FFR is designed to control big sub frequency failures which are caused by inertia. Normally, these failures appear during spring, summer, and autumn weekends, especially at nighttime. Potential players in FFR market are consumers, energy storages, and high voltage direct current (HVDC) links. (Kuivaniemi & Uimonen, 2019)

The technical requirements of FFR were released in Fingrid's Reserves day. Activation times for FFR are divided into three parts, which can be seen in Table 2. Activation time is at least five seconds, while deactivation time is 20 % of maximum capacity per second or at least 30 seconds when there is no restriction for deactivation time. The FFR should be capable of reactivation within 15 minutes. Recovery power can be 25 % of maximum capacity. (Kuivaniemi & Uimonen, 2019) Currently, the estimated amount of FFR in Nordic countries is somewhere between 0 and 300 MW. (Karttunen, et al., 2020)

Table 2. FFR's activation times for different frequencies. (Kuivaniemi & Uimonen, 2019)

Frequency (Hz)	49,7	49,6	49,5
Activation time (s)	1,3	1,0	0,7

5.1.2.2 Frequency Containment Reserve for Normal Operation

The Frequency Containment Reserve for Normal Operation (FCR-N) is the most activated reserve market in Finland. There are two markets inside the FCR-N: the yearly and the hourly market. The minimum bid size is 100 kW. The market price for yearly markets should be submitted in the autumn of the year before. Hourly market prices should be submitted at 6:30 pm on the previous day. (Fingrid, 2019c)

The total capacity of FCR-N is 120 MW in Finland and 600 MW in all Nordic countries combined. (Karttunen, et al., 2020) In addition to these, interconnections Vyborg DC link, Estlink 1 and Estlink 2 are capable to support FCR-N if needed. (Fingrid, 2019d) The FCR-N is activated locally every few minutes and Table 3 presents the compensation prices of the FCR-N yearly market. This reserve increases or decreases power based on frequency. Normally, frequency varies between 49,9 Hz and 50,1 Hz and the FCR-N's task is to keep the frequency within that range. Fingrid has several frequency measurement points around their transmission network which enables automatic frequency regulation. (Karttunen, et al., 2020)

Table 3. The FCR-N yearly market's average prices and capacities between 2011 and 2019. (Fingrid, 2019b)

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
Price (€/MWh)	9,97	11,97	14,36	15,80	16,21	17,42	13,00	14,00	13,50
Capacity (MW)	71,0	72,7	73,5	75,4	73,6	89,0	55,0	72,6	79,0

5.1.2.3 Frequency Containment Reserve for Disturbances

Sometimes frequency does not stay between 49,9 Hz and 50,1 Hz. When these situations occur, the Frequency Containment Reserve for Disturbances (FCR-D) starts to operate. Almost linear regulation should begin in 5 seconds and full capacity should be in use within 30 seconds. Currently, FCR-D is only for under-frequency events. Fingrid is capable of using 290 MW of FCR-D in Finland. Altogether, FCR-D's total capacity in the Nordic countries is 1 450 MW. (Karttunen, et al., 2020) Fingrid has decided to open the FCR-D market also for over-frequency events. This expansion of the FCR-D market is expected to happen at the end of 2021. (Frantti, 2020)

Declutch loads also participate in FCR-D markets. These loads are disconnected as a function of frequency and time. When frequency is 49,7 Hz, disconnection time is five seconds. If frequency is 49,6 Hz, disconnection time is three seconds and when frequency is 49,5 Hz or less, disconnection time is one second. Fingrid has declutch loads up to 100 MW for every hour. (Karttunen, et al., 2020) These loads are activated a few times in a year. (Fingrid, 2019c)

FCR-D includes yearly and hourly markets. Prices for the yearly market are submitted in the autumn of the year before. A big difference between FCR-D and FCR-N is FCR-D's minimum participation size, which is one megawatt. Under normal conditions, FCR-D activates several times in a day. Table 4 presents the compensation prices in the FCR-D yearly market. Compensation price varies from 1,48 €/MWh to 4,7 €/MWh. (Fingrid, 2019c) Hourly market compensations are a few tens of euros per megawatt hour. (Karttunen, et al., 2020)

Table 4. The FCR-D yearly market's average prices and capacities between 2011 and 2019. (Fingrid, 2019b)

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
Price (€/MWh)	1,48	2,80	3,36	4,03	4,13	4,50	4,70	2,80	2,40
Capacity (MW)	244,3	346,9	299,8	318,7	297,5	367,0	455,7	435,0	445,6

5.1.2.4 Automatic Frequency Restoration Reserve

The Automatic Frequency Restoration Reserve (aFRR) is designed to control frequency all the time. Fingrid sends up- or down-regulation requests to power plants or large industrial customers. These requests are sent in every few minutes. The activation time for aFRR is within five minutes. Currently, aFRR is active a couple of hours per day. Fingrid and other Nordic transmission system operators have planned a mutual aFRR market. The minimum bid size is 5 MW of power. (Karttunen, et al., 2020)

These reserves are normally activated in during certain morning and evening hours. Sometimes aFRR is acquired from Sweden when our hourly market cannot provide enough aFRR. (Fingrid, 2019d) Demand for aFRR has increased in recent years. Fingrid has openly stated that they need more aFRR to ensure the reliability of operation. Currently, the aFRR capacity in Finland is only 60 – 80 MW. The Nordic countries combined have 300 – 400 MW of aFRR. (Frantti, 2020)

The market price for the aFRR hourly market must be announced at 5 pm on the previous day. The compensation is paid on a pay-as-a-bid basis, in addition to the current price of energy in the Manual Frequency Restoration Reserve market. (Fingrid, 2019c) Normally, the capacity compensation is a few tens of euros per megawatt hour. (Karttunen, et al., 2020)

5.1.2.5 Manual Frequency Restoration Reserve

While all the previous ones were automatic products, Manual Frequency Restoration Reserve (mFRR) is the only manual reserve product. The mFRR includes three different reserves: balancing energy markets, fast disturbance reserve, and balancing capacity markets. (Karttunen, et al., 2020) Fingrid has 935 MW of power from its own back-up power plants and 299 MW of power from leasing reserve power plants. (Fingrid, 2019d) All three mFRR's must be fully activated within 15 minutes. (Fingrid, 2019c)

Fingrid maintains the balancing energy market which is part of the Nordic balancing market. Balancing energy markets are hourly markets and it includes both up- and down-regulation. The minimum bid size is 5 MW for electrical orders and 10 MW for others. (Karttunen, et al., 2020) Bids have to be submitted 45 minutes before every opening hour. (Fingrid, 2019c)

Bids in balancing energy markets are activated from smallest to largest based on price. Technical requirements are also taken into account. Compensation includes the ordered energy and the highest accepted bid during each hour. If Fingrid needs special regulation, then the pay-as-a-bid –principle is used. The price level is always higher than Nord Pool's Day-ahead prices. Sometimes prices increase to over one thousand euros. (Karttunen, et al., 2020)

The difference between the fast disturbance reserve and balancing energy markets is the guaranteed up-regulation capacity of the fast disturbance reserve. Nordic transmission system operators have agreed that each country must have enough fast disturbance reserve to protect at least their own hazards. In Finland, this means 880 – 1 100 MW of power, depending on the size of the hazard. These megawatts are produced in Fingrid's own back-up power plants and in long-term leased reserve power plants. Leased reserve power plants are not allowed to operate in other electricity markets. Since 2016, Fingrid have had declutching agreements with large-scale customers. Fingrid can buy fast disturbance reserves from other Nordic countries if demand exists. (Karttunen, et al., 2020)

Balancing capacity markets are designed to ensure enough up-regulation power to balancing energy markets for each day. During reserve power plants' yearly overhauls or production problems, balancing capacity markets are used to ensure the sufficient amount of fast disturbance reserve. (Karttunen, et al., 2020) The minimum bid size is 5 MW. Balancing capacity markets use weekly markets where bidding is conducted for one week at a time. These weekly bids need to be submitted at 12 pm on Tuesday of the previous week. (Fingrid, 2019c) The winner of the competition is committed to submit an up-regulation bid to the market at 1 pm on the previous day, each day of the week. This bid is known as a balancing capacity bid. The reserve provider receives revenue when an up-regulation bid is submitted. In addition to this, the provider gets the availability payment based on the activation and duration of the reserve. (Karttunen, et al., 2020)

5.1.3 Derivative markets

This market includes electricity spin-offs, such as options and futures contracts. Energy companies use the derivative market to minimize the risk of price fluctuations. The end users may use the derivative market to ensure lower prices for themselves. Sales companies use the derivative market to avoid high prices when users have a fixed price. Currently, there are a couple speculative operators, because companies are allowed to participate in the markets even if they do not produce electricity. (Fingrid, 2019a)

5.1.4 Power reserve

The Finnish Energy Authority is obliged to maintain the power reserve. The power reserve includes power reserve capacity and decoupling power. The system is designed for situations where the market supply cannot ensure the security of the electricity supply. Currently, the total capacity of the power reserve is 729 MW. The annual cost of maintaining the system is 13,8 million euros. (Energy Authority, 2019) The Energy Authority has decided the power reserve suppliers for the ongoing season which begun the 1st of July, 2020 and ends the 30th of June, 2022. Lahti Energia's 42 MW Kymijärvi KT natural gas turbine is selected to season 2020 – 2022. In theory, BESS could be a part of Energy Authority's power reserve capacity. However, the minimum increase in production that the Energy Authority requires is 10 MW within 10 minutes. The participating energy operator must be able to operate at full power 200 hours or more. When the increase in power is at least 10 MW and required continuous operation time is 200 hours, there is no battery which could fulfil the requirements. (Energy Authority, 2017)

5.2 Business models

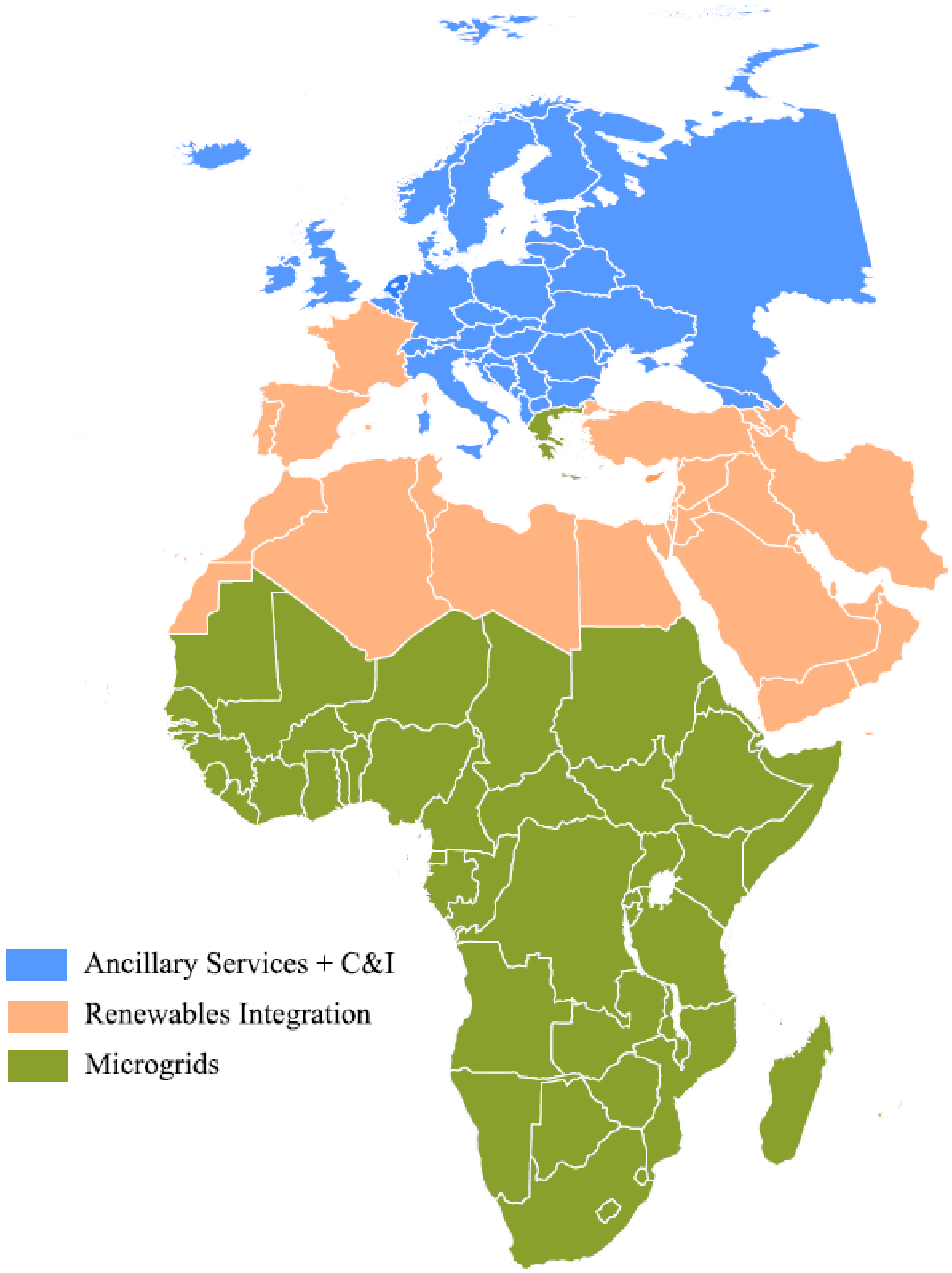

Figure 17. Rough generalization of the highest potential lithium-ion battery market applications in the Europe, Middle East and Africa (EMEA) region. (Killer, Farrokhseresht, & Paterakis, 2020)

Figure 17 claims that commercial and industrial (C&I) ancillary services would provide the most potential income for BESS here in Finland. (Killer, Farrokhseresht, & Paterakis,

2020) This section investigates the claim and other possible business models for stationary lithium-ion batteries.

5.2.1 Value proposition

The BESS improves the stability and reliability of both the distribution network and the transmission network. Frequency control, reserve products, and reserve power increases reliability. (Leisen, Steffen, & Weber, 2019) A battery next to a renewable energy source would give Lahti Energia several new options to be prepared for fluctuations, risks, and hazards. Placing a BESS next to renewable energy source improves the plant's flexibility. (Masiello, Roberts, & Sloan, 2014)

During the last few years, Lahti Energia has taken big steps towards fossil fuel free electricity and district heating production. As mentioned earlier, year 2019 was the last year the company used coal in its power plants. The abandonment of coal was one of the key reasons why the city of Lahti got the 2021 European Green Capital Award. (Lahti Energia, 2019b) The future goal could be emission-free energy production. Because of its versatility, BESS enables environmentally friendly solutions to reserve power.

In addition to reserve power, the load shifting is another valuable application that BESS permits. For the customers of LE-Sähköverkko, the load shifting enables cleaner energy for longer periods. In general, energy storage is an easy way to prepare for supply and demand changes. (Leisen, Steffen, & Weber, 2019)

5.2.2 Customers

The BESS can operate in both the Day-ahead and the Intraday market. In section 5.1.2, Fingrid's balancing markets were explored and BESS can participate in them. However, participating in the mFRR requires large batteries, because the minimum bid size is 5 MW. (Fingrid, 2019e) From BESS point of view, Lahti Energia itself may 'become a customer', if problems occur in the power plant. The storage brings surplus value to LE-

Sähköverkko because BESS can be used to shave peak loads and postpone investments. (Castillo & Gayme, 2014)

In Finland, distribution system operators are not allowed to own energy production facilities. The BESS operator can buy electricity from the markets and sell electricity to the markets, so it is quoted to facility which produces energy and is able to participate into energy markets. Even though a distribution system operator cannot own BESS, they can buy services from an energy production company. (Alaperä, et al., 2019)

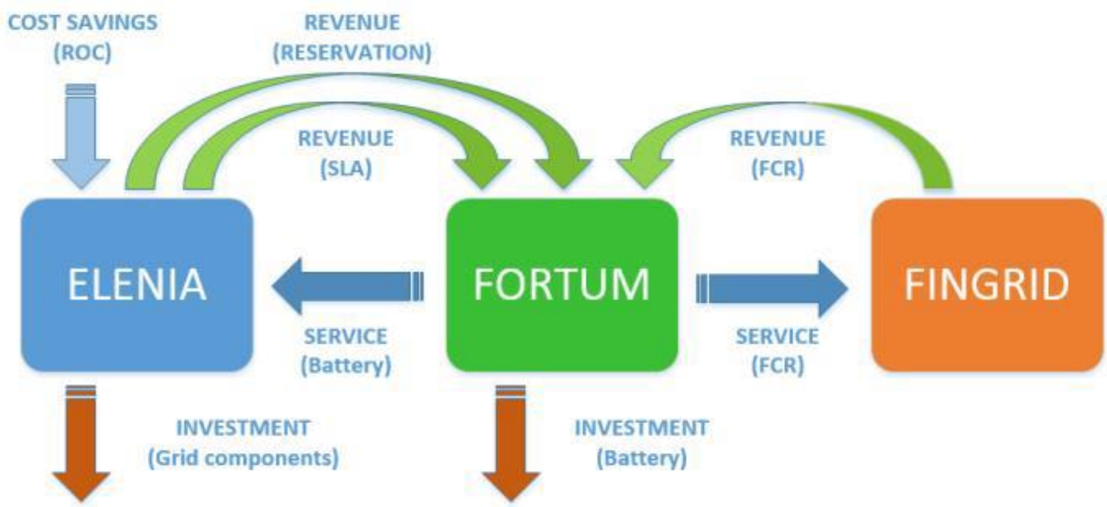

Figure 18. Visualized business model for battery-as-a-service in case Kuru. (Alaperä, et al., 2019)

In Kuru, Finland, distribution system operator Elenia and energy company Fortum have created a business model where the distribution system operator buys services from energy company. Because regulatory outage costs are high in Finland, Elenia buys battery-as-a-service from Fortum. Elenia buys a service, for example, if a storm is rising within next 12 hours. Remote power lines have more than 100 customers and occasionally weather conditions create power failures. If connection issues with the main grid appear, BESS enables island mode operation for three hours. When primary customer Elenia does not need BESS services, Fortum’s BESS participates in Fingrid’s balancing markets.

Elenia also pays an annual payment to Fortum who provides battery-as-a-service. Figure 18 presents business model for this case. (Alaperä, et al., 2019) (Alaperä, 2019)

Customer relationships consist of customer specific demands that a battery has to meet in order to serve its customers. Once BESS fulfils the customers' requirements, a binding agreement can be made. It might be difficult for a single BESS to meet multiple customer's requirements. After the binding agreement, communication between BESS and customer is fully automated. (Leisen, Steffen, & Weber, 2019)

5.2.3 Value creation

As mentioned earlier in chapter 4, purchasing a BESS enables multiple applications. When making an energy storage purchase decision, the company must consider the characteristics of BESS which are explored in section 3.1. Each manufacturer has a slightly different solution. Some solutions may not be suitable to Nord Pool's and Fingrid's markets. In addition to technical information, safety standards of BESS must be observed when purchase decisions are made. (Castillo & Gayme, 2014)

Currently, Lahti Energia participates in two of Fingrid's balancing markets, power reserve, and mFRR. The company also manages the emergency power plant. The mFRR is activated last, because its activation time is 15 minutes. The mFRR also has the highest number of other participants which are listed in APPENDIX 1. Lithium-ion batteries have the fastest response time of all storage systems, which enables the participation to each of Fingrid's reserve markets. (Fingrid, 2020b) (Fingrid, 2019c) (Karttunen, et al., 2020)

Although NordPool's markets are not profitable in daily trading, sometimes market fluctuations allow a profitable participation of energy storage. (ÅF-Consult Oy, 2019) These fluctuations should be utilized. Sometimes the price of energy on the Nord Pool's markets can be negative due to overproduction. (Roland Berger GMBH, 2017) Since Lahti Energia does not yet have large-scale heat pumps or electric boilers for district heating production, the BESS remains the only opportunity to take the advantage of the negative price of electricity. (Rosenlund, Olsen, Skytte, Sneum, & Sandberg, 2016) Currently, negative electricity prices only decrease Lahti Energia's revenue. Chapter 4 introduced various applications that would add value to Lahti Energia. Table 5 lists those applications' surplus value and application categories.

Table 5. A list of BESS applications and surplus value. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

Application	Surplus value	Category
Frequency control	Compensation from Fingrid, grid management	Ancillary
Black-start	Environmentally friendly black-start	Ancillary
Voltage control	Reliability	Ancillary
UPS	Reliability	Behind-the-meter
Ramping	Grid management	Behind-the-meter
Arbitrage	Compensation from NordPool	Energy Trade
Peak shaving / Load shifting / Load levelling	Less backup power, investment deferral, lower risk of overgeneration	Ancillary, Energy Trade, Grid Support, Capacity Deferral
Voltage support	Reliability	Grid Support
Electric vehicles charge support	Grid management	Grid Support
Multi-use	Value stacking	Multi-use
Island Mode & Microgrid	Grid management, less backup power, power control, etc.	Multi-use

5.2.4 Value capture

The biggest expense of BESS are the investment costs. In most cases, investment costs include battery racks, automation systems, power electronics, fire protection, and transformers. Some BESS manufacturers have products which include all of this in one or several ISO-containers. (Fu, Remo, & Margolis, 2018) Operation and maintenance costs are divided into two separate expenses. Fixed operation and maintenance costs are annual operational expenses. Even if BESS is not operating, these costs do not change. Variable operation and maintenance costs are dependent on produced energy. When BESS reaches the end of its service life, reutilization costs must be considered. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

Prices in Table 6 are Fingrid's own simplified calculations for reserve market revenues. The minimum bid sizes are the smallest possible size to participate to the market. Annual operation hours are Fingrid's statistics from previous years. In annual compensations, bid sizes are 1 MW, except in mFRR, where the bid size is 10 MW. (Fingrid, 2019e) As mentioned in section 2.3.2, it should be noted that the finite cycle life of BESS may complicate the annual operation hours. (Argyrou, Christodoulides, & Kalogirou, 2018)

Table 6. Simplified calculations of reserve markets. (Fingrid, 2019e)

Market		**Minimum bid size**	**Average yearly prices**	**Annual operation hours**	**Annual compensations**
FCR-N	Yearly	0,1 MW	14,0 €/MWh	7 000	98 000 € (1 MW)
FCR-N	Hourly	0,1 MW	27,4 €/MWh	4 000	109 600 € (1 MW)
FCR-D	Yearly	1 MW	2,7 €/MWh	7 000	18 900 € (1 MW)
FCR-D	Hourly	1 MW	17,3 €/MWh	1 000	17 300 € (1 MW)
mFRR	Hourly	5 MW	176 €/MWh	137	241 069 € (10 MW)

5.3 Battery operation in electricity markets

Fortum has openly stated that their BESS's primary revenue comes from frequency balancing markets. (Alaperä, et al., 2019) The primary markets for Helen's BESS are the FCR-N and the FCR-D markets, reactive-power compensation, stabilization of supply and demand, and grid maintenance during abnormal condition. (Karppinen, 2017) The annual costs of FCR-N and FCR-D are 30 million euros for Fingrid. (Lovio & Tuomi, 2018)

5.3.1 Suitability

Currently, hydropower is the most common electricity production method in Fingrid's reserve markets. The demand for balancing power is expected to increase in the future when traditional electricity production is replaced by irregular wind and solar power. (Finnish Energy, 2019) Hydropower cannot participate in the FFR market, because its response time is seconds. Other competitors in the FFR market are HVDC links and consumers. (Kuivaniemi & Uimonen, 2019)

Lithium-ion batteries have high power density and high energy density. Unfortunately, the problematic characteristics of BESSs, such as service life and costs, are more defining than densities. It is difficult to prove that BESS is the most suitable solution for a particular application by using only technical features. (IRENA, 2017, p. 42)

Luo, Wang, Dooner, and Clarke (2015) presented an application list for energy storages. The list included 25 different applications and seasonal energy storage was the only application which was not suitable for BESS. The only promising technologies for seasonal energy storing were thermal energy storages and pumped-storage hydroelectricity. For the other 24 applications, batteries were mentioned as experienced solutions. Based on Luo, Wang, Dooner, and Clarke's (2015) findings, it can be stated that if there are any market requirements, BESS is capable to fulfil them.

5.3.2 Competing technologies

ÅF-Consult Oy (2019) have estimated that hydropower will still be the biggest player in Fingrid's reserve markets in 2030. Hydropower is a cheaper production type when energy demand is hours. If water resources are slight in Finnish rivers and the use of hydropower is forbidden, Fingrid purchase cheap hydropower from neighboring countries.

From an economical point of view, the replacement of hydropower for BESSs would be extremely costly, and it would increase the Finnish power system's greenhouse gas emissions. The survey proved the known fact that hydropower is the most efficient production type when energy demand grows, but BESS is a potential operator when there is a demand for a rapid increase in power. (ÅF-Consult Oy, 2019)

Virtual power plants are the new arrivals in the energy markets. Virtual power plants may include for example wind energy, energy storage, and hydropower. These distributed entities are connected via cloud service. Siemens has captured the markets in Finland. More about Finnish virtual power plants is explored in section 6.3.1. (Siemens, 2019a)

The virtual energy storage system is another new competitor which can be easily mixed up with virtual power plant because there are several similarities. The biggest difference is that virtual power plant combines distributed energy sources to act as one power source, while virtual energy storage stores excess electricity and is capable to reduce electricity consumption during the peak demand hours. In addition to energy storage, there are several energy entities, such as flexible loads, electric vehicles, renewable energy sources, and microgrids which can together form a virtual energy storage system. Currently, there are a couple of case studies globally. (Cheng, Sami, & Wu, 2017) (Hasan, Sharma, & Brenna, 2019)

5.3.3 Other participants in Fingrid's balancing markets

Participants in Fingrid's reserve markets are listed in APPENDIX 1. Currently, there are six participants in aFRR markets. Most of them own hydropower. The most competed markets are FCR-N and FCR-D where there are 23 participants and mFRR where there are 29 participants. In addition to Fingrid's own power reserve plants, seven companies share the responsibility of reserve power plants. (Fingrid, 2020b)

Couple of balancing service providers are other than energy companies. For example, Kemira Chemicals Oy, SSAB Europe Oy and KOY Kauppakeskus Sello, are balancing service providers. (Fingrid, 2020b) KOY Kauppakeskus Sello has a virtual power plant and their solution is more comprehensively explored in section 6.3.1. The number of these small electricity providers is expected to increase in a future. (Ministry of Economic Affair and Employment of Finland, 2019)

5.4 The future of electricity production in Finland

A former Finnish cabinet, the cabinet of Juha Sipilä, decided to renounce coal power plants during the 2020s. Compensatory solutions were expected to be renewable energy sources, especially bioenergy, and the development of environmental technologies. (Finnish Government, 2015, p. 23) In their government programme the cabinet of Antti Rinne decided to prohibit coal power plants after May 2029. (Finnish Government, 2019, p. 34) The current cabinet has resumed the coal power renouncing program.

The use of coal will decrease rapidly after 2020. The drop has already begun, even though coal is still cheap. Natural gas can be seen as a transition solution before Finland has a fossil fuel free power system. (Salokoski, 2017) For example, natural gas, biogas, and BESSs are the transition energy sources when Germany tries to renounce nuclear and coal within the next decade. (BloombergNEF, 2020)

Between 2030 and 2050, European Union countries invest more in renewable energy sources, because countries need other solutions to replace nuclear power. It should be noticed that nuclear power plays a big role when the Finnish power system try to reach net zero carbon footprint. In the future, nuclear power plants' service life is expanded and technology is modernized even though new nuclear power plants might be prohibited. (Salokoski, 2017) In 2050, Finland is expected to be the only Nordic country which still has nuclear power. (IEA, 2016, p. 50)

5.4.1 The increase in distribution

The increase of distributed power systems in Europe has been rapid. The change from centralized to distributed has increased the demand for flexibility in power systems. In the future, the Finnish power system will be more flexible than it is now. (Salokoski, 2017) Figure 19 presents the current cost-decline of renewables and energy storages. This decline advances the growth of decentralized grids both locally and globally. (BloombergNEF, 2020)

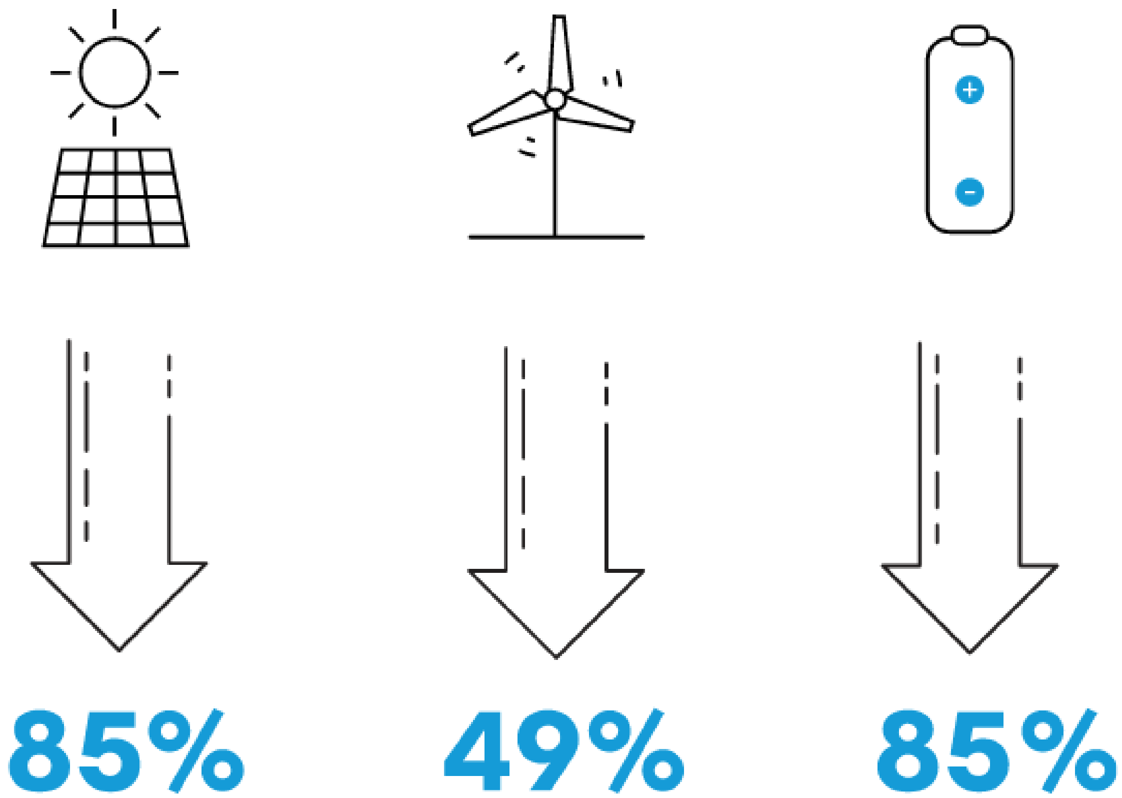

Figure 19. The price fall of photovoltaics, wind power and batteries since 2010. (BloombergNEF, 2020)

On-shore wind turbines have the highest growth potential of renewable energy sources. The size of a single wind turbine can reach up to 15 MW. Offshore wind farms become more common even though the technology has not reached its growth forecast. (Salokoski, 2017) Figure 20 presents one layout plan for offshore wind power in Finland. The size of those windmills at Oulunsalo-Hailuoto off-shore wind farm project were expected to be between 3 MW and 5 MW. (Pöyry Finland, 2014) Couple of years after Pöyry's appraisal, project team put the plan on hold. The reason was negative results that appear in environmental impact assessment. (YLE, 2016)

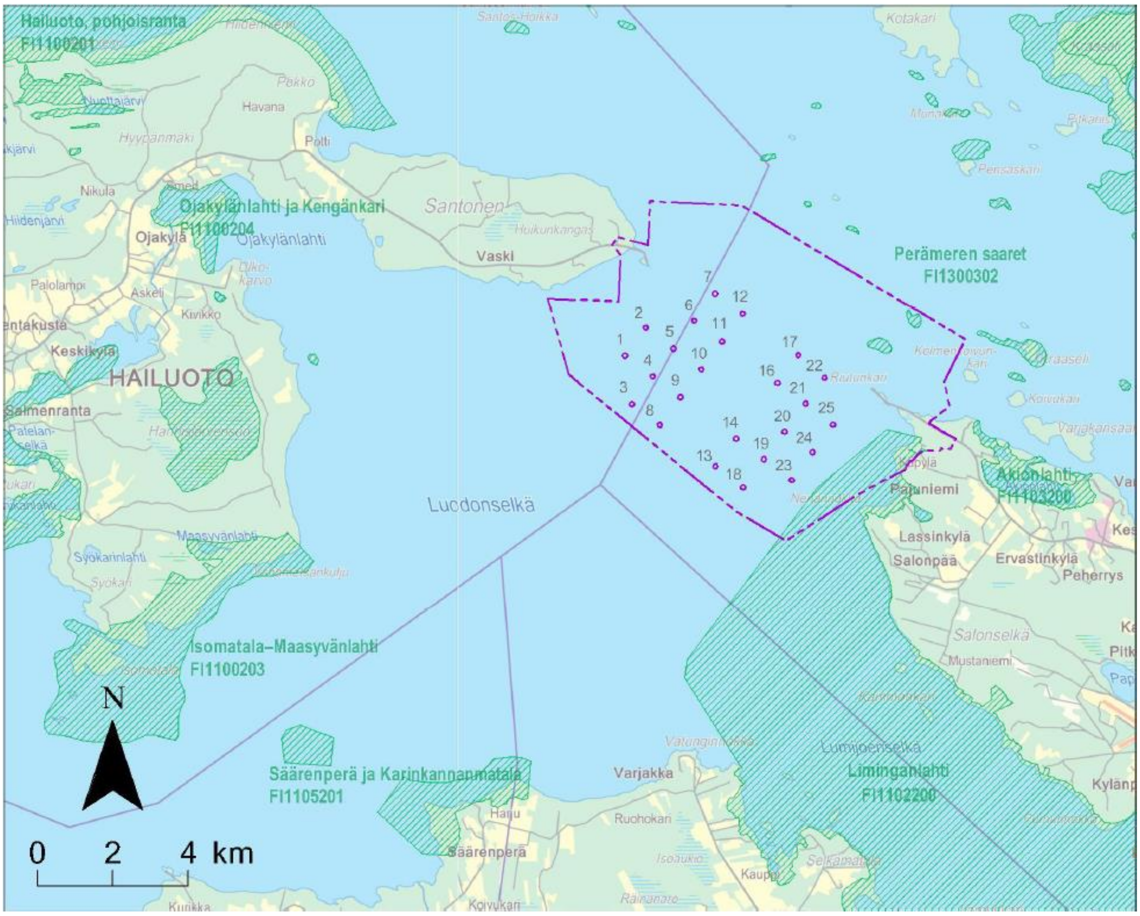

Figure 20. The project map of 24 offshore wind turbines close to municipality of Hailuoto and the city of Oulu. Even though there is a point number 25 in a map, the actual number of wind turbines was projected to be 24. (Pöyry Finland, 2014)

Photovoltaics has a large role in the future of distributed systems. The growth of solar power has been the fastest amongst renewables, and the growth is expected to increase during next decade. Photovoltaic is expected to be the most suitable solution for renewable energy in metropolitan areas. It is estimated that someday all of our electricity will come from the sun, but currently it is impossible to say when it will happen. When power generation reaches this state, energy might be free and there may be excess generation issues. (Salokoski, 2017)

Day by day, there are more individuals whose renewable energy sources create more electricity than they need. Small-scale producers sell their surplus to the markets. These small producers are new players in the electricity markets, but they need to be taken into consideration when future electricity markets are assessed. (Ministry of Economic Affair and Employment of Finland, 2019)

Like other renewable energy sources, bioenergy is expected to increase, especially in energy production and transportation. In the Nordic countries, bioenergy as a primary energy is estimated to grow from 300 TWh to 450 TWh by 2050. Ethical questions of bioenergy might affect the use of biomass. Especially the usage of wood as a fuel in electricity and heat generation has gained criticism. (IEA, 2016, pp. 54 - 59)

Altogether, the growth of renewables increases the distribution of energy systems and new hybrid power plants. These new hybrid solutions are highly automated and able to ramp up or down depending on energy demand. Hybrid power plants which combine multiple power production types become more popular, especially in microgrids. (Salokoski, 2017)

5.4.2 Energy storages

In 2017, there was roughly 4,7 TWh of energy storage capacity in the whole world. The share of stationary batteries was only 11 GWh. Within next ten years, the global energy storage capacity is expected to grow up to 12 – 16 TWh. While global storage capacity is expected to triple, stationary BESS's total capacity decuples up to 100 – 167 GWh. (Hesse, Schimpe, Kucevic, & Jossen, 2017)

When renewable weather dependent energy increases, the need for energy storages also increases. Energy storages are capable to discharge themselves when solar and wind power cannot keep up the balance between supply and demand. One reason for growth of photovoltaic is the better efficiency and lower cost of energy storage systems. (Salokoski, 2017)

If we believe current trends in energy systems, we might have fossil fuel free microgrids in 2025. These microgrids would also include energy storages. In the future, power-to-X solutions are able to challenge battery storages. For example, power to gas is one of the solutions with the highest potential for seasonal storing because synthetic gas can be stored into a natural gas pipeline system. (Salokoski, 2017)

6 BATTERY STORAGES AS AN INVESTMENT

6.1 Market scheme

Lithium-ion batteries used to be expensive. The development of the automotive industry declines the prices of stationary BESSs. Prices are expected to decline by 64% within the next ten years. The levelized cost of storage is also expected to decline by 64% within the next 20 years. In 2025, BESS is the cheapest way to produce peak power. (BloombergNEF, 2020)

As mentioned earlier in chapter 4, battery energy storages have some applications which are economically feasible. The BESS must be capable of offering several different applications in order to be a profitable investment. (Teng, et al., 2017) (Alaperä, et al., 2019) One of the biggest issues is the estimation of financial worth of those applications which do not have market places. Another issue is that none of these applications are new, so companies probably already have solutions for these applications. Storage purchasers have to estimate the incomes from each application, multi-use capabilities of BESS, operating costs, and residual value. From an economic and environmental point of view, the comparison between BESS and other systems in each application is recommended. (Yao, et al., 2016)

According to ÅF-Consult Oy (2019) differences between high and low prices need to be more than 125 €/MWh for profitable arbitrage operation. Normal difference in Finnish Day-ahead bidding zone prices is 25 €/MWh within one day. In practice, this means that arbitrage is rarely a profitable solution for the BESS owner.

6.2 Regulation, taxation, and subsidies

While most renewable energy sources produce energy irregularly and the EU has decided to renounce coal, there must be a reliable solution to ensure stability between supply and demand. The EU has pointed out general provisions on the security of electricity supply in Directive 2005/89/EC. Here are some general provisions that apply to Member States within the EU area:

"(a) the importance of ensuring continuity of electricity supplies;"
"(f) the need to ensure sufficient transmission and generation reserve capacity for stable operation;"
"(c) the importance of encouraging energy efficiency and the adoption of new technologies, in particular demand management technologies, renewable energy technologies and distributed generation;" (The European Parliament and the Council of the European Union, 2006, p. 3)

The Finnish Government has carried out changes in order to meet the objectives of the aforementioned directives. A couple of years ago, the cabinet of Juha Sipilä decided to abolish double taxation of energy storages. Double taxation occurred when electricity was charged from the grid and later electricity was discharged back to the grid. In the first section, the government decided to remove double taxation of large-scale battery energy storages. In the later section, the aim was to investigate the elimination of smaller battery energy storage's double taxation. This elimination would allow the use of electric vehicle batteries as a buffer storage in the power grids. (Ministry of Finance, 2018a)

In the government programme, the cabinet of Antti Rinne promised to remove double taxation of pumped-storage hydroelectricity and smaller battery energy storages. (Finnish Government, 2019, pp. 24, 33 & 34) Based on Energy taxation (191/2018), BESS is considered to be part of the power plant's taxation when BESS is alongside an energy source. In cases like these, the discharged electricity of the batteries should be reported together with the power plant's own production. If a stationary BESS is located in a place where it is directly connected to power consumption, the BESS owner has the right to apply for an exemption from electricity taxation. (Ministry of Finance, 2018b)

The Finnish government programme promises to modify energy practices that directly or indirectly affect to the profitability of BESS. The energy support system will change from production subsidies to new energy technology investments and demonstration subsidies. Like the previous government, the current one is also investing in renewable energy resources. Initially, the government promises to improve development of off-shore wind farms and, in general, remove administrative and land use planning barriers of wind power. Electricity transmission fees are also investigated. (Finnish Government, 2019, pp. 24, 33 & 34)

The government organization called Business Finland supports environment-friendly investigation projects and investments. In Finland, this subsidy is better known as an energy aid. The energy aid can be applied to projects or investments which advances energy production, efficiency, energy savings, the use of renewable energy or in other ways promotes carbon neutral energy system. Energy storage can receive a subsidy if project enhances energy efficiency or involves renewable energy capacity. The subsidy can cover up to 50% of the total investment costs. (Business Finland, 2021)

6.3 Current battery energy storage systems in Finland

As mentioned in the beginning of the thesis, BESS has gained curiosity among the energy companies in Finland. Some players already have own BESS, such as Fortum and Helen. Every BESS mentioned below has a lithium-ion battery.

6.3.1 Battery energy storage as a part of microgrid

In the autumn 2018, a Finnish company called Merus Power Dynamics (later Merus Power) announced a battery agreement with the German discount supermarket chain Lidl. The size of the energy storage was 2,6 MW/ 1,55 MWh. This energy storage is placed into Lidl's new delivery centre. (Merus Power, 2018) In addition to BESS, the distribution centre's smart microgrid includes 1 600 solar panels and two backup power systems. Solar panels produce most of the distribution centre's electricity demand, but the microgrid is also connected to a distribution network. Lidl is willing to utilize situations where cheap electricity is available in the Finnish bidding zone. The primary revenue for the microgrid is Fingrid's reserve markets. The indirect benefits are, for example, avoiding the high electricity prices during peak load hours and the distribution centre's self-managed real-time balance between supply and demand. (Sweco, 2019)

The largest shopping centre in Finland, Sello, decided to purchase a virtual power plant to cut electricity costs. Sello's microgrid includes 2 500 solar panels which create 750 kWp, 24 electric vehicle charging stations, and 2 MW/ 2,1 MWh BESS. This property contains Northern Europe's largest embedded energy storage which participates into Fingrid's reserve markets. (Sello, 2019) The solar panels' primary task is to produce electricity for mall itself and store surplus. The BESS is charged during night-time if Nord Pool's Day-ahead prices are low. As in the case of Lidl, Sello also aims to avoid buying electricity during expensive peak load hours. The virtual power plant in Sello was manufactured, designed, and implemented by Siemens in collaboration with Fingrid. (Kauppalehti, 2019)

The LEMENE-project is a new small-scale industry park which utilizes a smart grid solution instead of a distribution system operator's medium voltage network. This smart grid includes 15 000 solar panels which create 3 600 MWh energy capacity annually, six electric stations, 30 medium voltage switchgears, five electric stations, a distribution transformer, an auxiliary switchboard, gas engines, fuel cell, Fluence's 2,4 MW/ 1,6 MWh Siestorage BESS, and Merus Power's 2,4 MW/ 1,6 MWh BESS. Siemens' decentralized energy management system enables LEMENE's smart grid and BESS to be used as a virtual power plant and participate to Fingrid's reserve markets. The LEMENE-project in Marjamäki, Lempäälä is one of the key projects of the Ministry of Economic Affairs and Employment. Fluence is a subsidiary of Siemens. (Siemens, 2019a)

At the end of 2019, 11 new pyramids were completed in Könkä village, Kittilä. These Hullu Poro's glass-roofed pyramids are designed for admiring the beauty of the Aurora Borealis. In addition to admiring the natural wonders, the pyramids are environmentally friendly, because they are connected to the world's northernmost microgrid. This microgrid is manufactured by Siemens and it includes a 132 kWp photovoltaic system and BESS. The BESS size is 1,3 MW. In a business-as-usual situation, pyramids are connected to the main grid. In case of an emergency, the microgrid can operate in islanded mode for a short period of time. As in the aforementioned microgrids, the Aurora pyramids network is also able to act as a virtual power plant and participate in the reserve markets. (Siemens, 2019b)

A Finnish brewery and soft drinks company Sinebrychoff has made a virtual power plant contract with Siemens. This contract includes Fluence's 20 MW/ 20 MWh Edgestack energy storage which will be located at Sinebrychoff's production plant in Kerava, Finland. This lease-based BESS will be part of Siemens' virtual power plant solution. The BESS is expected to be in commission at the end of 2021. (Sinebrychoff, 2020) (Siemens, 2020)

6.3.2 Battery energy storage alongside a power plant in Finland

Currently, several BESSs alongside a power plant are connected to the Finnish electricity network. Helen, the energy company from the Finnish capital, purchased the first BESS in Finland. In 2015, Helen's BESS in Suvilahti, Helsinki, cost 2 million euros. (Energiatalous, 2018) It is a lithium titanate battery which has a nominal output of 1,2 MW and 0,6 MWh of energy capacity. This battery is manufactured by Toshiba and supplied by Landis+Gyr. (Toshiba, 2015)

In 2017, another large Finnish energy company purchased its own BESS. Fortum's Batcave is a lithium-ion battery which is located next to CHP plant in Järvenpää. This BESS cost 1,6 million euros and offers 2 MW output power and 1 MWh of energy capacity. (Energiatalous, 2018) The battery manufacturer is a French company called Saft. (Saft Groupe SA, 2016)

What both of these batteries have in common is their primary use in research and development in the beginning. (Energiatalous, 2018) Fortum's battery is a behind-the-meter solution which can be controlled from Fortum's hydropower monitoring room. This system is also a virtual power plant, of which the monitoring room is in Espoo, BESS in Järvenpää and hydropower in Lapland. (YLE, 2017) For the first three years, Helen's BESS was a joint research institute of Helen and Fingrid. In July 2019, BESS began to operate primarily in the Fingrid's reserve markets. (Karppinen, 2017)

One BESS was recently completed in Viinamäki, Ii. TuuliWatti had already five windmills in Viinamäki and they decided to purchase the largest energy storage system in Finland. This BESS creates six megawatts of power and the investment cost is 3,5 million euros. The energy capacity of TuuliWatti's BESS is 6,6 MWh. (Energiatalous, 2019) Saft is the battery's manufacturer, while other parts of TuuliWatti's BESS are provided by Merus Power. The project includes six 20-foot containers, an external transformer, and a medium voltage grid connection.

In Table 7, the power capital costs and the energy capital costs are calculated. Comparison between capital costs is unmeaningful, because each case is a bit different and several battery chemistries are used. Helen's and Fortum's BESSs were also the first ones in Finland and partly development projects with Fingrid. However, Table 7 presents the current price trend in BESS projects. Price decreases while size of projects increases. Figure 21 supports the same trend. (Goldie-Scot, 2019)

Table 7. Cost comparison of Finnish energy storages. (Energiatalous, 2018) (Energiatalous, 2019)

Company	Helen	Fortum	TuuliWatti
Price (million €)	2	1,6	3,5
Year	2015	2017	2019
Power (MW)	1,2	2	6
Power capital costs (€/kW)	1 666	800	583
Energy capacity (MWh)	0,6	1	6,6
Energy capital costs (€/kWh)	3 333	1 600	530

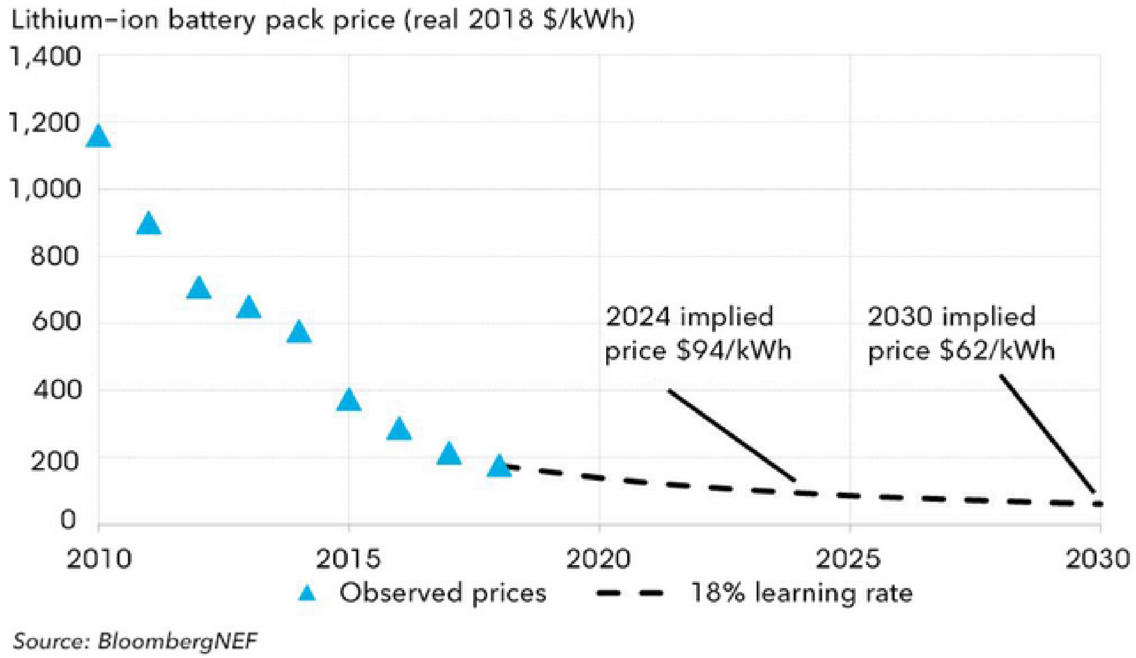

Figure 21. Price outlook for lithium-ion battery pack. (Goldie-Scot, 2019)

Table 7 supports the argument about the decrease in costs of energy storages. Helen's energy capital costs are enormous compared to current prices in Figure 21. (Goldie-Scot, 2019) Of course, all the investments listed in Table 7 include much more than a lithium-ion battery pack. Prices of lithium-ion batteries are expected to decline in the future. But as Figure 22 presents, the costs of other energy storage solutions decline faster than lithium-ion batteries costs.

When Figure 21 and Figure 22 are examined, it is important to see the difference of compared prices. Figure 21 presents the development of the lithium-ion pack price while Figure 22 presents the development of the levelized costs of energy storages. More about levelized cost of energy is presented in section 7.5.

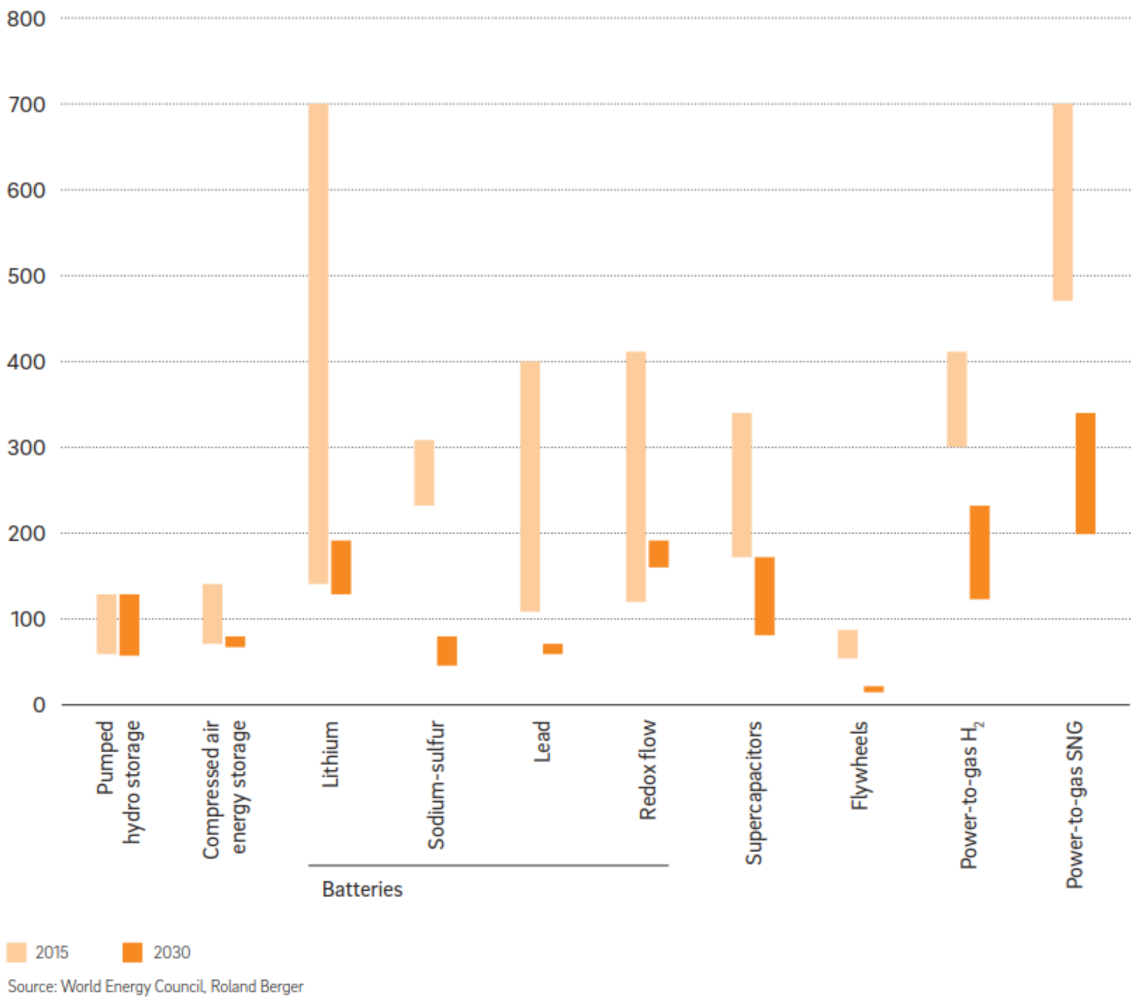

Figure 22. Levelized costs of energy storages in 2015 and expected costs in 2030 (€/MWh). The assumptions are current numbers and characteristics of BESS, and these assumptions remain unchanged during the service life of BESS. (Roland Berger GMBH, 2017) (World Energy Council, 2016)

Altogether, it can be stated that BESS prices decline in the future. The main reasons for this are an increase in production, developed performance, and modularity. Figure 23 and other studies support this statement. (Hesse, Schimpe, Kucevic, & Jossen, 2017), (IRENA, 2017), (Killer, Farrokhseresht, & Paterakis, 2020), (BloombergNEF, 2020) The only exception of energy storages is pumped-storage hydroelectricity, the price of which is estimated to be approximately the same in 2030. (Roland Berger GMBH, 2017)

6.3.3 Independent battery energy storage

While the aforementioned BESS cases have been next to a power plant or part of a microgrid, Yllikkälä Power Reserve One is the first case where BESS is independently connected to the transmission network and it will be built only for commercial purposes. In October 2019, a French renewable energy company, Neoen, enquired profitable locations for a large-scale BESS in Finland. Because Fingrid must ensure the reliability and stability on its network, they willingly decided to cooperate with Neoen. Less than a year later, construction work began in Yllikkälä, Lappeenranta. (Anteroinen, 2020)

When Yllikkälä Power Reserve One is completed, it is easily the largest BESS in Finland and also the biggest in the Nordic countries. Currently the biggest energy storage in Finland is TuuliWatti's BESS, but the 30 MW/ 30 MWh Yllikkälä Power Reserve One is approximately five times bigger than TuuliWatti. BESS has a strategic location because it is close to the 400 kV interconnection line between Russia and Finland. Neoen estimates that the BESS might be used for grid support. (Anteroinen, 2020) In this case, it means participation to Fingrid's balancing markets.

Yllikkälä Power Reserve One is an interesting case. Current BESSs in Finland are more or less experimental systems or their primary purposes are stability and reliability of microgrids. In each current BESS, owners can receive compensation from balancing markets, but BESSs also have secondary and tertiary applications. (YLE, 2017) Yllikkälä Power Reserve One does not support a power plant or microgrid. Instead, it will operate in Fingrid's and Nord Pool's energy and balancing markets on market terms.

6.4 Price estimation for battery energy storage system

Most facts of this thesis are based on scientific articles. In order to receive more commercial information about BESSs development, a questionnaire was sent to a couple BESS manufacturers. Luckily, several manufacturers filled the questionnaire. One of the manufacturers who responded was Markus Ovaskainen from Merus Power. The questionnaire can be found from APPENDIX 6**.**

This paragraph observes investment costs which are questions five and six in the questionnaire. Before price estimations of BESS are examined, Ovaskainen (2020) emphasized the uncertainty of €/MW and €/MWh prices because:

- Set up costs which are linked to multiple variables, such as voltage levels, necessary components, and other requirements, are uncertain.
- Demand for electrical installations and foundations are unknown.

However, when these notes are taken into account, Ovaskainen (2020) presents three prices for BESS with same default values:

- These BESSs are capable of participating in Fingrid's balancing markets.
- The containerized BESS is located next to the Kymijärvi 2 power plant and the project is a turnkey construction.
- Battery type is LFP.
- Cyclic life is 2,389 cycles/day and DoD is 96%.

Estimated investment costs are presented in Table 8.

Table 8. Investment costs for three BESS sizes. (Ovaskainen, 2020)

Name	**BESS A**	**BESS B**	**BESS C**
Size of BESS	1 MW/ 1 MWh	5 MW/ 5 MWh	10 MW/ 10 MWh
Investment costs (million €)	1,0	2,4	4,5
Capital costs (€/kW and €/kWh)	1 000	480	450

6.5 Risks

Leisen et al. (2019) found out that frequency regulation with a large-scale battery is a less risky solution than other new business models they have studied. Other new business models in the energy sector were direct marketing of renewable energy sources, virtual power plants, energy performance monitoring, battery storages for photovoltaic self-consumption, and tenant photovoltaic electricity. Another interesting observation from the research results of Leisen et al. (2019) was the low risk of technology and costs, even though the business model and technology are relatively new. Results revealed three major risk factors:

- *"Market entries triggered by new regulation that allows for participation of new technologies*
- *European integration of electricity markets*
- *Significant increase of storage capacity"* (Leisen, Steffen, & Weber, 2019)

All the risks mentioned above are related to the energy market or increased competition. The virtual power plant could have been compared as a business model in section 5.2, but Leisen et al. (2019) found 11 major risks in its business model. These major risks are presented in Table 9.

Battery-as-a-service is one solution to avoid risks. As mentioned earlier in case Kuru, the distribution system operator purchases BESS services from a service provider. When the distribution system operator does not need the BESS, the service provider can participate in regulation markets. In that case, the service provider and distribution system operator share the investment risk, because the distribution system operator pays an annual reservation fee to the service provider. (Alaperä, 2019b, pp. 66 - 70) This risk spreading reduces each three market risks that Leisen et al. (2019) discovered. The leasing of BESSs is another solution to reduce investment risks. (Sikorski, et al., 2019)

Perhaps the best solution to reduce risks that Leisen et al. (2019) have discovered is the multi-use of BESS. Multi-use may be hard to execute, but it reduces risks in the distribution network. While markets are risky and competition is getting fiercer, BESSs can bring stability and new tools in a distribution system. One example of new tools which BESSs enable is black start. In the future, wind power and photovoltaics increase fluctuations also in distribution networks. Especially, uncertainty in photovoltaic forecasting creates demand for stabilization. In that case, BESSs create surplus value to the distribution network and are less subject to the market. (Hauer, Balischewski, & Ziegler, 2020)

Table 9. Eleven risks for virtual power plants. (Leisen, Steffen, & Weber, 2019)

No.		Risk
1	▲	Declining revenues from reserve power
2	🟢	Market entries triggered by new regulation that allows for participation of new technologies
3	🟢	New pricing mechanisms for reserve power
4	🔴	Stricter regulatory requirements for the operation of a virtual power plant (operational)
5	🔴	Stricter requirements regarding the technical infrastructure of the virtual power plant (investment)
6	▲	Generally lower electricity price level
7	▲	Improved cost position of established suppliers
8	🟢	Elimination of subsidies for feed-in of electricity
9	🔴	Stricter regulatory requirements regarding qualification of staff
10	🔴	Stricter regulatory requirements for the operation of a virtual power plant for reserve power (pre qualification)
11	▲	Many market entries of small asset producers (e.g., smart heating systems)

7 BATTERY STORAGE INVESTMENT RELATED CASE STUDIES

It has been proved beyond doubt that BESS is a useful addition for energy producers in more ways than one. The benefits of the BESS are explored in the earlier parts of this thesis, so this chapter explores the profitability of investment. After an examination of companies who already have BESS in operation and a comparison of the sources of income, Fingrid's FCR-N is the most profitable market for BESS.

In this case study, the BESS will be placed into the Lahti Energia's power plant area. The BESS will be a behind-the-meter application, because then the company can avoid unnecessary electricity transmission fees. When the BESS is located in the power plant area, it creates investment postponement. Otherwise, it would create an unnecessary use of the distribution network. Helen and Fortum have used the same philosophy with their BESS.

Our case company Lahti Energia is a limited company, of which the purpose is to create profit for its owners. As then owner is the city of Lahti and therefore its citizens, big investments must be cost-effective. For that reason, BESS have to have a realistic repayment period.

7.1 Default values

Default values are assumptions and boundary conditions which should be defined before calculations. Some values are based on scientific articles, but some key values are from a survey. The questionnaire can be seen in APPENDIX 6**.** It should be noticed that this possible investment is in very early stages, so figures are approximated and only for feasibility study purposes.

In these case studies, the estimated value for service life of lithium-ion battery is ten years. Service life of lithium-ion batteries is something between 5 to 20 years in multiple sources. (Argyrou, Christodoulides, & Kalogirou, 2018) (Luo, Wang, Dooner, & Clarke,

2015) (Ovaskainen, 2020) The only exception is lithium titanate battery, which has a long service life. Lithium titanate's service life is expected to be 15 years. (IRENA, 2017)

Ovaskainen (2020) informed that current development of LFP batteries enable 2,389 cycles per day. Within a year, it is approximately 872 cycles. When the cycle life is 872 cycles per year, the service life of battery is ten years. (Ovaskainen, 2020) The 872 cycles per year determine market compensation from FCR-N hourly markets. It can be assumed that the BESS is able to participate in the the most profitable FCR-N hourly market hours. The compensation from the most profitable 872 hours annually have been approximately 57 250,04 €/MW between years 2015 and 2020. (Fingrid, 2020a)

Operation and maintenance costs vary a lot between different sources. Mongird et al. (2019) have stated that annualized operation and maintenance costs were 2,91 €/MWh and 11,47 €/kW in 2018. Assumed fixed operation and maintenance costs for lithium-ion batteries are 10 €/kW/year and the variable operation and maintenance cost 3,1 €/MWh. (Brinsmead, Graham, Hayward, Ratnam, & Reedman, 2015) A third estimation claims that fixed operation and maintenance costs are 16 €/kW/year and 4 €/MWh for variable operation and maintenance costs. (ADB, 2018) Because variance between several sources is so high, it is easier to use manufacturers assumptions from the survey. Ovaskainen (2020) stated that operation costs are 0 € and maintenance costs are 5 000 € annually.

If operation and maintenance costs vary between sources, the same can be said about round-trip efficiency. Earlier in the section 2.3, the round-trip efficiency of BESS is noted to be more than 90%. In the other studies, the most common round-trip efficiency is 92 %. (Staffell & Rustomji, 2016) (Mongird, et al., 2019) A round-trip efficiency of 92% is also used in this thesis. As mentioned in section 3.2.4, high operational voltages create degradation of electrolytes. An average annual round-trip efficiency degradation for lithium-ion batteries is 0,50% when expected service life is ten years. (Mongird, et al., 2019)

As mentioned in Table 1, self-discharge of lithium-ion batteries varies between 0,1% and 0,3%. For this reason, it is logical to use 0,2% for self-discharge per day. (Argyrou, Christodoulides, & Kalogirou, 2018) Based on Ovaskainen (2020), DoD percent in these calculations is 96%. This DoD percent is for the LFP battery when inlet temperature is 20 °C ± 3 °C.

As can be seen in Table 8, the size and investment cost of a BESS are based on the survey. (Ovaskainen, 2020) Other studies support Ovaskainen's (2020) prices, so those price estimations can be used in this case study. (ADB, 2018) (Roland Berger GMBH, 2017) The residual value of a battery is expected to be 20% of the battery's investment costs when the battery is in the end of its service life. (Ovaskainen, 2020) The ADB (2018) has calculated the price estimations for each component of a BESS, which can be seen in Figure 23. Based on their calculations, battery price is approximately one third of capital costs. When these two procentages are multiplied, the residual value of the battery after the service life is 6,666% of BESS's investment costs.

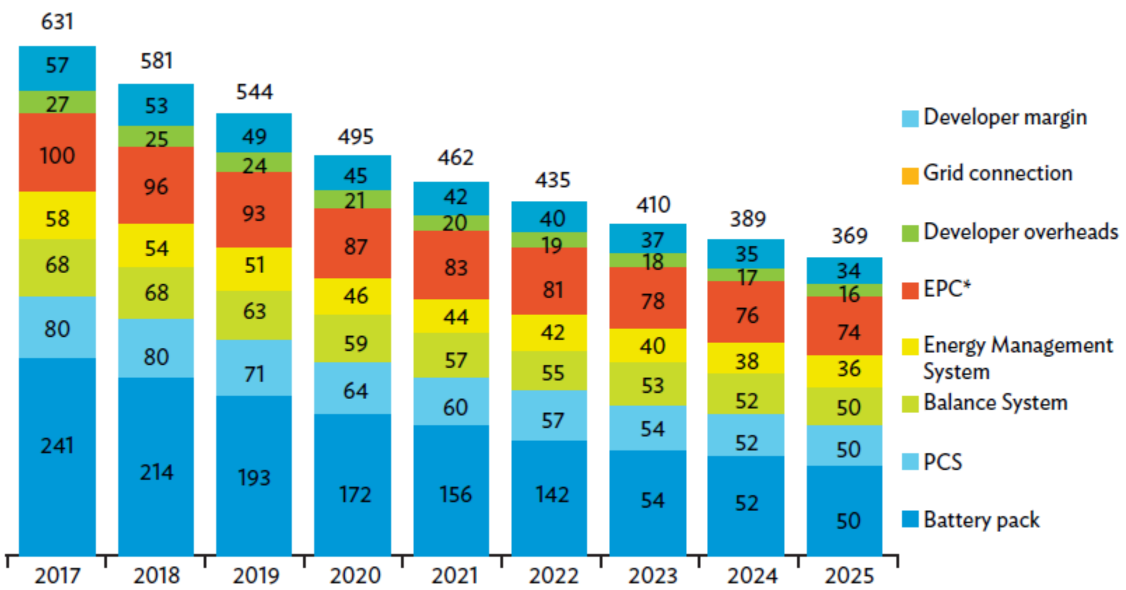

Figure 23. Capital cost calculations and expectations (€/kWh) for 1 MW/ 1 MWh stationary BESS. EPC = engineering, procurement, and construction. (ADB, 2018)

There is no one single discount rate number for energy industry investments, so it is easy to use 10% as a default value. The charging of a battery ‘uses electricity’, so charging costs should be considered. Even though a battery is located next to renewable energy source, charging costs in this case study are an average of NordPool’s Day-ahead prices in a Finnish bidding zone between the years of 2009 and 2019. The average market price in Finland between those years is 0,040262 €/kWh. (Nord Pool, 2019c) Calculations can be found from APPENDIX 2APPENDIX 3APPENDIX 4,APPENDIX 5. Default values in Table 10 are assumed to remain unchanged during the service life of BESS.

Table 10. Default values for case studies.

Name	**BESS A**	**BESS B**	**BESS C**	
Price	1,0	2,4	4,5	10^6 €
Output power	1,0	5,0	10,0	MW
Energy capacity	1,0	5,0	10,0	MWh
Service life		10		a
Annual cycles		872		
Residual value		6,666		%
Maintenance costs		5 000		€/a
Round-trip efficiency		92		%
Annual round-trip efficiency degradation		0,50		%
Self-discharge per day		0,20		%
DoD		96		%
Average charging costs		0,040262		€/kWh
Inlet temperature		20 ± 3		°C
Average income from the most profitable hours of FCR-N hourly market between 2015 and 2020		57 250,04		€/MW

7.2 Net present value

When energy investment decisions are made, it is important to take into account the time value of money. One euro is more valuable today than it will be in 2030. When the time value of money is connected to investment costs and annual revenues, the net present value (NPV) can be calculated. Discount rate must be predetermined before any calculation. If the result of the calculation is positive in a desired year, the return is bigger than initial investment. (DiOrio, Dobos, & Janzou, 2015) NPV can be calculated by means of the following equation:

$$NPV = \sum_{t=0}^{T} \frac{I_t + C_t}{(1+r)^t},$$

where t is number of time periods, r is discount rate, I_t is the initial investment and C_t is cash inflow during t. (Thiesen, Jauch, & Gloe, 2016) The NPVs are calculated for BESS operation in FCR-N hourly market. If BESS can participate to the 872 most profitable hours annually, an average return would be a little over 57 000 €/MW. (Fingrid, 2020a)

The costs during the service life include investment costs, charging costs and maintenance costs. The discount rate for total costs during service life is 10%. In this study the BESS is used only in the FCR-N hourly market which means single-use. As mentioned in section 4.5, the single-use of a BESS is not profitable, but this case study presents how much revenue a BESS can make from the most profitable market in Finland. Sections 7.3 and 7.4 use the same default values.

The NPV results were poor for BESS A. The capital costs are higher because a smaller BESS has higher set-up costs compared to bigger storages. (Ovaskainen, 2020) After ten years of operation, the BESS A has reached the end of its service life and the NPV is approximately - 800 000 €. The capital costs of BESS B are less than half of the BESS A's capital costs, but it is still unprofitable. The NPV is more than - 1 500 000 € after ten years of operation. The BESS C's NPV is more than - 2 700 000 €. Table 11 summarizes the NPVs.

The NPVs were as expected. The BESS is not profitable in single-use cases. If discount rate would be 1%, the BESS B would be profitable after 13 years of operation and BESS C after 12 years of operation. More accurate values can be found from the appendices at the end of this thesis.

As mentioned in Table 6, annual revenues are smaller in the other Fingrid's balancing markets, but sometimes the prices may be high. If the BESS's owner can utilize the profitable hours, the NPVs are better than in Table 11. Charging at nighttime is another way to improve NPV, because then electricity is cheaper than the average 0,040262 €/kWh.

7.3 Internal rate of return

Internal rate of return (IRR) is one of the most common formulas when investment decisions are made. The formula uses NPV to evaluate the rate of return. When NPV is equal to zero, IRR determines the discount rate. The equation for IRR is:

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + IRR)^t} - C_0 ,$$

where *IRR* is internal rate of return, *NPV* is net present value, *t* is number of time periods, C_t is net cash flow during *t* and C_0 is total initial investment costs. (Bradbury, Pratson, & Patiño-Echeverri, 2014)

Bradbury, Pratson and Patiño-Echeverri (2014) studied price arbitrage in the U.S. electricity markets. The calculations showed a negative IRR for lithium-ion batteries in each transmission system operator's territory. The IRR varied between – 5% to – 60% in each area. In their study, pumped-storage hydroelectricity, compressed air energy storage, supercapacitors and sodium nickel chloride battery were the only energy storages to get positive IRR for energy price arbitrage in the U.S.

Because the NPVs were heavily negative, the IRRs were also negative. The BESS C has the best IRR, but -1,68% is not a good number. After ten years of operation, the BESS B has an IRR of -2,51%. The -11,24% is a poor IRR result for the BESS A, but it is understandable because it is relatively the most expensive BESS. The results were similar to Bradbury's et. al (2014) result.

7.4 Return on investment

The first and the most important part of the correct sizing of BESS are the power capability and energy content. When performance metric decisions are made, the optimum return on investment (ROI) should also be taken into calculations. ROI for BESS can be calculated as

$$ROI = \frac{A_r - C_i}{C_i},$$

where A_r is overall return and C_i is overall investment costs. (Hesse, Schimpe, Kucevic, & Jossen, 2017) The ROI is no exceptions to the aforementioned values. Each BESS has a negative ROI. After 11 years of operation, the BESS C would have the IRR value of 0,11%, but after ten years of operation it is negative -8,99%. After the 10 years of service life, the BESS B has the IRR value of -13,26% and the BESS A has the IRR value of -51,92%. Table 11 summarize sections 7.2, 7.3 and 7.4.

Table 11. The investment calculations for BESSs in FCR-N hourly market.

Name	BESS A	BESS B	BESS C	
Annual cycles	872,00			
Discount rate	10			%
Service life	10			a
Total costs	1 168 809,52	3 299 961,24	6 290 567,56	€
Annual compensation from a single market (FCR-N hourly)	57 250,04	286 250,18	572 500,35	€
NPV	-817 032,84	-1 541 077,83	-2 772 800,74	€
IRR	-11,24	-2,51	-1,68	%
ROI	-51,02	-13,26	-8,99	%

7.5 Profitability of Fast Frequency Response

As mentioned in section 5.1.2.1, the FFR is the most recent balancing market. The market was launched in the beginning of May 2020. After couple of months of operation, the FFR market has been highly profitable. From May to August, the 872 most profitable hours have created 73 470,33 €/MW revenue. (Fingrid, 2020a) The lack of market experience is the reason why the FFR is not stated as 'the most profitable market' in this thesis. The profitability of investment cannot be proved by using a market which has been operating for only seven months, but the new market can be considered as a possibility in the future. Next paragraphs examine FFRs' profitability in the same way as in sections 7.2, 7.3 and 7.4.

Participation to the FFR market does not require any changes to the BESS. As can be seen from the APPENDIX 6, question five in the survey required that the BESS must be able to participate in the FFR market. Therefore, it can be stated that the FFR market is a more profitable market than the FCR-N hourly market on average.

The NPV of BESSs is still negative if the discount rate is 10%. For BESS A, the NPV is more than -700 000 €. Larger BESSs' NPVs are more than -1 000 000 € and more than -

1 700 000 €. The results are still negative from the BESS point of view, but for example the NPV of BESS C decreased almost one million euros. If the discount rate is 1%, both larger BESSs are profitable.

The expensive BESS A has a negative IRR and ROI, but both the IRR and the ROI are positive for bigger BESSs after ten years of operation. The IRR value for the BESS B is 2,00% and the ROI is 11,32%. For the biggest BESS, the IRR is 2,93% and the ROI is 16,79 after ten years of operation. Table 12 summarizes the FFRs market potential.

Table 12. The investment calculations for BESSs in FFR market.

Name	**BESS A**	**BESS B**	**BESS C**	
Annual cycles	872,00			
Discount rate	10			%
Service life	10			a
Total costs	1 168 809,52	3 299 961,24	6 290 567,56	€
Annual compensation from a single market (FFFR)	73 470,33	367 351,65	734 703,30	€
NPV	-717 366,15	-1 042 744,38	-1 776 133,83	€
IRR	-7,66	2,00	2,93	%
ROI	-37,14	11,32	16,79	%
If discount rate is 1%	-472 949,65	179 338,11	668 031,13	€

In reality, Table 12 does not prove the profitability of a BESS investment. It instead proves the possibilities in Fingrid's balancing markets. The new FFR is still trying to find its parties and regulations, and currently it is impossible to know the FFR prices in 2030. The most promising things in Table 12 are positive IRR and ROI values. Those positive values may be one of the reasons why Yllikkälä Power Reserve One is under construction. The market share of BESSs is quite secure in FFR markets because there are only a couple of competitive solutions which can participate in the market.

7.6 Levelized cost of storage

Economic viability and the evaluation of potential energy generation technologies can be a challenging task. Energy investments are often expensive with a long payback period and a large number of variables. Aforementioned NPV, IRR and ROI are indicative equations, but levelized cost of energy is more suitable to economic analyse of energy investments. (Belderbos, 2019) Levelized cost of energy is usable for all energy production technologies and the equation is:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}},$$

where I_t is investment costs per year t, M_t is operation and maintenance costs per year, F_t is fuel costs per year t, E_t is electricity generation per year t, r is discount rate and n is system's service life. (DOE, 2019)

Levelized cost of energy enables a comparison between different electricity generation methods. For BESS calculations, it is not the most suitable equation. Traditional electricity generation technologies burn fuel to create electricity, but batteries just store electricity. Even though electricity is transformed to electrochemical potential during the storage period, the 'fuel' and the end product are still the same commodity. (Belderbos, Delarue, Kessels, & D'haeseleer, 2017) For that reason, levelized cost of storage (LCOS) has been crated. LCOS has been developed from levelized cost of energy and they have some similarities. As the equation presents, fuel costs per year are changed to charging costs per year and generated electricity is now discharged electricity:

$$LCOS = \frac{\frac{\sum (C_t + O\&M_t + Ch_t)}{(1+r)^t}}{\frac{\sum D_t}{(1+r)^t}},$$

where C_t is total capital costs per year t, $O\&M_t$ is fixed operation and maintenance costs per year t, Ch_t is charging costs per year t, D_t is discharged electricity (MWh) per year t and r is discount rate. (Belderbos, Delarue, & D'haeseleer, 2016) All costs are already known values, but discharged electricity per year must be calculated. Discharged electricity per year t can be calculated as:

$$\sum_{t}^{N} \frac{D_t}{(1+r)^t} = Cyc_{pa} * DoD * Cap_{nom,E} * \eta_{RT} * \left(1 - \eta_{self}\right) * \sum_{t=0}^{N} \frac{(1 - Cyc_{Deg})^t}{(1+r)^t},$$

where Cyc_{pa} is annual cycles, DoD is depth of discharge, $CAP_{nom,e}$ is energy capacity, η_{RT} is round-trip efficiency, η_{self} is self-discharge and Cyc_{Deg} is annual round-trip efficiency degradation. (Schmidt, Melchior, Hawkes, & Stafell, 2019)

The LCOS results followed a predictable pattern. Results vary from 142 €/MWh to 265 €/MWh. When these case study results are compared to earlier studies of LCOS, the results show the development of BESSs. Pawel (2014) calculated 1 678 €/MWh for levelized cost of energy of storage, but default values were different. Expected service life was seven years, annual round-trip efficiency degradation was 2,0% and round-trip efficiency was 80%. Figure 23 also supports the positive price development of lithium-ion batteries.

It is appropriate to note that LCOS calculations do not give an answer to the profitability of the investment. LCOS presents the storage price of electricity over the service life of the storage. Even though it is not reasonable to compare LCOE and LCOS values, it is mentionable to know that solar photovoltaics have higher LCOE values than BESS's LCOS in this case study. (DOE, 2019) The notable difference between these two is 'fuel'. Photovoltaics has free fuel from the sky while in this case study the battery was charged from Nord Pool's Day-ahead market. Table 13 represents the LCOS values for each studied BESSs.

Table 13. LCOS values for each studied case.

Name	BESS A	BESS B	BESS C	
Total costs	1 168 809,52	3 299 961,24	6 290 567,56	€
Total output	4 409,167	22 045,839	44 091,567	MWh
Discount rate		10		**%**
LCOS	265,09	149,69	142,67	€/MWh

Schmidt, Melchior, Hawkes and Stafell (2019) presented more detailed formulas for LCOS. These formulas do not add value to this case study where most of the values are estimated. If Lahti Energia decides to purchase a BESS, it is good to use detailed formulas to get hold of actual revenues and costs.

8 SUMMARY AND CONCLUSIONS

8.1 Conclusions

Stationary energy storage systems draw a lot of research currently and will also in the future. The development and research of electric vehicles speed up the technological advancements of lithium-ion batteries. The mature lead-acid battery is a safe choice, but its technical characteristics are poorer than lithium-ion’s. NiMH and NaS are good challengers for lithium-ion. Currently, the lithium-ion battery has a clear advantage in the most vital technological characteristics, such as round-trip efficiency and cycle life. SMES, supercapacitor, and flywheel must be taken into account if there is demand for high power for a short period of time.

Other energy storages are currently more or less unfeasible for energy companies in Finland. Geographical location excludes pumped-storage hydroelectricity and molten salt, which is mostly used alongside concentrated solar power. Compressed air energy storage relies on natural gas, while Lahti Energia is looking for solution which does not rely on fossil fuels. The hydrogen fuel cell might be the solution for energy storing, but currently it is not competitive. Flow batteries came rapidly to large-scale BESS markets, but currently lithium-ion is a more advanced solution than flow batteries. In total, it can be stated that the lithium-ion battery is the most suitable energy storage solution for energy companies in Finland.

BESS is more than just a battery. Additionally, the system includes several components such as power electronic components, electrical wirings, and computers. Components can be classified from the smallest electrons to a grid connected transformer. Normally, BESSs are constructed into a container or into a building. The most defining characteristics of BESS are DoD, cycle life, and initial investment costs.

Lithium-ion batteries are a group of batteries where lithium-ions move from anode to cathode and vice versa. Currently, the most advanced lithium-ion batteries are NMC, NCA, LFP, and LTO. Introduced future solutions of lithium-ion batteries are promising, but these solutions are in the development state. Lithium metal and solid-state lithium batteries are expected to become commercial solutions in the future.

Flexible BESSs have multiple applications, which is the reason why it has caught the interest of energy companies and distribution system operator. Ancillary services are system wide or local services, such as frequency or voltage control. BESS is used especially for frequency regulation. The group of consumer applications which do not affect the grid directly are known as behind-the-meter applications. Energy trade enables additional income for BESS owners, while grid support and investment postponement are the surplus value of BESSs. The BESS is suitable to operate in every application in this paper except seasonal storage.

Combined applications enable value stacking and create the possibility for the profitable operation of BESSs. Business models also support that claim. The BESS can be offered as a battery-as-a-service for someone who has occasional demand for electrical energy storage. The possible new market, flexibility markets at the distribution system level, increases the profitability of the system in the future.

From the BESS point of view, there are two main market sustaining entities: Nord Pool and Fingrid. Nord Pool has the Day-ahead market to ensure electricity in every bidding zone and the Intraday market to ensure actual electricity demand for each hour. Fingrid has several markets to ensure voltage and frequency balance in its own grid. BESSs can participate in all of these markets, but it is competitive in the FFR, FCR-N, and FCR-D markets. At the moment, these three Fingrid reserve markets are also the most profitable markets for BESS.

Now and in the future, hydropower is the biggest player in Finnish energy balancing markets. The replacement of hydropower by BESSs would be inefficient and expensive. Virtual power plants have joined Fingrid's balancing markets and gained popularity. The cloud connected virtual power plant is more risky solution than BESS. The biggest profitability risks for BESS are the increased number of participants in the markets, integrated energy markets, and the high number of new storages. Multi-use of BESS, battery-as-a-service, and leasing reduce the aforementioned risks.

The government of Finland has removed obstacles that renewable energy integration and energy storages have faced. Recently, the government removed double taxation of energy storages. At the same time, government decided to prohibit coal power plants after May 2029. The EU has also pointed out the importance of new technologies, especially demand management, renewables, and distribution. When BESS is placed into a same power station area as renewable energy source, BESS and energy source are one single object of taxation.

The renounce of coal has already begun, and renewables have replaced coal power plants. Natural gas and nuclear power can be seen as transition solutions before renewable energy and energy storages can entirely control the supply and demand. The number of wind power, photovoltaics, hybrid power plants, and microgrids are expected to grow within next decades. In 2030, the estimated capacity of stationary batteries is more than 100 GWh globally while current capacity is 11 GWh.

The prices of photovoltaics, wind power, and batteries have decreased during the last ten years. This development is expected to continue, and in 2030 battery prices are expected to be 64% lower than currently. Even though prices fall, single-use of BESS may not be cost-effective. While prices of other energy storage types fall, pumped-storage hydroelectricity is the only energy storage type of which the price is expected to stay the same during the next ten years.

Over the past few years, the number of stationary battery energy storages has increased a lot. Currently, the biggest BESSs in Finland are TuuliWatti, Lidl, LEMENE, and Sello. Yllikkälä Power Reserve One, the biggest BESS in the Nordics, is under construction in

Lappeenranta. When the size of stationary BESS's in Finland increases, the other trend is small microgrids. These microgrids are able to operate in islanded mode if needed, and participate to Fingrid's balancing and reserve markets.

In the case study, BESS is located next to the renewable power plant in the Kymijärvi power plant area. Calculations include large numbers of default values and each of these have a small range of variation. All of the default values are expected to remain unchanged during the service life of BESS. NPV, IRR, and ROI give negative values for BESS after ten years of operation. The LCOS results vary between 143 €/MWh to 265 €/MWh. The results were as expected.

The calculations proved the unprofitability of BESSs in single-use cases. The FFR market has a high potential and only a few participants. The demand for balancing increases in the future, so the compensations also increase. Even though BESSs might not be profitable in single-use cases, the surplus value, flexibility, and market compensations together are profitable.

8.2 Summary

This study presents the possibilities and threats of lithium-ion batteries when it is located next to a renewable energy source in Finland. At first, other energy storages are shortly explored and competing technologies are compared to lithium-ion. The findings of the survey confirm that the lithium-ion battery is the most suitable energy storage technology for energy companies in Finland. After the survey verified the most suitable solution, BESS and lithium-ion batteries are explored in more detail. Next chapters introduced applications and markets for BESS, and the last chapters observed investment potential and payback periods.

The thesis observes the suitability of the BESS from two different dimensions. In the beginning, possible applications and their feasibility is explored. When research papers and real-life cases have proved the feasibility of BESS for multiple applications, it is time to count payback period for the investment. The results from the case study confirm that the lithium-ion BESS is not yet a profitable investment in single-use cases. When the number of renewables increases and the prices of BESSs decrease in the future, a single-use cases may become cost-effective. It is also good to take into an account those applications which do not create financial worth but are vital in abnormal circumstances. One of these applications is black start.

From this thesis topic's viewpoint, Yllikkälä Power Reserve One is a significant project. Even though this Master's thesis may not prove the the profitability of the BESS in a single-use case, a French company would not invest capital into a Finnish power system if they thought it would be unprofitable. Yllikkälä Power Reserve One is a commercial investment and supports the claim that balancing markets are an emergent market.

At this moment, it is not possible to ascertain the profitability of this investment. Instead, one can promise the surplus value of flexible BESS for energy company beyond any doubt.

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APPENDICES

APPENDIX 1. Participants in Fingrid's balancing markets 20.02.2020. (Fingrid, 2020b)

Reservitoimittaja / Balancing service provider	Reservituotteet / Reserve products			
	Automaattinen taajuudenhallinta-reservi / Automatic Frequency Restoration Reserve (aFRR)	Taajuusohjatut reservit, tunti- ja vuosimarkkinat / Frequency Containment Reserves, hourly and yearly markets (FCR-N ja FCR-D)	Säätösähkömark-kinat / Balancing Energy Market (mFRR)	Varavoimalaitokset / Reserve power plants
Boliden Kokkola Oy		x	x	
Elenia Palvelut Oy				x
EPV Tase Oy			x	
Fortum Power and Heat Oy	x	x	x	x
Gasum Consulting Oy		x	x	
Helen Oy	x	x	x	x
Jyväskylän Energia Oy			x	
Jyväskylän Voima Oy			x	
Kainuun Voima Oy		x		
Kemijoki Oy	x	x		
Kemira Chemicals Oy			x	
Kolsin Vesivoimantuotanto Oy		x		
Koskienergia Oy			x	
Koy Kauppakeskus Sello		x		
KSS Energia Oy				x
Kuopion Energia Oy			x	
Lahti Energia Oy			x	x
Lappeenrannan Lämpövoima Oy				x
Loiste Energia Oy			x	
Länsi-Suomen Voima Oy		x		
Metsä Board Oyj				x
Oulun Energia Oy			x	
Outokumpu Oyj			x	
Oy Alholmens Kraft Ab		x	x	
Oy Mankala Ab		x		
Oy Turku Energia-Åbo Energi Ab		x	x	
Pohjois-Karjalan Sähkö Oy	x		x	

PVO Power Management Oy			x	
PVO-Vesivoima Oy	x	x	x	
Raahen Voima Oy			x	
Sappi Finland Operations Oy		x	x	
Seinäjoen Voima Oy		x		
Savon Voima Oyj			x	
SSAB Europe Oy			x	
Stora Enso Oyj		x	x	
Sympower Oy		x		
Tampereen Sähkölaitos Oy		x	x	
UPM Energy Oy		x	x	
Vantaan Energia Oy			x	
Vaskiluodon Voima Oy		x	x	
Vattenfall Oy	x	x	x	
VIBECO - Virtual Buildings Ecosystem Oy		x		
Väre Oy		x		

APPENDIX 2. NPV, IRR and ROI calculations of 1 MW/ 1 MWh BESS in the FCR-N hourly and FFR markets

FCR-N hourly

NPV	Year												
Discount rate	3	4	5	6	7	8	9	10	11	12	13	14	15
0,01	-1 000 438,01 €	-945 421,86 €	-890 950,41 €	-837 018,29 €	-783 620,15 €	-730 750,70 €	-678 404,71 €	-626 577,00 €	-575 262,44 €	-524 455,94 €	-474 152,48 €	-424 347,07 €	-375 034,78 €
0,02	-1 003 707,10 €	-950 816,92 €	-898 963,80 €	-848 127,41 €	-798 287,80 €	-749 425,45 €	-701 521,18 €	-654 556,21 €	-608 512,13 €	-563 370,86 €	-519 114,73 €	-475 726,35 €	-433 188,73 €
0,03	-1 006 871,42 €	-956 005,51 €	-906 621,12 €	-858 675,12 €	-812 125,60 €	-766 931,90 €	-723 054,51 €	-680 455,11 €	-639 096,47 €	-598 942,44 €	-559 957,95 €	-522 108,94 €	-485 362,32 €
0,04	-1 009 935,46 €	-960 997,89 €	-913 942,54 €	-868 697,00 €	-825 191,68 €	-783 359,64 €	-743 136,53 €	-704 460,45 €	-667 271,92 €	-631 513,72 €	-597 130,83 €	-564 070,36 €	-532 281,45 €
0,05	-1 012 903,48 €	-965 803,73 €	-920 946,83 €	-878 225,97 €	-837 539,44 €	-798 790,36 €	-761 886,48 €	-726 739,93 €	-693 267,02 €	-661 388,05 €	-631 027,14 €	-602 111,98 €	-574 573,73 €
0,06	-1 015 779,49 €	-970 432,10 €	-927 651,55 €	-887 292,53 €	-849 217,99 €	-813 298,61 €	-779 412,40 €	-747 444,28 €	-717 285,67 €	-688 834,16 €	-661 993,11 €	-636 671,36 €	-612 782,93 €
0,07	-1 018 567,33 €	-974 891,56 €	-934 073,07 €	-895 924,96 €	-860 272,51 €	-826 952,47 €	-795 812,25 €	-766 709,23 €	-739 510,15 €	-714 090,45 €	-690 333,72 €	-668 131,17 €	-647 381,12 €
0,08	-1 021 270,63 €	-979 190,14 €	-940 226,73 €	-904 149,50 €	-870 744,65 €	-839 814,24 €	-811 174,97 €	-784 657,13 €	-760 103,57 €	-737 368,79 €	-716 318,07 €	-696 826,66 €	-678 779,07 €
0,09	-1 023 892,81 €	-983 335,44 €	-946 126,85 €	-911 990,52 €	-880 672,79 €	-851 940,93 €	-825 581,43 €	-801 398,39 €	-779 212,12 €	-758 857,75 €	-740 184,01 €	-723 052,14 €	-707 334,83 €
0,10	-1 026 437,16 €	-987 334,61 €	-951 786,84 €	-919 470,69 €	-890 092,37 €	-863 384,81 €	-839 105,20 €	-817 032,84 €	-796 967,05 €	-778 725,42 €	-762 142,13 €	-747 066,41 €	-733 361,20 €
0,11	-1 028 906,77 €	-991 194,40 €	-957 219,29 €	-926 611,08 €	-899 036,12 €	-874 193,81 €	-851 813,35 €	-831 650,78 €	-813 486,30 €	-797 121,90 €	-782 379,20 €	-769 097,49 €	-757 131,99 €
0,12	-1 031 304,60 €	-994 921,16 €	-962 435,96 €	-933 431,31 €	-907 534,30 €	-884 411,97 €	-863 767,03 €	-845 334,05 €	-828 876,04 €	-814 181,38 €	-801 061,15 €	-789 346,66 €	-778 887,29 €
0,13	-1 033 633,45 €	-998 520,93 €	-967 447,91 €	-939 949,65 €	-915 614,92 €	-894 079,75 €	-875 022,08 €	-858 156,89 €	-843 231,94 €	-830 024,02 €	-818 335,60 €	-807 991,86 €	-798 838,11 €
0,14	-1 035 896,01 €	-1 001 999,39 €	-972 265,51 €	-946 183,17 €	-923 303,92 €	-903 234,40 €	-885 629,56 €	-870 186,72 €	-856 640,36 €	-844 757,60 €	-834 334,12 €	-825 190,72 €	-817 170,19 €
0,15	-1 038 094,80 €	-1 005 361,91 €	-976 898,52 €	-952 147,75 €	-930 625,34 €	-911 910,21 €	-895 636,17 €	-881 484,84 €	-869 179,33 €	-858 478,89 €	-849 174,16 €	-841 083,09 €	-834 047,38 €
0,16	-1 040 232,27 €	-1 008 613,58 €	-981 356,09 €	-957 858,26 €	-937 601,51 €	-920 138,79 €	-905 084,72 €	-892 107,08 €	-880 919,45 €	-871 274,95 €	-862 960,72 €	-855 793,28 €	-849 614,46 €
0,17	-1 042 310,70 €	-1 011 759,22 €	-985 646,84 €	-963 328,57 €	-944 253,12 €	-927 949,32 €	-914 014,45 €	-902 104,30 €	-891 924,69 €	-883 224,16 €	-875 787,82 €	-869 431,97 €	-863 999,61 €
0,18	-1 044 332,32 €	-1 014 803,39 €	-989 778,87 €	-968 571,65 €	-950 599,43 €	-935 368,74 €	-922 461,37 €	-911 522,92 €	-902 253,05 €	-894 397,23 €	-887 739,75 €	-882 097,82 €	-877 316,53 €
0,19	-1 046 299,21 €	-1 017 750,41 €	-993 759,82 €	-973 599,65 €	-956 658,34 €	-942 421,95 €	-930 458,59 €	-920 405,35 €	-911 957,24 €	-904 858,00 €	-898 892,25 €	-893 879,01 €	-889 666,20 €
0,20	-1 048 213,38 €	-1 020 604,38 €	-997 596,87 €	-978 423,95 €	-962 446,52 €	-949 131,99 €	-938 036,55 €	-928 790,35 €	-921 085,18 €	-914 664,21 €	-909 313,40 €	-904 854,39 €	-901 138,55 €
IRR	-57,09 %	-43,64 %	-33,89 %	-26,71 %	-21,30 %	-17,14 %	-13,86 %	-11,24 %	-9,11 %	-7,36 %	-5,90 %	-4,67 %	-3,63 %
ROI	-85,31 %	-80,41 %	-75,51 %	-70,61 %	-65,71 %	-60,81 %	-55,92 %	-51,02 %	-46,12 %	-41,22 %	-36,32 %	-31,43 %	-26,53 %

FFR

NPV	Year												
Discount rate	3	4	5	6	7	8	9	10	11	12	13	14	15
0,01	-952 734,37 €	-882 130,82 €	-812 226,33 €	-743 013,95 €	-674 486,85 €	-606 638,23 €	-539 461,38 €	-472 949,65 €	-407 096,45 €	-341 895,26 €	-277 339,63 €	-213 423,17 €	-150 139,54 €
0,02	-956 929,66 €	-889 054,44 €	-822 510,09 €	-757 270,54 €	-693 310,20 €	-630 603,98 €	-569 127,30 €	-508 856,04 €	-449 766,56 €	-391 835,71 €	-335 040,76 €	-279 359,43 €	-224 769,89 €
0,03	-960 990,51 €	-895 713,07 €	-832 336,92 €	-770 806,68 €	-711 068,58 €	-653 070,42 €	-596 761,53 €	-542 092,70 €	-489 016,17 €	-437 485,56 €	-387 455,84 €	-338 883,30 €	-291 725,49 €
0,04	-964 922,67 €	-902 119,92 €	-841 732,66 €	-783 668,00 €	-727 836,58 €	-674 152,53 €	-622 533,25 €	-572 899,33 €	-525 174,41 €	-479 285,05 €	-435 160,68 €	-392 733,39 €	-351 937,93 €
0,05	-968 731,59 €	-908 287,37 €	-850 721,44 €	-795 896,75 €	-743 682,76 €	-693 955,15 €	-646 595,52 €	-601 491,11 €	-558 534,53 €	-517 623,50 €	-478 660,61 €	-441 553,10 €	-406 212,62 €
0,06	-972 422,45 €	-914 227,07 €	-859 325,76 €	-807 532,08 €	-758 670,11 €	-712 573,92 €	-669 086,94 €	-628 061,50 €	-589 358,24 €	-552 845,74 €	-518 399,98 €	-485 903,98 €	-455 247,38 €
0,07	-976 000,15 €	-919 949,99 €	-867 566,66 €	-818 610,28 €	-772 856,65 €	-730 096,25 €	-690 133,26 €	-652 784,67 €	-617 879,44 €	-585 257,74 €	-554 770,16 €	-526 277,10 €	-499 648,07 €
0,08	-979 469,35 €	-925 466,47 €	-875 463,80 €	-829 165,03 €	-786 295,79 €	-746 602,06 €	-709 848,60 €	-675 817,63 €	-644 307,46 €	-615 131,38 €	-588 116,49 €	-563 102,71 €	-539 941,80 €
0,09	-982 834,47 €	-930 786,23 €	-883 035,56 €	-839 227,60 €	-799 036,81 €	-762 164,53 €	-728 336,75 €	-697 302,09 €	-668 829,92 €	-642 708,67 €	-618 744,22 €	-596 758,48 €	-576 588,08 €
0,10	-986 099,68 €	-935 918,46 €	-890 299,17 €	-848 827,08 €	-811 125,18 €	-776 850,73 €	-745 692,14 €	-717 366,15 €	-691 615,24 €	-668 205,33 €	-646 923,60 €	-627 576,56 €	-609 988,35 €
0,11	-989 268,99 €	-940 871,81 €	-897 270,75 €	-857 990,51 €	-822 602,91 €	-790 722,18 €	-762 000,81 €	-736 125,70 €	-712 814,79 €	-691 813,97 €	-672 894,31 €	-655 849,58 €	-640 493,96 €
0,12	-992 346,18 €	-945 654,46 €	-903 965,42 €	-866 743,07 €	-833 508,82 €	-803 835,39 €	-777 341,25 €	-753 685,77 €	-732 564,81 €	-713 706,80 €	-696 869,30 €	-681 835,81 €	-668 413,06 €
0,13	-995 334,86 €	-950 274,13 €	-910 397,38 €	-875 108,22 €	-843 878,87 €	-816 242,28 €	-791 785,12 €	-770 141,62 €	-750 988,08 €	-734 038,04 €	-719 038,01 €	-705 763,64 €	-694 016,42 €
0,14	-998 238,45 €	-954 738,12 €	-916 579,93 €	-883 107,83 €	-853 746,35 €	-827 990,66 €	-805 397,95 €	-785 579,78 €	-768 195,43 €	-752 945,99 €	-739 569,29 €	-727 835,35 €	-717 542,41 €
0,15	-1 001 060,22 €	-959 053,32 €	-922 525,58 €	-890 762,33 €	-863 142,11 €	-839 124,53 €	-818 239,67 €	-800 078,93 €	-784 286,98 €	-770 554,85 €	-758 613,87 €	-748 230,41 €	-739 201,31 €
0,16	-1 003 803,27 €	-963 226,27 €	-928 246,08 €	-898 090,76 €	-872 094,78 €	-849 684,46 €	-830 365,22 €	-813 710,70 €	-799 353,36 €	-786 976,34 €	-776 306,49 €	-767 108,35 €	-759 178,92 €
0,17	-1 006 470,58 €	-967 263,14 €	-933 752,50 €	-905 110,93 €	-880 630,96 €	-859 707,90 €	-841 824,95 €	-826 540,37 €	-813 476,63 €	-802 311,05 €	-792 767,81 €	-784 611,19 €	-777 639,73 €
0,18	-1 009 064,97 €	-971 169,79 €	-939 055,23 €	-911 839,51 €	-888 775,33 €	-869 229,42 €	-852 665,09 €	-838 627,52 €	-826 731,27 €	-816 649,71 €	-808 106,01 €	-800 865,59 €	-794 729,64 €
0,19	-1 011 589,13 €	-974 951,77 €	-944 164,08 €	-918 292,06 €	-896 550,88 €	-878 280,97 €	-862 928,11 €	-850 026,54 €	-839 184,89 €	-830 074,26 €	-822 418,27 €	-815 984,66 €	-810 578,27 €
0,20	-1 014 045,63 €	-978 614,34 €	-949 088,26 €	-924 483,19 €	-903 978,97 €	-886 892,12 €	-872 653,08 €	-860 787,21 €	-850 898,99 €	-842 658,80 €	-835 791,98 €	-830 069,63 €	-825 301,00 €
IRR	-52,55 %	-38,94 %	-29,30 %	-22,32 %	-17,13 %	-13,17 %	-10,10 %	-7,66 %	-5,70 %	-4,09 %	-2,77 %	-1,66 %	-0,73 %
ROI	-81,14 %	-74,86 %	-68,57 %	-62,28 %	-56,00 %	-49,71 %	-43,43 %	-37,14 %	-30,85 %	-24,57 %	-18,28 %	-12,00 %	-5,71 %

APPENDIX 3. NPV, IRR and ROI calculations of 5 MW/ 5 MWh BESS in the FCR-N hourly and FFR markets

FCR-N hourly

NPV	Year												
Discount rate	3	4	5	6	7	8	9	10	11	12	13	14	15
0,01	-2 458 103,71 €	-2 183 022,92 €	-1 910 665,70 €	-1 641 005,08 €	-1 374 014,38 €	-1 109 667,14 €	-847 937,21 €	-588 798,66 €	-332 225,84 €	-78 193,34 €	173 323,98 €	422 351,03 €	668 912,47 €
0,02	-2 474 449,15 €	-2 209 998,23 €	-1 950 732,63 €	-1 696 550,67 €	-1 447 352,66 €	-1 203 040,90 €	-963 519,55 €	-728 694,71 €	-498 474,27 €	-272 767,96 €	-51 487,27 €	165 454,59 €	378 142,69 €
0,03	-2 490 270,74 €	-2 235 941,17 €	-1 989 019,26 €	-1 749 289,24 €	-1 516 541,65 €	-1 290 573,12 €	-1 071 186,20 €	-858 189,19 €	-651 395,97 €	-450 625,85 €	-255 703,41 €	-66 458,33 €	117 274,77 €
0,04	-2 505 590,95 €	-2 260 903,10 €	-2 025 626,32 €	-1 799 398,65 €	-1 581 872,04 €	-1 372 711,84 €	-1 171 596,27 €	-978 215,90 €	-792 273,25 €	-613 482,23 €	-441 567,80 €	-276 265,45 €	-117 320,89 €
0,05	-2 520 431,02 €	-2 284 932,29 €	-2 060 647,79 €	-1 847 043,50 €	-1 643 610,84 €	-1 449 865,46 €	-1 265 346,04 €	-1 089 613,27 €	-922 248,72 €	-762 853,91 €	-611 049,33 €	-466 473,54 €	-328 782,31 €
0,06	-2 534 811,10 €	-2 308 074,15 €	-2 094 171,37 €	-1 892 376,29 €	-1 702 003,58 €	-1 522 406,67 €	-1 352 975,64 €	-1 193 135,03 €	-1 042 342,01 €	-900 084,44 €	-765 879,19 €	-639 270,46 €	-519 828,27 €
0,07	-2 548 750,31 €	-2 330 371,43 €	-2 126 279,01 €	-1 935 538,43 €	-1 757 276,21 €	-1 590 676,00 €	-1 434 974,87 €	-1 289 459,79 €	-1 153 464,40 €	-1 026 365,90 €	-907 582,25 €	-796 569,50 €	-692 819,26 €
0,08	-2 562 266,78 €	-2 351 864,35 €	-2 157 047,29 €	-1 976 661,13 €	-1 809 636,90 €	-1 654 984,84 €	-1 511 788,48 €	-1 379 199,27 €	-1 256 431,47 €	-1 142 757,59 €	-1 037 503,99 €	-940 046,96 €	-849 808,97 €
0,09	-2 575 377,70 €	-2 372 590,86 €	-2 186 547,89 €	-2 015 866,26 €	-1 859 277,61 €	-1 715 618,30 €	-1 583 820,77 €	-1 462 905,60 €	-1 351 974,25 €	-1 250 202,38 €	-1 156 833,68 €	-1 071 174,33 €	-992 587,77 €
0,10	-2 588 099,42 €	-2 392 586,70 €	-2 214 847,86 €	-2 053 267,10 €	-1 906 375,50 €	-1 772 837,68 €	-1 651 439,66 €	-1 541 077,83 €	-1 440 748,89 €	-1 349 540,76 €	-1 266 624,28 €	-1 191 245,67 €	-1 122 719,65 €
0,11	-2 600 447,48 €	-2 411 885,62 €	-2 242 010,07 €	-2 088 969,04 €	-1 951 094,23 €	-1 826 882,70 €	-1 714 980,41 €	-1 614 167,55 €	-1 523 345,14 €	-1 441 523,16 €	-1 367 809,66 €	-1 301 401,10 €	-1 241 573,57 €
0,12	-2 612 436,62 €	-2 430 519,46 €	-2 268 093,42 €	-2 123 070,17 €	-1 993 585,13 €	-1 877 973,49 €	-1 774 748,80 €	-1 682 583,91 €	-1 600 293,82 €	-1 526 820,53 €	-1 461 219,38 €	-1 402 646,92 €	-1 350 350,09 €
0,13	-2 624 080,90 €	-2 448 518,30 €	-2 293 153,18 €	-2 155 661,91 €	-2 033 988,23 €	-1 926 312,40 €	-1 831 024,06 €	-1 746 698,10 €	-1 672 073,35 €	-1 606 033,75 €	-1 547 591,62 €	-1 495 872,93 €	-1 450 104,17 €
0,14	-2 635 393,67 €	-2 465 910,58 €	-2 317 241,21 €	-2 186 829,48 €	-2 072 433,23 €	-1 972 085,64 €	-1 884 061,44 €	-1 806 847,22 €	-1 739 115,46 €	-1 679 701,63 €	-1 627 584,23 €	-1 581 867,22 €	-1 541 764,58 €
0,15	-2 646 387,65 €	-2 482 723,18 €	-2 340 406,26 €	-2 216 652,41 €	-2 109 040,36 €	-2 015 464,67 €	-1 934 094,51 €	-1 863 337,84 €	-1 801 810,31 €	-1 748 308,10 €	-1 701 784,45 €	-1 661 329,09 €	-1 626 150,53 €
0,16	-2 657 074,97 €	-2 498 981,54 €	-2 362 694,11 €	-2 245 204,94 €	-2 143 921,18 €	-2 056 607,59 €	-1 981 337,25 €	-1 916 449,03 €	-1 860 510,91 €	-1 812 288,39 €	-1 770 717,25 €	-1 734 880,06 €	-1 703 985,94 €
0,17	-2 667 467,16 €	-2 514 709,74 €	-2 384 147,84 €	-2 272 556,48 €	-2 177 179,24 €	-2 095 660,24 €	-2 025 985,87 €	-1 966 435,14 €	-1 915 537,07 €	-1 872 034,45 €	-1 834 852,72 €	-1 803 073,47 €	-1 775 911,71 €
0,18	-2 677 575,23 €	-2 529 930,58 €	-2 404 807,99 €	-2 298 771,90 €	-2 208 910,80 €	-2 132 757,33 €	-2 068 220,49 €	-2 013 528,25 €	-1 967 178,90 €	-1 927 899,79 €	-1 894 612,40 €	-1 866 402,75 €	-1 842 496,27 €
0,19	-2 687 409,69 €	-2 544 665,67 €	-2 424 712,72 €	-2 323 911,91 €	-2 239 205,36 €	-2 168 023,38 €	-2 108 206,59 €	-2 057 940,38 €	-2 015 699,86 €	-1 980 203,63 €	-1 950 374,87 €	-1 925 308,68 €	-1 904 244,66 €
0,20	-2 696 980,55 €	-2 558 935,52 €	-2 443 897,99 €	-2 348 033,39 €	-2 268 146,22 €	-2 201 573,57 €	-2 146 096,37 €	-2 099 865,37 €	-2 061 339,54 €	-2 029 234,68 €	-2 002 480,62 €	-1 980 185,58 €	-1 961 606,38 €
IRR	-45,80 %	-32,08 %	-22,65 %	-15,98 %	-11,11 %	-7,47 %	-4,68 %	-2,51 %	-0,77 %	0,62 %	1,76 %	2,70 %	3,49 %
ROI	-73,98 %	-65,30 %	-56,63 %	-47,95 %	-39,28 %	-30,61 %	-21,93 %	-13,26 %	-4,58 %	4,09 %	12,77 %	21,44 %	30,12 %

FFR

NPV	Year												
Discount rate	3	4	5	6	7	8	9	10	11	12	13	14	15
0,01	-2 219 585,47 €	-1 866 567,76 €	-1 517 045,27 €	-1 170 983,39 €	-828 347,88 €	-489 104,79 €	-153 220,55 €	179 338,11 €	508 604,10 €	834 610,04 €	1 157 388,20 €	1 476 970,53 €	1 793 388,68 €
0,02	-2 240 561,96 €	-1 901 185,82 €	-1 568 464,11 €	-1 242 266,36 €	-922 464,64 €	-608 933,55 €	-301 550,12 €	-193,82 €	295 253,54 €	584 907,81 €	868 882,58 €	1 147 289,22 €	1 420 236,91 €
0,03	-2 260 866,19 €	-1 934 479,01 €	-1 617 598,25 €	-1 309 947,02 €	-1 011 256,52 €	-721 265,73 €	-439 721,28 €	-166 377,15 €	99 005,49 €	356 658,55 €	606 807,15 €	849 669,87 €	1 085 458,91 €
0,04	-2 280 526,97 €	-1 966 513,24 €	-1 664 576,96 €	-1 374 253,62 €	-1 095 096,55 €	-826 676,30 €	-568 579,90 €	-320 410,29 €	-81 785,67 €	147 661,09 €	368 282,97 €	580 419,40 €	784 396,73 €
0,05	-2 299 571,58 €	-1 997 350,47 €	-1 709 520,84 €	-1 435 397,38 €	-1 174 327,42 €	-925 689,37 €	-688 891,22 €	-463 369,17 €	-248 586,27 €	-44 031,13 €	150 783,30 €	336 320,84 €	513 023,27 €
0,06	-2 318 025,89 €	-2 027 048,98 €	-1 752 542,45 €	-1 493 574,04 €	-1 249 264,21 €	-1 018 783,24 €	-801 348,36 €	-596 221,12 €	-402 704,85 €	-220 142,34 €	-47 913,55 €	114 566,44 €	267 849,45 €
0,07	-2 335 914,41 €	-2 055 663,60 €	-1 793 746,95 €	-1 548 965,03 €	-1 320 196,89 €	-1 106 394,88 €	-906 579,92 €	-719 836,97 €	-545 310,85 €	-382 202,32 €	-229 764,45 €	-87 299,15 €	45 846,00 €
0,08	-2 353 260,41 €	-2 083 245,98 €	-1 833 232,62 €	-1 601 738,77 €	-1 387 392,61 €	-1 188 923,94 €	-1 005 156,66 €	-835 001,77 €	-677 450,94 €	-531 570,55 €	-396 496,11 €	-271 427,18 €	-155 622,62 €
0,09	-2 370 085,97 €	-2 109 844,80 €	-1 871 091,43 €	-1 652 051,64 €	-1 451 097,71 €	-1 266 736,31 €	-1 097 597,40 €	-942 424,09 €	-800 063,26 €	-669 456,99 €	-549 634,73 €	-439 706,05 €	-338 854,05 €
0,10	-2 386 412,06 €	-2 135 505,94 €	-1 907 409,47 €	-1 700 049,04 €	-1 511 539,55 €	-1 340 167,30 €	-1 184 374,34 €	-1 042 744,38 €	-913 989,86 €	-796 940,31 €	-690 531,62 €	-593 796,45 €	-505 855,38 €
0,11	-2 402 258,61 €	-2 160 272,70 €	-1 942 267,37 €	-1 745 866,18 €	-1 568 928,17 €	-1 409 524,55 €	-1 265 917,69 €	-1 136 542,14 €	-1 019 987,59 €	-914 983,50 €	-820 385,21 €	-735 161,53 €	-658 383,44 €
0,12	-2 417 644,56 €	-2 184 185,95 €	-1 975 740,75 €	-1 789 628,98 €	-1 623 457,75 €	-1 475 090,58 €	-1 342 619,89 €	-1 224 342,49 €	-1 118 737,67 €	-1 024 447,65 €	-940 260,13 €	-865 092,70 €	-797 978,93 €
0,13	-2 432 587,94 €	-2 207 284,29 €	-2 007 900,53 €	-1 831 454,73 €	-1 675 308,00 €	-1 537 125,05 €	-1 414 839,26 €	-1 306 621,75 €	-1 210 854,03 €	-1 126 103,84 €	-1 051 103,68 €	-984 731,85 €	-925 995,72 €
0,14	-2 447 105,88 €	-2 229 604,22 €	-2 038 813,28 €	-1 871 452,81 €	-1 724 645,38 €	-1 595 866,93 €	-1 482 903,38 €	-1 383 812,55 €	-1 296 890,77 €	-1 220 643,59 €	-1 153 760,10 €	-1 095 090,37 €	-1 043 625,70 €
0,15	-2 461 214,73 €	-2 251 180,23 €	-2 068 541,53 €	-1 909 725,28 €	-1 771 624,19 €	-1 651 536,28 €	-1 547 112,01 €	-1 456 308,30 €	-1 377 348,56 €	-1 308 687,91 €	-1 248 982,99 €	-1 197 065,68 €	-1 151 920,19 €
0,16	-2 474 930,01 €	-2 272 044,97 €	-2 097 144,06 €	-1 946 367,42 €	-1 816 387,56 €	-1 704 335,96 €	-1 607 739,75 €	-1 524 467,15 €	-1 452 680,43 €	-1 390 795,33 €	-1 337 446,10 €	-1 291 455,39 €	-1 251 808,22 €
0,17	-2 488 266,56 €	-2 292 229,33 €	-2 124 676,15 €	-1 981 468,30 €	-1 859 068,43 €	-1 754 453,15 €	-1 665 038,39 €	-1 588 615,51 €	-1 523 296,81 €	-1 467 468,87 €	-1 419 752,67 €	-1 378 969,60 €	-1 344 112,28 €
0,18	-2 501 238,49 €	-2 311 762,60 €	-2 151 189,81 €	-2 015 111,17 €	-1 899 790,29 €	-1 802 060,73 €	-1 719 239,07 €	-1 649 051,22 €	-1 589 570,00 €	-1 539 162,18 €	-1 496 443,69 €	-1 460 241,58 €	-1 429 561,82 €
0,19	-2 513 859,28 €	-2 330 672,50 €	-2 176 734,02 €	-2 047 373,95 €	-1 938 668,02 €	-1 847 318,49 €	-1 770 554,18 €	-1 706 046,36 €	-1 651 838,10 €	-1 606 284,95 €	-1 568 004,99 €	-1 535 836,95 €	-1 508 804,99 €
0,20	-2 526 141,79 €	-2 348 985,33 €	-2 201 354,94 €	-2 078 329,61 €	-1 975 808,51 €	-1 890 374,25 €	-1 819 179,04 €	-1 759 849,70 €	-1 710 408,58 €	-1 669 207,65 €	-1 634 873,54 €	-1 606 261,78 €	-1 582 418,65 €
IRR	-39,74 %	-26,01 %	-16,81 %	-10,44 %	-5,87 %	-2,51 %	0,04 %	2,00 %	3,54 %	4,76 %	5,75 %	6,56 %	7,22 %
ROI	-66,60 %	-55,47 %	-44,34 %	-33,21 %	-22,08 %	-10,94 %	0,19 %	11,32 %	22,45 %	33,58 %	44,72 %	55,85 %	66,98 %

APPENDIX 4. NPV, IRR and ROI calculations of 10 MW/ 10 MWh BESS in the FCR-N hourly and FFR markets

FCR-N hourly

NPV	Year												
Discount rate	3	4	5	6	7	8	9	10	11	12	13	14	15
0,01	-4 606 852,50 €	-4 056 690,92 €	-3 511 976,48 €	-2 972 655,25 €	-2 438 673,84 €	-1 909 979,37 €	-1 386 519,50 €	-868 242,40 €	-355 096,76 €	152 968,23 €	656 002,88 €	1 154 056,98 €	1 647 179,86 €
0,02	-4 639 543,38 €	-4 110 641,55 €	-3 592 110,34 €	-3 083 746,41 €	-2 585 350,41 €	-2 096 726,87 €	-1 617 684,19 €	-1 148 034,50 €	-687 593,63 €	-236 181,01 €	206 380,38 €	640 264,10 €	1 065 640,29 €
0,03	-4 671 186,57 €	-4 162 527,42 €	-3 668 683,59 €	-3 189 223,56 €	-2 723 728,39 €	-2 271 791,32 €	-1 833 017,48 €	-1 407 023,45 €	-993 437,02 €	-591 896,79 €	-202 051,91 €	176 438,27 €	543 904,46 €
0,04	-4 701 826,97 €	-4 212 451,27 €	-3 741 897,72 €	-3 289 442,37 €	-2 854 389,16 €	-2 436 068,76 €	-2 033 837,61 €	-1 647 076,89 €	-1 275 191,58 €	-917 609,55 €	-573 780,67 €	-243 175,99 €	74 713,14 €
0,05	-4 731 507,11 €	-4 260 509,66 €	-3 811 940,65 €	-3 384 732,07 €	-2 977 866,76 €	-2 590 375,99 €	-2 221 337,16 €	-1 869 871,61 €	-1 535 142,51 €	-1 216 352,90 €	-912 743,74 €	-623 592,16 €	-348 209,70 €
0,06	-4 760 267,28 €	-4 306 793,38 €	-3 878 987,82 €	-3 475 397,66 €	-3 094 652,23 €	-2 735 458,43 €	-2 396 596,35 €	-2 076 915,15 €	-1 775 329,10 €	-1 490 813,97 €	-1 222 403,47 €	-969 186,01 €	-730 301,62 €
0,07	-4 788 145,71 €	-4 351 387,93 €	-3 943 203,09 €	-3 561 721,94 €	-3 205 197,49 €	-2 871 997,08 €	-2 560 594,82 €	-2 269 564,67 €	-1 997 573,88 €	-1 743 376,88 €	-1 505 809,58 €	-1 283 784,08 €	-1 076 283,60 €
0,08	-4 815 178,63 €	-4 394 373,78 €	-4 004 739,67 €	-3 643 967,33 €	-3 309 918,88 €	-3 000 614,75 €	-2 714 222,04 €	-2 449 043,61 €	-2 203 508,02 €	-1 976 160,26 €	-1 765 653,07 €	-1 570 739,00 €	-1 390 263,02 €
0,09	-4 841 400,48 €	-4 435 826,80 €	-4 063 740,85 €	-3 722 377,60 €	-3 409 200,30 €	-3 121 881,68 €	-2 858 286,61 €	-2 616 456,28 €	-2 394 593,59 €	-2 191 049,83 €	-2 004 312,44 €	-1 832 993,74 €	-1 675 820,61 €
0,10	-4 866 843,92 €	-4 475 818,48 €	-4 120 340,81 €	-3 797 179,29 €	-3 503 396,08 €	-3 236 320,44 €	-2 993 524,41 €	-2 772 800,74 €	-2 572 142,86 €	-2 389 726,61 €	-2 223 893,65 €	-2 073 136,41 €	-1 936 084,38 €
0,11	-4 891 540,03 €	-4 514 416,32 €	-4 174 665,22 €	-3 868 583,16 €	-3 592 833,55 €	-3 344 410,48 €	-3 120 605,91 €	-2 918 980,17 €	-2 737 335,36 €	-2 573 691,39 €	-2 426 264,39 €	-2 293 447,27 €	-2 173 792,21 €
0,12	-4 915 518,32 €	-4 551 684,00 €	-4 226 831,92 €	-3 936 785,43 €	-3 677 815,34 €	-3 446 592,05 €	-3 240 142,69 €	-3 055 812,90 €	-2 891 232,73 €	-2 744 286,15 €	-2 613 083,84 €	-2 495 938,93 €	-2 391 345,26 €
0,13	-4 938 806,87 €	-4 587 681,69 €	-4 276 951,43 €	-4 001 968,91 €	-3 758 621,54 €	-3 543 269,89 €	-3 352 693,20 €	-3 184 041,27 €	-3 034 791,77 €	-2 902 712,57 €	-2 785 828,32 €	-2 682 390,93 €	-2 590 853,42 €
0,14	-4 961 432,41 €	-4 622 466,25 €	-4 325 127,50 €	-4 064 304,05 €	-3 835 511,54 €	-3 634 816,36 €	-3 458 767,95 €	-3 304 339,53 €	-3 168 876,00 €	-3 050 048,34 €	-2 945 813,55 €	-2 854 379,52 €	-2 774 174,24 €
0,15	-4 983 420,38 €	-4 656 091,45 €	-4 371 457,59 €	-4 123 949,89 €	-3 908 725,81 €	-3 721 574,43 €	-3 558 834,10 €	-3 417 320,77 €	-3 294 265,69 €	-3 187 261,29 €	-3 094 213,97 €	-3 013 303,27 €	-2 942 946,13 €
0,16	-5 004 795,01 €	-4 688 608,17 €	-4 416 033,30 €	-4 181 054,96 €	-3 978 487,43 €	-3 803 860,25 €	-3 653 319,58 €	-3 523 543,14 €	-3 411 666,89 €	-3 315 221,86 €	-3 232 079,58 €	-3 160 405,21 €	-3 098 616,96 €
0,17	-5 025 579,40 €	-4 720 064,56 €	-4 458 940,76 €	-4 235 758,03 €	-4 045 003,56 €	-3 881 965,55 €	-3 742 616,83 €	-3 623 515,35 €	-3 521 719,22 €	-3 434 713,98 €	-3 360 350,53 €	-3 296 792,02 €	-3 242 468,51 €
0,18	-5 045 795,55 €	-4 750 506,24 €	-4 500 261,06 €	-4 288 188,87 €	-4 108 466,68 €	-3 956 159,74 €	-3 827 086,06 €	-3 717 701,58 €	-3 625 002,88 €	-3 546 444,65 €	-3 479 869,88 €	-3 423 450,59 €	-3 375 637,63 €
0,19	-5 065 464,46 €	-4 779 976,43 €	-4 540 070,52 €	-4 338 468,91 €	-4 169 055,79 €	-4 026 691,83 €	-3 907 058,25 €	-3 806 525,83 €	-3 722 044,80 €	-3 651 052,34 €	-3 591 394,82 €	-3 541 262,44 €	-3 499 134,39 €
0,20	-5 084 606,17 €	-4 808 516,11 €	-4 578 441,06 €	-4 386 711,85 €	-4 226 937,51 €	-4 093 792,23 €	-3 982 837,83 €	-3 890 375,82 €	-3 813 324,15 €	-3 749 114,43 €	-3 695 606,33 €	-3 651 016,24 €	-3 613 857,84 €
IRR	-44,69 %	-30,96 %	-21,57 %	-14,96 %	-10,15 %	-6,56 %	-3,82 %	-1,68 %	0,02 %	1,38 %	2,49 %	3,41 %	4,17 %
ROI	-72,70 %	-63,60 %	-54,50 %	-45,39 %	-36,29 %	-27,19 %	-18,09 %	-8,99 %	0,11 %	9,21 %	18,31 %	27,41 %	36,51 %

FFR

NPV	Year												
Discount rate	3	4	5	6	7	8	9	10	11	12	13	14	15
0,01	-4 129 816,02 €	-3 423 780,59 €	-2 724 735,61 €	-2 032 611,87 €	-1 347 340,84 €	-668 854,67 €	2 913,82 €	668 031,13 €	1 326 563,13 €	1 978 575,00 €	2 624 131,31 €	3 263 295,98 €	3 896 132,28 €
0,02	-4 171 769,00 €	-3 493 016,72 €	-2 827 573,30 €	-2 175 177,80 €	-1 535 574,36 €	-908 512,17 €	-293 745,32 €	308 967,29 €	899 862,00 €	1 479 170,53 €	2 047 120,08 €	2 603 933,36 €	3 149 828,74 €
0,03	-4 212 377,46 €	-3 559 603,10 €	-2 925 841,58 €	-2 310 539,13 €	-1 713 158,11 €	-1 133 176,54 €	-570 087,64 €	-23 399,39 €	507 365,91 €	1 022 672,02 €	1 522 969,22 €	2 008 694,65 €	2 480 272,74 €
0,04	-4 251 699,02 €	-3 623 671,56 €	-3 019 799,00 €	-2 439 152,31 €	-1 880 838,19 €	-1 343 997,68 €	-827 804,89 €	-331 465,66 €	145 783,59 €	604 677,10 €	1 045 920,87 €	1 470 193,71 €	1 878 148,38 €
0,05	-4 289 788,25 €	-3 685 346,02 €	-3 109 686,76 €	-2 561 439,85 €	-2 039 299,93 €	-1 542 023,82 €	-1 068 427,52 €	-617 383,43 €	-187 817,62 €	221 292,67 €	610 921,51 €	981 996,60 €	1 335 401,45 €
0,06	-4 326 696,86 €	-3 744 743,03 €	-3 195 729,99 €	-2 677 793,15 €	-2 189 173,49 €	-1 728 211,55 €	-1 293 341,80 €	-883 087,32 €	-496 054,78 €	-130 929,75 €	213 527,83 €	538 487,80 €	845 053,82 €
0,07	-4 362 473,90 €	-3 801 972,27 €	-3 278 138,97 €	-2 788 575,14 €	-2 331 038,85 €	-1 903 434,84 €	-1 503 804,93 €	-1 130 319,02 €	-781 266,78 €	-455 049,73 €	-150 173,98 €	134 756,63 €	401 046,92 €
0,08	-4 397 165,90 €	-3 857 137,04 €	-3 357 110,32 €	-2 894 122,62 €	-2 465 430,30 €	-2 068 492,96 €	-1 700 958,40 €	-1 360 648,61 €	-1 045 546,96 €	-753 786,17 €	-483 637,29 €	-233 499,44 €	-1 890,32 €
0,09	-4 430 817,02 €	-3 910 334,68 €	-3 432 827,94 €	-2 994 748,37 €	-2 592 840,50 €	-2 224 117,69 €	-1 885 839,88 €	-1 575 493,27 €	-1 290 771,60 €	-1 029 559,07 €	-789 914,54 €	-570 057,18 €	-368 353,17 €
0,10	-4 463 469,20 €	-3 961 656,96 €	-3 505 464,01 €	-3 090 743,15 €	-2 713 724,19 €	-2 370 979,68 €	-2 059 393,76 €	-1 776 133,83 €	-1 518 624,81 €	-1 284 525,69 €	-1 071 708,32 €	-878 237,98 €	-702 355,85 €
0,11	-4 495 162,29 €	-4 011 190,47 €	-3 575 179,82 €	-3 182 377,44 €	-2 828 501,41 €	-2 509 694,19 €	-2 222 480,47 €	-1 963 729,37 €	-1 730 620,27 €	-1 520 612,07 €	-1 331 415,50 €	-1 160 968,14 €	-1 007 411,95 €
0,12	-4 525 934,20 €	-4 059 016,97 €	-3 642 126,59 €	-3 269 903,03 €	-2 937 560,57 €	-2 640 826,23 €	-2 375 884,85 €	-2 139 330,06 €	-1 928 120,41 €	-1 739 540,38 €	-1 571 165,34 €	-1 420 830,49 €	-1 286 602,94 €
0,13	-4 555 820,95 €	-4 105 213,66 €	-3 706 446,15 €	-3 353 554,54 €	-3 041 261,08 €	-2 764 895,19 €	-2 520 323,60 €	-2 303 888,57 €	-2 112 353,15 €	-1 942 852,77 €	-1 792 852,43 €	-1 660 108,78 €	-1 542 636,51 €
0,14	-4 584 856,85 €	-4 149 853,51 €	-3 768 271,64 €	-3 433 550,70 €	-3 139 935,84 €	-2 882 378,95 €	-2 656 451,85 €	-2 458 270,18 €	-2 284 426,61 €	-2 131 932,26 €	-1 998 165,28 €	-1 880 825,82 €	-1 777 896,47 €
0,15	-4 613 074,53 €	-4 193 005,54 €	-3 827 728,15 €	-3 510 095,64 €	-3 233 893,45 €	-2 993 717,64 €	-2 784 869,11 €	-2 603 261,69 €	-2 445 342,19 €	-2 308 020,89 €	-2 188 611,07 €	-2 084 776,44 €	-1 994 485,45 €
0,16	-4 640 505,10 €	-4 234 735,01 €	-3 884 933,21 €	-3 583 379,93 €	-3 323 420,21 €	-3 099 317,00 €	-2 906 124,57 €	-2 739 579,38 €	-2 596 005,94 €	-2 472 235,73 €	-2 365 537,28 €	-2 273 555,85 €	-2 194 261,52 €
0,17	-4 667 178,20 €	-4 275 103,75 €	-3 939 997,38 €	-3 653 581,68 €	-3 408 781,93 €	-3 199 551,38 €	-3 020 721,85 €	-2 867 876,10 €	-2 737 238,71 €	-2 625 582,81 €	-2 530 150,43 €	-2 448 584,28 €	-2 378 869,63 €
0,18	-4 693 122,06 €	-4 314 170,27 €	-3 993 024,69 €	-3 720 867,42 €	-3 490 225,66 €	-3 294 766,54 €	-3 129 123,22 €	-2 988 747,53 €	-2 869 785,08 €	-2 768 969,44 €	-2 683 532,46 €	-2 611 128,23 €	-2 549 768,73 €
0,19	-4 718 363,65 €	-4 351 990,07 €	-4 044 113,12 €	-3 785 392,99 €	-3 567 981,11 €	-3 385 282,06 €	-3 231 753,44 €	-3 102 737,79 €	-2 994 321,29 €	-2 903 214,98 €	-2 826 655,05 €	-2 762 318,98 €	-2 708 255,06 €
0,20	-4 742 928,66 €	-4 388 615,73 €	-4 093 354,95 €	-3 847 304,30 €	-3 642 262,10 €	-3 471 393,59 €	-3 329 003,17 €	-3 210 344,48 €	-3 111 462,25 €	-3 029 060,38 €	-2 960 392,16 €	-2 903 168,64 €	-2 855 482,38 €
IRR	-38,48 %	-24,76 %	-15,61 %	-9,30 %	-4,80 %	-1,48 %	1,01 %	2,93 %	4,43 %	5,62 %	6,58 %	7,36 %	8,00 %
ROI	-64,96 %	-53,28 %	-41,60 %	-29,92 %	-18,24 %	-6,56 %	5,11 %	16,79 %	28,47 %	40,15 %	51,83 %	63,51 %	75,19 %

APPENDIX 5. LCOSs

Variables				Size				Year	Av. price		
Initial investment costs	1 000,00	€/kW		1 MW/ 1 MWh				2019	44,04	€/MWh	
O&M costs	5 000,00	€, a			1 000,00	kW		2018	46,80	€/MWh	
Annual cycles	872,00				1 000,00	kWh		2017	33,19	€/MWh	
Annual charging costs	0,040262	€/kWh						2016	32,45	€/MWh	
Annual electricity input	872 000,00	kWh						2015	29,66	€/MWh	
Assumed lifespan	10,00	years						2014	36,02	€/MWh	
Discount rate	10 %							2013	41,16	€/MWh	
DoD	96 %							2012	36,64	€/MWh	
Round trip efficiency	92 %							2011	49,30	€/MWh	
Self-discharge per day	0,20 %							2010	56,64	€/MWh	
Annual round trip degradation factor	0,50 %							2009	36,98	€/MWh	
Battery's residual value	66 666,67							average	40,26	€/MWh	
								average	0,0403	€/kWh	
Total costs											
Year	-	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00
Initial investment	1 000 000,00										
O&M costs		5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00
Fuel costs		35 108,46	35 108,46	35 108,46	35 108,46	35 108,46	35 108,46	35 108,46	35 108,46	35 108,46	35 108,46
Discount factor	100,00 %	90,91 %	81,00 %	72,90 %	65,61 %	59,05 %	53,14 %	47,83 %	43,05 %	38,74 %	34,87 %
Present value of costs	1 000 000,00	36 462,24	32 487,86	29 239,07	26 315,16	23 683,65	21 315,28	19 183,75	17 265,38	15 538,84	13 984,96
Residual value	-	-	-	-	-	-	-	-	-	-	66 666,67
NPV total costs	1 168 809,52	€									
Total energy output											
Yearly output		764 767,05	760 943,21	757 138,50	753 352,80	749 586,04	745 838,11	742 108,92	738 398,38	734 706,38	731 032,85
Discount factor	100,00 %	90,91 %	81,00 %	72,90 %	65,61 %	59,05 %	53,14 %	47,83 %	43,05 %	38,74 %	34,87 %
Present value of costs		695 242,77	616 364,00	551 953,96	494 274,78	442 623,06	396 368,95	354 948,40	317 856,29	284 640,31	254 895,39
NPV of total output	4 409 167,91	kWh									
LCOS	0,27	€/kWh	265,09	€/MWh							

1 MW/ 1 MWh BESS

Variables				Size				Year	Av. price		
Initial investment costs	480,00	€/kW		5 MW/ 5 MWh				2019	44,04	€/MWh	
O&M costs	5 000,00	€, a			5 000,00	kW		2018	46,80	€/MWh	
Annual cycles	872,00				5 000,00	kWh		2017	33,19	€/MWh	
Annual charging costs	0,040262	€/kWh						2016	32,45	€/MWh	
Annual electricity input	4 360 000,00	kWh						2015	29,66	€/MWh	
Assumed lifespan	10,00	years						2014	36,02	€/MWh	
Discount rate	10 %							2013	41,16	€/MWh	
DoD	96 %							2012	36,64	€/MWh	
Round trip efficiency	92 %							2011	49,30	€/MWh	
Self-discharge per day	0,20 %							2010	56,64	€/MWh	
Annual round trip degradation factor	0,50 %							2009	36,98	€/MWh	
Battery's residual value	160 000,00							average	40,26	€/MWh	
								average	0,0403	€/kWh	
Total costs											
Year	-	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00
Initial investment	2 400 000,00										
O&M costs		5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00
Fuel costs		175 542,32	175 542,32	175 542,32	175 542,32	175 542,32	175 542,32	175 542,32	175 542,32	175 542,32	175 542,32
Discount factor	100,00 %	90,91 %	81,00 %	72,90 %	65,61 %	59,05 %	53,14 %	47,83 %	43,05 %	38,74 %	34,87 %
Present value of costs	2 400 000,00	164 129,38	146 239,28	131 615,35	118 453,82	106 608,43	95 947,59	86 352,83	77 717,55	69 945,79	62 951,21
Residual value	-	-	-	-	-	-	-	-	-	-	160 000,00
NPV total costs	3 299 961,24	€									
Total energy output											
Yearly output		3 823 835,24	3 804 716,07	3 785 692,49	3 766 764,02	3 747 930,20	3 729 190,55	3 710 544,60	3 691 991,88	3 673 531,92	3 655 164,26
Discount factor	100,00 %	90,91 %	81,00 %	72,90 %	65,61 %	59,05 %	53,14 %	47,83 %	43,05 %	38,74 %	34,87 %
Present value of costs		3 476 213,86	3 081 820,01	2 759 769,82	2 471 373,88	2 213 115,31	1 981 844,76	1 774 741,98	1 589 281,44	1 423 201,53	1 274 476,97
NPV of total output	22 045 839,56	kWh									
LCOS	0,15	€/kWh	149,69	€/MWh							

5 MW/ 5 MWh BESS

Variables				**Size**				**Year**	**Av. price**		
Initial investment costs	450,00	€/kW		10 MW/ 10 MWh				2019	44,04	€/MWh	
O&M costs	5 000,00	€, a			10 000,00	kW		2018	46,80	€/MWh	
Annual cycles	872,00				10 000,00	kWh		2017	33,19	€/MWh	
Annual charging costs	0,040262	€/kWh						2016	32,45	€/MWh	
Annual electricity input	8 720 000,00	kWh						2015	29,66	€/MWh	
Assumed lifespan	10,00	years						2014	36,02	€/MWh	
Discount rate	10 %							2013	41,16	€/MWh	
DoD	96 %							2012	36,64	€/MWh	
Round trip efficiency	92 %							2011	49,30	€/MWh	
Self-discharge per day	0,20 %							2010	56,64	€/MWh	
Annual round trip degradation factor	0,50 %							2009	36,98	€/MWh	
Battery's residual value	300 000,00							average	40,26	€/MWh	
								average	0,0403	€/kWh	
Total costs											
Year	-	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00
Initial investment	4 500 000,00										
O&M costs		5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00	5 000,00
Fuel costs		351 084,64	351 084,64	351 084,64	351 084,64	351 084,64	351 084,64	351 084,64	351 084,64	351 084,64	351 084,64
Discount factor	100,00 %	90,91 %	81,00 %	72,90 %	65,61 %	59,05 %	53,14 %	47,83 %	43,05 %	38,74 %	34,87 %
Present value of costs	4 500 000,00	323 713,31	288 428,56	259 585,70	233 627,13	210 264,42	189 237,98	170 314,18	153 282,76	137 954,49	124 159,04
Residual value	-	-	-	-	-	-	-	-	-	-	300 000,00
NPV total costs	6 290 567,56	€									
Total energy output											
Yearly output		7 647 670,49	7 609 432,13	7 571 384,97	7 533 528,05	7 495 860,41	7 458 381,11	7 421 089,20	7 383 983,76	7 347 063,84	7 310 328,52
Discount factor	100,00 %	90,91 %	81,00 %	72,90 %	65,61 %	59,05 %	53,14 %	47,83 %	43,05 %	38,74 %	34,87 %
Present value of costs		6 952 427,72	6 163 640,03	5 519 539,65	4 942 747,75	4 426 230,61	3 963 689,51	3 549 483,96	3 178 562,89	2 846 403,06	2 548 953,94
NPV of total output	44 091 679,12	kWh									
LCOS	0,14	€/kWh	142,67	€/MWh							

10 MW/ 10 MWh BESS

APPENDIX 6. The questionnaire

Mika Laakso - Master Thesis Questionnaire

Hey!

Thank you for taking the time to complete this survey.

The answers of this questionnaire are used as a source in this Mater thesis, and explicit references are never used. The blank questionnaire is added as an appendix to the end of the thesis. So, your answers are not recorded to the thesis. The answer you give are confidential information, and the answers are not assigned to any third person. The response time for this questionnaire is approximately ten to fifteen minutes.

Remember to answer into each section ja send your answers when you are ready!

Respondent's contact information

Email address *

Name *

First name and last name

Company *

Date *

PP KK VVVV

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Question 1

What are the annual operation costs for lithium-ion battery energy storage?

Question 2

What are the annual maintenance costs for lithium-ion battery energy storage? Are there differences between the years?

Question 3

What is the residual value of lithium-ion battery, when energy storage is at the end of its service life?

Question 4

Can energy market's arbitrage be profitable future business for lithium-ion batteries in Finland?

Question 5

Price estimation

What is the price estimation (€/MW and €/MWh) for 1 MW/ 1 MWh lithium-ion battery energy storage, if storage is able to participate to Fingrid's FCR-N, FCR-D and FFR markets? Energy storage would be located next to power plant, where is an asphalth area for it. The energy storage would be provided as a turnkey solution including connection to power plant and possible other costs.

Question 6

Does the price estimation (€/MW and €/MWh) change if the size of the energy storage is 5 MW/ 5 MWh or 10 MW/ 10 MWh? Requirements and background informations are same as in aforementioned question.

Question 7

What is the cyclic life of the lithium-ion battery you offer? Then what is the depth of discharge (DoD) of the battery.

Question 8

What is the service life of the battery you offer?

Question 9

What lithium-ion battery type (LTO, NMC, etc.) you offer?

Free speech

Questions and comments regarding to the questionnaire or the thesis?