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TAMPERE UNIVERSITY OF TECHNOLOGY

ANTTI LEINONEN

USING BATTERY ENERGY STORAGES IN THE FUTURE FLEXIBLE POWER SYSTEMS

Master of Science thesis

Examiner: Prof. Pertti Järventausta
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ABSTRACT

ANTTI LEINONEN: Using battery energy storages in the future flexible power systems
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The power grid will change in the future when customers' energy consumption habits change, more renewable energy sources are integrated into the grid and more Smart Grid functions are used. This will create some new challenges to the energy system, therefore, the power grid and supporting systems need to be able to react in different velocities to guarantee high-quality and reliable electricity distribution.

The focus of this thesis is to find out which issues are creating different challenges to the energy system in in the timeframe of 4 hours of less, and to sort out alternative solutions to these challenges with evaluating their cost effectiveness.

Market regulations are not covered in this thesis since they will be modified in the future. The main focus will be on Toshiba's SCiB™ power energy storage. How it can be used to solve the new challenges and what would be the break-even point to make it a competitive choice.

Visio 2035 is a research made by universities in Finland. That is the background with our own opinions and interviewing members of energy companies to predict changes in the future power system. When it is known what are the biggest challenges in the future, it is possible to discuss how power storages can be used as solutions. After knowing the possible solutions, it is calculated how much value can each service of power storage provide. Time of use for each service can be get from pilot projects.

With the pilot project information and calculations for singular services, it is possible to know yearly income, operative costs and investment costs. Using these values, it was calculated that power storages are profitable investments already at present. It is also calculated break-even points for investments if the payback time needs to be shorter.

TIIVISTELMÄ

ANTTI LEINONEN: Akkuvaraston hyödyntäminen tulevaisuuden joustavassa sähköenergiajärjestelmässä
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Avainsanat: energiavarasto, akusto, BESS, tehovarasto, tulevaisuuden sähköenergiajärjestelmä

Sähköverkko tulee muuttumaan tulevaisuudessa, kun loppukuluttajien energiankäyttötavat muuttuvat, verkkoon liitetään yhä enemmän uusiutuvia energialähteitä ja verkon Smart Grid ominaisuudet lisääntyvät. Tämä luo sähkönjakeluun erilaisia haasteita, joihin verkon ja sitä tukevien järjestelmien tulee reagoida eri nopeudella turvatakseen sähkön laadukas ja varma toimitus.

Tämän diplomityön tavoitteena on syventyä sähkönjakeluverkon muutoksesta johtuviin haasteisiin, jotka tapahtuvat alle neljän tunnin ajanjaksolla. Näihin haasteisiin selvitetään vaihtoehtoisia ratkaisuja ja arvioidaan niiden kustannustehokkuuksia.

Koska tämän päivän regulaatiomalli ei vastaa kaikilta osin tulevaisuuden haasteisiin ja sitä tultaneen tulevaisuudessa muuttamaan, se jätetään tässä työssä huomioimatta. Työssä perehdytään erityisesti, kuinka Toshiban SCiB™ tehoakku soveltuu ratkaisuksi esiintyviin ongelmiin ja millä hintatasolla se olisi kilpailukykyinen vaihtoehto. Alle neljän tunnin käyttöön tarkoitetut tehoakut on valittu työn rajaukseksi, koska nykypäivän teknologioilla ne ovat kustannustehokkaimpia ratkaisuita.

Lähtökohtana sähköverkon muutosten ennustamiseen käytettiin vuonna 2016 valmistuneen tutkimusprojektin, visio 2035, tulosaineistoa, omia arvioitamme sekä energiayhtiöiden edustajien haastatteluja. Kun oli selvitetty suurimmat haasteet ja miten tehoakustot soveltuvat niihin ratkaisuiksi, laskettiin yksittäisten palveluiden tuottama arvo. Pilottiprojekteista saatavilla tiedoilla voidaan arvioida, kuinka paljon mitäkin ominaisuutta voidaan käyttää yhtä aikaa muiden ominaisuuksien kanssa.

Saatujen vuotuisten tuottoarvioiden, kustannuksien ja investointikustannuksien perusteella voidaan todeta, että tehoakustot ovat kannattavia ratkaisuja jo tänä päivänä. Lisäksi tuottoarvioiden ja kustannuksien perusteella saatiin laskettua suurin investointikustannus pienemmille takaisinmaksuajoille.

PREFACE

This thesis is made in Jyväskylä for Landis+Gyr Oy between September 2016 and December 2016. The idea in this thesis was to find out the break-even point for battery energy storages and calculate if battery energy storages are profitable already. Also there is discussed how the power system is going to change in the future and what kind of challenges changes will bring.

I would like to thank the examiner of the thesis, professor Pertti Järventausta from the Department of Electrical Engineering in Tampere University of Technology, for the help and opinions which he was able to give with the tight schedule. I would also like thank my thesis supervisor, M.Sc. Sami Haapamäki respectively for guidance and conversations we had.

Many thanks to all my friend during the studies as you made these years unforgettable. At last, I want to thank my family and especially my father, Rauno Leinonen, who supported me through my whole studies.

Jyväskylä, 19.12.2016

Antti Leinonen

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LIST OF ABBREVIATIONS AND SYMBOLS

AC	Alternating current
AMR	Automatic meter reading
BESS	Battery energy storage system
BMC	BESS master control
BMS	Battery management system
CAES	Compressed air energy storage
CIC	Customer interruption cost
COP15	United Nations Climate Change Conference
DC	Direct current
DOD	Depth of discharge
EV	Electric vehicle
FCR-D	Frequency contained reserves in disturbance
FCR-N	Frequency contained reserves in normal operation
HMI	Human-machine interface
HVAC	Heating, ventilation and air conditioning
LAES	Liquefied air energy storage
Li-ion	Lithium ion
LTO	Lithium titanate oxide
LV	Low voltage
LVDC	Low voltage direct current
MV	Medium voltage
NaS	Sodium sulfur
Ni-Cd	Nickel cadmium
PCS	Power control system
PV	Photovoltaics
RES	Renewable energy resources
SCiB™	Super Charge ion Battery
SOC	State of charge
TOU	Time of use
UPS	Uninterruptible power supply

A	Ampere
a	Year
Ah	Ampere-hour
C_0	Initial investment cost
C_t	Net cash flow
E_{aux}	Energy absorbed by auxiliaries
E_{in}	Energy absorbed during battery charge
E_{out}	Energy released during battery discharge
f	Frequency
Hz	Hertz
i	Discount rate
kVAr	Kilovolt ampere reactive
kWp	Kilowatt-peak
MWp	Megawatt-peak
n_s	Synchronous speed
NPV	Net present value
P	Real power

p	Amount of pole pairs
Q	Reactive power
rpm	Rounds per minute
t	Time of cash flow
THD_U	Total harmonic distortion in voltage
U_{RMS}	Root mean square voltage
V	Voltage
W	Watt

1. INTRODUCTION

Drivers for instance climate change and reliability of electricity are forcing changes to the power system. When the infrastructure is changing, there will be new challenges. These challenges are related e.g. power quality and quality of supply. Nowadays customers are relying on electricity supply so, therefore, are needs for solutions to these challenges.

Increasing amount of intermittent production is one big challenge. High volatility in production will affect the voltage frequency. Also, the times with low production are needed to be compensated. Energy storages are considered as an option to secure electricity delivery with high quality. Hydro power is used for frequency regulation and energy compensating but it will not be enough in the future. Improving technology and lowering prices are making battery energy storages a viable option.

Landis+Gyr Oy has delivered a battery energy storage system (BESS) to Helen in Helsinki, Finland. The BESS is using Toshiba's Super Charge ion Battery (SCiB™) technology. It is the biggest BESS in the Nordics and it is used for a pilot project.

1.1 Goals of the Thesis

BESSs are an option to solve many challenges in the future power system. A BESS can react quickly for changes and produce high amount of power in a short period of time. Some customers still consider that the price of BESS is too high.

The objectives of this thesis are to define possibilities of BESSs during a four hours' timeframe and calculate the costs and benefits of a BESS whether it would be a good business case or not. This is done by calculating the value of each services that a BESS has. As it is known how much each service has value, the total profit can be calculated. The total profit is based on the time of use (TOU) for each service during a year.

When the total profit, operating costs and suggested payback time for a BESS is known, it is possible to calculate the price for the investment. The usage of less than 4 hours is selected because it is expected that with technologies of today, it is the most profitable and the best option.

1.2 Thesis structure

The purpose of the chapter 2 is to discuss the changes which would probably happen in the power grid in the future. The information is based on our own opinions, Visio 2035 and interviews. Visio 2035 is a part of a research that was made by Tampere University of Technology, Lappeenranta University of Technology, University of Vaasa and Oy Merinova Ab. The purpose of Visio 2035 was to find out the possible scenarios how a Finnish power system will look like in 2035.

The chapter 3 includes an overview of different energy storages. There are introduced different energy storage technologies and their capabilities.

The chapter 4 focuses more on battery energy storages. There it will be introduced how battery energy storages can be used today. Battery energy storages are divided into centralized and distributed solutions. Centralized storages can still be divided into energy storages and power storages. As the focus is on the storages with usage less than four hours, there is a more specific look into SCiB^{TM} technology and how it can be used as a power storage. After chapter 4, BESS refers to power storages.

The chapter 5 focuses on challenges which are caused by changes in the power system and where a power storage could be seen as a solution. These challenges are technical and commercial.

The chapter 6 calculates approximated values that each singular service of BESS can generate. These approximated values are used to calculate the total profit for real life cases. Using these values, it is possible to calculate the suggested investment cost of a BESS.

The chapter 7 discuss how BESSs may and should evolve in the future. The future is divided into a near future and long term possibilities.

The chapter 8 is the summary and conclusions of the results that are found out in this thesis.

2. POWER GRID IN THE FUTURE

This chapter discusses and analyses about how the power grid will become more flexible in the future and what possibilities and challenges it brings. It is mostly based on Visio 2035 but there are only estimations what probably will happen and what are the drivers for changes as there are many things that may cause different solutions in the far future.

2.1 Distributed energy resources

European Commission among other countries are setting goals to reduce emissions by a huge amount in a near future and that is one reason why energy production will change. In 2009 United Nations Climate Change Conference (COP15) different countries made promises for these pollution reductions. As the biggest examples, USA was planning to reduce emissions by 17 % from the level of 2005 by 2020 and European Union made the 20-20-20 targets. 20-20-20 targets mean that greenhouse emissions should be reduced by 20 %, usage of renewable energy resources would be increased by 20 % and in cause of better energy efficiency, energy consumption would be dropped by 20 %. All these targets should be accomplished by 2020. [1]

Targets for 2030 have also been made already as the three key points are reducing greenhouse gas emissions at least 40 % from the levels of 1990. The second point is that renewable energy resources should provide at least 27 % of energy consumption in generation. The last point is to improve energy efficiency by 27 % in minimum. [2]

Mostly the emission reduction is planned by reducing coal as energy source which means that the amount of renewable energy sources will increase rapidly as this was mentioned in the COP15. Another reason is that renewable energy sources are getting cheaper to manufacture. Thus, energy production price will decrease too.

There were new records made about the lowest price in Chile and Arab Emirates for solar power plants. In Chile, the new contract was 29,10 USD for MWh which is low rate compared to other energy sources. Wind power was the second cheapest with the price of 38,10 USD/MWh, natural gas-fired plants 47,00 USD/MWh, coal 57,00 USD/MWh, hydropower 60,00 USD/MWh and geothermal 66,00 USD/MWh. [3] There was already a huge drop in prices in Chile but only a month later it was announced that solar power price in Abu Dhabi was 24,20 USD/MWh [4]. This confirms that the trend of solar power price is decreasing worldwide.

One needs to remember that adding large renewable energy power plants is not so simple as there are many stakeholders holding back the progress, for instance, people of the area where windmills are considered to be built [5]. Large size windmills create noise to the nearby area, and many places are nature preserved which disallow to build anything to the area even if it would be the best or the only option by condition [6].

Increasing renewable energy sources are making the energy system from centralized to distributed in some cases. Nowadays, the market mechanics have been set by centralized energy production but this may change with the modification of energy production system. Consumers will start to produce more and more of their own electricity [7] and leftover production could be transferred to the grid if regulations in taxes are changed to make it profitable. That will cause challenges for the grid itself and especially to the electricity price and predictability. Consumers who are an active part of the system and produce electricity are called prosumers in this Thesis. Taxing problems are discussed in chapter 5.2.2.

Markets will decide the price of electricity but the technical challenges will need cost-effective solutions. Adding intermittent production to the grid is going to make harder to sustain the voltage quality in the required level. Sometimes it may cause overvoltage but mostly the unstable and dropping production will cause undervoltage. Power balance is also a hard task to manage when the production relies on the weather. These problems are mostly random and cannot be predicted, therefore, the grid must be built as prepared for worst case scenarios which is not a very cost effective solution. [8]

2.2 Microgrids

Microgrids are areas which can operate self-contained and separated from grid as a separate island but they still require frequency regulation and safety. Common examples of microgrids are hospitals and industrial areas. Most of these methods to run a microgrid are distributed energy resources and have the challenges as discussed before. A bigger challenge within microgrids is how to keep the system up during blackouts. Nowadays the possibilities are using diesel generators, gas turbines and uninterruptible power sources (UPS). For example, diesel powered generators take quite a lot of time to start running and UPSs are designed only for short time power cuts so there might be needs for different solutions. [9]

To be able to be self-contained, microgrids need to have their own electricity production and back-ups. This means that when operating in island mode, the island needs a main power source such as a diesel generator or a gas turbine. Windmills, photovoltaics or other smaller sources will add more capacity to the grid. Overview of a microgrid operating in island mode is shown in figure 1. [9]

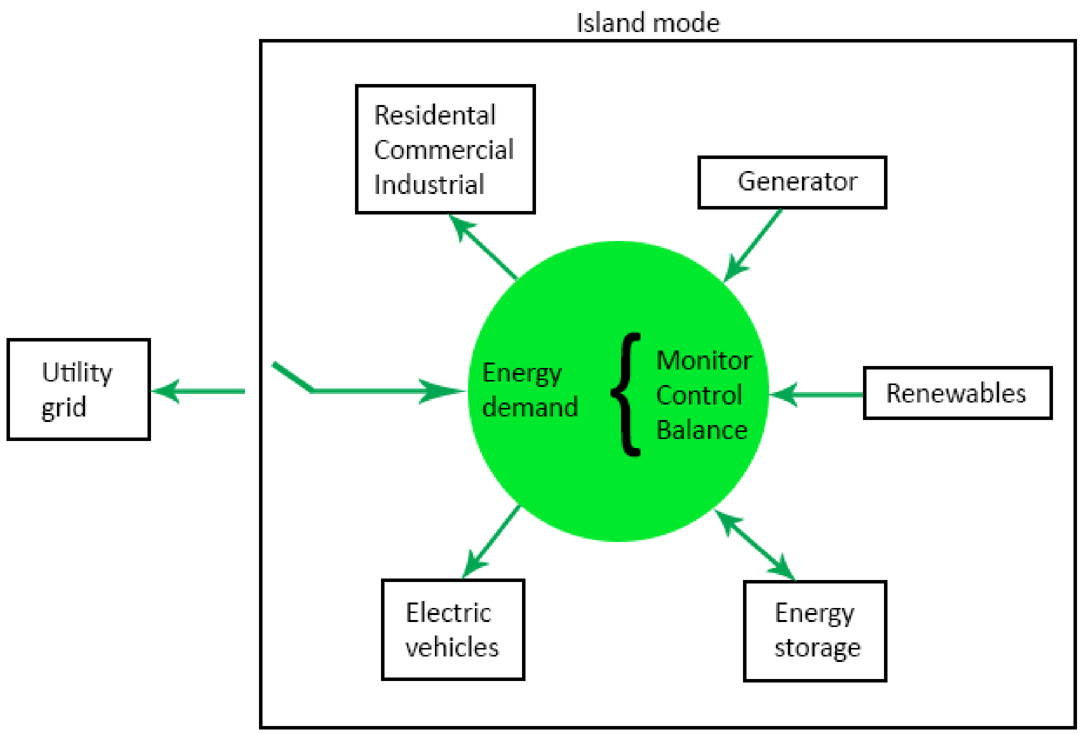

Figure 1. *Microgrid operating in an island mode [9]*

In figure 1 the microgrid island is separated from the utility grid. There is a generator to provide the most of the power needed in the area and set up the frequency. Renewable energy resources are providing more energy and energy storage is used to have backup power or store the overproduction for later use. This image is an example of populated area instead of hospital as it has energy demand system for electric vehicles, residential and commercial needs.

2.3 Delivery reliability

Nowadays more and more applications are using electricity and the amount of devices will increase a lot in the future. As a result, even a short time power cut may cause a lot of economical or other damage, and increases the need of more stable and reliable delivery of electricity.

There are multiple indexes to measure reliability of supply. Using these indexes, it is possible to calculate customer interruption cost (CIC). CIC is used to calculate how much harm has been done during the interruptions. [10]

In a few years, there have been some major storms in Finland which made thousands of apartments to be without electricity for long periods of time [11]. Power cuts that last over 12 hours generate costs to electricity distribution system operators (DSO). That is one of the reasons why as an example, a Finnish company Elenia, is replacing their distribution network with underground cables to prevent the disturbances caused by natural forces [12].

In the future, the development progress of protective relays will bring smarter function, in order to make the grid communicate with itself, the way we are pointing out on Smart Grid today. This would help to locate the problems within the grid quicker and more accurately, which would help to solve the problems as soon as they occur.

2.4 Prosumer behavior

One of the biggest concerns in the future is how customers will use their loads. One example is heat pumps for warming and cooling. The average temperature is rising [13] and that will make more and more people to buy heat pumps to set temperature of their apartments. In a scenario where two people come home at 5 pm during a hot summer day and turns on their heat pump about a same time, it may create a huge spike in the current and cause harmonics and distortion for the whole area.

Traffic creates a huge amount of emissions and that is why car manufacturers are developing electric vehicles (EV). Prices of EVs are currently high but prices will decrease in time and cause more EVs to take in use. When EVs are more common it is necessary to add more charging points into the grid. Charging points on the road require ability to quick charge but most of the charging is probably going to happen at homes or at working places. Multiple cars charging at the same time may overload the power grid and create challenges on how to deal with these peak loads.

While EVs are waiting to get revolutionized, electric busses are already more common way in public transport in some areas. Electric busses' routes are known, therefore, they can be designed to travel specific distances with a one charge. Moreover, the routes can be planned that many busses can use the same main charging spots and smaller charging spots can be built at the routes depending what kind of charging type the busses are using. There are three different ways how to charge electric busses. The first is that there are very fast chargers which are also expensive. The second option is that there are efficient batteries which could travel longer distances and the battery is expensive instead of chargers. The last option is a decent charger and batteries where costs come from both, charging systems and batteries. [14]

While the load is increasing in the grid, it is necessary to create solutions to divide usage to as many hours as possible to avoid huge spikes. One possibility is to develop the smart abilities in the grid to make connected devices to communicate with each other. With advanced algorithms and information from users, devices should be able to decide when it is a good time to charge EV batteries. Anyhow EVs are not the only problems to the grid since they can be used as battery energy storages to solve some minor quality issues at households as example.

Pricing is one method to control when people are willing to use electricity. If it is known when electricity is cheap, most people want to use electricity during these hours. That causes the peak hours and creates problems into the grid. There are solutions to make pricing more flexible, in order to, make people use electricity evenly at different hours but this needs changes in regulations or business models. [15]

Demand response is one these suggested solutions. Main point is to create a system where a part of on-peak hours could be moved into off-peak hours and the whole generation and consumption would be more balanced.

2.5 New grid technologies

New technologies will help the power grid to operate and increase the smart abilities. Smart meters with automatic meter reading (AMR) abilities are developing. They are expected to have huge role in the future as they have the ability to manage and control the energy usage of consumers. Moreover, AMR meters are used to locate problems in the grid more accurate and faster. [7]

As mentioned that underground cables replace overhead lines nowadays. Direct current distribution at low voltage level is considered as a good option in the future. Since the underground cables are heavy investments they might stay in the infrastructure but new microgrids could be built as low voltage direct current (LVDC) areas. AC has been used in transmission since Nikola Tesla proved it to be better than Thomas Edison's DC transmission but now there have been researches that DC systems would be more cost effective choices. Biggest issues within AC systems are that frequency needs to be within the limits [16]. DC systems require only adjustments in voltage, and most of the prosumer devices uses DC voltage so AD/DC and DC/AC transforms will lower the efficiency.

There has been a demo project already made by Lappeenranta University of Technology with Suur-Savon Sähkö Oy. The test site they have developed has been successful. That conclusion is based on test results and customers' feedback which was only positive. Weather did not affect the reliability of the grid and there was a need of back-up supply only once. Voltage quality was great since THD_U value was below 3 % at max and ΔU_{RMS} value in between -2 and 2 %. [17]

On the other hand, there are reasons why the amount of LVDC grids is not quickly increased. There is still a need for many DC-DC converters as many house devices uses different voltage levels such as 5V, 7V, 9V and 12V [73]. That is why DC could be a better option in transferring higher voltages. Rural areas with some branches are good locations to be made of LVDC.

Active network management solutions are also necessary as they could improve the system stability. Active network solutions mean components like relays and other IEDs that could have more smart abilities integrated to their operations. Communication prices are very low today, therefore, improvements made to the grid components should make faster and easier to locate problems in the system.

2.6 Information and communication technologies

Information and communication technologies (ICT) are methods how data is transferred between devices. ICT can be divided into three categories: wide area network (WAN), neighbourhood area network (NAN) and home area network (HAN). In figure 2 is shown an architecture model of network types in smart grid.

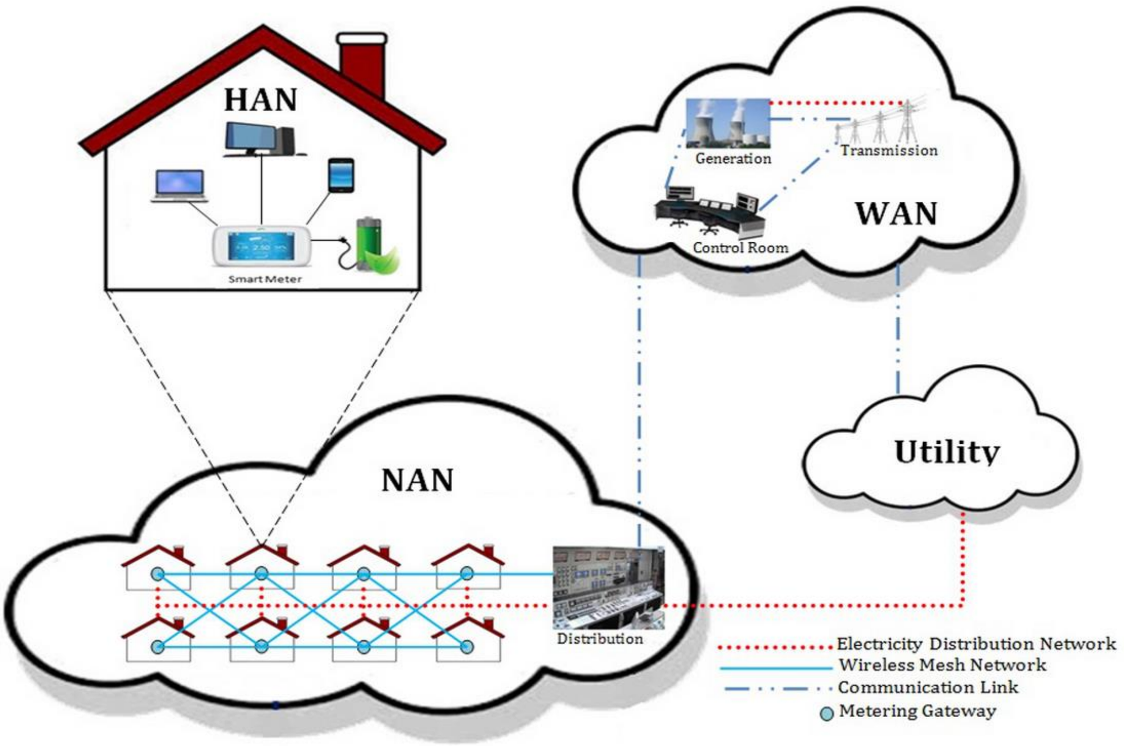

Figure 2. *Illustration of smart grid architecture with three major communication network types [18]*

HAN includes communication between home devices. This kind of communication is needed in home automation for an example. In chapter 2.4 is mentioned that EV charging may require smart abilities and this is the level where prosumers can affect to the system. Some technologies used in HANs are WiFi, bluetooth, Zigbee and wireless M-Bus.

NAN is wider area than one household. Still using EV charging as an example, the system should communicate with other household charging devices. This could balance the consumption locally and keep power balanced without spikes that are created by charging many EVs simultaneously. NAN technologies are different powerline communications and radio frequencies.

WAN is used when data is needed to transfer for long distances. WAN technologies can also be used for NANs. The most common WAN technologies for consumers are cellular technologies (2G, 3G, 4G) and wired solutions (xDSL, fiber, cable). These are the basic methods used for today's internet connections. Other technologies are satellites, Sigfox and LoRa.

Developing ICT creates the basis to the power grid to evolve into Smart Grids. Different cloud services are used already that allows data to be available almost everywhere. With 4G technology it is possible to have fast internet connections within the 4G network but 5G technology is going to have different infrastructure. It is planned to install small devices in buildings to work as 5G amplifiers for signals. The solution is called as device-to-device communication and it is used to prevent areas without 5G signal [19]. This means there would not need to be only big concentrators that have limited radius and causes to have small areas where signal is weak or does not exist. Comparison of 4G and 5G coverage is shown in figure 3.

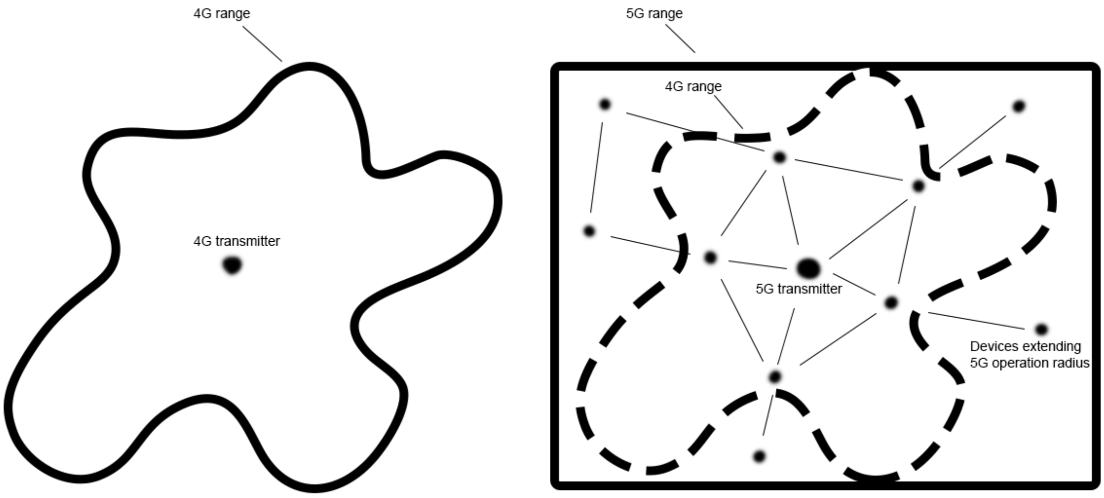

Figure 3. *Coverage areas by using 4G and 5G technologies*

On the left side, there is the area that is covered by 4G transmitter and on the right side is 5G transmitter with device-to-device communication. When devices are working as amplifiers, the covered area is wider without blank spots where is no signal available.

One of the biggest problems with developing ICT systems is cyber security. When more devices are controllable over network, it is also possible to gain access into the system by wrong people. As an example, there was a large area in Ukraine without power after a cyber-attack that took down the whole power grid in December 2015. These kinds of attacks may be caused by loopholes or backdoors in the system or because of humanly mistakes like this one in Ivano-Frankivskin. [20]

Power cuts are not the only possible risks since there are a lot of information in the system like customer’s personal information. These are the reasons that woke up European Union to start creating directives about cyber security [21]. This is a good start but it is needed have more universal solutions to keep data safe.

3. OVERVIEW OF ENERGY STORAGES

Energy storages can be sorted in different categories: solid state batteries, flow batteries, flywheels, compressed air energy storages, thermal storages and pumped hydro-power. In this chapter we discuss what are the main principles for each energy storage type to operate and how are the energy storages evolved in the history. Lithium-ion (Li-ion) batteries are discussed wider as they are the most common electrical energy storage solutions today and there are already many types of Li-ion batteries used in different purposes.

3.1 Operating principles of batteries

Battery is a system that contains multiple electrochemical cells joined together. The electrochemical cell includes two electrodes, a positive and a negative, and an electrolyte which separates the electrodes. The negative electrode is called an anode and the positive electrode is called a cathode. The electrolyte must be an electronic insulator to prevent the battery to self-discharge or create short circuit inside the battery but it also needs to be able to conduct ions from anode to cathode. [22]

Battery gives electricity during discharging cells which is a result of chemical reactions. In the anode happens oxidation reaction and in the cathode is cathodic reaction. Negative ions called anions move to the negative electrode and positive ions called cations move to the positive electrode. These reactions cause the electrodes to flow from negative electrode to positive electrode and give electricity to connected devices by passing through. [22]

Secondary batteries are batteries with the ability of recharging. Recharging happens in an electrolysis process making the electrochemical cell to become as an electrolysis cell. In the recharging process anodes become cathodes and cathodes become anodes. Moreover, the movement directions of anions and cations are revised. The operative voltage of batteries can be increased by connecting multiple batteries in series and the capacity can be increased by connecting multiple batteries in parallel. [22]

There are a couple of important values that measures batteries. The C-rate measures how fast a battery can be discharged and as an example, 1 C means that 1 A output power can be taken from 1 Ah battery and 2 A from 1 Ah battery equals for 2 C-rate. Depth of Discharge (DOD) is the percentage of how much of maximum battery capacity is left compared to a maximum capacity of a new battery. Cycle life measures how many times battery can be charged and discharged before the maximum capacity is dropped to 80 % from original value. State of Charge (SOC) is how much battery capacity is currently left compared to the maximum capacity. [23]

Different energy storages have different capabilities. Some storages may have high output power but low duration and vice versa. In figure 4 is shown how different energy storage solution could be used. [24]

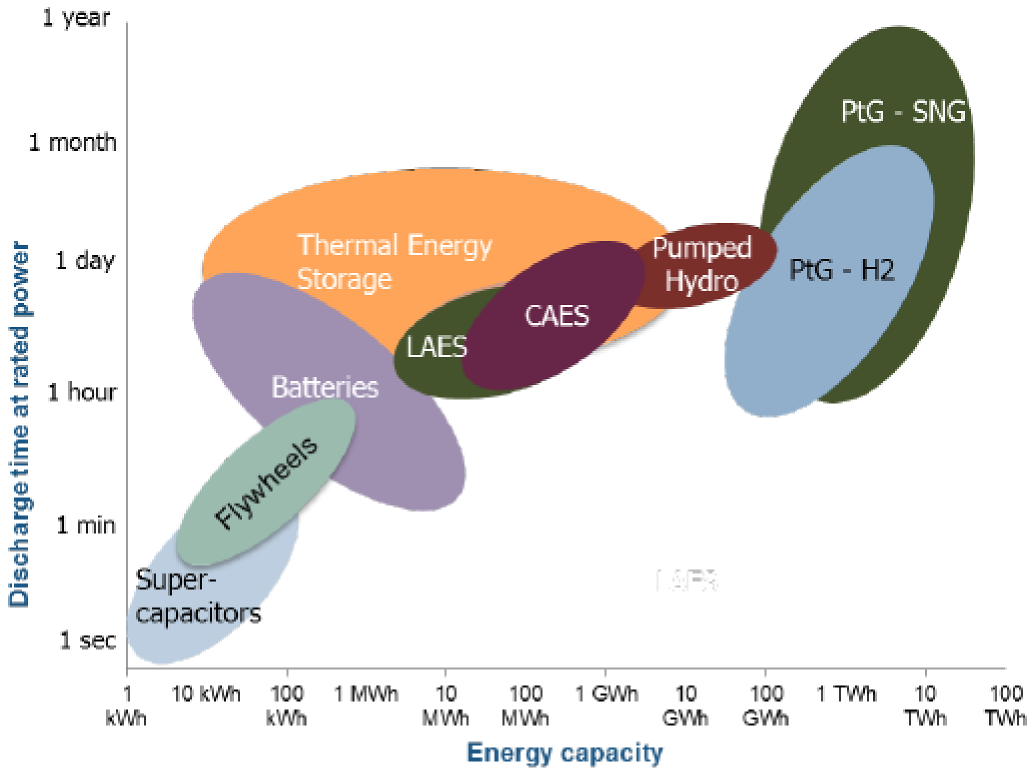

Figure 4. *Energy capacity and time of use for various energy storages [24]*

Batteries and supercapacitor are good option when there is a need for fast discharge with quite small need of energy. Natural gas could deliver high amount of energy for a long period instead. [24]

3.2 Solid state batteries

Solid state batteries include the types of advanced chemistry batteries and capacitors. Alessandro Volta's voltaic cell was the first battery in history and was created in the late 1700s and published in 1800. That created the basis to develop batteries to become what they are nowadays after many changes. [25]

3.2.1 Lead acid batteries

Lead acid batteries were the first commercialized rechargeable batteries. They were invented in 1859 by Gaston Planté. Even the technology is old, lead acid batteries are still used. The main reason for their usage is that lead acid batteries have a low cost per watt. [26]

The biggest cons for lead acid batteries are that they are heavy, slow charging and do not have a long lifetime. The future applications need lighter batteries and more cycles in lifetime. Slow charging also creates limitations compared to other batteries. [26]

3.2.2 Supercapacitors

Electrochemical capacitors or as we refer in this thesis, supercapacitors, usually contain two layers made of carbon. When charging, ions are moving to the edges of these layers so one layer contains negative ions and the other contains positive ions. Discharging happens when the layers are connected with an external path, the current begins to flow until the ions are balanced as in a normal state. [27]

Supercapacitors can be divided in two categories: symmetric designs and asymmetric designs. Symmetric designs have the both carbon layers made of same material and asymmetric designs have different materials. Asymmetric capacitors have the ability to storage 20 Wh/kg when symmetric capacitors are able to storage only around 6 Wh/kg. [27]

Because capacitors are not using any chemicals, they are expected to have a longer lifetime as usual batteries. Moreover, they are very fast and reliable to charge and discharge. [27]

3.2.3 Lithium-ion batteries

First commercial lithium-ion battery was released in 1991. Li-ion batteries are type of batteries that are mostly used in today’s solutions. Electricity production in Li-ion batteries is caused by movement of lithium ions between electrodes. [28]

Good thing in Li-ion batteries is that they have a decent capacity in a compact size. Mobile phones are good example and battery lifetime is one thing that mobile phone producers use as advantage in the markets. On the other hand, some Li-ion products are unstable and Samsung was the latest company which had problems as their mobile phones were exploding after the battery overheat. That is why there is a need for development to make these batteries safe while they still have the high expectations in abilities. [28]

There are many different Li-ion combinations used in BESSs and in table 1 are gathered which type of batteries companies are using. It is also discoverer how much AC/AC efficiency of different batteries can be calculated by formula 1:

$$\eta = \frac{E_{out} - E_{aux,out}}{E_{in} + E_{aux,in}} \tag{1}$$

where E_{out} is energy released during discharging phase, E_{in} is energy absorbed during charging phase and E_{aux} is energy absorbed by auxiliaries during charging and discharging phases. [29]

Table 1. *AC/AC efficiency for different type Li-ion batteries [29]*

System	*Technology*	*AC/AC Efficiency*
FIAMM	Sodium nickel chloride	~80 %
Toshiba	Lithium titanate	~86 %
BYD	Lithium iron phosphate	~83 %
SAFT	Lithium nickel cobalt alumina	~84 %
Samsung	Lithium manganese	~85 %
Siemens	Lithium nickel manganese cobalt	No data

As table 1 shows, Lithium titanate (LTO) battery has slightly the best value in AC/AC efficiency compared to other batteries. Some other values are listed in table 2.

Table 2. *Expected values for different batteries [30]*

	Lithium iron phosphate	*Lithium titanate*	*Lithium nickel cobalt alumina*
Price (€/kWh)	500	1300	250
C-rate	1	6	0.33
Cycle life	2500	15000	500

Table 2 shows that LTO batteries are more expensive than other type of batteries but researches have noticed that it has the biggest payback value as LTO batteries have a lot longer lifetime and C-rate compared to competitors. [30] LTO batteries are discussed more in chapter 4.3.

3.2.4 Nickel-cadmium batteries

Nickel-cadmium (Ni-Cd) batteries have been in the commercial markets since the 1910s. Compared to other batteries, Ni-Cd batteries are lacking the capability to have a high energy density and they are quite expensive to buy. [31]

Ni-Cd batteries provide long lifetime and they are reliable with simple implementation. That is why they are still in the markets and was used in one of the earlier BESS in 2003. That BESS had the capacity of 27 MW for 15 minutes. [31]

3.2.5 Sodium sulfur batteries

The first sodium sulfur (NaS) batteries were created in the 1960's. Nowadays NaS batteries are used in high temperatures, usually in more than 300 °C. NaS batteries have a solid material as electrolyte. While discharging, electrons strip off from a sodium metal to form positively charged sodium-ions which are able to travel through the electrolyte. Recharging happens when the sodium-ions go to the positive electrode and form polysulfide as a production combined with molten sulfur. [32]

NaS technology is mostly used in Japan, where is over 190 sites. Largest site has 34 MW and 245 MWh and is used for wind power stabilization. Other applications are daily peak shaving and backup power. [32]

3.3 Flow batteries

Flow battery is a system where a membrane separates two chemical components. It produces electricity and charges by dissolving liquids trough the membrane. Flow batteries are related to batteries and fuel cells as the liquid energy source is able to charge and discharge within the same system. Flow batteries have the ability of almost instant recharge by replacing the electrolyte liquid. Today's solutions of flow batteries are:

- Redox Flow Battery
- Iron-Chromium Flow Battery
- Vanadium Redox Flow Battery
- Zinc-Bromine Flow Battery [33]

Redox flow batteries are the most common used flow batteries. Redox relates to reduction and oxidation reactions that happens in the battery. Reactions in discharge are shown in formulas 2 and 3 where 2 is reduction and 3 is oxidation.

$$C^{3+} + e^{-} \rightarrow C^{2+} \tag{2}$$

$$A^{2+} \rightarrow A^{3+} + e^{-} \tag{3}$$

Charge reactions are shown in formulas 4 and 5 where 4 is oxidation and 5 is reduction.

$$C^{2+} \rightarrow C^{3+} + e^{-} \tag{4}$$

$$A^{3+} + e^{-} \rightarrow A^{2+} \tag{5}$$

Redox flow batteries are an economical choice and possible solutions for applications with power ratings between 10 kW to tens of MW for the duration between two to dozens of hours. Compared to electrochemical storages, redox flow batteries do not have as good energy density which makes the systems require more volumetric space. [34]

3.4 Other energy storages

Alternative energy storages include energy storages that are not battery based energy storages. These kind of energy storages are flywheels, compressed air energy storages, thermal storages and pumped hydro-power. These solutions are discussed only shortly as they are not in the focus of this thesis but are important part of energy storages.

3.4.1 Flywheels

Flywheels are rotating devices that storages electric energy in a form of kinetic energy. The rotor is a spinning mass that spins in an almost frictionless casing. With the inertia of the rotor, it keeps spinning and converts the kinetic energy back to electricity when needed. [35]

Flywheels are placed in a vacuum to reduce drag and to have as high as possible efficiency. Flywheel system includes a composite rim, hub, motor, shaft, vacuum chamber and magnetic bearing. Flywheels can operate as a short time power source or long time energy source depending of the structure and inertia of the rotor. Currently flywheels are used in aerospace and UPS applications. [35]

3.4.2 Compressed air energy storage

The first compressed air energy storages (CAES) was created in 1870. Since the 1970's, they have been used by storing energy generated during off-peak hours and using it on peak load periods. In CAES air is compressed and stored in an underground cavern with high pressure. The air can be converted into electricity by heating it up and expand it to start a turbine that drives a generator. [36]

Air can be stored by using diabatic or adiabatic methods. Adiabatic method has a better efficiency with 70 % efficiency. CAES's need a lot of space since they have low energy density. Salt caverns are the best possible options for CAES as there are no pressure losses, reactions with the oxygen in the air and salt caverns has a high flexibility. [37]

3.4.3 Thermal storages

Thermal storages are divided into three categories: pumped heat electrical storage, hydrogen energy storage and liquid air energy storage. Pumped heat electrical storage pumps heat from the cold to the hot to store the energy and generates electricity by reversing the operation producing mechanical work to drive a generator. Pumped heat electrical storage systems have around 75 to 80 % of AC/AC round-trip efficiency. [38]

Hydrogen energy storage uses electrolysis to convert electricity into hydrogens. These hydrogens work as a fuel for fuel cells or gas turbines that re-electrificate hydrogens to electricity. Today’s solutions have the round-trip efficiency from 30 to 40 %. [39]

Liquid air energy storages lower the air temperature to transform air gas into liquefied form and then store that liquid in tanks. The liquid can be then transformed back into gas to drive a turbine and generate electricity. Liquid air energy storages are large energy storages with hundreds of MWs output power with a long duration. [40]

3.4.4 Pumped hydro-power

Pumped hydroelectric storage uses low electricity prices to pump water in reservoirs located on top of hills or mountains. During the time of high electricity demand the water is released to flow through turbines as in the normal hydropower stations to run generators and provide electricity. [41]

Hydropower is a renewable energy resource and it provides many abilities that are needed in the power grid like spinning reserves, black start and reactive power. The problem with pumped hydro-power is that it has limitations where they can be placed as they need mountains near water areas. There are also environmental problems as natural regulations and rules do not allow to build hydro-power stations even if the area would be otherwise suitable for the station. [41]

4. BATTERY ENERGY STORAGES TODAY

Energy storages can be sorted in different categories based on their usage. Bigger separation can be done between distributed and centralized energy storages. They can be divided also into more categories like energy and power storages.

4.1 Distributed battery energy storages

Distributed energy storages are usually smaller batteries used by prosumers. Mainly these consumers used battery energy storages are electric vehicles and storages used in households.

4.1.1 EVs

The number of electric vehicles are increasing and one could say that Tesla is the pioneer in this industry. The other car manufacturers are following to the markets with their hybrid and fully electric solutions. The biggest problem today is that the distance is limited in which you can travel with EV and Finland as for example does not have a very good infrastructure for charging stations outside the Southern area. Norway is an example when they had a huge increase in amount of EVs, they needed to build a lot of charging stations. Finland will probably have the need to increase the amount of charging stations as the government is planning to increase the amount of new EVs by 250 000 units until year 2030 [42].

Even the EV is designed for traveling, it could be used as an energy storage in the households. If there is no need to travel for a while and the car is just staying in the yard plugged in. The Smart Grid could use its battery as a backup power to the household, peak shaving or any other functions that is possible to do with rechargeable battery energy storages [43]. Anyhow this might not be the thing you want to do nowadays as the Li-ion battery used by Tesla as an example have only around 500 charge-discharge cycles in its lifetime [30], but there might be other batteries used in electric vehicles in the future.

4.1.2 Home storages

Home storages could be necessary in the future as it is expected that consumers are getting their own photovoltaic production. The photovoltaic production is highest during the daytime when usually the consumption is at its lowest, the production could be stored and used when needed. Since there are transmission costs and taxes for supplying energy to the power grid, it is necessary to use or store all the energy produced by the photovoltaics or any other sources. [44]

There is a research of how consumers could benefit by using battery energy storages in households. The results show that it has a possibility that household storages may never payback themselves [45]. But prosumers do not always expect products to bring monetary value, as a television as for example does not bring any monetary value. This means that a prosumer could buy battery energy storages driven by the idea of supporting green energy and reducing emissions.

In Sweden the government covers 60 % up to 5 600 USD of system costs when buying home energy storage if the prosumer has solar panels. [46] This lowers the possibility that home energy storages would not ever payback themselves and supports prosumers to invest in solar panels.

There was an idea that old batteries used in EVs could be reused as home storages. Even the DoD of the battery is dropped dramatically to be used in EV, it could be enough to be used in a household system. The problem here is that the batteries in EV are designed for EV use and may not pass the safety issues in households. Anyway, it should be researched if there is a possibility in regulations to make safe enough reused batteries for households to lower the costs and support the LVDC system. [44]

4.2 Centralized battery energy storages

Centralized battery energy storages are systems that are connected to the power grid and supports the whole system. Centralized storages can be divided in energy storages and power storages.

4.2.1 Energy storages

Energy storages are batteries which contain a lot of energy for a long period. In smaller devices like cellphones it is important to have a battery with a capacity to use the device as long as possible. As we are discussing a system such as a power grid, there is need to have a huge battery that could deliver energy for days.

With the available technologies of today, it would cost too much to have a BESS which could be able to provide energy for a long period of time. Pumped hydropower, thermal energy and natural gases are much more cost effective choices nowadays. Hence, battery technologies should be developed for power usage.

4.2.2 Power storages

Power storages are batteries which can provide a high amount of power output for a short period. Usually when speaking of power storage, it consists of time frame from less than one second to dozens of hours but this thesis focus on usage less than four hours. That is why from now on, by BESS is meant power storages. Power storages could be used to balance frequency in a power grid as they are able to adjust the amount of production in a short time. They are also capable to do peak shaving in energy consumption and fill the gaps that are caused by intermittent production using renewable energy resources.

Supercapacitors are used for very short periods, from one second to a few minutes, as they are cost effective in that range. Batteries with a high C-rating are also capable to do the fast adjustments and frequency regulation. If the only usage is frequency regulation, a supercapacitor would be a more cost effective choice, but battery power storages can be bought to other purposes and then used also as a frequency regulator. The other possibilities of power storages are discussed in chapter 4.3.

The is already one pilot project ongoing in Helsinki, Finland. Companies participating in the pilot are Helen, Helen Electricity Network and Fingrid Oyj. A BESS contains a power of 1,2 MW and a capacity of 0,6 MWh. The BESS is manufactured by Toshiba and delivered by Landis+Gyr Oy.

Fortum is also planning a pilot project in Finland. Their BESS will be located in Järvenpää. Fortum's BESS will have a power of 2 MW and a capacity of 1 MWh. The main target of the pilot is frequency regulation for Fingrid. [74]

These pilot projects will probably have a high impact on how BESSs will be developed and used in the future.

4.3 Toshiba SCiB™

SCiB™ is a battery energy storage invented by a Japanese organization Toshiba. The letters come from Super Charge ion Battery. The main specifications and abilities are discussed in the next section.

4.3.1 Specifications

Toshiba SCiB™ is a Lithium-titanate oxide battery. Specs of the battery are designed for a power storage usage. One battery cell provides 23 Ah of nominal capacity and 2.3 V nominal voltage as it weighs 550 g. Energy density of one cell is 99 Wh/kg and 202 Wh/L with an operating voltage of 1.5-2.7 V. One thing that separates SCiB™ from other batteries is that it has an operating temperature of -30 °C to 55 °C. Operating temperatures for SCiB™ and conventional Li-ion batteries are shown in figure 5. All specifications are shown in table 3. [47]

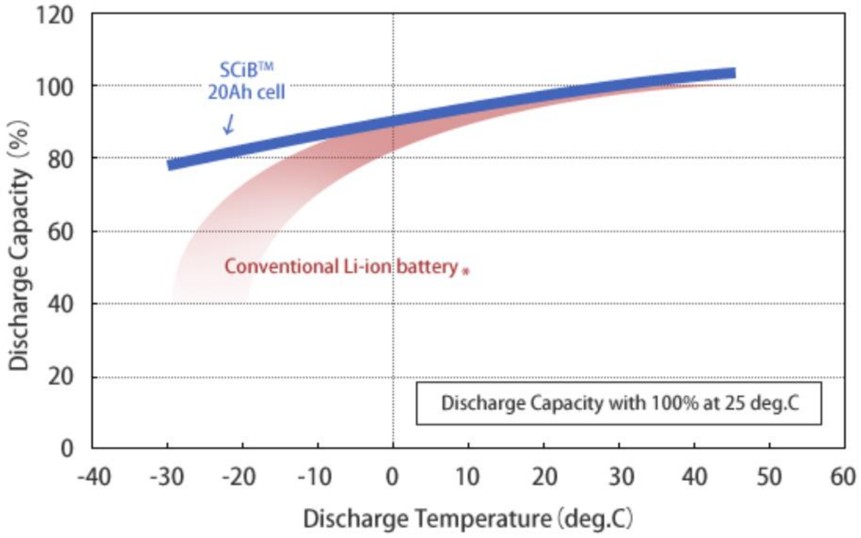

Figure 5. *Discharge capacity of Li-ion batteries in different temperatures [48]*

Measurements have been done to older 20 Ah SCiB™ cell but the newer 23 Ah cell has the same operating temperatures. With lower operating temperatures, SCiB™ is also possible to use in artic locations.

Table 3. *Specifications of one SCiB™ battery cell [47]*

Nominal Capacity	*23 Ah*
Nominal Voltage	2,3 V
Weight	550 g
Energy / Weight	99 Wh/kg
Energy / Volume	202 Wh/L
Impedance (AC, 1kHz)	0,53 mΩ
Operating Voltage	1,5 to 2,7 V
Operating Temperature	-30 °C to 55 °C
Charging Method	CC-CV

Connecting these battery cells in series and parallel, it is possible to make a battery with the values needed in a specific solution. One SCiB™ module contains 12 couple of cells in parallel for a total of 24 cells, and has a capacity of 1,2 kWh as a one panel contains

22 modules with 27 kWh. For example, 1 MW and 2 MWh battery system has 84 of battery panels with two sets of 500 kW power control systems (PCS). [49] Helen's 1,2 MW battery has 28 modules and 20 modules.

As mentioned, the operation temperature was the first advantage against other Li-ion batteries but the biggest advantage is that SCiB^{TM} has a long lifetime with providing over 90 % of capacity after 10 000 charge-discharge cycles as many of other types have only 80 % of capacity left after 5 000 cycles. As total a LTO battery has a lifetime of 16 000 charge-discharge cycles and more than 15 years. Comparison between SCiB^{TM} and other Li-ion batteries lifetime is shown in figure 6. [48]

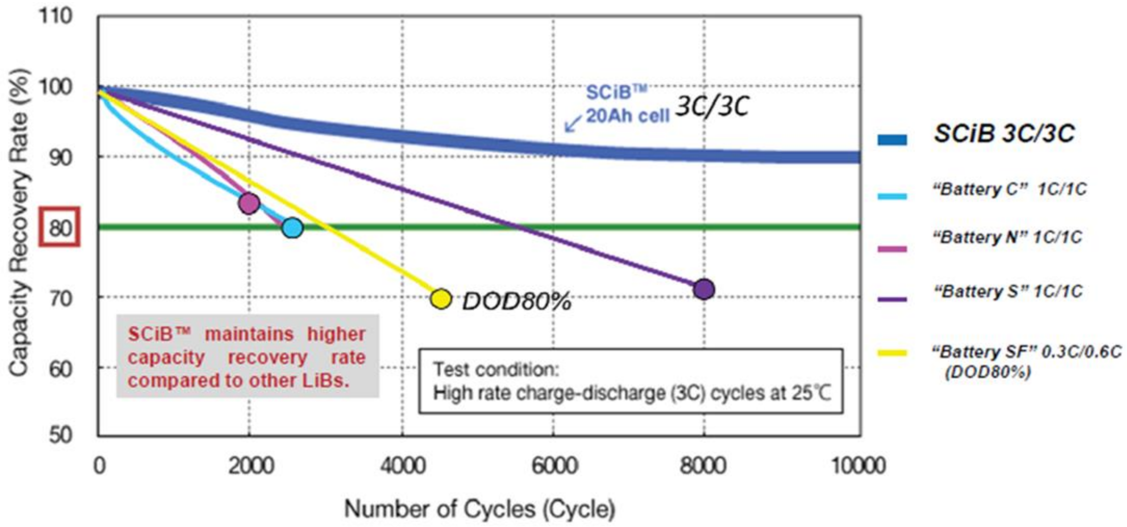

Figure 6. *Capacity recovery rates after different number of cycles between different Li-ion batteries [48]*

Safety issues have been in the news when talking about Li-ion batteries and Samsung Galaxy Note tablets were the last ones as they were randomly exploding and they were not allowed to take into planes because of that [50]. SCiB^{TM} provides also safe operations as the largest BESS in Nordics in Helsinki passed the fire fight tests. The battery also passes the Blunt Nail Crush test without having any fire or even a bit of smoke when a normal Li-ion battery heats up and explodes [48]. Passing the Blunt Nail Crush test is a result of having a phase transformation in the anode that prevents short circuiting inside the battery [48].

Comparison of SCiB^{TM} and other battery energy storages are shown in figure 7 [48].

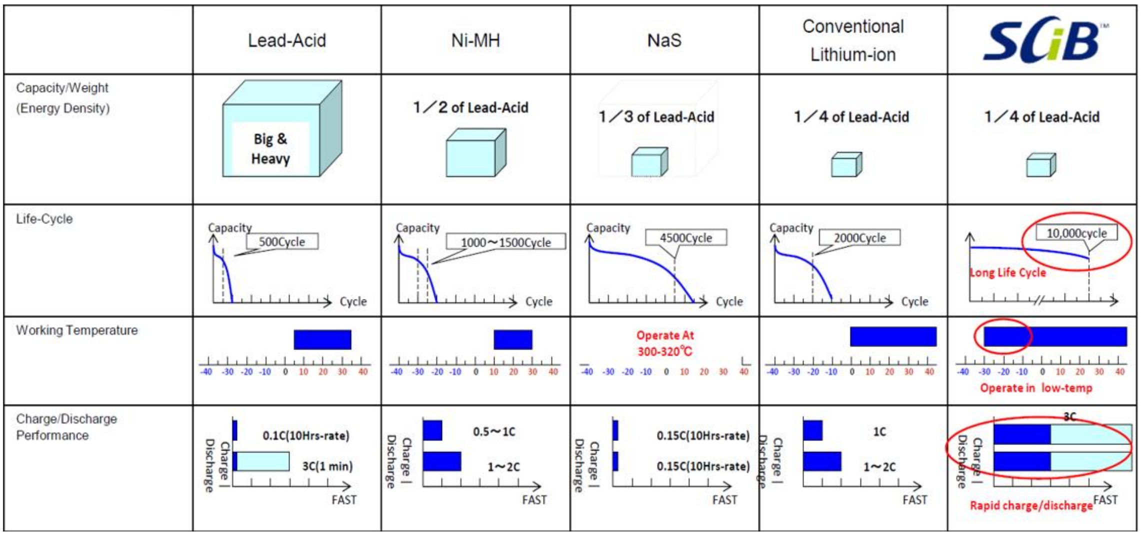

Figure 7. *Comparison of battery technologies [48]*

4.3.2 Operating modes

It is necessary to differ battery energy storages and battery energy storage systems. Battery energy storages includes only the storage itself. BESS instead has many other functions and abilities. An example of parts that BESS includes are listed below:

- Battery modules
- PCS
- Firefighting system
- Heating, ventilation and air cooling (HVAC)
- MV/LV transformer
- MV switchgears
- SCADA system
- Human-machine interface (HMI)

SCiB^{TM} can be programmed in various ways to do different tasks in the power system. At first it can be used in parallel connected to the main grid or in island mode usually used in microgrids. There are three different operating modes: following grid, grid forming and grid supporting. [51]

Following grid mode is used when the PCS is in parallel to the grid. The operation works by synchronizing the PCS to the mains voltage and it injects or absorbs active and reactive power based on master controllers calculated set point. [51]

Grid forming mode is used in island grids and the main ability of PCS is to keep the voltage and the output frequency in the island in the values that is wanted. The PCS is following the generator production or the load demand in the islanded grid and sets the active and reactive power by the need. [51]

Grid supporting works on both situations, in parallel and in island. In grid supporting mode the battery works as a synchronous generator and is connected in parallel to other generators or microgrids. The whole system is responding to the changes happened in load or generation in the microgrid and the PCS is changing the voltage and the frequency at the terminals based on the reactive power and active output. [51]

4.3.3 Control functions

Black start is an important ability to the power storage system. Black start is used when the grid is offline and all the generators are shut down. Running up big generators is not so simple and it needs a lot of power from outside to make it happen. One sequence of black start is shown in figure 8. [51]

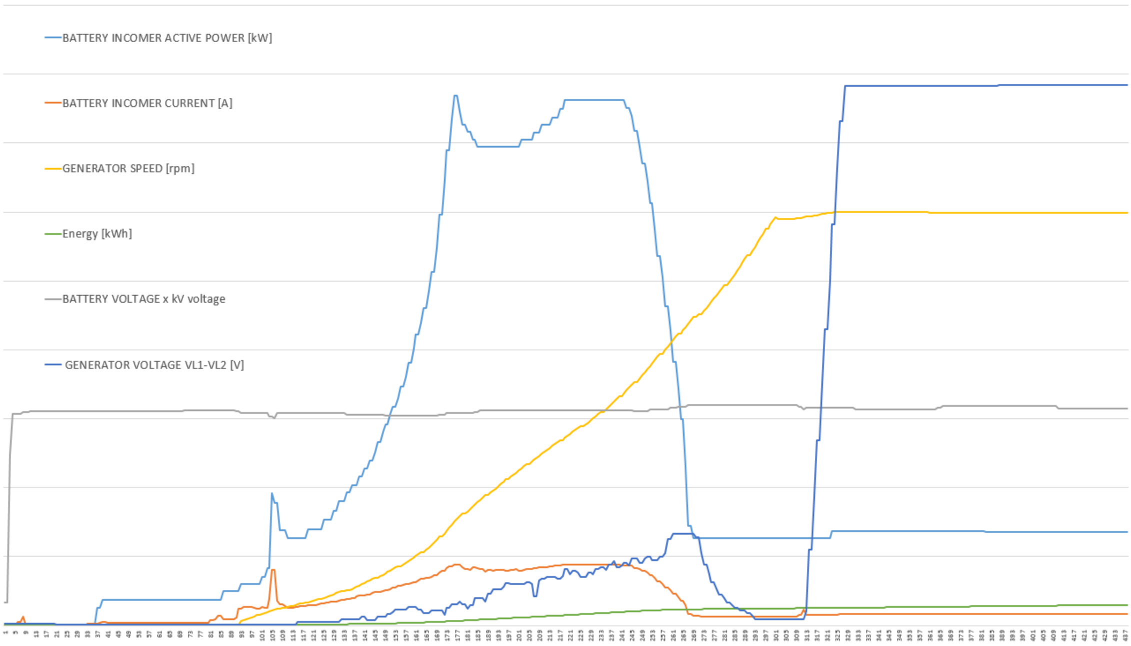

Figure 8. *Black start*

At first the BESS master control (BMC) commands to do black start and verifies that the MV switches are closed, and there is really a lack of voltage on the MV connection point. After the conditions are secured, the battery management system (BMS) starts to synchronize the PCSs and when all the PCSs are synchronized and connected, the BMS starts to slowly energize the system and PCSs will generate a ramp voltage that is shown as a gray line in figure 8.

The light blue line shows how the power storage is starting to generate power to the system. There are two spikes in the line that are presenting the system driven to overspeed to avoid generator from resonating and damaging the system [52]. After a while it drops to the system supporting value.

The yellow line presents how the speed of the generator is increasing and it balances to the required level. In Finland the frequency of power grid is 50 Hz so the generator speed can be calculated using equation 6:

$$n_s = \frac{60 \cdot f}{p} \tag{6}$$

where n_s is the generator speed (rpm), f is the frequency (Hz) and p is the number of pole pairs [53].

The dark blue line is the output voltage of the generator as it slowly starts increasing. Then it drops again for a while and after the generator is reached the needed value of rpm, the generator quickly increases the output voltage to the correct level.

This shows how basically black start is done but there is a requirement that a black start needs to be done three times in a row. Also the values in the figure varies depending on the grid where the power system is installed. After the generator is fully synchronized and connected in voltage control mode, the turbine operating in speed control mode and the grid is energized, the BMC stops the black start sequence. [51]

Grid support is the other possible control function and the main task is the frequency regulation. The PCS measures the grid frequency and based on that, the BMC define on which level the active power must be set. There is a dead band value what is measured and when the grid frequency is in the dead band, there is no need to active power regulation. There is a control law that makes a linear correlation outside the dead band and fixes the active power based on the measured frequency. If the frequency falls under the lower dead band value, the system will increase the amount of active power and when the frequency rises too much, the system will decrease the active power. Outside the linear region is a need of constant power that equals the maximum and minimum power values that can be set by the system operator. [51]

5. TECHNICAL AND COMMERCIAL CHALLENGES

Chapter 2 introduced some challenges that are caused by modifications in the power system in the future. In this chapter those problems are discussed deeper and how they are linked to the drivers that makes the changes necessary. Challenges can be divided into technical challenges and commercial challenges.

5.1 Technical challenges

Technical challenges are challenges that are physically affecting to the power grid. Those challenges are caused by electricity production and consuming and these are discussed more closely in next chapters.

5.1.1 Power quality

Power quality is measured how voltage and current are following the perfect sine wave. Devices connected to the power grid are causing different disturbances so that wave form may include harmonics and spikes with the specific frequency. The perfect sine wave is shown in figure 9 and a sine wave with quality issues is shown in figure 10. [54]

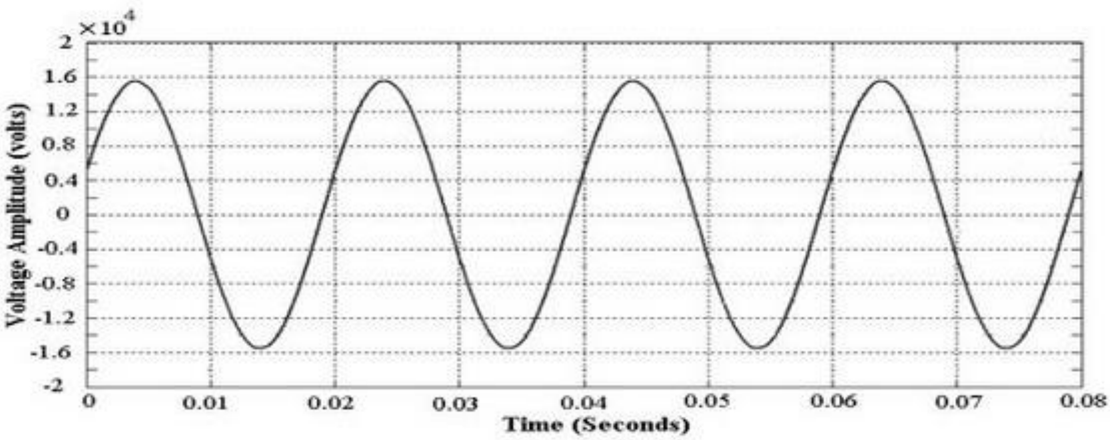

Figure 9. *The perfect sine wave voltage [54]*

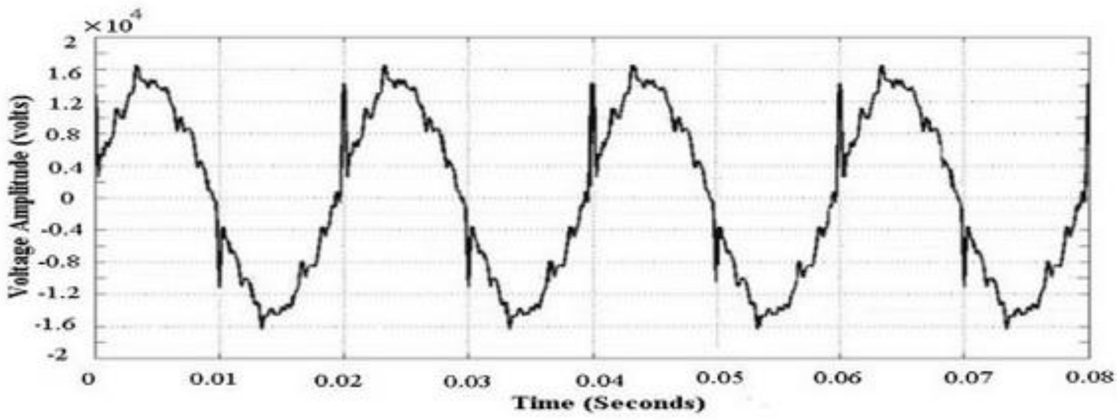

Figure 10. *Voltage with distortion [54]*

The standard EN50160 defines the quality requirements for voltages [55]. A normal quality is $U_n \pm 10$ % for 95 % in time of use. Good quality is $U_n \pm 4$ % and the average $U_n \pm 2,5$ %. The voltage quality is measured in 10 minute cycles during a one-week period. [55]

As mentioned, adding renewable energy resources will bring some quality issues to the power grid. This is mostly caused by an intermittent energy production. In case of solar panels, even smallest clouds disturb the intensity that light will hit the panel and makes the energy generation have a lot of variations. That is why it is necessary to have very fast devices to compensate the negative differences that occur in frequency and voltage. Disturbances in a photovoltaic generation caused by clouds are shown in figure 11 [56]. Intermittent production is discussed widely in chapter 5.1.2.

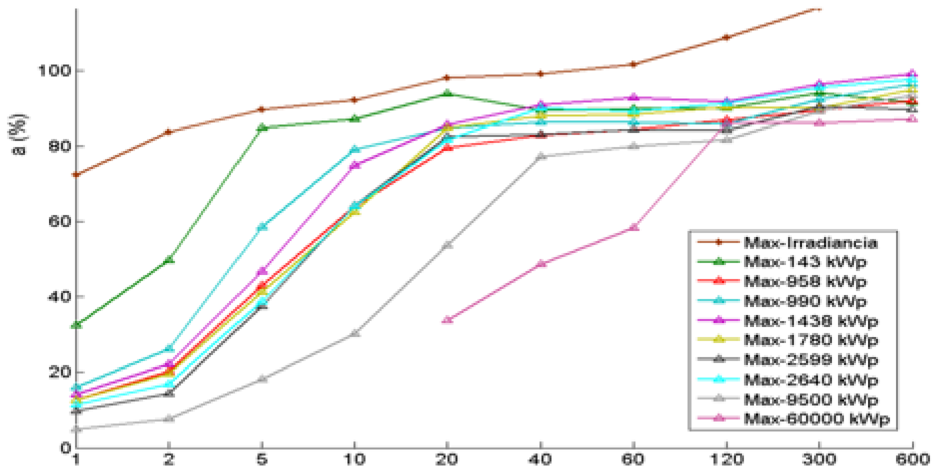

Figure 11. *Maximum power fluctuation for different sized PV plants during one year [56]*

As seen in figure 11, the production can be dropped 50 % in 5 seconds in smaller PV plants due to clouds which is drawn as green line. For bigger plants, drawn in a grey line, the changes could still happen in less than a minute and the amount of drop can be nearly 80 %. The line on top shows that irradiance is possible to go above 100 %. This effect is caused by polarization of passing clouds. [56]

Heat pumps cause problems for voltage quality. Turning on a heat pump creates a huge spike in current. In weak grids this may cause flickering and voltage dips. [57] There is also a problem as the current spike might be more than a fuse allows. In Finland, there is a basic payment for the grid connection that is based on the size of the fuse. If the momentary current is more than the fuse size that the customer has, distribution network companies can charge the price of the fuse that is bigger than the momentary current spike.

5.1.2 Production with renewable energy resources

Energy produced by renewable energy resources is free of emissions. That is the biggest driver today to increase the amount of electricity produced by renewable energy resources. The optimal day is sunny with a breeze wind to maximize the power generation of both solar panels and windmills. Solar power production in a sunny day in Finland at a solar power plant is shown in figure 12.

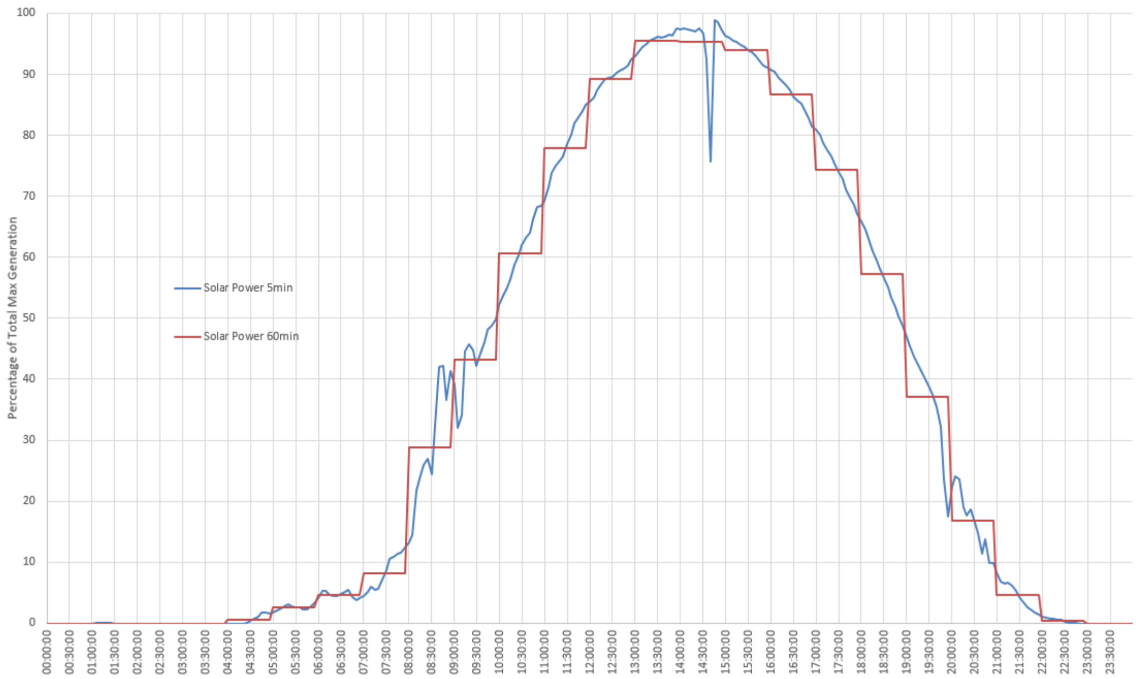

Figure 12. *Measured solar power production at sunny day in Finland 29th of June 2016*

This was the best day in the summer of 2016 at this solar power plant. There is only a little volatility in 5 minute measures and a short duration of production decrease due to a cloud in a middle of the day. This kind of production is easy to predict and rely on. Even though the amount of production never reaches the peak of the possible production. Around 9 am the production is over 30 % of max generation.

The challenge is that in the Nordics the summer is only a short period. Only a few months later the day is much shorter and the weather is much more volatile. An example of an intermittent production of a solar power plant in autumn is shown in figure 13.

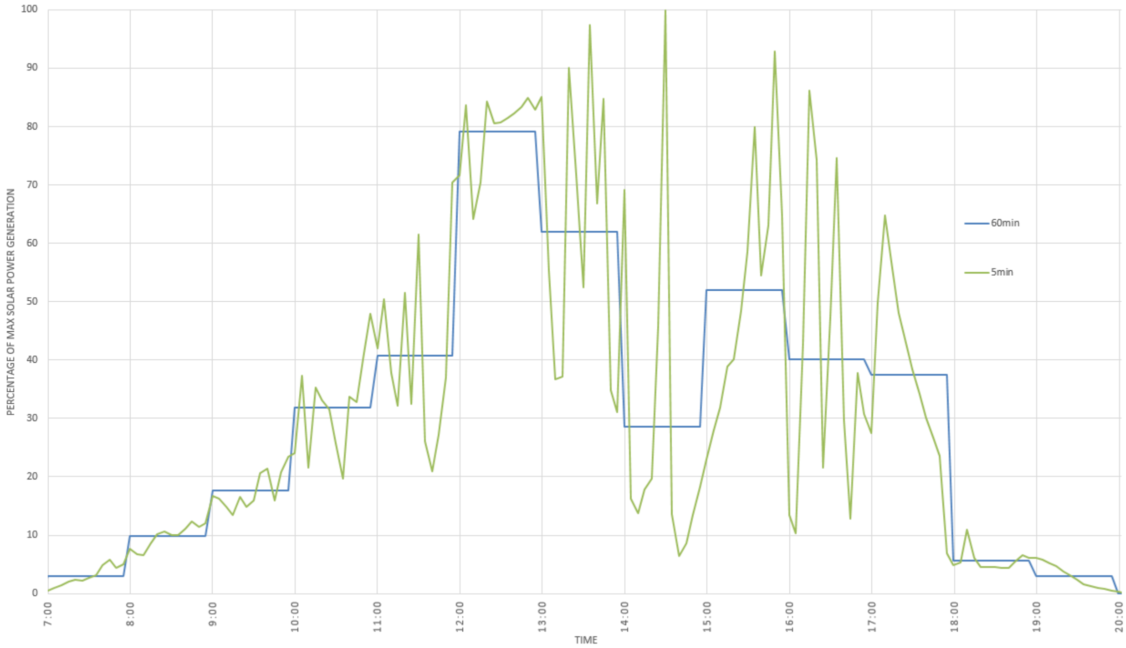

Figure 13. *Measured solar power production at a cloudy day in Finland 5th of September 2016*

In September, the solar power plant reaches over 30 % of max generation around 10 am. That is one hour later than in the middle of summer. Also, the drop below 30 % is two hours earlier than in the mid-summer. That will directly affect to the total power generated in one day. The bigger issue is the volatility of the production. When a cloud is passing, the power plant reaches its peak for a while. In 10 minutes the production drops over 90 % points. In overall, the 60-minute measurement is quite stable. More realistic values that are measured in 5 minute cycles are much more intermittent.

Wind power has also some problems. In October 2016, there was a period in Finland when the wind was calm or nonexistent. Power production during that period of a wind power plant is shown in figure 14.

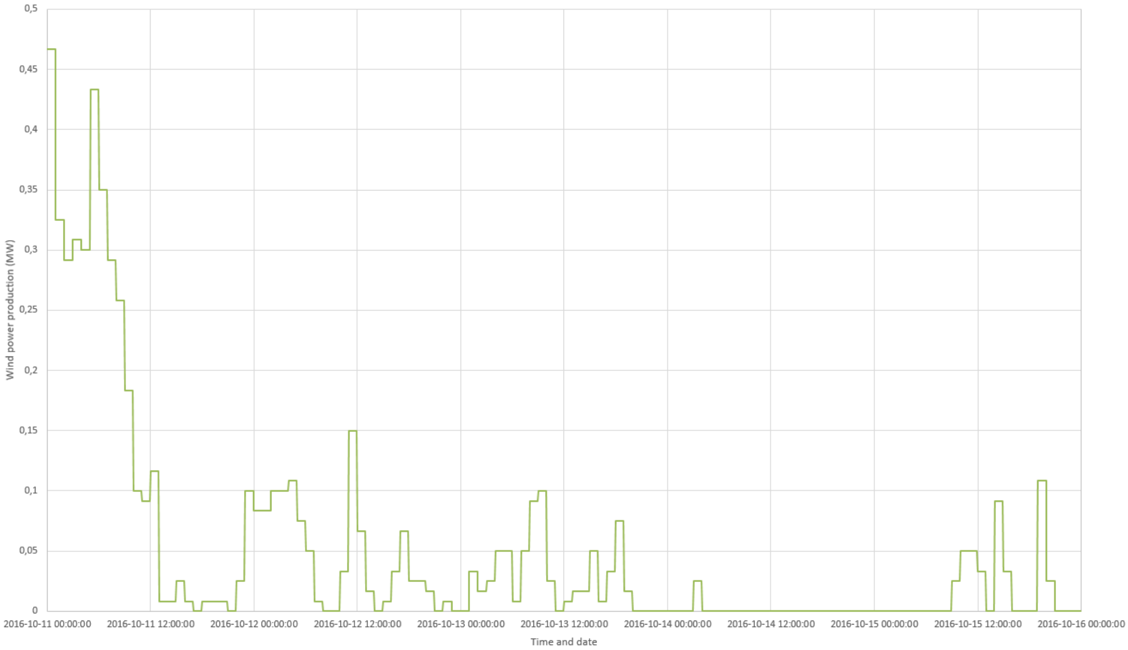

Figure 14. *Measured wind power production during a calm period in Finland between 11th of October and 16th of October*

Solar power plants are still quite small but wind power plants are usually much bigger. They also have much more stable production and they can produce electricity also during nights. That is why many countries are investing in wind power. For example, Finland is planning a legislation to forbid using coal in energy production after 2030 [58]. When the production is not even near the amount they should produce as seen in the figure, there needs to be back up power available. This kind of scenario in the future where the percentage of renewable energy resources is bigger part of total production could be a challenging thing. Probably the energy would be bought from neighbouring countries. But what if the whole Nordic area and Russia have the calm weather and this happens in January when there is -30 °C outside? If the neighbouring countries need the production themselves, where could we get electricity for our needs when we do not have enough own production? [75]

5.1.3 Frequency

The normal frequency in the Finnish power grid is 50 Hz and it can be between 49,9 and 50,1 Hz. When the frequency is under 50 Hz, the energy consumption is bigger than the energy production and frequency over 50 Hz means that there is more production than consumption. Standard EN50160 defines that frequency must be in average of 50 Hz ± 1 % in 10 second cycles during one week. [55]

The whole Nordic power grid shares the same frequency. Every country has its own transmission system operator (TSO); Statnett SF in Norway, Svenska Kraftnät in Sweden, Fingrid Oyj in Finland and Energinet.dk in Denmark [59]. One of their tasks is to keep frequency in 50 Hz. Inertia is the ability of power grid to avoid changes in frequency. The amount of inertia is based on how much kinetic energy generators and turbines generate. With more inertia there will be less changes in frequency. Frequency drop with different inertia values when 1 300 MW production drops is shown in figure 15. [60]

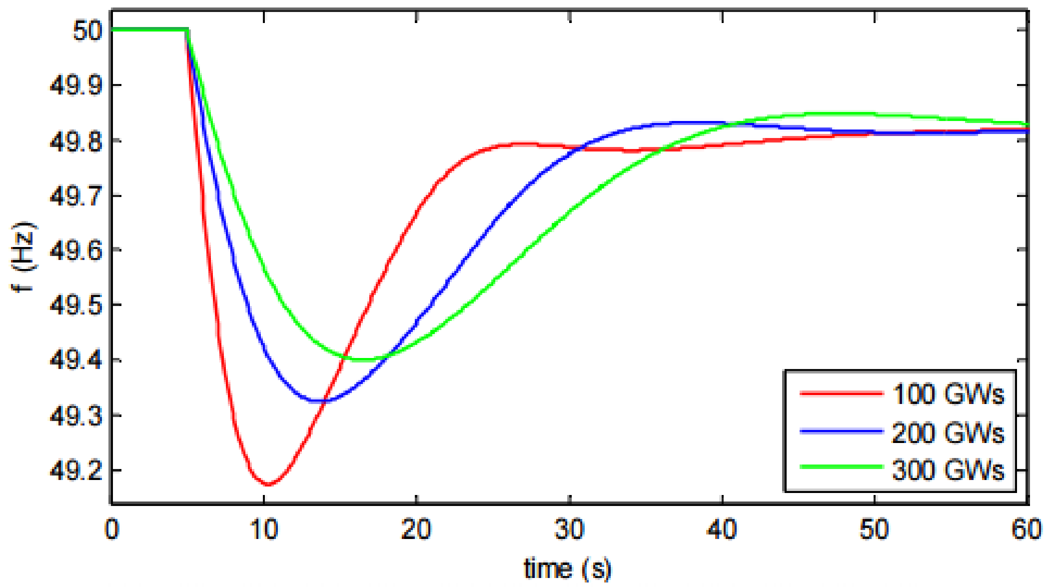

Figure 15. *Frequency drop with different inertia values after 1 300MW drop in production [60]*

The red line shows the biggest drop when there is only 100 GWs inertia. In 2020 it is estimated that the Nordic power system will have 124 GWs kinetic energy with low load and 305 GWs with high load. In 2025 low load kinetic energy increases to 138 GWs and high load to 313 GWs. There is also a scenario where in 2025 there could be only 95 MWs kinetic energy in the system. [61]

With the traditional energy producing technologies inertia have been foregone conclusion. The challenge is when the amount of combined heat and power (CHP) power plants and nuclear power plants are decreasing and windmills and solar power plants are increasing. Wind and solar power do not include generators directly connected to the grid, but only via converters, so they are not having any inertia. As a result, there is a need for synthetic inertia. Power storages are one possibility to create this kind of needed synthetic inertia.

Supercapacitors are one choice for fast frequency regulation. They have the ability to react fast enough and since they do not use any chemicals, they have a lifetime of hundreds of thousands of cycles. Power battery storages have also the ability of fast reaction times. For example, Toshiba BESSs using SCiB^{TM} batteries are able to react in 180 ms which is enough to do frequency regulation fast enough to keep frequency under the limits as standards require. Frequency regulation is one of the main usage of both supercapacitors and power storages.

5.1.4 Consumption spikes

When the number of devices are increasing, it requires a lot of capacity from a power system. Heat pumps are a problem already if they are started simultaneously in a small area. Also saunas in Finland generate consumption spikes as they multiple household consumption for a couple of hours. It is a traditional habit to warm up sauna around 5pm in a Saturday so there are many houses in the same time to have this spike. The other example is that air coolers or heaters in the office buildings start to work around 4 am in the Monday mornings so the buildings have decent level of air when people come to work.

One big problem in the future will be EVs as they require fast charging and it is more likely to have more EVs to be charged at a same time than a couple of heat pumps starting up same time. It is already proven that people are more likely to charge their cars at home instead of charging stations. The only exception is Tesla’s charging stations as they provide fast charging but also it is free for use for Model S owners. That is why people are ready to travel a bit to charge their cars. [73] This will change as Tesla will stop the free service after the end of 2016. Anyhow, supercharger stations are challenges for grid connections. Superchargers require a lot of current and usually that causes the amount of current to exceed the fuse size. Fortum has a pilot project in Norway to use batteries in charging stations to make it possible to have smaller fuses in these stations. [74] Using battery compensates the current spikes. The same problem exists in households with heat pumps and batteries can be used to compensate current spikes made by heat pump startups.

One way to solve home charging problems is making the home charging devices to be able to communicate with other charging devices. When the user plugs in his or her EV, it is required to enter an estimated time when the car will be used next time. That could be combined with the smart charging. Sony is one example who has invented a smart charging system to increase the lifetime of their mobile phone batteries [62]. Basic idea of smart charging of mobile phone batteries is shown in figure 16.

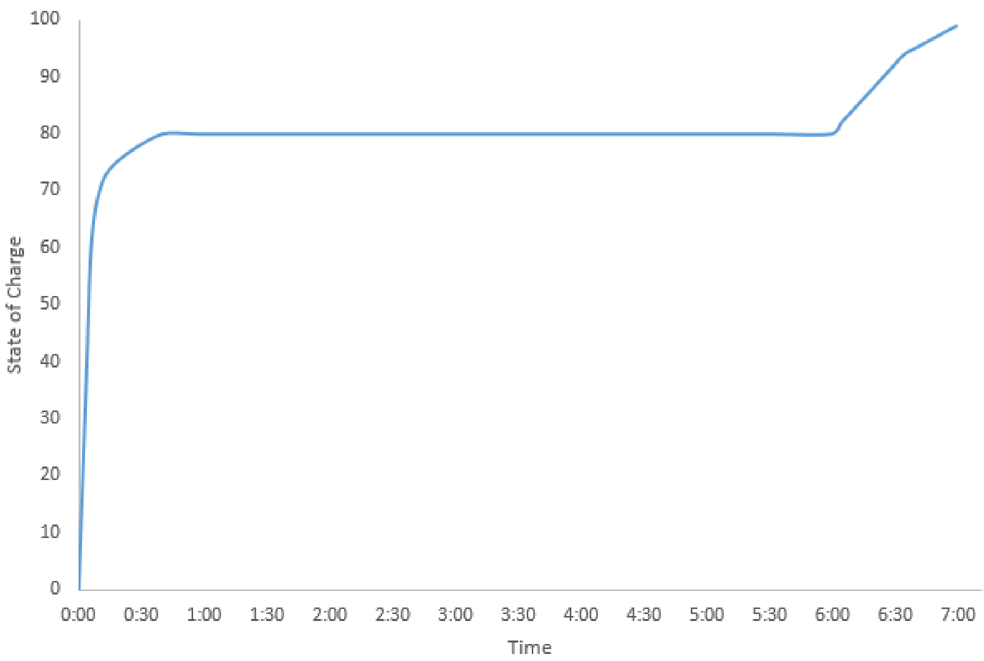

Figure 16. *Smart battery charging [62]*

The battery will be charged fast to a defined level and then it will be charged slowly to another defined level, around 80 %, based on the value that is entered to the system. Battery is then kept in the defined level. Finally, there have been set a time value when the device is needed again. The battery is charged again slowly as it reaches almost full charge just before the need of use. This is to prevent the battery being in 100 % state of charge for longer times. Smart ability should be used for charging EVs at home but also for every type of battery and especially Li-ion batteries.

This kind of recharging will secure the lifetime of EVs batteries assuming that Li-ion or other chemical batteries are used in the future. The other benefit is that those quick charges could be easier to adjust for different timings so the grid would not be loaded too heavily at once. Moreover, the time of slow charging could make the EV used as a home BESS to either add capacity to the power grid or improve power quality and give backup power to households. Slow charging makes EV possible to use as a load for demand response for example if it is not fully charged.

However, in cases where consumption spikes cannot be avoided, it is necessary to have backup power systems to provide enough electricity when it is needed. Once again energy storages are an option but in this case power storages are more viable as the power spikes can be huge and requires large amount of energy quickly.

5.1.5 Overproduction

Consumption spikes are not the only problem with the renewable energy resources. When photovoltaics prices are getting lower and more end customers are buying solar panels to provide self-production, there are some situations when the production go over the own consumption.

The sun shines and wind blows mostly during the middle of the day and the production is highest in those times. But these hours are the same hours when most of the people are working and their houses are on idle mode which means there are no need of that much produced electricity. One option is to sell this overproduction as factories are still running during those times and willing to buy cheap electricity but with the regulations we have today, prosumers might still consider this option as they need to pay taxes for this action. They also need to pay transmission costs which also lowers the possible income. Changes in regulations are needed if it is wanted that people supply overproduction to the power grid.

A small size BESS could storage this production during the day and be able to provide electricity during the evening and night when photovoltaics are not providing electricity anymore. As mentioned that EVs could operate as energy storages in households, people use them to travel to work and they are not able to be used as storages during the days which means they have the same problem as they are gone when needed. This means that there should be smaller installed energy storages at houses.

5.1.6 Continuous delivery

Frequency and voltage values are not the only parameters that define quality of electricity as the continuous delivery is an important aspect. Like mentioned that distribution network companies are building ground cable distribution networks to assure that weather effects will not have impact to the power grid. Ground cables are still quite expensive and not so easy to fix if repairs are needed.

BESSs could be a good option instead of ground cables if they are positioned correctly. If a part of a grid is disconnected, BESS could operate in an island mode to deliver electricity to the area that would be without electricity otherwise. The thing with overhead lines with BESS instead of ground cables is that BESS would give the benefits of frequency regulation and extra capacity with the ability to provide continuous electricity delivery.

Microgrids are especially needed for uninterrupted electricity supply. Hospital or an area of manufacturing companies operating as a microgrid relies on continuous delivery. Even short interruptions may have a huge impact in their businesses. UPSs, diesel generators and gas turbines are usually used today but they all have some problems. UPSs lack the capacity which makes them to have only a short period of working time at once without recharge. Diesel generators instead requires some time to start working, usually around 15 minutes and using diesel as a power source creates emissions.

Diesel generators are still needed as today's batteries are quite expensive if wanted to have enough capacity. That is why hybrid solutions containing diesel generator and a BESS is a solid choice right now but in the future when prices are getting lower, there should be only a BESS running the backup power. The black start function in BESSs raise the voltage level high enough to start other backup devices running and provide electricity.

5.2 Commercial challenges

Commercial challenges are the type of challenges which bring monetary issues. As for example, there are difficulties regarding different regulation of taxes and other related issues.

5.2.1 Market participation of renewable energy resources

Nowadays energy consumption is measured in 60 minute cycles. This might be changed for 15 minute cycles. The amount of energy that will be produced and sold is decided for each hour for the next day. One hour's energy production is the average of that hour. If the markets change for 15 minute cycles, it will become much more difficult to predict the production of intermittent energy resources. Power production is much more volatile when the measured average is 15 minutes than 60 minutes. This can be seen in figure 17.

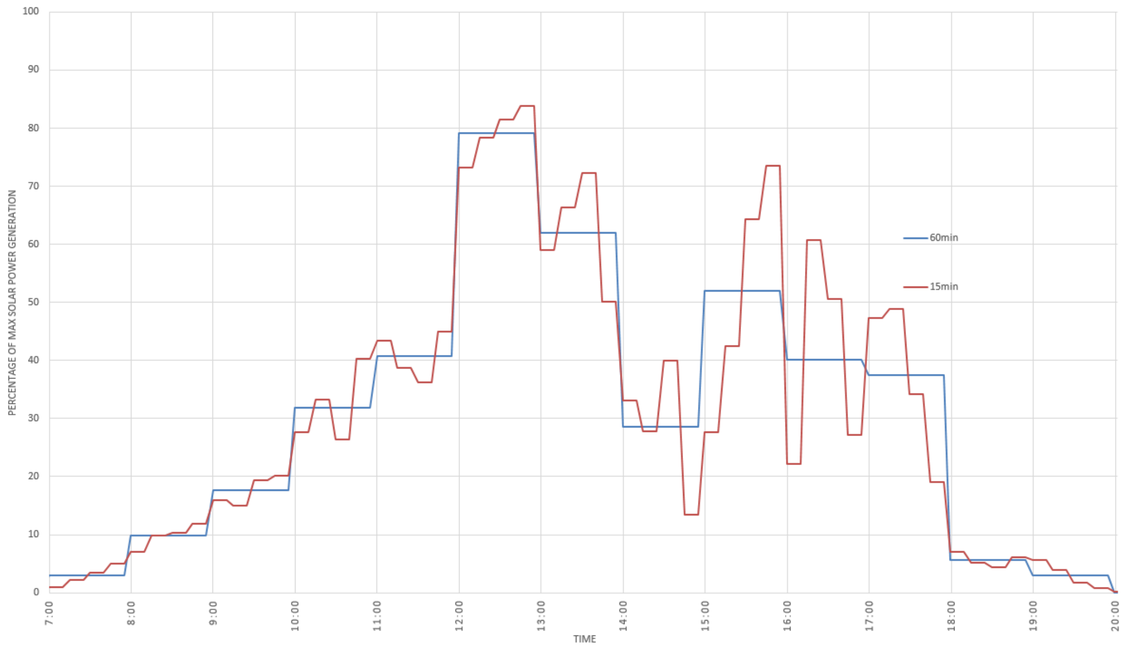

Figure 17. *Solar power production at one solar power plant in 5th of September 2016*

The blue line is the average of solar power generated in 60 minutes and the red line is the average of solar power generated in 15 minutes. The drop just before 16.00 a good example how the measurement differs between 15 minute and 60 minute cycles. 60-minute average decreases just around 12 % point when 15-minute average decrease over 40 % point.

As the amount of energy to be sold is decided day before, this scenario causes expenses. If it is promised to sell 1 MWh of energy and production is only 0,7 MWh. The remaining 0,3 MWh is needed to buy from other markets so it is possible to sell the full 1 MWh. [75] On the other hand, when the production exceeds the promised amount of energy, the exceeding part of production can be considered as non-profitable production.

5.2.2 Transmission costs

Delivering electricity to the power grid have costs in a form of taxes and transmission. These lower the value of creating photovoltaic power plants since one needs to pay taxes for every kilowatt one provides to the system.

Finnish law does not verify storing electricity. Finnish Energy Authority treats energy storages similar as production. That is why DSOs and TSOs have limitations to own BESSs as they have limitations to own electricity production. DSO and TSO owned stored electricity is possible to use for specific defined uses that have been set in electricity market act. [63]

Delivering electricity into a storage is taxed as it would have been taxed as using it for normal transmission. If a BESS is charged from the grid, there is need to pay transmission taxes. When the stored electricity is delivered back into the grid, it will be taxed again. There is an exception when the stored electricity is used locally within the production plant instead of delivering it to the grid. In this situation, there is no need for double taxes. In case where electricity is used to compensate transmission losses, there is also no need to pay transmission taxes. [63]

Delivering electricity has also transmission costs. The price of transmission costs is set by local DSO who own the distribution grid. Energy Market Authority controls the price of transmission costs.

These problems have been faced already in practice, when the BESS was delivered to Helen as there were risks of double taxing.

6. BUSINESS OPPORTUNITIES FOR POWER BATTERY STORAGES

Eventhough, there are many drivers to support usage of different energy storage systems, companies are finding solutions which can be built to a business case. The purpose of this chapter is to find out solutions how power storages can create value to customers. At first singular services are introduced. Then singular services are combined to create the best possible solutions creating profit. To help with calculations, there are shown two different cases with different solutions. These cases are Helen and Lempäälä.

6.1 Singular services

It is important to understand that power storages have abilities to multitask various services at the same time. From HMI it is possible to set priorities for every task how they operate in a selected time frame. The BESS can be configured to have a weekly schedule. For every day, it is possible to set operating tasks and priorities for 15 min accuracy. More about the multitasking is explained in the case examples.

To calculate the combined profit, it is necessary to know how BESSs are doing singular services and how much profit each task could generate. Overall, black start is expected to have the most value. For daily use, frequency containment reserves in normal operation (FCR-N) and in frequency containment reserves in disturbances (FCR-D) are expected to be the most profitable. Figure 18 presents expected value propositions for each singular service.

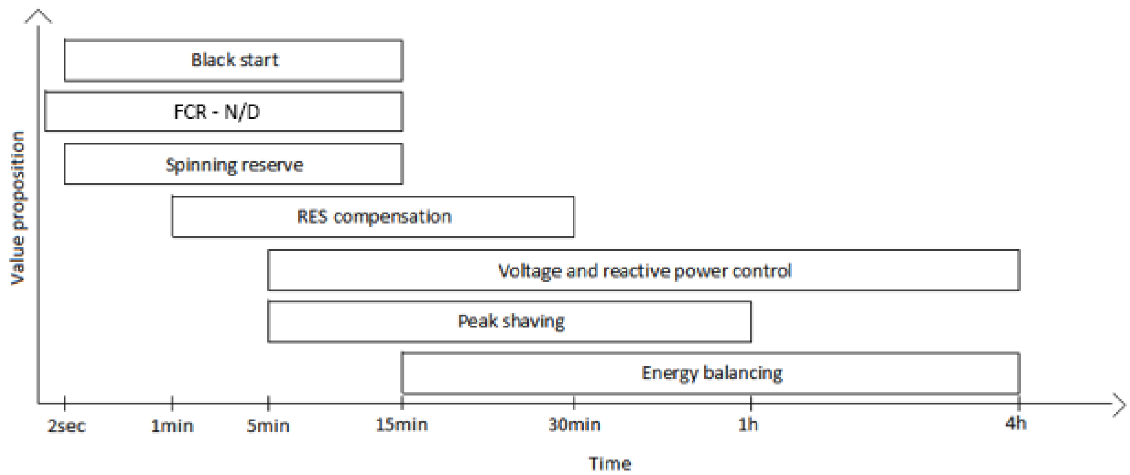

Figure 18. *Value proposition for singular BESS services*

The value proposition also shows a raw estimate on how long will different services need to operate. Because of low energy prices and volatility of today, it is expected that peak shaving and energy balancing cannot bring much monetary value.

6.1.1 Black start

Black start is an operation where the BESS will raise the voltage level high enough to ramp up other power sources. There are two different situations how the black start should be done. A simplified single-line diagram from a black start system is shown in figure 19.

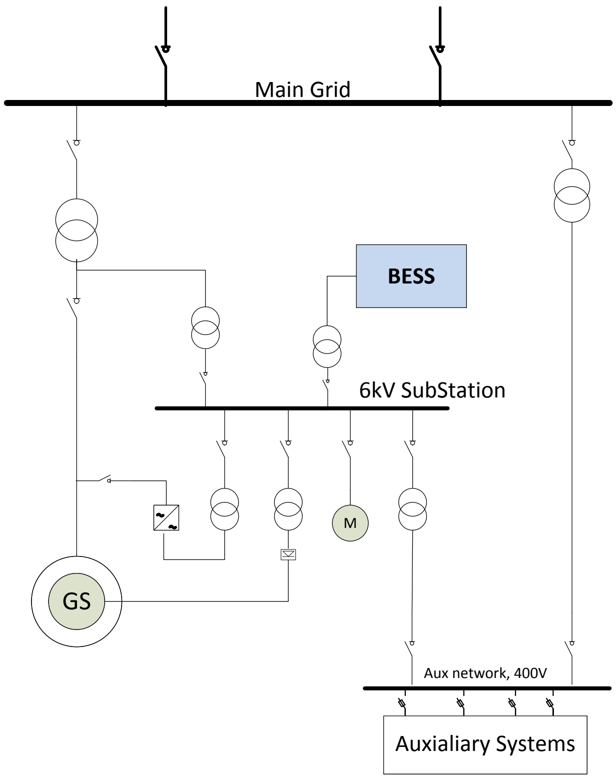

Figure 19. *A simplified single-line diagram for black start system*

If the BESSs is connected to MV grid that is not operating in an island, the main function is to do the black start when needed, and there is nothing else happening in the BESS when this is done. In figure 19, the BESS is connected to the 6 kV substation busbar increasing the voltage level and providing required power to energize the gas turbine. This was explained more accurate in figure 8.

The other possible scenario of a black start is a BESS operating in an island. When the part of the grid is disconnected from the utility grid, the BESS will do a black start. The difference between these scenarios is that now the BESS is needed to provide electricity to the island meanwhile it is also doing the black start operation.

Even the black start probably has the most value of BESS services, it is impossible to calculate monetary value. Thus, it is known that the value of the black start depends on the facility, power and location [75].

LVDC islands could be good possibilities to use black start function. As rural areas are considered the best choices for LVDC areas, a BESS with black start ability could operate in island mode. The main idea when the island separates from the grid, the BESS works as UPS but also can start up the whole island if needed. This is how continuous electricity delivery in rural areas could be improved. More about island mode is discussed in chapter 6.3.1.

6.1.2 Frequency regulation

Frequency regulation with BESS is done by charging and discharging. It was explained that that frequency will rise above 50 Hz when there is too much production compared to consumption. Setting frequency down is done by using the BESS as a load. This means the BESS will be charged when the consumption is higher than production. When the frequency is below 50 Hz, the BESS will be discharged. That is how it balances power and adjusts frequency.

In chapter 4.3.2 were introduced the BESS operating modes. Frequency regulation will happen in grid supporting mode. If a part of a grid is disconnected to an island, the BESS can use grid forming mode to set the correct frequency within the island.

Reserve markets are the most important function for today’s BESSs in a daily use. By collecting data from Fingrid, it is possible to calculate how much savings could be done if the power storage would deal with the power balancing. This value has already been calculated in a research [64]. With 1 MW BESS, the rounded and approximated values make the total yearly income 300 000 EUR with FCR-N markets and voltage support. [64] Later this value has been decreased [73] so the value estimation would be 80 % of the calculated amount. The amount is then rounded for 260 000 EUR/a and it is based on electricity prices of 2014.

With higher power, the profit will be increased as will the price of the BESS, too. Moreover, today’s electricity prices were used in these calculations. Today’s electricity prices can be considered cheap. More intermittent production causes electricity prices to be more volatile. With higher electricity costs and especially with more volatility, value from frequency regulation will be higher. Higher volatility in electricity prices would also affect to the FCR-D markets to make it more profitable.

When the total capacity of BESSs is over 5 MW, it can participate in fast disturbance reserve or balancing power markets. As there will be more and bigger BESSs, there should be done calculations on how much value will BESSs create in participating for fast disturbance reserve or balancing power markets.

6.1.3 Spinning reserves

Spinning reserves are used to create inertia. There is no formula to calculate directly the value which is gained by using battery as a spinning reserve. Anyhow there are a few things that brings value.

The first matter to consider is when the amount of inertia is low, the frequency of the power grid is more vulnerable to changes. This means that the value of this feature is how much harm can be avoided with more inertia in the system.

The other matter to consider is how much does it costs to have another device to create more inertia. As some power plants are shut down, is it possible to still run the generator just to create inertia? If it is possible, how much would it cost and who would pay it? At last, how much costs a device that is used only to generate inertia to the system? Is there a need for inertia markets in the future?

6.1.4 Compensating renewable energy resources

Compensating the sudden drops in intermittent production might be a hard task. The difficulty comes from many variables which need to be taken into consideration. This makes accurate calculations also difficult. At first, the battery needs to have enough charge to be able to compensate drops. The other thing is that weather cannot be forecasted accurate enough and it is different in each year. That is the reason why calculations are only estimations. As large wind power farms are too large to be compensated with battery energy storages, calculations are only made for solar power plants. For bigger plants it is still possible to make hybrid solution by using BESS and diesel generators as an example for cost effective solution.

Solar power data available is from mid-summer and autumn. The day length and the weather are somewhat similar in autumn and spring. Therefore, the calculations for March and April are almost the same as in September and October. Mid-summer data is used for May, June, July and August. For the rest of the year the sun is shining such short durations that it is not necessary to compensate solar power production during those months.

There are two methods to calculate the profit of solar power compensation. In the first method, there are two levels set. The first level is a percentage of production. When the production falls below the level, it is compensated to the level that has been set. The other level is maximum compensation. This means that in big drops, it is not necessary and maybe even possible to compensate the whole drop. As an example, if the first level is 60

% and second level is 30 %. When the production falls from the level of 70 % of maximum capacity into the level of 20 % of maximum capacity, the compensation starts after the production is below 60 %. In this case, it will compensate it up to 50 % as the drop is so big that the second level limits the compensation to 30 % up. Also, the compensation will happen only during 11 am to 18 pm. The rest of the time there is so low amount of production that it will be used to charge the battery. This is the way to secure that the battery has enough energy to compensate the drops during the day. The first method for compensation is visualized in figure 20.

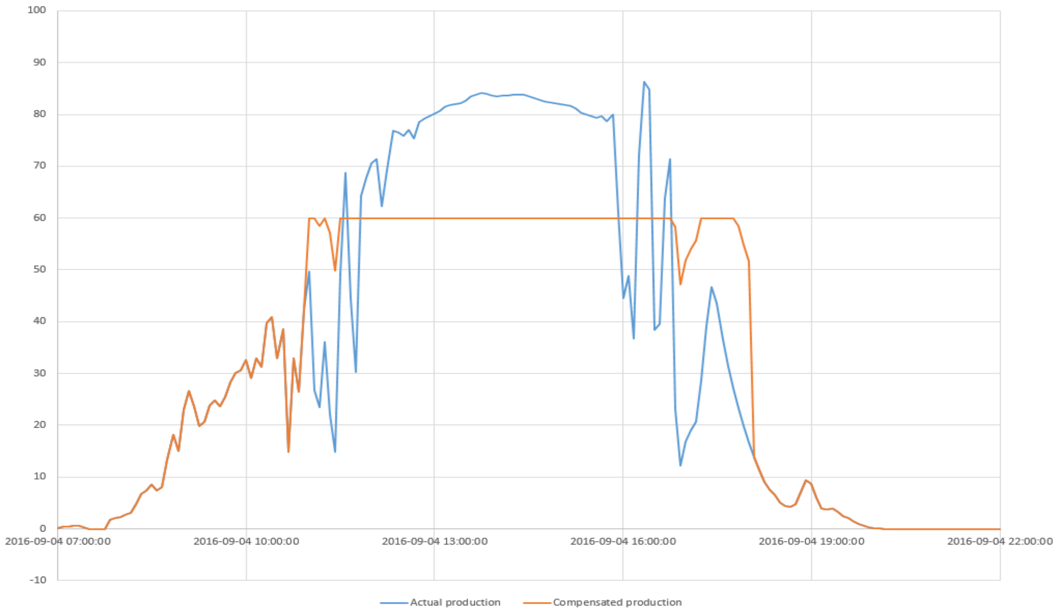

Figure 20. *Visualization for RES compensation using the 1st method*

Level 1 is set to 60 % as the orange line is not going above 60 %. Level 2 is the maximum compensation. In this case level 2 is set to 35 %. There are a few bigger drops where the orange line is below 60 % line because the maximum compensation is less than the drop for the moment. It is also noticeable that actual production and compensated production are different only from 11 am to 18 pm as this is when the compensation will happen.

The first level also defines the point when there is a need to start a backup power. If the production is below the first level for 15 minutes, the system will prepare to start the backup power. If the low production continues for 30 minutes, the backup power is started. Drops with duration between 15 to 30 minutes are considered to make profit with the amount of how much it costs to start a backup power. This is based on the number of startups within a lifetime of the backup power.

The second method for calculating value is based on comparing the average of 15-minute cycle and the average of 60-minute cycle. This is based on the possible changes in electricity markets. When the 15-minute average is below 60-minute average, there is calculated the difference how much 15-minute average should be compensated up to 60-minute average level. This is also done in hours between 11 am to 18 pm. When it is known that how much power is needed to be compensated, the amount is multiplied with the price of imbalance power from Fingrid [65] during that time. There is an exception as if the forecasted price of imbalance power is over 80 EUR, all the production will be sold to markets in order to gain the maximum income. The calculation results for both methods are collected in table 4.

Table 4. *Profit calculations for RES compensating*

	1st method	***2nd method***	***1st method***	***2nd method***	***1st method***	***2nd method***
Max power of a plant (MWp)	1		5		5	
Required level (%)	60		60		50	
Max compensation (%)	30		20		25	
Number of backup power starts avoided in a year	146		146		284	
Value of avoided startups (EUR)	7 300		7 300		11 200	
Income in spring & autumn (EUR)	8 470	1 806	31 275	9 032	34 402	9 032
Income in summer (EUR)	18 252	16 881	87 839	84 406	87 412	84 406
Total yearly income (EUR)	**34 022**	**25 987**	**126 414**	**100 738**	**133 014**	**104 638**

As mentioned, these calculations are only approximations and based on a specific data from a short period and one location. The point is to show how different values and acts affect to the total income. The size of the solar power plant is the biggest factor to the value gained but also bigger power plants need bigger and more expensive batteries.

6.1.5 Reactive power regulation

Finnish TSO, Fingrid Oyj, is changing the amount of charging for reactive power transmission. The costs of charges will come as steps in the next few years. To help with the investments needed to do for avoiding reactive power transmission. In 2019 the amount of charge is in full level. Reactive power transmission will cost 1000 EUR/MVAr and reactive energy 5 EUR/MVArh. These prices are for the amount that exceeds the maximum limits. [66]

For an example, if a power plant is producing 2 MVAr over the limits and a BESS can compensate 1,5 MVAr energy for 10 hours a day, savings with a BESS would be 1500 EUR/month in transmission and 75 EUR/day which is 2250 EUR/month in all.

As the BESS can do reactive power regulation with other functions, there is no need to buy a distributed static synchronous compensator (D-STATCOM) only for this purpose. That is why the price of D-STATCOM could be calculated as profit for BESS if the BESS is bought to an area where D-STATCOM is needed. D-STATCOM price varies depending on ratings of equipment and brands but less than 3 MW D-STATCOM is around 38 800 EUR [67].

6.1.6 Peak shaving

With low energy prices of today, constant peak shaving does not bring much monetary value. Probably with the high amount of cycles that are required for constant use, it will lower the lifetime of the battery so much that it would have a negative value [64].

It is still a needed feature to be used for occasional power balancing. Also, if there are hours with high energy prices, it should be used. These are still quite small numbers and it should be considered that the value is already included in RES compensation profits in chapter 6.1.4. If there is used a power tariff, it should be discussed if peak shaving is more viable then.

6.2 Case Helen

A BESS of 1,2 MW at the point of connection and capacity of 0,6 MWh is currently the biggest BESS in nordics. C-rate of the BESS is 2C. Every ten minutes the BESS can be used with 150 % overload for 30 seconds. That is located in Kalasatama, Helsinki, and it is placed next to the Hanasaari power plant. The location is in highly populated area and that is why firefighting system is important part of BESSs. Good firefighting system is also the reason why fire department permitted to construct the BESS in the middle of a city.

Helen's BESS is used to secure the distribution network area. With 2C rate it can provide power and energy for 30 minutes. Because of the location and local grid where it is used, the BESS do not have island mode function. Helen is using seven different services:

- frequency regulation in normal operations and disturbances
- voltage regulation
- reactive power compensation
- peak shaving
- energy balancing
- RES compensation.

As mentioned, these services can be prioritized for every 15 minutes in the week. Manual select for priorities is shown in figure 21.

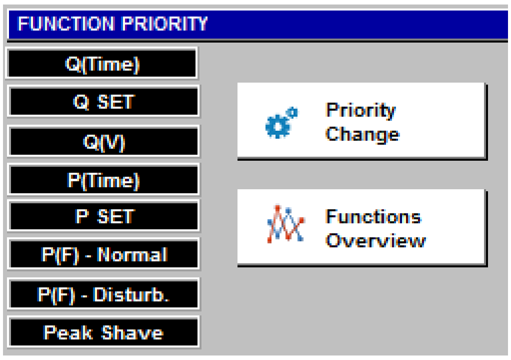

Figure 21. *HMI for the change of BESS service priorities*

Figure 21 shows priority options that can be set. An example of a weekly schedule for these functions is shown in figure 22.

DAY	PROG	TIME [hhmm]	PTIME [kW]	FUNCT(1-PREN-PSHAVE-PTIME-PFREQD-PFREQN-RESVD-QVOLT-QSET)	MRK
01	01	0000	50	100100001	99
01	02	0015	100	100100010	99
01	03	0030	-200	100100000	99
01	04	0045	100	100100000	99
..	..	....	.....	....	..

Figure 22. *Part of a BESS weekly schedule*

In figure 22, there is the day in the first column. The second column is a sequential number. The third column is the starting time for the program at the selected day. The fourth column adjusts the active power and the fifth column shows what services are in use in the program. Zero means that the service is not in use during the timeframe and one means that the service is activated. There are tools for creating a weekly schedule and export it in a correct file form as one-week schedule has many 15 minute periods. Also, it is easier to perceive which mode is in what position of the series of numbers. It is also necessary to know that real power and reactive power operations have different logical controls. This is shown in figure 23.

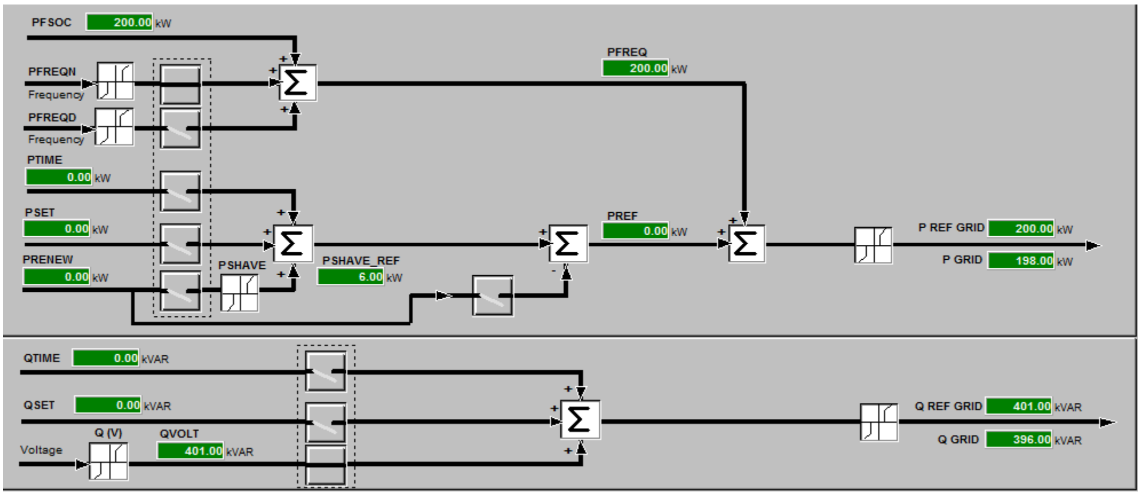

Figure 23. *Screencap from HMI*

It is possible to calculate profit using the values of singular services and their TOU. Frequency regulation is used all the time. As the Helen battery is 1,2 MW and rounded value for 1 MW BESS was 250 000 EUR/a, in this case the income is interpolated to be 260 000 EUR/a. The BESS is compensating 900 kVAr for 9 hours a day. If all of the compensating can be used to decrease the exceeding amount of reactive energy after 2019, yearly savings would be 10 800 EUR/a for transmission and 14 782 EUR/a for energy. There is also a solar power plant that is around 350 kWp located near the BESS. As the peak is not reached almost ever, the normal output power can be considered to be 300 kW. Because the solar power plant is only ¼ of the size of the BESS, the levels used for calculations in 6.1.4 can be set for 70 %. There are no backup power sources so the annual income is 10 000 EUR/a which is rounded down. With raw rounding, the total annual income is 300 000 EUR/a, taking account overlapping services and their times of use. The investment cost of the BESS is 1,8 MEUR and operating costs are 70 000 EUR/a [68]. 70 000 EUR/a operating costs can be used in every calculation.

6.3 Case Lempäälä

Marjamäki is a part of Lempäälä which a town near Tampere, Finland. There will be industrial buildings and the area is connected to the public distribution network but it can also operate in a separate island. Main power source in the area is planned to be 4 MW solar power plant with solar panels installed to the buildings in the area. Backup power sources would be one or more BESSs, fuel cells and gas turbine for longer use.

The BESS used in calculations is 1 MW with around 300 kWh capacity making it 4 C-rate solution. The real one is 1 to 2 MW depending on how much capacity can be stored in one container. The reason for limiting capacity to one container is to make it as easy as possible to deliver and install the container to the selected location. The BESS is a hybrid solution with the gas turbine. They are connected to a large scale cold storage in example freezer of logistic warehouse to secure continuous electricity delivery to that storage. One main purpose of this hybrid solution is to balance the solar power production to the area. As the area can operate in an island mode, the BESS has a black start ability to start other power sources. While operating in the island mode, the BESS adjust first the frequency for the island. Later the BESS will support the frequency that is managed by the gas turbine. If the area is connected to the public distribution network, the BESS can do normal frequency regulation offered to TSO's reserve market. Reactive power regulation is also an important service. More about island mode and calculations are discussed in chapter 6.3.1.

As the solar power production is used to industry, it would be better to use the first method from chapter 6.1.4. The solar power plant has 4 MWp, the wanted level 1 is 60 % and level 2 is 20 %. Shorter production drops that can be compensated using only the BESS create value as there is no need to start the gas turbine. This increases the lifetime of the gas turbine and saves fuel so every avoided start can be count as 50 EUR value. With the given level 1, there is 134 avoided starts in a year so the total value of avoided starts is 6 700 EUR/a. Combined value of avoided starts and savings from compensation using only the BESS in this case is rounded down for 100 000 EUR/a.

The BESS can compensate 900 kVAr reactive power in a year so this creates 25 000 EUR/a value. As this is a new area and the BESS can do reactive power compensation, there is no need for D-STATCOM investment. The investment cost of D-STATCOM is 38 800 EUR.

While in normal operation and good weather forecast or during nights, there is no need for solar power compensation. This is the time that the BESS can be used for frequency regulation. As the TOU is 60 % from maximum TOU, there is used this 60 % of the 260 000 EUR/a which is calculated in chapter 6.1.2. The total value from frequency regulation in this case is then 156 000 EUR/a. There could be more value if the BESS is used by an aggregator so it could be used for automatic frequency regulation services or power balance markets.

Some value for the BESS comes from EV charging stations support if the BESS is in the same distribution area. In this case the BESS balances power spikes as it is used for peak shaving reducing needed fuse size.

6.3.1 Island mode

In chapter 4.3.2 the operating modes of BESSs were introduced. Grid forming and grid supporting modes were usable in an island mode. Grid forming is used in black start situations as the mode forms the wanted frequency to the island area. In grid supporting mode the BESS is in parallel with the gas turbine. The BESS is working as a synchronous generator.

Value for black start in this case and operating in the island mode can be estimated from CIC. In this case, there is CIC for the whole island. CIC value for unexpected 15 min length interruptions for the industries is 6,2 EUR/kW. CIC value for expected interrupts like maintenances is 2,1 EUR/kW [69]. As the battery size is 1 MW, CIC values are needed to multiply with 1 000. As the area is part of Elenia's grid, there is an average of 4,2 unexpected interruptions per year and the average duration is 7,9 hours per year [70]. The average amount of expected interrupts is 0,2 per year and the average duration is 0,1 hours. The total cost from unexpected interruptions is about 26 000 EUR/a and about 400 EUR/a for expected interrupts. [70] Real values from interruptions will be more accurate after the project have been in use.

6.4 Total cost of ownership analysis

It was calculated that a BESS would have a positive net present value (NPV) after 15 years [64]. That calculation included the need to change a battery after 10 years as an operative cost. It is expected the LTO battery have a lifetime over 15 years and the wanted payback time is 7 years. That is why there is only need for maintenances and services as operative costs.

The expected return of capital is 10 %. There is known the wanted payback time, the expected return of capital and the value that a BESS will have yearly. With these values, it is possible to calculate how much should the investment cost of BESS be. The calculation can be done with formula 7:

$$C_0 = \sum_{t=1}^{n} \frac{C_t}{(1+i)^t} - NPV \tag{7}$$

where t is the time of cash flow, i is the discount rate, C_t is the net cash flow in euros and C_0 is the initial investment cost in euros. As the NPV is wanted to be positive, it has value of 0 in this calculation.

Calculations are made by using values of today. It is possible that discount rate will be more or less in the future or the volatility of electricity price changes. These things can make results more positive or negative. Also, more possible income from inertia markets or automatic frequency regulations are not used in these calculations.

Using the results from chapter 6.2, it is possible to calculate net present value for the case Helen. Using the discount rate of 3,5 %, 300 000 EUR/a net cash flow and 1,8 MEUR investment cost, NPV is positive in 8 years. In 16 years as it is the expected minimum lifetime of the BESS, the NPV is over 1,2 MEUR. The return of capital is 4,2 % which is less than expected 10 %. Cumulative NPV of the BESS in case Helen is presented in table 5.

Table 5. *BESS costs and net present value yearly in case Helen*

Year	***Investment, EUR***	***Income, EUR***	***Costs, EUR***	***NPV yearly, EUR***	***NPV cumulative, EUR***
2015	-1800000	300000	-70000	-1570000,0	-1570000,0
2016	0	300000	-70000	222222,2	-1347777,8
2017	0	300000	-70000	214707,5	-1133070,3
2018	0	300000	-70000	207446,8	-925623,5
2019	0	300000	-70000	200431,7	-725191,8
2020	0	300000	-70000	193653,8	-531538,0
2021	0	300000	-70000	187105,1	-344432,8
2022	0	300000	-70000	180777,9	-163654,9
2023	0	300000	-70000	174664,7	11009,8
2024	0	300000	-70000	168758,1	179767,9
2025	0	300000	-70000	163051,3	342819,2
2026	0	300000	-70000	157537,5	500356,7
2027	0	300000	-70000	152210,2	652566,9
2028	0	300000	-70000	147063,0	799629,9
2029	0	300000	-70000	142089,8	941719,7
2030	0	300000	-70000	137284,8	1079004,5
2031	0	300000	-70000	132642,4	1211646,9

As the Ministry of Economic Affairs and Employment in Finland supports the investment for about 30 % of the investment costs, this case could use investment cost of 1 200 000 EUR. Using this investment cost, NPV would be positive in 5 years. The return of capital in this case would be 9,4 %.

In case Lempäälä, the rounded yearly income using values from chapter 6.3 is 310 000 EUR/a, yearly operational costs are 70 000 EUR/a and the investment cost is 1,5 MEUR. The investment cost includes BESS, spare parts, transformers, substation including equipment and civil works. Also the D-STATCOM savings are removed from investment costs. With the same 3,5 % discount rate NPV is positive in 6 years. The return of capital in case Lempäälä is 10,3 % which is more than expected 10 %. Cumulative NPV of the BESS in case Lempäälä is presented in table 6.

Table 6. *BESS costs and net present value yearly in case Lempäälä*

Year	*Investment, EUR*	*Income, EUR*	*Costs, EUR*	*NPV yearly, EUR*	*NPV cumulative, EUR*
2015	-1 500 000	310000	-70000	-1260000,0	-1260000,0
2016	0	310000	-70000	231884,1	-1028115,9
2017	0	310000	-70000	224042,6	-804073,4
2018	0	310000	-70000	216466,2	-587607,1
2019	0	310000	-70000	209146,1	-378461,0
2020	0	310000	-70000	202073,6	-176387,4
2021	0	310000	-70000	195240,2	18852,7
2022	0	310000	-70000	188637,8	207490,6
2023	0	310000	-70000	182258,8	389749,3
2024	0	310000	-70000	176095,4	565844,8
2025	0	310000	-70000	170140,5	735985,3
2026	0	310000	-70000	164387,0	900372,2
2027	0	310000	-70000	158828,0	1059200,2
2028	0	310000	-70000	153457,0	1212657,2
2029	0	310000	-70000	148267,6	1360924,9
2030	0	310000	-70000	143253,7	1504178,6
2031	0	310000	-70000	138409,4	1642588,0

Last calculations are break-even points for 1 MW BESSs. The discount rate is once again 3,5 %. With 300 000 EUR/a income and 70 000 EUR/a operating costs, the investment cost should be 1 636 345 EUR to make NPV zero in 7 years. 7 years is used because it is still less than half of the expected lifetime of a BESS. If the income is 350 000 EUR/a and operating costs are 70 000 EUR/a, the investment cost can be 1 992 072 EUR to make NPV zero in 7 years. Also, there are cases that D-STATCOM is not needed because of the BESS investment, 38 800 EUR can be added to the maximum investment cost. To demonstrate how changes in values affect, there is more break-even points and cumulative NPV calculations using different values shown in appendix 1.

7. FUTURE POSSIBILITIES FOR USING BESS

Future possibilities can be divided in two categories. The first one is near future and the other one is long term development.

7.1 Near future

With the calculations made in chapter 6, it can be said that BESSs are already profitable. In the near future if the amount of BESSs increase, materials will become cheaper. That will shorten payback times even more and it is possible to reach the 10 % return of capital easier. Cheaper prizes do affect for long term development as well.

Ongoing and upcoming pilot projects are one factor to decide how BESSs will be used in the future. It is hard to tell if small household BESSs will dominate the markets or are large grid connected BESSs a better option. Increasing amount of home installed solar panels support small size BESSs. Renewable energy resources and decreasing battery prices will make large capacity BESSs a better choice. [74]

Services that BESSs have today are needed ones. When having these pilot projects, there is a possibility to learn more about these services. That is how these services can be developed into better ones. [73] Especially there is need to find out how different services can be used by the best possible way in multitasking.

There is researches if aggregators would operate multiple BESSs. The minimum capacity to participate power balance markets is 5 MW at present. If there are six 1 MW BESSs all over Finland, one aggregator could operate them to be used for power balance markets when needed. This will require standards for communication interface at least. Anyhow, there might be companies already that could operate as aggregators. [71]

7.2 Long term development

As power storages are probably more cost-effective choice today than energy storages, cheaper prices in the future can change the situation. BESSs today are not large enough to operate as longer energy reserves. They have enough capacity to balance small size solar power plant production. Biggest windmill farms are too large for today’s BESSs if wind power production is wanted to be compensated. This will change if a BESS with a power of 50 MW and a capacity of 25 MWh or even higher could be bought with a decent price and payback time. Probably this will not happen anytime soon but the changes in technology have sometimes been surprisingly fast.

The reason that BESSs are used for these pilot projects is because of their scaling potential. Home storages are quite similar to operate as centralized storages so results from pilot projects can be used for home storages as well. Also, there are different capacity BESSs between home storages and centralized storages. [73]

If it is easy to connect a BESS to the power grid, there is a possibility that BESSs could be movable energy storages. That would require better capacity per volume ratios to make high capacity BESSs easier to move. But many things in the past have gotten better abilities with smaller prices like personal computers as an example.

Things that will affect a lot of BESS development is laws and regulations. As mentioned, Energy Authority is treating BESSs like production sources. On European Union level BESSs are now recognized as own units but it is unknown how much time will it take for Energy Market Authority to notice this [72]. There is a need to change these legislations to make BESSs even more profitable and available. By availability is meant that TSOs and DSOs cannot own BESSs as they are considered as production. Markets and regulations usually defines how things will go but the biggest question is what are the political decisions. Like the example from Sweden where government supports buying household batteries will increase the sales of household batteries. An another example is that some decisions made in Germany are affecting in Sweden and then in Finland [74].

8. SUMMARY AND CONCLUSION

There are drivers like climate change and emissions that requires actions. This will affect also to the power system. Prizes of solar panels are getting lower and governments makes pressure to increase the amount of wind power. The increasing amount of renewable energy resources is one example that brings new challenges.

One challenge is decreasing amount of inertia that makes the power grid more vulnerable to frequency changes. Another challenge is the intermittent production that will make harder to keep power in balance.

There are ongoing and upcoming pilot projects to prove how BESSs are able to help with electricity quality. BESSs are capable to create synthetic inertia, frequency regulation, voltage regulation, reactive power compensation and RES compensation with many other functions. They are still expected to be too expensive for customers.

Helen’s BESS is the biggest BESS in Nordics and it is made by Toshiba and delivered by Landis+Gyr Oy. Case Lempäälä is one of the upcoming projects and there the BESS is used as a hybrid solution with gas turbine to compensate solar power production in an industrial area that can also operate as a grid separated island. According to calculations from these cases, power storages that operate for less than four hours are cost effective enough to be profitable already.

With more developing and capacity, BESSs will have new market opportunities to make them even more profitable. Profitability for some market opportunities may require changes in regulations and standards. At last, when the prizes get lower, BESSs can be used for longer energy delivery and BESSs will be a part of the future power system.

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APPENDIX 1: BREAK-EVEN POINTS FOR 7 YEAR PAYBACK TIME FOR 1 MW BESS USING DIFFERENT VALUES

Calculation does not include savings from cases where D-STATCOM is not needed.

Yearly income = 300 000 EUR/a, operational costs = 70 000 EUR/a, discount rate = 5%

Year	*Investment, EUR*	*Income, EUR*	*Costs, EUR*	*NPV yearly, EUR*	*NPV cumulative, EUR*
2015	-1560865,88	300000	-70000	-1330865,9	-1330865,9
2016	0	300000	-70000	219047,6	-1111818,3
2017	0	300000	-70000	208616,8	-903201,5
2018	0	300000	-70000	198682,6	-704518,8
2019	0	300000	-70000	189221,6	-515297,3
2020	0	300000	-70000	180211,0	-335086,2
2021	0	300000	-70000	171629,5	-163456,7
2022	0	300000	-70000	163456,7	0,0
2023	0	300000	-70000	155673,1	155673,1
2024	0	300000	-70000	148260,1	303933,1
2025	0	300000	-70000	141200,0	445133,2
2026	0	300000	-70000	134476,2	579609,4
2027	0	300000	-70000	128072,6	707682,0
2028	0	300000	-70000	121973,9	829655,9
2029	0	300000	-70000	116165,6	945821,5
2030	0	300000	-70000	110633,9	1056455,5
2031	0	300000	-70000	105365,7	1161821,1

Break-even point = **1 560 865,88 EUR**

Yearly income = 350 000 EUR/a, operational costs = 70 000 EUR/a, discount rate = 5%

Year	*Investment, EUR*	*Income, EUR*	*Costs, EUR*	*NPV yearly, EUR*	*NPV cumulative, EUR*
2015	-1900184,55	350000	-70000	-1620184,6	-1620184,6
2016	0	350000	-70000	266666,7	-1353517,9
2017	0	350000	-70000	253968,3	-1099549,6
2018	0	350000	-70000	241874,5	-857675,1
2019	0	350000	-70000	230356,7	-627318,4
2020	0	350000	-70000	219387,3	-407931,1
2021	0	350000	-70000	208940,3	-198990,8
2022	0	350000	-70000	198990,8	0,0
2023	0	350000	-70000	189515,0	189515,0
2024	0	350000	-70000	180490,5	370005,5
2025	0	350000	-70000	171895,7	541901,2
2026	0	350000	-70000	163710,2	705611,4
2027	0	350000	-70000	155914,5	861525,9
2028	0	350000	-70000	148490,0	1010015,9
2029	0	350000	-70000	141419,0	1151434,9
2030	0	350000	-70000	134684,8	1286119,7
2031	0	350000	-70000	128271,2	1414390,9

Break-even point = **1 900 184,55 EUR**

Yearly income = 250 000 EUR/a, operational costs = 70 000 EUR/a, discount rate = 5%

Year	*Investment, EUR*	*Income, EUR*	*Costs, EUR*	*NPV yearly, EUR*	*NPV cumulative, EUR*
2015	-1221547,21	250000	-70000	-1041547,2	-1041547,2
2016	0	250000	-70000	171428,6	-870118,6
2017	0	250000	-70000	163265,3	-706853,3
2018	0	250000	-70000	155490,8	-551362,6
2019	0	250000	-70000	148086,4	-403276,1
2020	0	250000	-70000	141034,7	-262241,4
2021	0	250000	-70000	134318,8	-127922,6
2022	0	250000	-70000	127922,6	0,0
2023	0	250000	-70000	121831,1	121831,1
2024	0	250000	-70000	116029,6	237860,7
2025	0	250000	-70000	110504,4	348365,1
2026	0	250000	-70000	105242,3	453607,3
2027	0	250000	-70000	100230,7	553838,1
2028	0	250000	-70000	95457,8	649295,9
2029	0	250000	-70000	90912,2	740208,2
2030	0	250000	-70000	86583,1	826791,2
2031	0	250000	-70000	82460,1	909251,3

Break-even point = **1 221 547,21 EUR**

Yearly income = 300 000 EUR/a, operational costs = 70 000 EUR/a, discount rate = 7%

Year	*Investment, EUR*	*Income, EUR*	*Costs, EUR*	*NPV yearly, EUR*	*NPV cumulative, EUR*
2015	-1469536,56	300000	-70000	-1239536,6	-1239536,6
2016	0	300000	-70000	214953,3	-1024583,3
2017	0	300000	-70000	200890,9	-823692,4
2018	0	300000	-70000	187748,5	-635943,9
2019	0	300000	-70000	175465,9	-460478,0
2020	0	300000	-70000	163986,8	-296491,2
2021	0	300000	-70000	153258,7	-143232,4
2022	0	300000	-70000	143232,4	0,0
2023	0	300000	-70000	133862,1	133862,1
2024	0	300000	-70000	125104,8	258966,9
2025	0	300000	-70000	116920,3	375887,2
2026	0	300000	-70000	109271,3	485158,5
2027	0	300000	-70000	102122,8	587281,3
2028	0	300000	-70000	95441,8	682723,1
2029	0	300000	-70000	89198,0	771921,1
2030	0	300000	-70000	83362,6	855283,7
2031	0	300000	-70000	77909,0	933192,6

Break-even point = **1 469 536,56 EUR**

Yearly income = 350 000 EUR/a, operational costs = 70 000 EUR/a, discount rate = 7%

Year	*Investment, EUR*	*Income, EUR*	*Costs, EUR*	*NPV yearly, EUR*	*NPV cumulative, EUR*
2015	-1789001,03	350000	-70000	-1509001,0	-1509001,0
2016	0	350000	-70000	261682,2	-1247318,8
2017	0	350000	-70000	244562,8	-1002755,9
2018	0	350000	-70000	228563,4	-774192,5
2019	0	350000	-70000	213610,7	-560581,9
2020	0	350000	-70000	199636,1	-360945,8
2021	0	350000	-70000	186575,8	-174369,9
2022	0	350000	-70000	174369,9	0,0
2023	0	350000	-70000	162962,5	162962,5
2024	0	350000	-70000	152301,4	315264,0
2025	0	350000	-70000	142337,8	457601,8
2026	0	350000	-70000	133026,0	590627,8
2027	0	350000	-70000	124323,3	714951,1
2028	0	350000	-70000	116190,0	831141,2
2029	0	350000	-70000	108588,8	939730,0
2030	0	350000	-70000	101484,9	1041214,9
2031	0	350000	-70000	94845,7	1136060,6

Break-even point = **1 789 001 EUR**