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Value of Battery Energy Storage at Ancillary Service Markets

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology.

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Tiivistelmä

Diplomityön tavoitteena oli tutkia sähkövaraston soveltuvuutta ja kaupallista kannattavuutta kantaverkkoyhtiö Fingrid Oyj:n reservimarkkinoilla. Akkukäyttöisen sähkövaraston etuja ovat välitön tehontuotanto ja säädön tarkkuus. Toisaalta heikkouksia ovat rajattu energian kapasiteetti, rajattu akkujen elinikä ja korkea investointikustannus. Sähkövaraston erilaisuus verrattuna perinteisiin tehoreserveihin asettaa haasteita markkinaregulaatioon ja epävarmuutta investointeihin.

Työssä tunnistettiin sähkövaraston soveltuvan taajuusohjattuihin reservimarkkinoihin, mutta sähkövaraston katsottiin soveltuvan kaupallisesti ainoastaan taajuusohjatun käyttöreservin tuntimarkkinalle. Lisäksi todettiin sähkövaraston kykenevän kompensoimaan sähköverkon loistehoa jännitteen ylläpitämiseksi.

Sähkövaraston käyttäytymistä simuloitiin eri säätökäyrillä taajuusohjatussa käyttöreservissä Matlab- ja Apros-ohjelmistojen avulla. Simulaatiot tehtiin vuoden 2013 taajuusdataa käyttäen, jolloin saatiin kattava käsitys sähkövaraston käyttäytymisestä eri säätökäyrillä.

Tuloksista havaittiin, että taajuusohjatun käyttöreservin markkinavaatimuksilla on huomattavan suuri vaikutus sähkövaraston toimintaan ja kannattavuuteen. Lisäksi huomattiin, että nykyinen markkinavaatimus taajuusohjattuun käyttöreserviin osallistumisesta ei ole sähkövaraston kannalta optimaalinen. Markkinasääntöjä muuttamalla, voidaan kasvattaa sähkövaraston hyötyjä huomattavasti ja edesauttaa sähkövarastojen kaupallistumista. Tuloksia käytettiin hyväksi Helen Oy:n Kalasataman sähkövarastohankkeen kustannusten ja käytön arvioimiseen.

Avainsanat Sähkövarasto, kysyntäjousto, taajuusohjattu käyttöreservi, taajuusohjattu häiriöreservi

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Abstract

The purpose of this thesis is to study applicability and economic viability of a battery energy storage system (BESS) in the national transmission system operator Fingrid Oyj held ancillary service markets. The advantages of a battery energy storage are immediate active power generation and accuracy of the control. On the other hand, it's weaknesses are limited energy capacity, limited lifetime of batteries, and high initial investment costs. Difference of battery energy storages compared to conventional power generation sets challenges for market regulation and uncertainty to investments.

A battery energy storage was found to be suitable for frequency containment reserve markets, but could only be economically viable at the hourly auctioned frequency containment reserve for normal operation (FCR-N) market. A BESS can also be used simultaneously for the reactive power compensation to maintain appropriate voltage level.

Behavior of different control logics in the frequency containment reserve was simulated in Matlab and Apros applications. A full year of 2013 was simulated using available frequency data.

Simulation results showed the high impact of FCR market regulation to BESS operation in FCR-N market and its economic viability. The results also show that the current market regulation model in use is not optimal for battery energy storage. Advantages of a BESS can be increased significantly by altering market rules, thus helping commercialization of the BESS in general. The results of this thesis were used to evaluate costs and use in Helen Oy's BESS project.

Keywords Battery energy storage system, BESS, ancillary service markets, demand response, frequency control, frequency containment reserve

Acknowledgements

This master's thesis has been written as an assignment for Helen Oy during the late 2014 and early 2015. As a summer intern, I became involved in a project, in which Helen Oy was planning to purchase a battery energy storage system as part of Smart energy systems in the Kalasatama district project. Simultaneously, Helen Oy participated in the European Union funded Cityopt – energy efficiency research project. The topic of this thesis was chosen to support the use of battery energy storage systems at the competitive electricity markets.

I would like to express my sincere gratitude to my thesis advisor Perttu Lahtinen and to my supervisor Matti Lehtonen. I would like to acknowledge the European Union for funding the Cityopt project, and also thank the Cityopt coordinator Åsa Hedman and Ha Hoang from VTT for the assistance. Furthermore, I thank Minna Laasonen from Fingrid for the data and insights. Lastly, I would like to thank my colleagues, friends and family for the support.

In Espoo 20.4.2015

Janne Huvilinna

Janne Huvilinna

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TIIVISTELMÄ

ABSTRACT

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Abbreviations

A	Ampere
AC	Alternating current
Ah	Ampere-hour
BESS	Battery Energy Storage System
BMS	Battery management system
CAES	Compressed Air Energy Storage
DC	Direct current
DOE	The United States Department of Energy
ENTSO-E	European Network of Transmission System Operators for Electricity
ESS	Energy Storage System
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve in Disturbance
FCR-N	Frequency Containment Reserve in Normal operation
FERC	Federal Energy Regulatory Commission
kV	Kilovolt
kVA	Kilovolt-ampere
kVAr	Kilovolt-ampere reactive
kW	Kilowatt
kWh	Kilowatt-hour
$LiCoO_2$	Lithium cobalt oxide
Li-ion	Lithium-ion
$LiFePO_4$	Lithium iron phosphate
$LiNiMnCoO_2$	Lithium nickel manganese cobalt oxide
NaS	Sodium sulfur
NiMH	Nickel metal hydride
Pb-acid	Lead acid
PCC	Point of common coupling
SOC	State of charge
UPS	Uninterruptable power source
V	Voltage
W	Watt

1 Introduction

An electric power system requires a steady balance between supply and demand to maintain nominal grid frequency. If balance is not sustained, frequency will deviate to either low or high frequency. A serious low frequency situation can result in a power outage, whereas high frequency can damage electric equipment. Frequency deviation caused by power and load fluctuation is closely associated with intermittent renewable energy sources e.g. wind and solar power due to their inherent variability. An ever more increasing share of renewable energy sources requires more flexibility from the power system. In the Nordic power system, the time of frequency deviation outside normal has been increasing over the few years, see Figure 1.

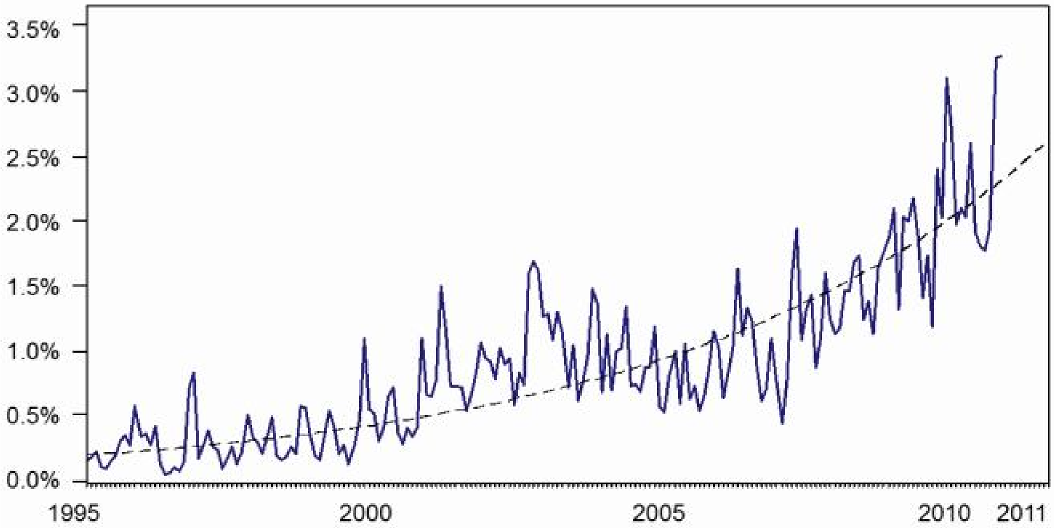

Figure 1: Evolution of frequency deviation outside 49.90 – 50.10 Hz at Nordic countries (ENTSO-E, 2013a)

Traditionally, interconnections of the power system and flexible power generation have been employed to meet the demand of flexibility. Today, customer side demand response is also becoming an attractive form of flexibility. Furthermore, energy storing has been developed to provide emission free flexible power generation. For a more detailed characterization of different balancing options see Appendix 1.

Nevertheless, storing energy is nothing new. Pumped hydro plants have been operating now for decades, but are geologically restricted. Also traditional lead-acid battery energy storages have been used, but their profitability has been questionable. However, energy storage technologies have improved considerably by new battery inventions e.g. lithium batteries, which has become the second most utilized storing medium after pumped hydro storage. Energy storages have become a hot topic of the power industry, and many expect energy storages to disruptively revolutionize the industry.

Helen Oy has been studying purchasing a utility scale battery energy storage system (BESS) as a R&D project in conjunction with Helen Sähköverkko Oy and Fingrid Oyj. Furthermore, this thesis is partly funded by the Cityopt project, which is a separate energy efficiency research project funded by the European Union.

1.1 The scope of thesis

This Master's thesis focuses on Finnish ancillary service markets held by Fingrid Oyj from the point of view of the battery energy storage operator. Different primary frequency control logics are studied by simulations and evaluated. The purpose of simulations is to verify applicability of a battery energy storage to studied ancillary service markets and to evaluate monetary compensation and profitability. Usability and availability of a battery energy storage is studied within the current primary frequency control market rules. Results of the simulations are used to propose better, and more suitable market rules for the battery energy storage. Furthermore, results are used to support the purchase decision of the Helen Oy's BESS.

1.2 Structure of the thesis

In chapter 2, Finnish electricity markets including ancillary service markets applicable for the utility scale energy storages are studied. Focus of the chapter is in the frequency containment reserve markets, which are particularly lucrative markets for a utility scale energy storages.

In chapter 3, battery energy storage system is presented. Chapter focuses on technology, utility applications, and utilization of battery energy storage system projects globally.

In chapter 4, CityOpt project is introduced. This thesis is partly funded by European Union's CityOpt project, which aim is to procure tools to simulate energy storages and energy efficiency for city planning. Business plan of the planned battery energy storage system is studied.

In chapter 5, Apros application and the model of the battery energy storage system is presented. This chapter describes principal model and how the simulations are conducted.

In chapter 6, frequency control simulations are conducted. Simulation results are compared and discussed.

In chapter 7, profit and cost model at ancillary services is studied.

In chapter 8, final results are presented and market models are discussed.

2 Electricity markets in Finland

There are two electricity market places for physical electricity trade in the Nordic countries – the Nord Pool Spot and the local transmission system operators' (TSO) markets. Trading is done by closed tendering, where supply and demand determine market prices. Nord Pool Spot has market places for day-ahead and intraday trading. In Finland, local TSO, Fingrid Oyj holds ancillary service markets. Figure 2 illustrate electricity markets in Finland.

Corresponding market depends on the application of the BESS. Nord Pool Spot markets trade energy, as opposed to Fingrid Oyj power markets. Currently, BESS's generally have very limited energy capacity, but high power discharge capability, therefore BESS is more suitable for power market, where discharging time is limited to seconds or minutes. Today, the most valuable markets in Finland for the BESS are deemed to be Fingrid Oyj's primary frequency control markets, which are studied in section 2.2.

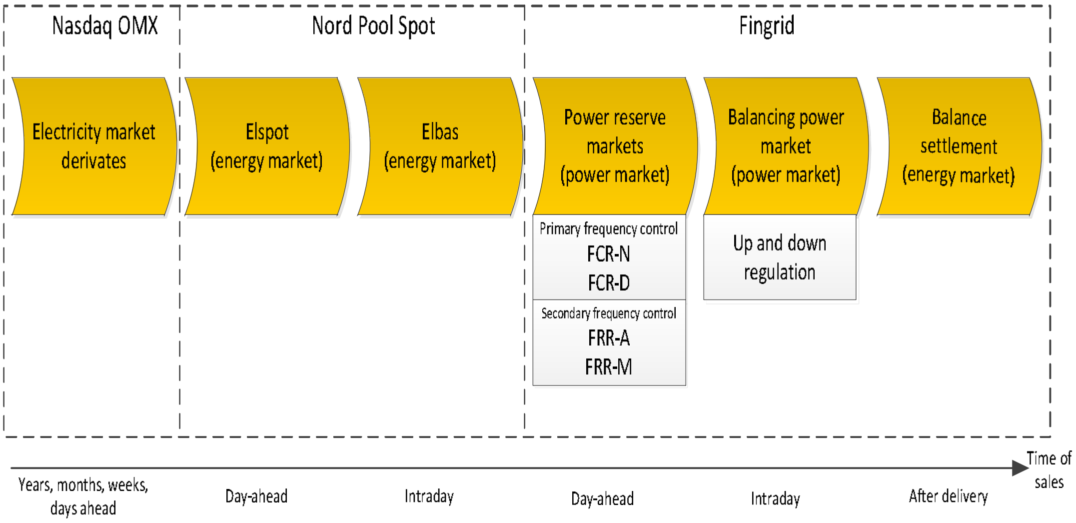

Figure 2: Electricity markets in Finland

2.1 Nord Pool Spot markets

Nord Pool Spot is the common electricity market in the Nordic power system. It is owned by the national TSO's: Fingrid Oyj, Energinet.dk, Statnett SF, Svenska Kraftnät, Elering, Litgrid, and Augstsprieguma tikls. Nord Pool Spot was established in the 90's in the wake of deregulation of electricity markets in Nordic countries. In the following years, Nord Pool Spot market area grow to include all Nordic and Baltic states. Today, Nord Pool Spot is the largest international power market in the world by all the trades accounted. (Nord Pool Spot, 2014)

2.1.1 Day-ahead Elspot

Most of the electricity trades in Nord Pool Spot are conducted in a day-ahead Spot market. Spot market is based on open auctions. The auction takes place each day for every hour of the day. The auction closes in Finland at 13:00 GMT +2 and market price is announced at 13:45. (Nord Pool Spot, 2014)

Transmission line capacities affect to different area prices, since production and demand doesn't always match geographically. Area price integration varies greatly from year to year due to inadequate transmission line capacities and transmission faults. For example, in 2008, area price of Finland and Sweden was the same in 98 % of all hours, but in 2012, only 53 %. (Fingrid, 2014a)

2.1.2 Intraday Elbas

Intraday Elbas market operates continuously and it is possible to trade electricity until 45 minutes prior to actual trading hour. The Elbas can be also utilized as an aftermarket for already bought or sold spot electricity. The Elbas is more flexible market place than the Elspot market, as participants can for example sell weather dependent wind power more accurately. The Elbas market volume is growing, and will probably become much more important market place in future due to increasing renewable power generation.

2.2 Fingrid Oyj held ancillary service markets

Fingrid Oyj is responsible for the stability and the security of the power system in Finland. Fingrid Oyj carry out its statutory responsibilities by providing competitive market places for the ancillary services. Different definitions of ancillary services exist, but commonly accepted definitions of ancillary services are:

- Frequency control (primary control, secondary control, tertiary control)
- Voltage support
- Compensation of active power losses
- Black start

In Finland, ancillary services markets held by Fingrid Oyj are: power reserve market, balancing power market, and balance settlement market, see Figure 2. Balance settlement market is for utilities to correct imbalances of electricity trades.

Balancing power market include separate up- and down- power regulation. In up-regulation, bidder sells power to Fingrid Oyj by producing power or reducing consumption. In down-regulation, bidder reduce power production or increase consumption. Block size of a bid for the balancing power market is 10 MW, which can be aggregated from multiple sources and has to be available in 15 minutes. Balancing power market is traded throughout the day, which requires constant monitoring and participation.

Power reserve markets are divided to Frequency Containment Reserves (FCR) and Frequency Restoration Reserves (FRR). FCR is used for primary frequency control and FRR as a secondary control to relieve FCR sources. Frequency containment reserves are activated continuously, but FRR only very rarely. Frequency Containment Reserves holds Frequency Containment Reserve in Normal operation (FCR-N) and Frequency Containment Reserve in Disturbance (FCR-D). FCR-N and FCR-D are explained more detailed in sections 2.2.1 and 2.2.2 respectively. FRR-M is a manual reserve type, which is activated by the request of Fingrid Oyj. FRR-A is a new reserve type, which is maintained only at morning and evening peak hours. In Figure 3 is illustrated frequency control process. Table 1 presents reserve power obligations for Finland in 2014.

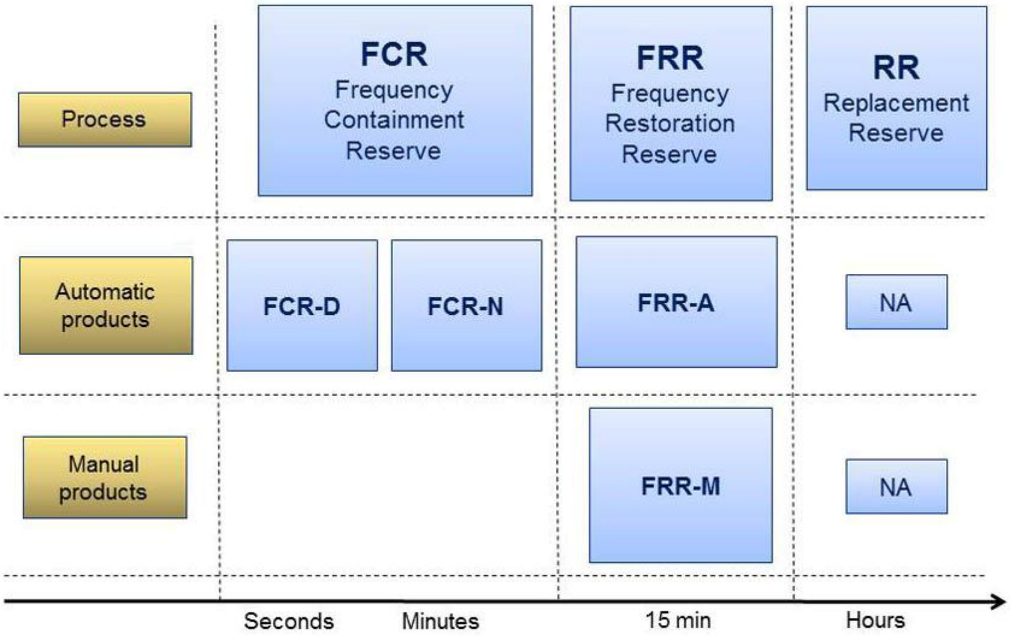

Figure 3: Frequency control process of power reserve markets (Fingrid, 2014b)

Table 1: Reserve obligations for Finland 2014 (Fingrid, 2014c)

Reserve product	Obligation
Frequency Containment Reserve for Normal operation (FCR-N)	about 140 MW
Frequency Containment Reserve for Disturbances (FCR-D)	about 260 MW
Automatic Frequency Restoration Reserve (FRR-A)	about 70 MW (maintained only at morning and evening hours)
Manual Frequency Restoration Reserve (FRR-M)	about 880 MW (dimensioning fault reserve)

2.2.1 Frequency Containment Reserve in Normal operation (FCR-N)

FCR-N is used to stabilize power system’s frequency between normal band of 49.9 Hz and 50.1 Hz. In the Nordic power system, FCR-N is required to be controlled symmetrically up and down, hence injecting power or consuming power. Minimum bid size is 0.1 MW and the power has to be fully activated in 3 minutes after the frequency step of ±0.1 Hz. The Deadband is set between 49.95 and 50.05 Hz, however European Network of Transmission System Operators for Electricity (ENTSO-E) is planning to reduce the deadband to ±10 mHz, effectively bringing the deadband between 49.99 and 50.01 Hz (ENTSO-E, 2013b: 7).

This might have implications to the economic viability of a BESS due to higher activation times, which would lead to greater energy losses and faster battery degradation. However, market value of service might increase correspondingly. In Figure 4 is presented current FCR-N control curve.

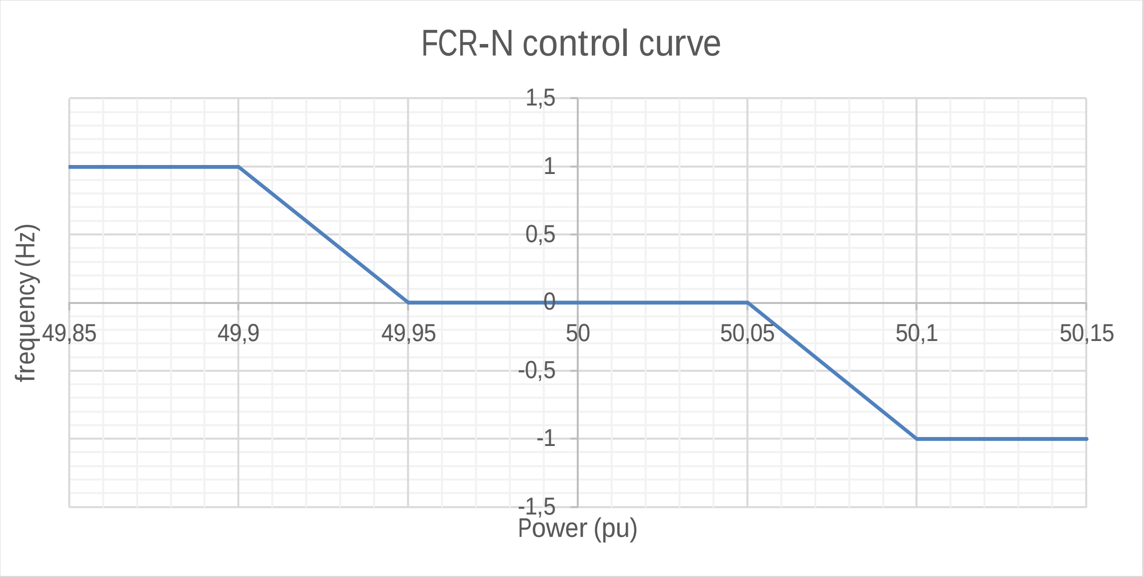

Figure 4: FCR-N control curve

2.2.2 Frequency Containment Reserve in Disturbance (FCR-D)

FCR-D is activated in serious frequency deviation. Activation time depends on participating resource, see Table 2. Due to the lack of grid code, it is uncertain how a BESS should be considered in the FCR-D market. Minimum bid size of FCR-D is 1 MW, which can be aggregated from multiple sources.

Table 2: FCR-D market rules for different resources (Fingrid, 2014d)

Resource	Full activation time	Other
Power plant reserves	5s / 50 % 30s / 100 %, with frequency 49.50 Hz	
Relay-connected loads	Immediately with frequency 30s ≤ 49.70 Hz or 5s ≤ 49.50 Hz	Load can be reconnected to grid, when frequency is at least 49.90 Hz for five mins
Idle reserve power machines	Reserve should be activated, when frequency 30s ≤ 49.70 Hz	Machine can be disconnected from grid, when frequency is at least 49.90 Hz for five minutes

In Figure 5 is presented FCR-D control curve with the activation at 49.70 Hz. The control curve illustrate ideal control, which can only be achieved by a disconnectable load or very fast ramping BESS.

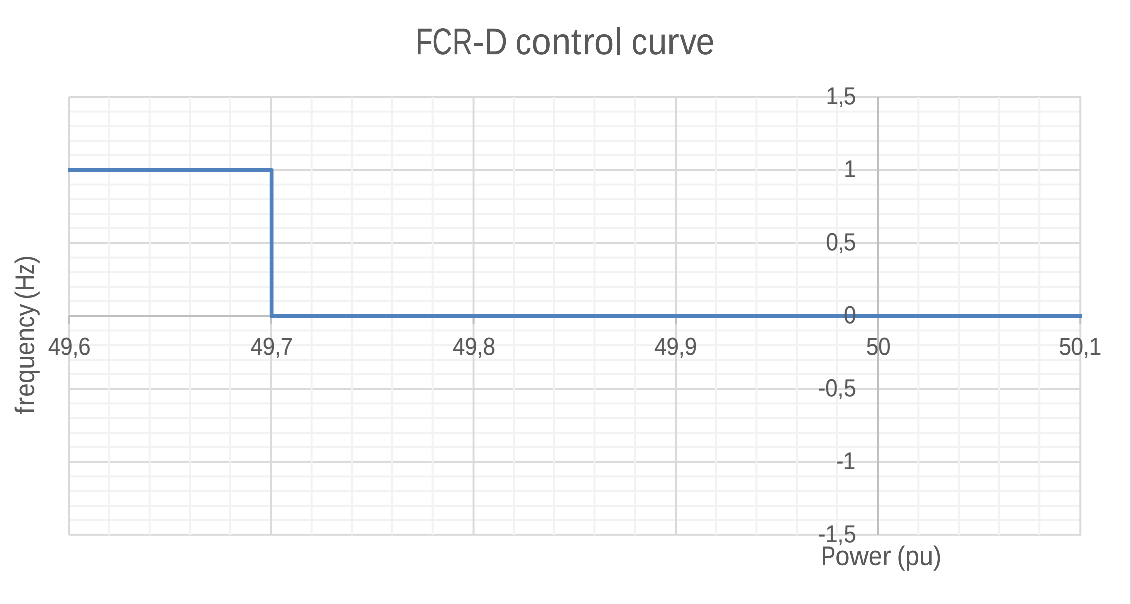

Figure 5: FCR-D control curve

2.2.3 FCR market size and value

In Finland, approximately 85 % of the FCR-N and 90 % of the FCR-D is produced by the hydropower. Therefore hydropower dominates FCR markets, with the greatest share of the market. Competing against the hydropower is very difficult due to cheap power production capabilities of the hydropower. Where the hydropower can theoretically generate power without any marginal costs, battery energy storage has to take account energy losses and battery wear. On the other hand, hydropower is mostly built already, and capacity can’t be increased significantly anymore.

FCR market size and value is affected mainly by (Pöyry, 2014):

- Electricity production mix
- Interconnections
- Customer side demand response
- Market rule changes

FCR market trading is done by yearly contracts and hourly auction bidding. The great majority of the trading is done as yearly contracts. In Table 3, yearly contract FCR market size and value is presented. Yearly market price at FCR markets has steadily risen, however the prices are considerably lower than hourly markets, as seen later, and therefore are not attractive for expensive battery energy storages.

Table 3: FCR yearly contracts market size and value (Data: Fingrid)

	FCR-N price (EUR /MW)	FCR-N market size (MW)	FCR-D price (EUR /MW)	FCR-D market size (MW)
2011	9.97	71	1.48	244.3
2012	11.97	72.7	2.80	346.9
2013	14.36	73.5	3.36	299.8
2014	15.80	75.4	4.03	318.7
2015	16.21	73.6	4.13	297.5

In Appendix 2, hourly auctioned FCR market values for 1 MW between years 2011 and 2014 are presented. However, if the Fingrid Oyj bought less capacity than 1 MW, it is still calculated as 1 MW bought, thus following tables give slightly erroneous market values. In Appendix 2, the seasonal market value variation of FCR markets is clearly visible, where in the summer months the market values are much higher compared to the winter months.

In Tables 4 and 5 are listed yearly average market sizes, average prices, and total market values of FCR hour auctions.

Table 4: FCR-D hourly market size and value (Data: Fingrid)

FCR-D	Avg. market size (MW)	Avg. market price (EUR/MW)	Total market value (EUR)
2011	6	16.94	890 000
2012	2	6.02	105 000
2013	11	23.38	2 253 000
2014	6	7.98	419 000

Table 5: FCR-N hourly market size and value (Data: Fingrid)

FCR-N	Avg. market size (MW)	Avg. market price (EUR/MW)	Total market value (EUR)
2011	2	14.94	262 000
2012	7	30.41	1 865 000
2013	10	36.33	3 183 000
2014	15	31.93	4 196 000

As seen from the market data, hourly FCR markets have much higher value than yearly contracts. FCR-N has also a much higher value than FCR-D, therefore making it more viable for the BESS in terms of absolute monetary compensation. Market size is however relatively small, see the hourly average size of 15 MW for FCR-N in 2014. This implicates, that only a few megawatt-size BESS is enough to fulfill the market requirement and can cause market saturation, in other words, cannibalize mutual market share.

This is the single most problematic factor in the Fingrid's hourly auctioned FCR-N market, as a low market size possess obvious market risk.

It is also important to note, that hourly auctioned FCR markets have considerable high amount of zero value hours, when Fingrid Oyj does not purchase capacity from the hourly markets. These hours could be potentially used for other markets. However, zero value hours are only known after bid closing, day before actual hours. One of the Cityopt project aim is to study multiuse and multiuser case use of a BESS, and zero value hours of FCR-N market are particularly interesting from the point of view of multiuse.

In Figure 6 is illustrated FCR-N hour price distribution in 2014. Approximately 30 % of the hours had no value. Median price was 23.80 euros, shown in red vertical line. Highest price was 520 euros. If a BESS operator participates FCR-N market and price margin is set to median price due to marginal costs, the BESS will be operating only at half of the hours in a year.

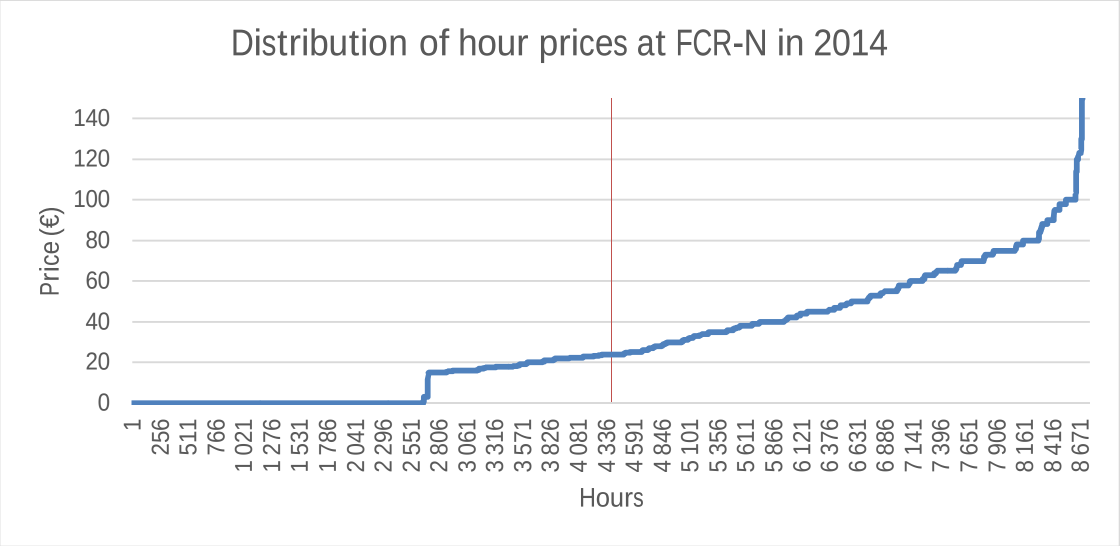

Figure 6: Distribution of hour prices at FCR-N in 2014 (Data: Fingrid)

3 Battery energy storage systems

Battery Energy Storage System or BESS is a type of energy storage system, which stores energy and injects energy back to grid when needed. Electricity cannot be stored in the power system without medium, and in the case of BESS, the medium is the electrochemical battery. This thesis focuses on electrochemical battery operated storage systems, but also other energy storage systems will be introduced in the section 3.1 below. All energy storages generally have similar components except the storing medium. Different types of batteries will be introduced in the section 3.3.1. Other components of the BESS will be introduced in sections 3.3.2, and 3.3.3. Utility applications of the BESS will be introduced in section 3.5 and a few example BESS projects are introduced in section 3.6.

3.1 Benefits of Energy storage systems

Energy storage systems (ESS) have a direct effect on power quality and power reliability. ESS can reduce energy losses of the grid, and increase availability and efficiency of other energy sources. Also, ESS can have an investment deferral potential e.g. reducing transmission line investments, if technology becomes more common in the power system.

Fast response time of ESS enable effective compensation of fluctuating renewable power generation such as wind and solar generation. ESS can be seen as a direct replacement for rapid response fossil fuel fired generators. Rapid power ramp rate of ESS can outmatch conventional power generator capabilities without direct emissions. Furthermore, battery energy storage doesn’t have any geographical restrictions. The difference of fast ramping capable resource can be seen in Figures 7 and 8. In Figure 7, the power delivery of fast ramping resource greatly exceeds the slow ramping resource.

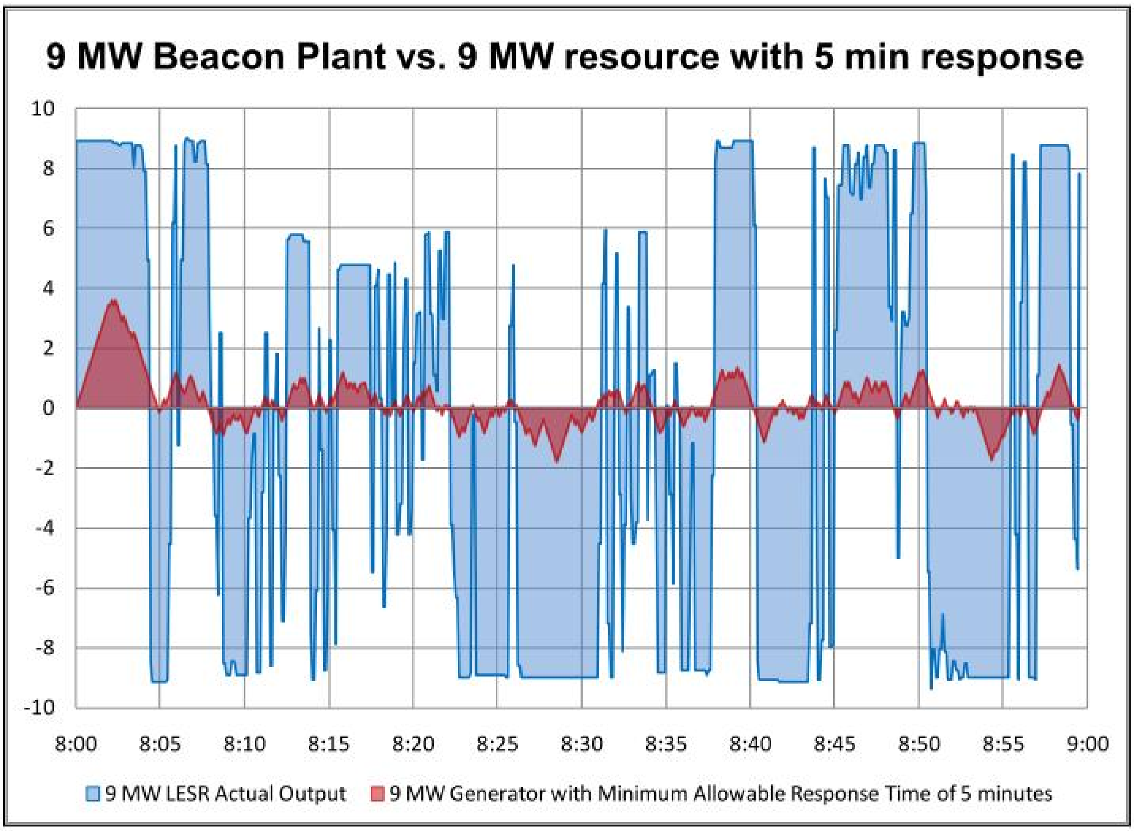

Figure 7: Difference of fast response ramping and slow ramping power (ESA, 2011: 9)

In Figure 8, FCR-N ramp time requirement is 3 minutes to full power, at which time 1 MW fast ramp up capable resource has generated 50 kWh, which is twice as much energy as compared to the slow ramp rate's 25 kWh.

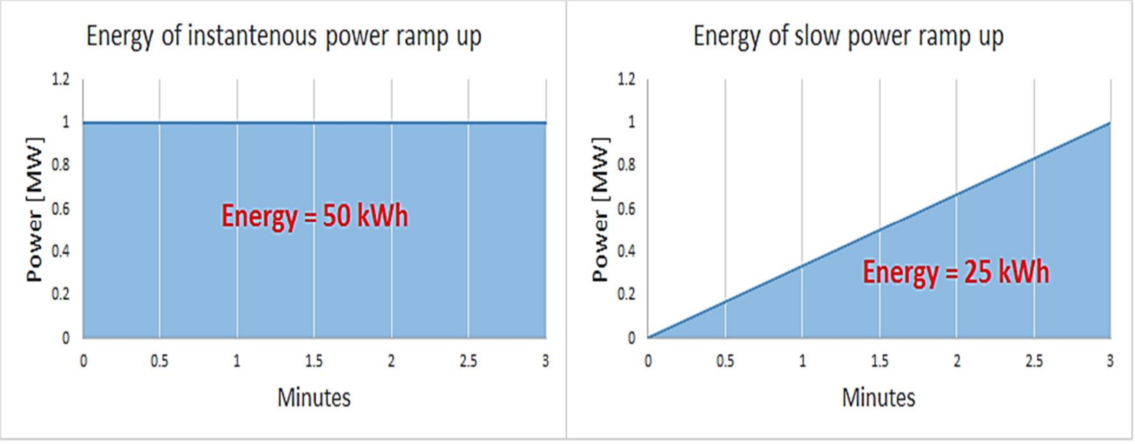

Figure 8: Energy output difference of fast ramping and slow ramping resources

It is clear that the fast ramping resources contributes much more to frequency regulation than the slow ramping resources. This difference is not currently taken into account in the Nordic frequency regulation markets.

3.2 Energy storing technologies

The seven major energy storage system technologies include (Corey and Eyer, 2010: 11), also see Appendix 3:

- Electrochemical batteries, including Flow batteries
- Capacitors
- Compressed Air Energy Storage (CAES)
- Flywheel Energy Storage
- Pumped Hydroelectric
- Superconducting Magnetic Energy Storage
- Thermal Energy Storage

Different technologies can be classified to **power** and **energy** applications (Corey and Eyer, 2010: 21). Power application is capable of producing large amount of power for a shorter period of time. Energy application produces less power, but for a longer period of time. Capacitors and flywheels are good examples of power applications, as they excel in generating power, but lack serious energy capacity. On the other hand, CAES and pumped hydroelectric have generally very high energy capacity, where only limiting factor for the pumped hydro is the size of water pool, and for the CAES; the underground geologic cavern or tanks.

Technologies can be further classified between **energy** and **capacity** applications (Corey and Eyer, 2010: 22). Capacity applications are seen as onetime investments for reducing other necessary equipment investments. Capacity application can be for example uninterruptable power source (UPS) type of equipment, which is required in many applications, but is activated rarely. Energy application discharges large amount of energy during the year, whereas capacity application might not be activated at all.

Different technologies can be compared further by: energy and power densities, response time, reactive power capability, round-trip efficiency, storage losses, charge-discharge lifetime, and costs. For example, power converters for electrochemical batteries are capable of generating reactive power. Thermal energy storages have high storage losses due to heat conduction, and pumped hydroelectric due to water evaporation. Also, lifetime of pumped hydroelectric is practically unlimited as electrochemical batteries have generally lifetime less than 10 years. Different technologies have also different fixed and variable costs. Pumped hydroelectric can be expensive to build, but offers cheap operational costs. Electrochemical batteries have a limited lifetime, which increase operating costs considerably.

3.3 Basic layout of the BESS

In Figure 9 below is presented basic layout of the BESS. The main components are battery, power converter, transformer, controller, and battery management system. Many equipment manufacturer prefer shipping containers as the structural basis. Shipping containers offer flexibility for the system design and easy transportability. Ready built system also minimize works on-site.

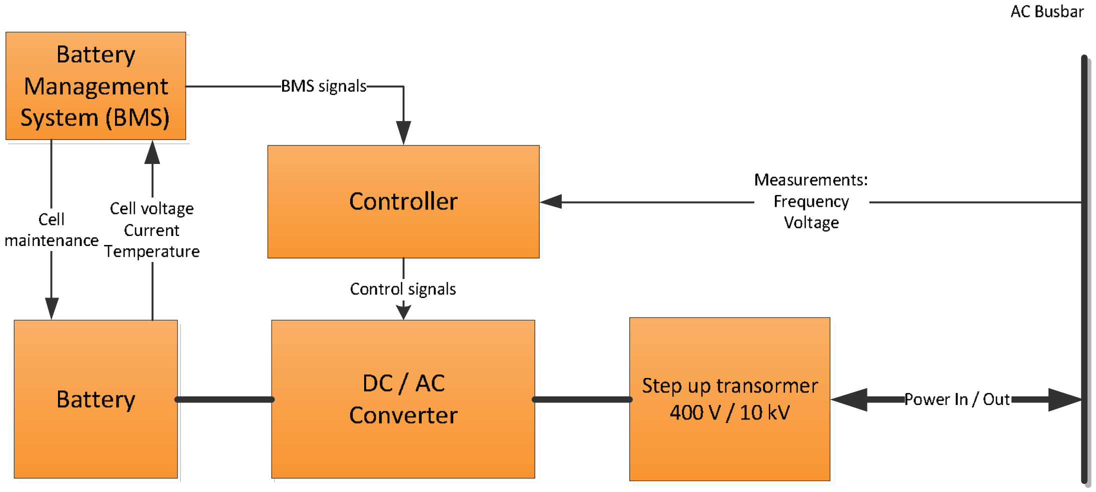

Figure 9: Layout of the BESS

The battery block describes not the individual battery cell, but all the battery cells in a battery pack. Battery packs usually consist of many cells in different configurations. Required voltage level can be achieved by connecting multiple cells in series, and capacity by connecting cells in parallel.

The battery is connected to the power converter, which acts as an inverter when discharging and as a rectifier when charging the battery. Converter is connected to a step up transformer, which transforms low voltage to high voltage and vice versa. Very large systems usually consists of multiple converter modules and transformers.

Battery Management System (BMS) is connected to the battery and controller. BMS monitors each cell and maintains them if necessary. Controller has the logic of the BESS and controls the converter by the defined algorithm.

3.3.1 Batteries

The oldest and the most well-known battery is the lead-acid (Pb-acid) battery. Other more recent batteries are nickel-metal hydride (NiMH), nickel-cadmium (NiCd), sodium-sulfur (NaS), redox flow batteries (RFB), and lithium-ion chemistries such as lithium cobalt oxide ($LiCoO_2$), lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$ or NMC) and lithium iron phosphate ($LiFePO_4$ or LFP).

Traditional uninterruptable power sources mostly rely on proven Pb-acid batteries. Pb-acid batteries are relatively cheap and easy to use, but they are inherently toxic, heavy and have a short lifetime. Pd-acid batteries are highly widespread and used in many applications, including energy storages (Chen et al. 2009: 297).

NiMH batteries were used in portable consumer electronics and are now displaced by newer li-ion batteries. Toyota used NhMH batteries in Prius hybrid car until year model of 2015, which is using li-ion batteries.

Sodium-sulfur or molten salt battery has a high energy density, high charge-discharge efficiency and long cycle life. Therefore sodium sulfur battery is an attractive battery type for grid storage, but it has few distinctive down sides. Molten salt requires high operating temperature (300 – 350 °C) and is highly corrosive, thus usability of sodium sulfur battery is greatly reduced. Pure sodium presents also a fire hazard. (Rastler, 2010: 4-9)

Vanadium redox (reduction-oxidation) battery or VRB is an electrochemical system, in which energy is stored in two liquid electrolyte solutions. Electrolytes are pumped separate of each other. Circulation of solutions is closed and reversible. The VRB has a long cycle lifetime – up to 12000 and it is very safe, and can be reused and refueled. On the other hand, the VRB has a low energy density. The VRB is easily scalable and becomes more economical by scale. (Bolton et al, 2012: 21)

Li-ion has become the most common battery type in cell phones and in small electronics. Today, li-ion cells are also used in electric cars. Li-ion batteries have high energy and power density, long lifetime, and low self-discharge. Li-ion batteries have improved gradually and are becoming cheaper and more viable in grid storage application. Downside of some lithium-ion battery chemistries is their susceptibility to thermal runaway and in extreme cases to combustion, if the cell is short circuited, overcharged or ruptured. A major advantage of li-ion is its versatility. It can be adapted to variety of different voltages and capacities. The three most common li-ion chemistries are presented below (Buchmann, 2014a):

- $LiCoO_2$
- $LiNiMnCoO_2$
- $LiFePO_4$

$LiCoO_2$ is mostly used in consumer electronics. It has the highest power and energy density of listed lithium batteries. On the other hand, it is the most volatile battery and require high safety caution. Lifetime is also shortest of listed cell chemistries.

$LiFePO_4$ has the lowest energy and power density. It is inherently much safer and contains no cobalt, which is fairly expensive material. $LiFePO_4$ has the longest lifetime, thus would be well suitable for a BESS.

$LiNiMnCoO_2$ properties are somewhere between $LiCoO_2$ and $LiFePO_4$. It has a longer lifetime, but lower energy and power density than $LiCoO_2$. It is also less volatile, therefore being safer chemistry than $LiCoO_2$. Many auto manufacturers are using $LiNiMnCoO_2$ chemistry in electric vehicles. This type of battery is used in electric cars, such as Nissan Leaf and Chevrolet Volt.

C-rating of a battery is comparison of Ah capacity and charge or discharge current. If a battery rated at 100 Ah is discharged at 1C, the battery current would be 100 A and the battery would be fully discharged in one hour. Similarly, if a discharge rate is 0.5C, the battery would be fully discharged in two hours. Lithium batteries are typically C-rated between 2C and 10C. The C-rate is a very important attribute in designing the battery capacity and the power of the BESS. (Buchmann, 2014b)

Typical end-of-life of the battery is determined to be at the capacity of 80 % of the initial capacity while fully charged. Life expectancy of lithium batteries has been studied extensively, but it is very difficult to accurately predict life of battery due to many effecting factors. There are however few factors found to effect battery life, which are (Xu, 2013: 5):

- C-rate

- State of charge (SOC)
- Depth of discharge (DOD)
- Battery temperature
- Time

High C-rate effect on current throughput, therefore leading to higher voltage sag and battery temperature. High SOC denote high open terminal voltage, which reduces battery life. High DOD denote to deep discharge and low open terminal voltage. High battery temperature is found to degrade batteries significantly as well. Also time degrades batteries gradually, which is defined as a calendar age.

3.3.2 Battery Management System

Typically, Battery Management System (BMS) is used to monitor, compute and protect li-ion batteries (Buchmann, 2014c). BMS is a common system included in li-ion batteries. High quality li-ion batteries under normal quality control and in normal operation don't cause battery fires, but using them outside their normal operation voltage and temperature can cause damage, and in worst case – fire. Task of BMS is to protect batteries and ensure safe operation of the BESS. However, BMS is probably the most critical part of the system and many battery faults can be traced to a faulty BMS.

The most typical and simplest use of BMS is to monitor cell voltages. Cell voltage monitoring is used to avoid over and under voltage situations during charging and discharging. Charging and discharging of li-ion batteries cause heat. Some battery types are more sensitive to low and high temperatures, therefore BMS is used to monitor temperature of the cells as well.

Computational features can include calculations of: internal impedance, charge-discharge cycles, operational time, and coulomb counting. Coulomb counting is used to determine SOC, but can be inaccurate in constant use. BMS can be very sophisticated system, which actively balances cell voltages of different battery cells, thus preventing local under or over voltages.

3.3.3 Other components

In addition to batteries and BMS, a typical BESS has the following main components:

- Power converter
- Transformer and switchgear
- Controller

A BESS can have multiple power converters and transformers depending of the size and design of the BESS.

Batteries are inherently direct current (DC) equipment, but on the other hand, power grid is operating on alternating current (AC). A bi-polar power converter is required to invert AC waveform to DC and rectify DC to AC. The power converter either charges or discharges battery. The power converter can also generate and consume reactive power, therefore supporting voltage level of the point of common coupling (PCC).

Utility scale BESS's connects to a medium or high voltage power grid, therefore transformer is required. Transformer converts AC electricity voltage to a desired level between a power converter and a power grid. The size of a transformer used between low voltage power converter and high voltage power grid depends on the power level of the BESS.

Controller is the interface between the user and the BESS. Controller takes inputs from user, BMS, and from various measurements. Controller has the logic of the converter. Usually, controller is integral part of the converter.

3.4 Efficiency

Efficiency of the BESS can be important aspect of the monetary compensation. Energy losses of the equipment turn to excess heat, which has to vent out by air conditioning. Losses of the system can be traced to individual components, such as batteries, converters, transformer and other auxiliary components. Electricity of the losses and the electricity required by the auxiliary components has to be bought, either from the wholesales markets or the retail markets depending on the operator and regulation rules. In a study of similar power level BESS as the one proposed to Kalasatama, found the round trip efficiency to be 84 % in frequency regulation (Schmutz, 2013: 36).

3.5 Utility applications of the BESS

Applications for the BESS can be divided to utility applications and customer side applications. Customer side applications are: peak shaving, time of use cost management (load shifting), and off-grid supply (EUROBAT, 2013). Peak shaving and load shifting can be described as customer side demand response. Utility applications are related to power generation, transmission and distribution systems. Utility applications are generally speaking ancillary service applications, which are: frequency regulation, spinning reserve, voltage support, and black start. Many sources also include investment deferral as a utility application. Off-grid supply application is not investigated in this thesis due to the qualitative nature of it. Below is list of applications which are studied, but only frequency regulation is simulated and studied more detailed.

- Frequency regulation
- Spinning reserve
- Voltage support
- Peak power shaving (arbitrage)
- Load leveling
- Island grid
- Black start

3.5.1 Frequency regulation and spinning reserve

The frequency regulation is done with spinning reserve and supplemental reserve, which is not connected to the power system, but can be brought in use relatively quickly. The concept of "spinning reserve" can be confusing as rapid response capable generation is generally called spinning reserve. Although, BESS is not really "spinning", but it can ramp up power production in matter of milliseconds and thus could be referred as spinning reserve.

Fingrid Oyj held FCR-N and FCR-D markets are regarded as a primary frequency control markets. Fast ramp rate capable BESS will easily comply with today's market regulations regarding ramp rate, see section 2.2 of FCR regulations. Once dedicated to the day-ahead FCR markets, operator of the BESS must comply with the given bid, thus simultaneous operation at different markets might not be possible. However, it is possible to bid for both FCR markets, but operator of the BESS must then reserve energy capacity for the FCR-D accordingly. Although it is possible to participate FCR-D market, it is probably not economically viable nor will it be in near future due to low market value of the FCR-D market, see section 2.2.3.

As the FCR market rules doesn't recognize battery energy storages explicitly, Fingrid Oyj has made a set of rules regarding energy storages. To be able to participate FCR markets, Fingrid Oyj requires a BESS to be able to operate 15 minutes at 2C power rating in FCR-N and 30 minutes at 2C in FCR-D. Therefore, time requirement and 2C determine the minimum capacity in relation to power rating. Optimal investment size would be exactly 2C, as higher C-rating is not required. For example, to be able to provide 1 MW power, the system has to have at least 500 kWh energy capacity.

3.5.2 Voltage support

The aim of voltage support is to minimize active power losses and maintain voltage stability in the power system. If the power system encounter voltage sag, increased current flow is required to maintain power. Increasing current amplify reactive power consumption, therefore lowering voltage further. High current can overheat power lines tripping them. Voltage sag may also force some generators to disconnect to protect themselves, as a consequence situation may lead to cascading failures. (Parmar, 2011)

Voltage support is traditionally produced by static VAr compensators and synchronous generators capable of generating reactive power. In a case of BESS, the BESS is capable of producing and controlling reactive power generation accurately, thus supporting adequate voltage level. Reactive power is produced by switching solid-state power electronics similarly as in static synchronous compensator devices. It is also beneficiary to have a distributed compensation near the load centers, since reactive power is not required to be transmitted over long distances.

In Finland, Fingrid Oyj as a TSO is required to maintain voltage stability. Distribution system operators are liable to compensate reactive power locally. Each DSO has a specific window of reactive power, in which one has to stay within. If DSO's are not able to fulfill this requirement, they have to pay Fingrid Oyj for the compensation.

In the beginning of 2016, Fingrid Oyj is planning to reform reactive power compensation costs (Kuronen, 2014:16). The reactive power cost of 1000 EUR/MVAr for consuming reactive power and 1500 EUR/MVAr for injecting reactive power per month has been proposed. Tariff of 5 EUR/MVAr in an hour of uncompensated reactive power is also added to the total cost. The total monthly cost of reactive power compensation is calculated by highest exceeding hourly average reactive power plus the tariff of MVAr-hour consumed or injected during the month.

It is possible to assess the value of a BESS in reactive power compensation by comparing costs of similar reactive power compensation capable equipment, such as shunt reactor and series capacitor. The value of injected reactive power is higher than consuming reactive power due to the higher cost of compensation reactor compared to compensation capacitor. If a BESS is capable of generating and consuming 1.0 MVAr of reactive power, it should be able to replace that amount of other compensation equipment. Comparable investment value of a BESS (V_{BESS}) for reactive power compensation is calculated in Equation 1.

$$V_{BESS} = Price\ of\ compensation\ capacitor\,\frac{[\mathrm{EUR}]}{[MVAr]} + Price\ of\ compensation\ reactor\,\frac{[\mathrm{EUR}]}{[MVAr]} \quad (1)$$

Price of compensation equipment may vary according to equipment producer and type, but one price estimate for capacitor is 20 000 EUR/MVAr and for reactor 50 000 EUR/MVAr (Pihkala, 2015). Therefore Equation 1 gives investment value of 70 000 EUR for the reactive power compensation.

However, generation of reactive power compensation is proportional to the ratio of active power generation, thus availability of the reactive power compensation varies. If the frequency regulation is used as a primary control, availability of the reactive power compensation can be measured by comparing instantaneous frequency deviation with the converter's PQ-diagram. Figure 10 illustrates a converter of 1 MVA capable of generating 0.8 per unit of reactive power. This translates into 800 kVAr of reactive power if no active power is generated simultaneously.

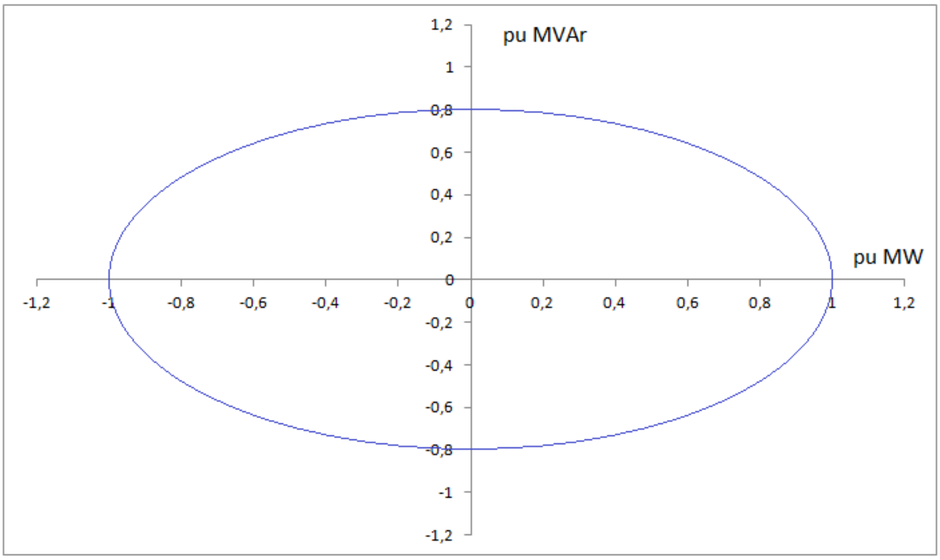

Figure 10: PQ-diagram of the converter

3.5.3 Peak power shaving and load leveling

Peak power shaving or energy time shift (Corey and Eyer, 2010: 53) has two purposes. Operator of the BESS can benefit from arbitrage at spot energy market by buying cheap electric and selling when the price is higher. In the Nord Pool Spot, the price of electricity is usually low at nights due to low demand, and high at the peak power hours. The other possible way to benefit is to reduce momentary peak power as utilities bill by the peak power load. Peak power is used to determine power systems' capacity investments, therefore peak power effects on system investments. Reducing peak power has an effect on power system investment deferral. Literature also lists transmission congestion relief as a benefit of peak power shaving, reducing price differences between different areas. Optimal location of the BESS would be in this case at the higher price area. (Bray et al. 2012: 6)

Power system investment deferral benefits DSO's and TSO, but not directly electricity wholesales utility companies. Business model of multiuser R&D project is discussed in chapter 4. Figure 11 illustrate peak power shaving, in which charging is done at the lower utility rate and discharging at the peak hours.

Concept of load leveling is closely related to peak power shaving. Load leveling is the ideal situation, where energy capacity and power of the BESS is enough to level the instantaneous load to an average load. Load leveling is illustrated in Figure 12. Monetary benefits of the peak power shaving and the load leveling are:

- Energy arbitrage
- Reduction of peak power transmission charges
- Cost savings due to reduced peak power generation
- Investment deferral

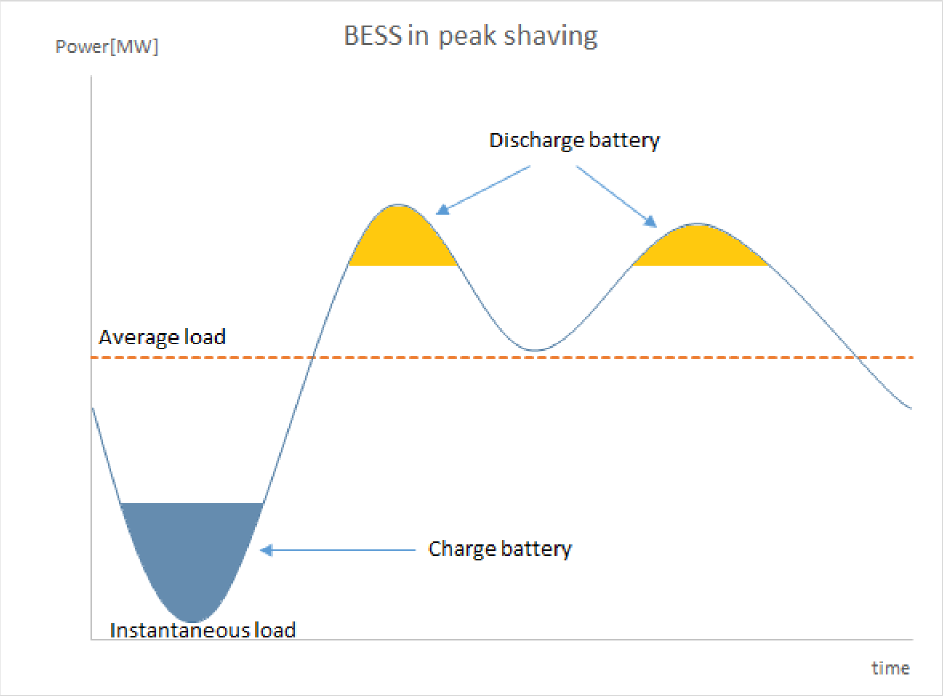

Figure 11: BESS in peak shaving

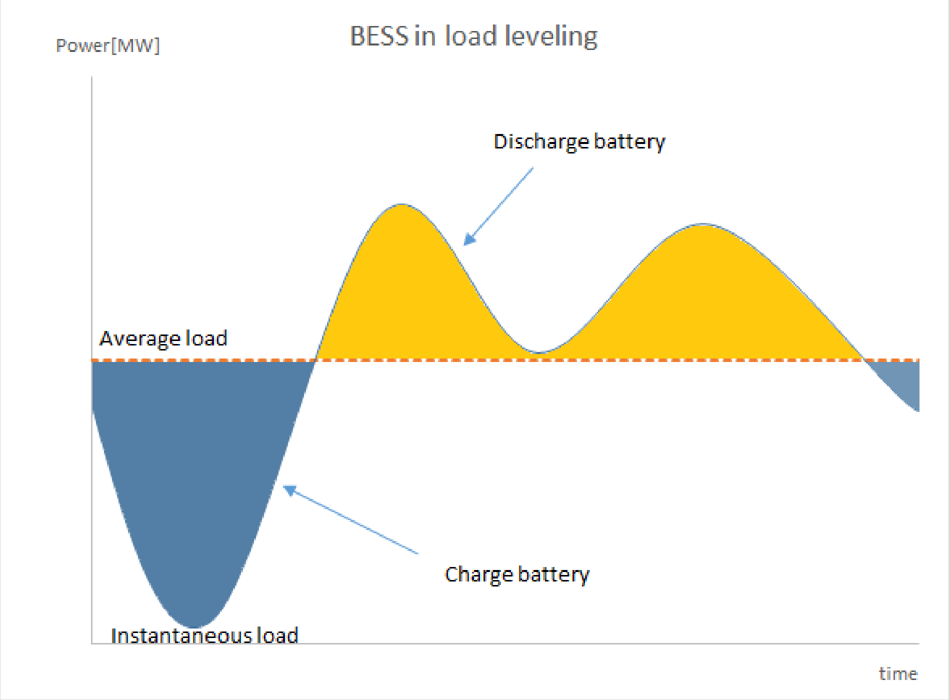

Figure 12: BESS in load leveling

Helen Oy had a public competition to make an open source optimal demand response algorithm for the BESS in hourly wholesale electricity i.e. spot markets. The principality was to buy low and sell high. The BESS was defined to have a capacity of 1000 kWh and sales markup of 20 %. Winning algorithm generated a meager profit of 11 000 euros and charge-discharge cycled about 500 times using the Finnish area price data of 2014. In this demand response use, batteries would degrade in a matter of few years. Obviously, an expensive BESS with a limited cycle-life and a capacity of 1000 kWh would never had a payback time in such application.

3.5.4 Island grids

Operation in an islanding is rarely required, but UPS's are designed to upkeep vital systems, such as telecommunications, data centers and hospital equipment. Islanding operation is normally denied by the DSO's, due to dangers associated, thus distributed generation is required to cut power in case of blackout. In cases, where operation in islanding is allowed, a BESS could be used in long duration low voltage ride through and act like a UPS.

In the island of Metlakatla, the BESS is used to reduce the use of diesel generator directly (DOE, 2014). This meant considerable savings in fuel during the operational years. The value of islanding operation of a BESS should be calculated case by case, and thus is not studied further in this thesis.

3.5.5 Black start capability

If a blackout occurs in the power system, system operator begin repairs and gradually restore power. Typically, synchronous power generators are not capable of producing black start power due to lack of synchronizing power. Black start capable generators produce this synchronizing power, of which synchronous generators synchronize. Generally speaking, power electronics of the BESS are capable of producing black start power, of which other generators can synchronize. Though, total system blackout is very unlikely in Finland, thus the black start capability is seen less useful. However, black start capability is inherently available in the planned Kalasatama BESS, but it is not studied further in this thesis.

3.5.6 Overview of applications and markets

In Table 6 is categorized different applications to corresponding market places and market requirements for a quick review.

Table 6: Overview of applications and markets

				Ancillary service markets			
		Peak power shaving	Load leveling	Frequency control	Black start	Voltage support	Market requirements
Nord Pool Spot	Elspot	X	X				Produce or consume energy
	Elbas	X	X				Produce or consume energy
Fingrid markets	Balancing power			X			Produce or consume power for one hour
	FCR-N			X			Produce and consume power for 30 minutes
	FCR-D			X			Produce power for 30 minutes
	FRR-A/M			X			Produce or consume power for one hour
	Bi-lateral deals				X	X	

3.6 *Overview of global BESS projects*

In this section, a few notable BESS projects are introduced. These projects were chosen to give a broad view of BESS technologies and applications used.

The United States Department of Energy (DOE) hosts a database service, where all the known BESS projects in the world are represented. Table 7 below illustrates how different BESS technologies are employed world-wide in 2014 (DOE, 2014). Sites include all operational, under construction, contracted, and announced projects. List also include small, non-utility scale BESS's. However, this table should only be used as an estimate, because of variances in values e.g. duration at rated power varies and other possible inaccuracies at the DOE database. The DOE database implies, that the frequency regulation application is the dominating use case for the majority of the utility size battery energy storages.

Table 7: Comparison of different technologies used world-wide until 2014 (DOE, 2014)

Technology	Sites	Rated power (MW)
Li-ion	326	643
Sodium-sulfur based batteries	57	153
Pb-acid	52	88
Vanadium redox flow	64	75
Pumped hydro [1]	336	175 000

[1]Non-electrochemical

3.6.1 Golden Valley Electric Association (NiCd), USA

Golden Valley Electric Association (GVEA) implemented in 2003 world's most powerful BESS in Fairbanks, USA. The BESS is capable of producing 26 MW for 15 minutes or 40 MW for 7 minutes. ABB supplied converters and control electronics, and SAFT supplied NiCd batteries. The BESS contains 13760 individual SAFT SBH 920 NiCd battery cells. Batteries weigh some 1300 tons total, and the BESS facility area is about 3120m^2. Batteries are in four strings, but can be expanded up to eight strings. Converters of the BESS have integrated gate commuted thyristors (IGCT) as an active switching devices. Lifetime of the system is planned to be 20 years. GVEA is using the BESS in continuous voltage and frequency control. Projected costs were $35 million. In Figure 13 is represented the layout of different components of the BESS. (DeVries et al, 2004: 38-43; ABB, 2011)

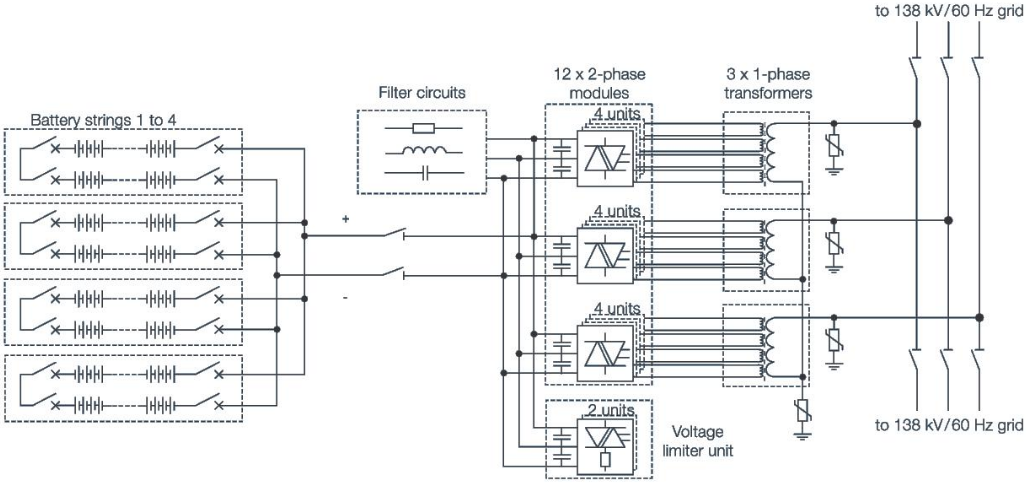

Figure 13: GVEA BESS layout (Devries et al, 2004)

Applications of the BESS (DOE, 2004):

- Frequency regulation
- Voltage support

3.6.2 Berliner Städtische Elektrizitätswerke Akt.-Ges (Pb-acid), West Germany

Berliner Elektrizitätswerke (BEWAG) commissioned a BESS at West Berlin in 1986. When commissioned, it was the largest lead-acid BESS in the world. At the time, BEWAG utility was operating in island due to cold war. During the 7 year operation, the BESS produced frequency control and spinning reserve. The lead-acid batteries had a capacity of 14 MWh. Converters had a power of 8.5 MW in frequency control, and 14 MW in spinning reserve. (Parker, 2001: 20)

Applications of the BESS (DOE, 2014):

- Frequency regulation
- Electric supply reserve capacity - spinning

3.6.3 Metlakatla Power and Light (Pb-acid), USA

Metlakatla Power and Light (MP&L) acquired in 1996 a lead-acid BESS, capable of generating 1.6 MVA at rated maximum of 2.1 MWh capacity depending on discharge rate. Metlakatla is an isolated island at Alaska, where one utility company – the MP&L operates hydro and diesel power generation. The BESS was acquired to reduce use of diesel generator and increase grid stability by providing voltage support and spinning reserves. In 2008, MP&L replaced aged batteries, and the plant was off-line for only six days. The BESS has been very economical due to immediate saving in diesel generator use. (Parker, 2001: 24; Rastler, 2010: 4-7)

Applications of the BESS (DOE, 2014):

- Electric supply reserve capacity - spinning
- Frequency regulation
- Voltage support

3.6.4 Japan Wind Development Co., Ltd. (NaS), Japan

NGK Insulators Ltd. has built many operational NaS powered BESS's, and the largest one is located in Rokkasho, Japan. It is owned by the Japan Wind Development Co., Ltd (JWD). The JWD owns 51 MW of wind power near the BESS. The BESS has a power of 34 MW, and it is used to level the variation of production of a large 51 MW wind power park nearby. The plant has been in operation since 2008. (NGK Insulators, 2013; Rastler, 2010: 4-9)

Applications of the BESS (DOE, 2014):

- Renewables capacity firming
- Renewables energy time shift
- Electric supply reserve capacity - spinning

3.6.5 AES Energy storages (Li-ion), Globally

The AES Corporation is a global power product supplier and power producer. The AES have built a few notable BESS's based on li-ion batteries: 24 MW BESS at Atacama Desert, Chile (2010), 32 MW BESS at West Virginia, USA (2011), 40 MW BESS at

Northern Chile (2012), and 20 MW BESS at Ohio, USA (2013). (AES, 2014; DOE, 2014)

Applications of the BESS's (DOE, 2014):

- Frequency regulation
- Electric supply reserve capacity – spinning
- Ramping

3.6.6 RES Americas (Li-ion), USA

RES Americas built a 4 MW BESS in 2014 at Ohio, USA. The batteries are $LiFePO_4$ type of li-ion batteries rated at 2.4 MWh capacity. The system is built in three containers. The batteries are located in two ISO 20-foot container and the converter in one. (DOE, 2014; RES, 2014)

Applications of the BESS (DOE, 2014):

- Frequency regulation

3.6.7 WEMAG AG (Li-ion), Germany

Younicos AG delivered a 5 MW BESS to WEMAG AG at Schwerin, Germany in 2014. The batteries are based on lithium-manganese oxide chemistry, which the battery supplier Samsung SDI guarantees for 20 years. The BESS is used for frequency control at an area of high renewable penetration, thus the BESS supports fluctuating solar and wind power generation. Younicos claims, that the BESS is able to produce similar power for frequency control as a conventional 50 MW turbine. (Younicos, 2014)

Applications of the BESS (DOE, 2014):

- Frequency regulation
- Voltage support
- Black start

3.6.8 Elektrizitätswerke des Kantons Zürich (Li-ion), Switzerland

The Swiss distribution utility (EKZ) and ABB commissioned a 1 MW BESS in 2012 in Switzerland. The BESS has a li-ion battery capacity of 580 kWh and employs ABB's latest PCS100 converter technology. The battery supplier is LG Chem. The BESS is built in container. (DOE, 2014)

In an EKZ simulation study (Schmutz, 2013), primary frequency control algorithms are studied and found to be capable of producing high availability of the system during the worst frequency periods.

Applications of the BESS (DOE, 2014):

- Frequency regulation
- Electric energy time shift
- Electric supply capacity
- Stationary transmission/distribution upgrade deferral
- Grid-connected commercial (reliability & quality)

4 Cityopt project

Cityopt is a collaboration project between different European cities, companies and research institutes. The project is scheduled to last until 2017. The project is co-funded by European commission on the FP7-Smartcities programme 2013. Members are:

- VTT – Technical Research Centre of Finland
- City of Helsinki & Helen Oy
- AIT – Austrian Institute of Technology
- CSTB – Scientific and Technical Center for Building
- Experientia
- EDF Group
- Nice Côte d'Azur Métropole

CityOpt is characterized followingly: *”CityOpt's mission is to optimise energy systems in smart cities. Applications and guidelines will support efficient planning, detailed design and operation of energy systems in urban districts.”* (CityOpt, 2014)

CityOpt project is divided to work packets, which are done in collaboration between participants. Objective of the project is to create a set of applications and guidelines to be used in city planning and design of energy systems. Pilot cases for the CityOpt project are in: Helsinki, Finland; Vienna, Austria; Nice Côte d'Azur, France.

In Vienna study case, utilization of excess waste heat to heat office buildings is studied. CityOpt investigates optimal design and implementation of the existing energy management with the waste heat utilization. Higher energy efficiency and reduced CO2 emissions are expected.

In Nice Côte d'Azur study case, customer side demand response and behavior of customers in demand response is studied. Fragile electricity supply requires innovative demand response schemes. Local households are recruited to participate in energy community, where different incentives are studied.

Helsinki study case is divided to two different cases: the Kalasatama case and the Östersundom case. The Kalasatama case evaluates different electricity storage solutions and business models in the Kalasatama district. In the case Östersundom, placement of heat storages and business models are studied. Objective of Helsinki cases is to provide city planners tools to find optimal energy solutions. (CityOpt, 2014)

4.1 Introduction of Kalasatama study case

CityOpt Kalasatama case will study optimal placement strategy of a single BESS and distributed BESS's of different sizes. Different business models and multi-user aggregation models will be studied. As part of the Kalasatama case, this thesis focuses on value generation of a single planned BESS from the point of view of the BESS owner. In the section 4.2 business model of the planned BESS is presented.

4.2 Kalasatama – Business Model

Business model for the Kalasatama case is divided to two distinct chronological phases. The first pilot phase consists of R&D-focused operations separately agreed between the project partners. The costs and risks related to the operation and availability of the Battery Energy Storage System (BESS) are mutually shared and agreed. The pilot phase will last three years. The second phase is focused on commercialization, during which the capabilities of the BESS are offered to the competitive markets. The emphasis below is on description of the pilot phase. The execution of the second phase will largely depend on the experiences on the optimal practices obtained during the pilot phase.

Figure 14 illustrates the interactions between the project participants within the pilot phase of the BESS project. The owner and operator of the BESS will be Helen Oy. Fingrid Oyj and Helen Sähköverkko Oy are partners and customers for Helen Oy. The ministry of employment and the economy has an auxiliary role in providing funding for the project. The BESS system provider will also be engaged to the R&D project to optimize the system to meet the specific needs of all the project partners (Helen Oy, Helen Sähköverkko Oy and Fingrid Oyj). All the aforementioned partners have discussed together sharing costs and required R&D investments.

The BESS realized in this project is unique in Finland in terms of capacity and capabilities. As such, the project will attract the interest of other utility companies and service providers.

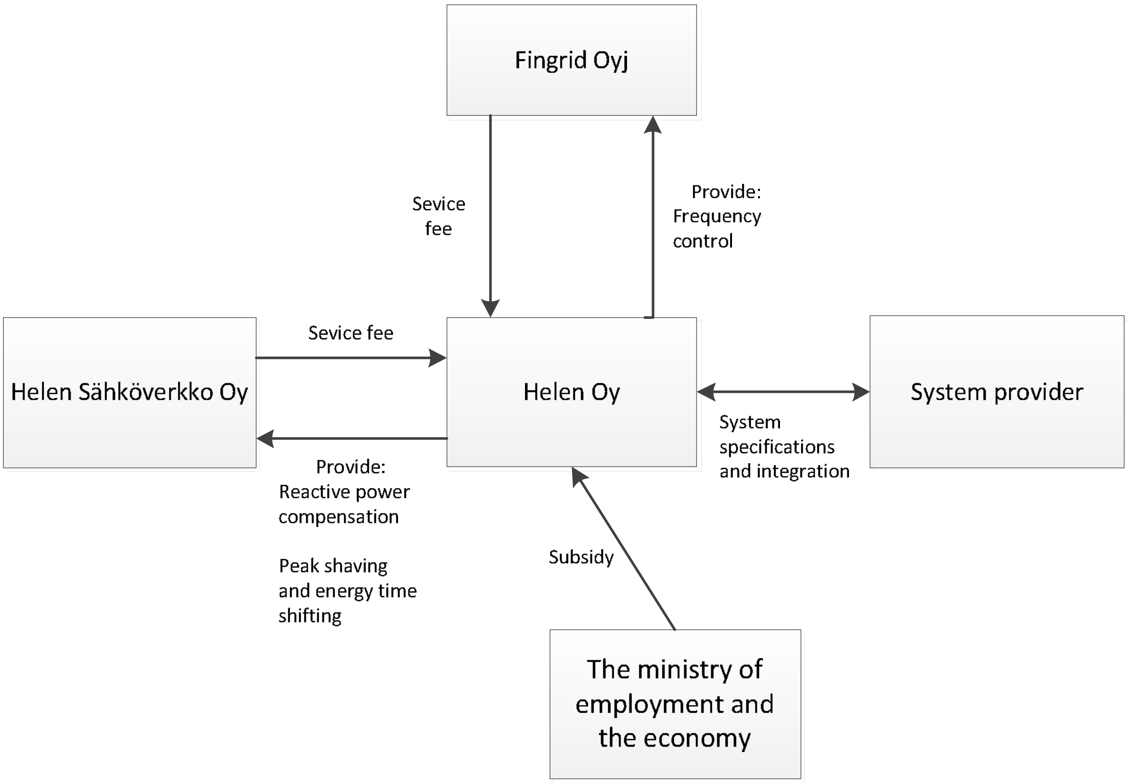

Figure 14: The BESS project scheme during the three year pilot phase

4.2.1 Partners and stakeholders

Different stakeholders and partners are:

- Helen Oy (utility company)

- Helen Sähköverkko Oy (DSO)
- Fingrid Oyj (TSO)
- BESS system provider
- The ministry of employment and the economy in Finland
- The city of Helsinki

Helen Oy will be the owner, operator and capital investor of the BESS. Helen Oy is obligated to promote energy savings and reduce carbon footprint. The BESS will help in fulfillment of these objectives and may enable development of more efficient energy production and grid supporting services.

Helen Sähköverkko Oy is the local distribution system operator, which is owned by Helen Oy. Helen Sähköverkko Oy will provide the site for the BESS and required 10 kV medium voltage switchgear connection.

Fingrid Oyj is the national electric power transmission system operator. Fingrid Oyj is a market enabler due to Frequency Containment Reserve (FCR) markets held by Fingrid, but also very important entity in defining regulation and grid code.

System provider is the key partner for the definition and procurement of the BESS technology.

The ministry of employment and the economy in Finland will subsidy the acquisition of the BESS.

The city of Helsinki is the owner of the Helen Oy and has a political control over the company. City of Helsinki will provide necessary building permits.

4.2.2 Customers, relationships and channels

During the 3-year project pilot phase, the BESS owned and operated by Helen Oy will be used for R&D purposes and to serve two customers:

- Helen Sähköverkko Oy (DSO)
- Fingrid Oyj (TSO)

Helen Sähköverkko Oy is responsible to maintain voltage regulation throughout its distribution network. Voltage is a local attribute, which can be regulated by injecting or consuming reactive power. Traditionally, voltage is regulated at the local substation using shunt capacitors and reactors in series. These are investments, which could be neglected by having the BESS in a 4-quadrant PQ-use. However, operating a BESS solely for reactive power compensation is not economically feasible. In addition to voltage regulation, a BESS provides opportunity for electric energy peak shaving. Efficient utilization of peak shaving enables savings in distribution network capacity investments, as the BESS can provide additional power to meet short-term local peak loads.

As there are no markets for reactive power compensation, a bilateral deal is required between the DSO and the owner of the BESS. In this case, Helen Sähköverkko Oy provides the site for the BESS and pays for the reactive power compensation service. In addition to possible financial gain, Helen Sähköverkko Oy views this project as a valuable testbed to a new way of generating reactive power compensation.

Fingrid Oyj is the statutory frequency regulator in Finland. Fingrid Oyj is required to maintain power system frequency within acceptable limits. Frequency, unlike voltage is not a local variable, but a common value in the Nordic power system. Thus, the location of the BESS for Fingrid Oyj is not as crucial as in reactive power compensation for Helen Sähköverkko Oy. Frequency can be controlled by increasing or decreasing active power. Also reducing power demand is a viable alternative.

Frequency can be regulated by:

- having reserve power capacity available
- employing demand response
- employing reserve power more effectively with stronger interconnections

Traditionally, Fingrid Oyj used to have reserve power generators, but today, Fingrid Oyj rather purchase reserve power from competitive markets. Demand side response has a definitive impact on a system frequency, but at current stage, demand response is not utilized optimally. In this case, Helen Oy and Fingrid Oyj have agreed on a deal, in which the Helen Oy's BESS system will be producing frequency control for Fingrid Oyj. If grid frequency is between 49.95 Hz and 50.05 Hz, no control is required. If frequency is below 49.95 Hz, the BESS injects active power to the grid and above 50.05 Hz, the BESS absorbs active power, thus charging batteries.

4.2.3 Value proposition and products

Utilizing the BESS unit, Helen Oy is capable of producing reactive power compensation, frequency control and peak load shaving as an independent aggregated service. Today, the most economically profitable market in Finland for the BESS is Frequency Containment Reserves (FCR). Helen Oy will provide reserve power in case of grid disturbances (FCR-D) and frequency control in normal operation (FCR-N). In addition, the BESS will provide reactive power compensation and peak shaving functions for Helen Sähköverkko Oy.

In the context of FCR, the BESS can be viewed as an alternative power source for conventional reserve power generation. As such, BESS provides the opportunity to reduce the need of conventional fossil fuel fired reserve power, such as gas turbines in a frequency control. Due to peak shaving capabilities, the BESS also reduces need for new distribution lines and reactive power compensation equipment. The energy used by the BESS to realize the above mentioned functions can be produced with renewable energy sources whenever they are available, thus increasing the utilization of environmentally friendly energy production. The optimized utilization of different energy sources and grid stabilization capabilities create added value and new business opportunities for Helen Oy as a comprehensive energy services provider.

Future business opportunities might include demand response in different electricity markets and operation as an uninterrupted power source in islanding. Viability of these markets will be investigated during the course of the 3-year pilot phase. A value proposition summary of all the stakeholders is given in the Table 8.

Table 8: Value proposition summary of the BESS project 3-year pilot phase

Party	Required investment	Added value
Helen Oy	Capital investment of BESS Wages of operating and R&D personnel	R&D knowledge of BESS business opportunity Revenue from Fingrid and HSV
Helen Sähköverkko Oy	Provide site for the BESS Provide grid connection for BESS Fee for provided reactive power compensation and peak shaving	R&D knowledge of BESS technology possibilities Reactive power compensation service Peak shaving service
Fingrid Oyj	Fee for provided FCR-N and FCR-D services	R&D knowledge of BESS technology possibilities FCR-N and FCR-D services
System provider	BESS system design, construction and erection R&D support during the project pilot phase for BESS usage optimization Maintenance and service of BESS during the project pilot phase	Revenue from BESS system sale R&D experience from system optimization
City of Helsinki	Provision of site construction permit	Guidance of Helsinki city towards increased use of renewable energy sources and new business opportunities through Helen Oy

4.2.4 Key activities and resources

Key resources of the project will be the BESS and the building site. The BESS is specified to meet certain power and capacity requirements. Active power and reactive power capabilities were chosen accordingly to pilot program technical requirements and financial constraints.

In FCR-N market, service operator has to be able to inject and receive power from the power grid. According to Fingrid Oyj FCR requirements, a BESS has to be able to provide full active power for 15 minutes, thus system was specified to have 1.2 MW power, 960 kVAr reactive power and 600 kWh energy capacity. To be able to both provide and receive power, the battery State Of Charge (SOC) has to be at 50 %, denoting to average of 300 kWh capacity if the BESS is dedicated fully to FCR-N market. Having a dedicated FCR-D capacity reserve with FCR-N operations will be further investigated.

Helen Sähköverkko Oy and Fingrid Oyj require Helen Oy to provide service usability above 90 % during the pilot phase. Usability requirement of 90 % gives Helen Oy possibility to experiment with 10 % of total time in different markets.

Other key activity will be data sharing and communication between partners. All the partners are committed to give and share operational and historical data of the BESS.

4.2.5 Cost and revenue structure

During the three-year pilot contract, partners have agreed to share costs according to value of service. Helen Oy will be the owner and operator of the BESS and is paid according to service usability until the end of the three-year pilot programme. This income model reduces the financial risk for the Helen Oy to an acceptable level. The income customers pay, also ensures the sustainability of the planned operations for the first three years.

Capital investment cost of the BESS is the single largest cost factor of the project. This investment can be straight line depreciated during the BESS operational years. Book value of the BESS is estimated to be negligible after operational years compared to the initial investment value. Estimates for battery life vary between 5 and 10 years, as a consequence impose distinct uncertainty on total profitability.

Employee wages constitute another cost factor. Operating the BESS will take human resources and generate R&D costs. Service and maintenance is divided to two parts. During the warranty period, equipment supplier will guarantee service and operation. After the warranty period, Helen Oy is responsible for all the required maintenance. Costs due to operating energy losses are constant, but are considered negligible compared to other costs.

After the pilot period, Helen Oy will be offering reserve power to competitive FCR markets. Helen Oy will continue to offer reactive power compensation to Helen Sähköverkko Oy. Helen Oy has also possibility to expand to different markets e.g. peak load shaving and demand response markets; whatever is the most valuable market at that time. Finally, Fingrid Oyj held reserve power markets may change in future unprofitable due to higher competition and market rule changes, which in turn effects poorly on total profitability of the BESS project.

4.2.6 Discussion regarding business model

As for now, ancillary service markets, such as FCR markets are deemed to be the most profitable markets in Finland. However, in some special applications the value of uninterruptible power source (UPS) can be notable. Therefore, UPS’s, which are essentially battery energy storages are widely adopted already. System’s ability to compensate reactive power is beneficial to DSO’s for voltage regulation purposes. Grid voltage is a local attribute, thus the site of the BESS is required to be where the compensation is required. Offering a site for the BESS, DSO can have a relatively cheap reactive power compensator. Additionally, owner of the BESS can have a secure site, with a medium or high voltage connection to grid.

Environmental benefits are not in the scope of business model, but nevertheless, they should not be forgotten. Environmental benefit of a BESS can be calculated by using a peak shaving case. In a peak power demand situation, the energy is usually produced by polluting energy sources, such as gas turbines. Using a BESS for peak load shaving would replace this polluting power generation with average power generation, which includes a larger share of renewable energy sources. Other environmental benefit would be the reduced need to erect new transmission and distribution lines, preserving natural landscape. There are no definite calculations of how the BESS would reduce carbon footprint in different scenarios and countries, but this could be interest of future research.

The BESS project is relatively unique for its size, multipurpose and multiuser aspect. Partners share mutual R&D interest, which is the fundamental reason for acquiring the BESS. At current energy production and transmission costs, the BESS is not considered financially competitive against more conventional reserve power generation methods. However, the operating environment for the energy industry is rapidly changing due to increased environmental awareness and BESS technology is seen as a promising and versatile tool for the future.

This project is regarded as a necessary and valuable R&D project towards future commercialization of BESS technology. Commercialization could be further expedited by introduction of new non-monetary incentives, such as the “right of first offer” or the “right of first refusal” at the competitive FCR markets. This would promote cleaner energy technology, such as BESS over conventional fossil fuel driven technology. In addition, grid code for ancillary service markets should be revised to consider the advantages and limitations of technologies, such as BESS.

5 Modelling battery energy storage system

The lossless models of the BESS was made in Matlab and in Apros applications. Primary simulations were made in Matlab and the Apros was used to verify results. The Apros model was also prepared for possible later use in the Cityopt project.

Matlab model of the BESS was made to represent an ideal BESS without energy losses or battery degradation model. A model of BESS with energy losses and battery degradation would have been unnecessarily complicated for control algorithm testing. Matlab code is presented in Appendix 4.

Apros is a process and simulation software developed by Technical Research Center of Finland (VTT) jointly with Fortum Power and Heat Oy. Apros is a registered trade mark of VTT and Fortum. Apros is designed for nuclear and thermal power plant applications. It can be used to model power plant automation and processes. Apros is also capable of dynamic simulation and safety analysis. In this chapter, basic principality of the model is explained.

5.1 Block diagram of the BESS in Apros

In Figure 15 is presented the Apros BESS model layout. At the upper left corner is the model of the battery. At the lower left corner is the controlled DC power source and at the right upper corner is the controlled load. The switches in the middle are switching the BESS operation between charge and discharge. The load represent model of the inverter, which discharges the battery. The power source represents rectifier, which charges the battery.

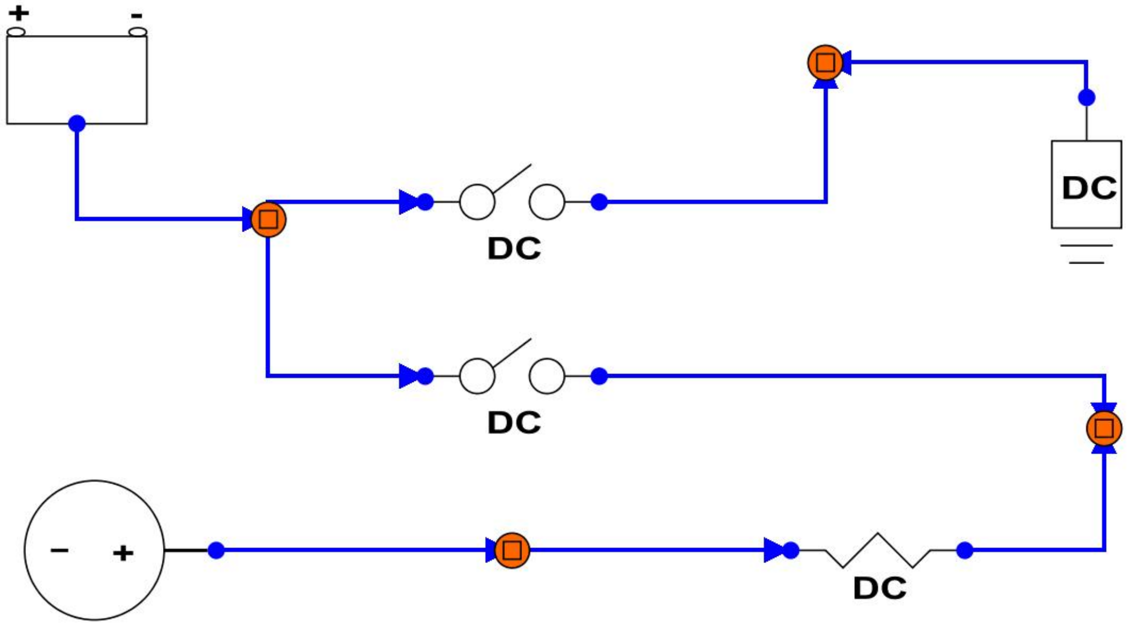

Figure 15: Apros layout of the BESS model

Simulation time-step was set to 0.5 seconds and full months were simulated individually. Battery degradation model is not included in Apros BESS model, and therefore is not included in the simulations. However, simple battery degradation due to cycles is calculated using discharged energy divided with nominal battery energy capacity of 500 kWh to represent cycles. This method gives very conservative approximation of the cycles, because cycling around SOC 50 % is less deteriorating than zero to full cycling.

5.2 Block diagram of the control block

The control block has two principal purposes: control charging and discharging of the BESS, and data logging. The control block has two inputs: state of charge and system frequency. It has one output: power request for the converter. In frequency control, system frequency is the primary control signal, which the BESS follows. The SOC determines if the BESS is capable of providing power to the system or not.

Below is listed different data logged for performance evaluation:

- SOC (%)
- Power request (kW)
- System frequency (Hz)
- Total discharged energy (kWh)
- Undelivered discharged energy (kWh)
- Undelivered charged energy (kWh)
- Total time of discharging
- Total time of charging
- Total time at SOC 0 %
- Total time at SOC 100 %
- Total idling time

Each simulated control logic is evaluated statistically. Energy delivered and undelivered to the power system is used to evaluate performance of the control logic. Similarly, time count of different operating modes are calculated for performance evaluation. In lossless simulations, mean energy charged is as much as mean energy discharged. Undelivered energy calculations are calculated while the SOC is at 0 % or 100 % depending on the direction of requested power flow. Total idling time is the time when the system is not charging or discharging. In Appendix 5 is shown the Apros control block.

5.3 Frequency data used

The frequency data used in the simulations is unofficial Nordic system frequency of the year 2013. The frequency data had missing measurements, in which the BESS was considered idling during the simulation. Therefore, the frequency does not represent actual years of 2013. The frequency measurement is averaged to 1 second at time steps of 1 second. Table 9 below has listed frequency data availability and frequency deviations of each month of year 2013.

Table 9: Frequency availability and deviations of the data

Year 2013	Data availability (%)	Outside [49.99;50.01] (%)	Outside [49.95;50.05] (%)	Outside [49.90;50.10] (%)	Outside <49.70 (s)	Outside <49.50 (s)
1	96.8	80.9	22.7	1.9	4s	0
2	53.6	78.4	20	1.4	0	0
3	99.9	78.4	19.9	1.9	0	0
4	92.9	79.6	22.0	2.2	0	0
5	100	81.1	24.0	2.3	13s	0
6	67.9	82.0	25.9	2.3	12s	0
7	99.9	82.3	26.1	2.3	13s	2s
8	100	83.5	29.3	3.0	0	0
9	99.9	83.0	27.7	3.0	21s	3s
10	97.3	82.1	26.6	3.2	26s	10s
11	99.9	79.2	20.4	1.3	0	0
12	99.9	80.4	22.3	1.8	18s	0

6 Simulation of BESS at frequency containment reserve markets

In this chapter, different control logics at FCR-N market are experimented and compared to each other. The point of simulations is not to study how a BESS affects to a power system e.g. micro grid, but to evaluate how a BESS reacts to a frequency signal. Power grid is thus assumed to be a rigid system, where a BESS doesn't have any impact on total system performance.

The aim of the simulations is to understand how a BESS would operate in the current FCR-N regulation scheme and to compare this to imaginary control schemes. To be able to compare different control logics, a few performance metrics were chosen. Battery charge-discharge cycles can be used to evaluate battery degradation. Battery cycles are calculated using a simple method, where discharged energy is divided with the nominal battery capacity. However, this method doesn't represent actual battery cycles, but gives a comparable value. In reality, battery cycles would be less than calculated in this study. High amount of cycles is undesirable, since charging and discharging degrades batteries, generates energy losses, and also, purchased electricity is more expensive than sold electricity due to transmission fees. Other metrics are: mean yearly idle time, mean charging time, mean discharging time, mean time unable to deliver up-regulation and down-regulation due to limited energy capacity of battery.

Simulations are conducted with following specifications:

P_{max} = 1 MW,	(Maximum power output)
E_n = 500 kWh,	(Nominal energy capacity)
C-rating = 2C.	

Nominal capacity of 500 kWh is the full usable capacity, thus usable range of SOC is between 0 % and 100 %. In reality, equipment manufacturer would probably have slightly higher capacity to ensure safe operation margin of the batteries and to compensate battery degradation.

6.1 Simulating FCR-N market

Simulations were conducted using full year availability. This means, that the BESS contributed all year in the FCR-N market. If simulations would have been done in the hourly markets, the BESS market participation would have been greatly reduced due to zero value hours, see Figure 6.

Six different control logics were chosen to be simulated. The control logic 1 is the base case of the simulations. It is the currently used control curve in Fingrid Oyj held FCR-N market. The control logics 2 has much narrower deadband and also larger area of power generation in control curve. The control logic 3 has no deadband at all. The control logics 4 and 5 study asymmetric control curves. The control logic 6 has an additional SOC optimization, which aims for higher availability of the BESS.

In Tables 10, 11, 12, 13, 14, and 15 are represented results of the simulations, where:

- **Up_E** is the energy charged in up-regulation, where $f < 50$Hz.
- **Down_E** is the energy discharged in down-regulation, where $f > 50$Hz.

- **F_up_E** is the undelivered up-regulation energy i.e. energy not discharged due to SOC being at 0 %.
- **F_down_E** is the undelivered down-regulation energy i.e. energy not charged due to SOC being at 100 %.
- **Avg F_up_B** is the mean time of unavailability at up-regulation due to limited battery capacity.
- **Avg F_down_B** is the mean time of unavailability at down-regulation due to limited battery capacity.
- **Avg up_B** is the mean time of operation at up-regulation.
- **Avg down_B** is the mean time of operation at down-regulation.
- **Avg idle_B** is the mean idle time.

6.1.1 Control logic 1, deadband of [49.95; 50.05] Hz

The control logic 1, in Figure 16 is particularly interesting, because it is the current control curve in use at the FCR-N frequency control market. This control logic can be therefore be used as a baseline for further simulations. The control logic 1 can be expressed using linear equation:

$$y = -\frac{x}{0.05} + \frac{49.90}{0.05} = -20x + 999 \tag{2}$$

Where, y is power request in per unit (pu) and x is system frequency, while $x = [49.90, 49.95]$. Therefore:

$P = -20f + 999$, while $f = [49.90; 49.95]$. (Power injected)

Similarly,

$P = 20f - 1001$, while $f = [50.05; 50.10]$. (Power consumed)

Constant power areas are:

$P = 1$, while $f < 49.90$. (Power injected)

$P = 0$, while $f = [49.95; 50.05]$. (Idle)

$P = -1$, while $f > 50.10$. (Power consumed)

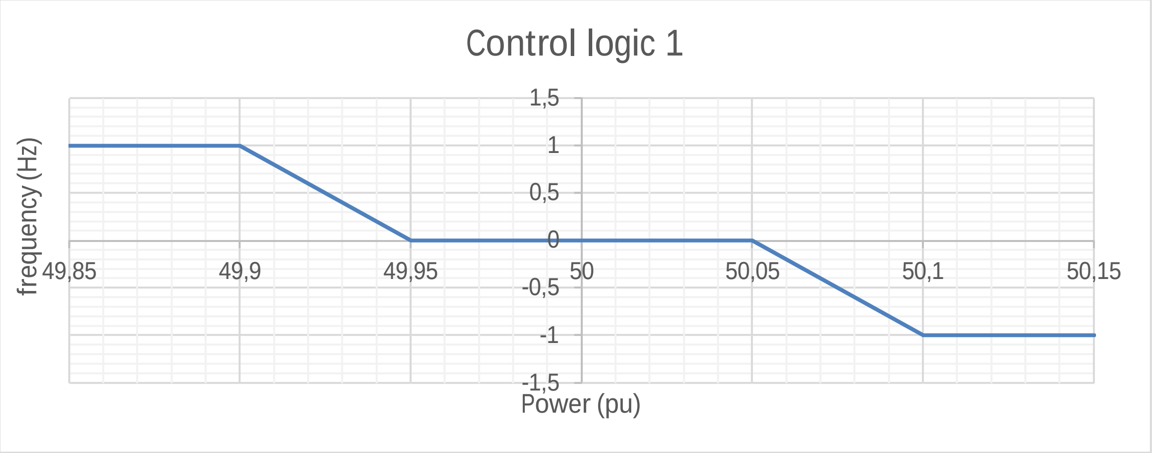

Figure 16: Control logic 1

Results of the simulation is in Table 10. Full monthly results are in Appendix 6. Conservative approximation of total charge-discharge cycles are counted as discharged energy divided by nominal capacity:

$$Cycles = \frac{268762kWh}{500kWh} \approx 538$$

The ratio of discharged energy and undelivered discharged energy is:

$$Ratio = \frac{268.762MWh}{106.724MWh} \approx 2.52$$

The ratio of charged energy and undelivered charged energy is:

$$Ratio = \frac{269.392MWh}{153.714MWh} \approx 1.72$$

Table 10: Results of control logic 1

Logic 1 (2013)	Monthly mean	Total
Up_E	22.397 MWh	268.762 MWh
Down_E	22.449 MWh	269.392 MWh
F_up_E	8.894 MWh	106.724 MWh
F_down_E	12.809 MWh	153.714 MWh
Avg F_up_B	2.8 %	
Avg F_down_B	3.6 %	
Avg up_B	8.0 %	
Avg down_B	7.7 %	
Avg idle_B	84.4 %	

6.1.2 Control logic 2, deadband of [49.99; 50.01] Hz

The control logic 2, in Figure 17 has a narrower deadband compared to control logic 1. Narrower deadband would force a BESS to activate more frequently. The control logic 2 can be expressed using linear equations:

$P = 1$, while $f < 49.90$. (Power injected)

$P = -\frac{f}{0.09} + \frac{49.9}{0.09} + 1$, while $f = [49.95; 49.99]$. (Power injected)

$P = 0$, while $f = [49.99; 50.01]$. (Idle)

$P = -\frac{f}{0.09} + \frac{50.01}{0.09}$, while $f = [50.01; 50.10]$. (Power consumed)

$P = -1$, while $f > 50.10$. (Power consumed)

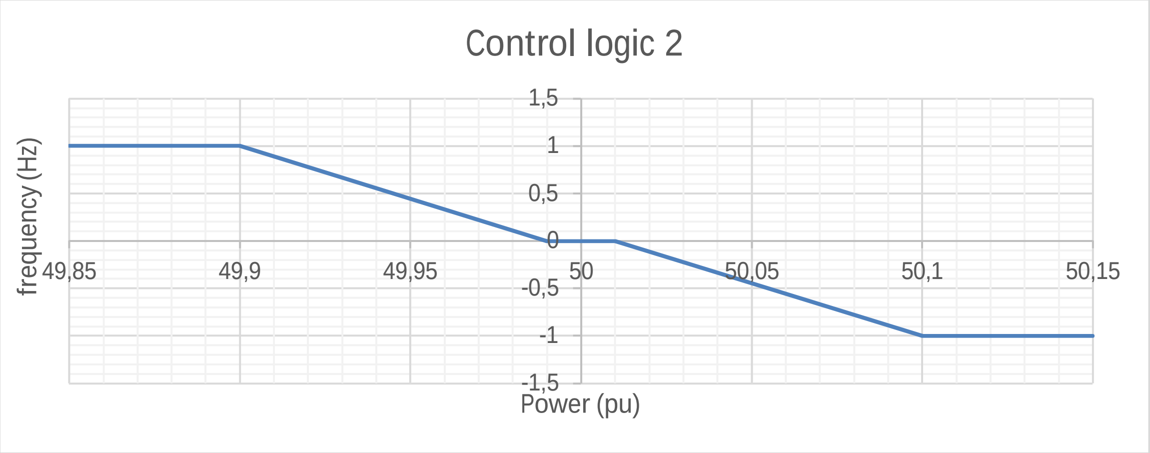

Figure 17: Control logic 2

Results of the simulation is in Table 11. Full monthly results are in Appendix 6. Conservative approximation of total charge-discharge cycles are counted as discharged energy divided by nominal capacity:

$$Cycles = \frac{672345kWh}{500kWh} \approx 1345$$

The ratio of discharged energy and undelivered discharged energy is:

$$Ratio = \frac{672.345MWh}{524.444MWh} \approx 1.28$$

The ratio of charged energy and undelivered charged energy is:

$$Ratio = \frac{672.978MWh}{531.571MWh} \approx 1.27$$

Table 11: Results of control logic 2

Logic 2 (2013)	Monthly mean	Total
Up_E	51.719 MWh	672.345 MWh
Down_E	51.768 MWh	672.978 MWh
F_up_E	40.342 MWh	524.444 MWh
F_down_E	40.890 MWh	531.571 MWh
Avg F_up_B	13.6 %	
Avg F_down_B	12.6 %	
Avg up_B	24.2 %	
Avg down_B	23.9 %	
Avg idle_B	51.9 %	

6.1.3 Control logic 3, no deadband

The control logic 3, in Figure 18 has no deadband, in which case a BESS would be active most of the time. The control logic 3 can be expressed using linear equations:

$P = 1$, while $f < 49.90$. (Power injected)

$P = -10f + 500$, while $f = [49.90; 50.10]$. (Power injected and consumed)

$P = -1$, while $f > 50.10$. (Power injected)

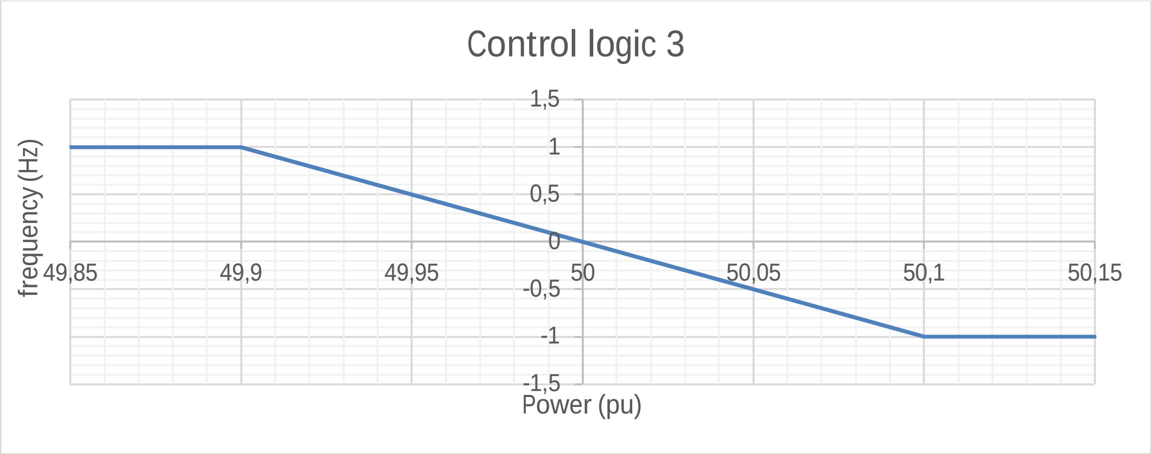

Figure 18: Control logic 3

Results of the simulation is in Table 12. Full monthly results are in Appendix 6. Conservative approximation of total charge-discharge cycles are counted as discharged energy divided by nominal capacity:

$$Cycles = \frac{831015kWh}{500kWh} \approx 1662$$

The ratio of discharged energy and undelivered discharged energy is:

$$Ratio = \frac{831.015MWh}{648.274MWh} \approx 1.28$$

The ratio of charged energy and undelivered charged energy is:

$$Ratio = \frac{831.535MWh}{642.453MWh} \approx 1.29$$

Table 12: Results of control logic 3

Logic 3 (2013)	Monthly mean	Total
Up_E	63.924 MWh	831.015 MWh
Down_E	63.964 MWh	831.535 MWh
F_up_E	49.867 MWh	648.274 MWh
F_down_E	49.419 MWh	642.453 MWh
Avg F_up_B	15.5 %	
Avg F_down_B	14.3 %	

Avg up_B	31.1 %	
Avg down_B	30.9 %	
Avg idle_B	38.1 %	

6.1.4 Control logic 4, asymmetric deadband

The control logic 4, in Figure 19 has an asymmetric control curve, which emphasize up-regulation.

The control logic 4 can be expressed using linear equations:

$P = 1$, while $f < 49.90$. (Power injected)

$P = -20f + 999$, while $f = [49.90; 49.95]$. (Power injected)

$P = 0$, while $f = [49.95; 50.00]$. (Idle)

$P = -10f + 500$, while $f = [50.00; 50.10]$. (Power consumed)

$P = -1$, while $f > 50.10$. (Power consumed)

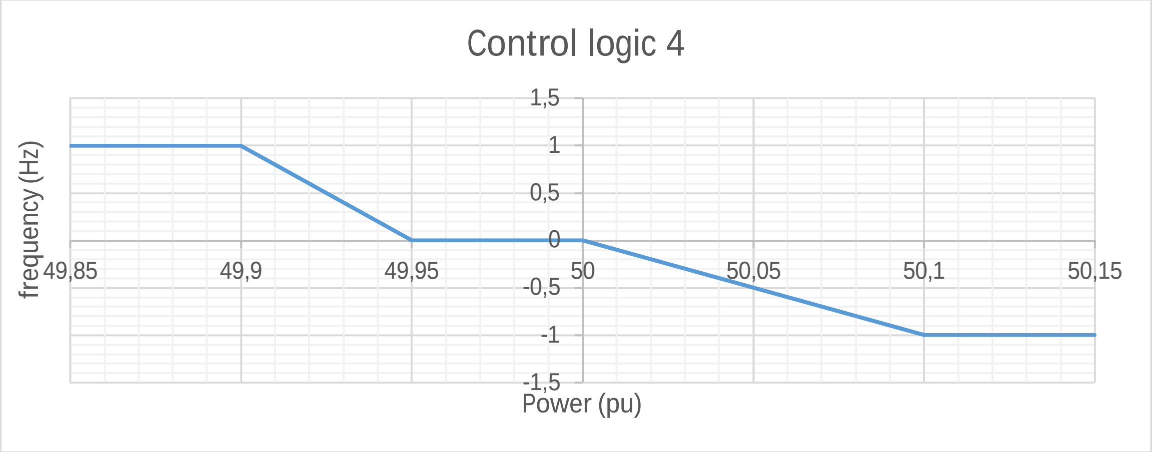

Figure 19: Control logic 4

Results of the simulation is in Table 13. Full monthly results are in Appendix 6. Conservative approximation of total charge-discharge cycles are counted as discharged energy divided by nominal capacity:

$$Cycles = \frac{361731kWh}{500kWh} \approx 723$$

The ratio of discharged energy and undelivered discharged energy is:

$$Ratio = \frac{361.731MWh}{45.045MWh} \approx 8.03$$

The ratio of charged energy and undelivered charged energy is:

$$Ratio = \frac{364.378MWh}{1109.512MWh} \approx 0.33$$

Table 13: Results of control logic 4

Logic 4 (2013)	Monthly mean	Total
Up_E	27.825 MWh	361.731 MWh
Down_E	28.029 MWh	364.378 MWh
F_up_E	3.465 MWh	45.045 MWh
F_down_E	85.347 MWh	1109.512 MWh
Avg F_up_B	1.0 %	
Avg F_down_B	30.7 %	
Avg up_B	9.8 %	
Avg down_B	14.4 %	
Avg idle_B	75.7 %	

6.1.5 Control logic 5, asymmetric deadband

The control logic 5, in Figure 20 has an asymmetric control curve, which emphasize up-regulation as in control logic 4, but control logic 5 has equal area of control as in control logic 1. This means, that the total area of up and down regulation equals, even though the instantaneous power differs.

The control logic 5 can be expressed using linear equations:

$P = 1$, while $f < 49.90$. (Power injected)
$P = -20f + 999$, while $f = [49.90; 49.95]$. (Power injected)
$P = 0$, while $f = [49.95; 50.00]$. (Idle)
$P = -5f + 250$, while $f = [50.00; 50.10]$. (Power consumed)
$P = -1$, while $f > 50.10$. (Power consumed)

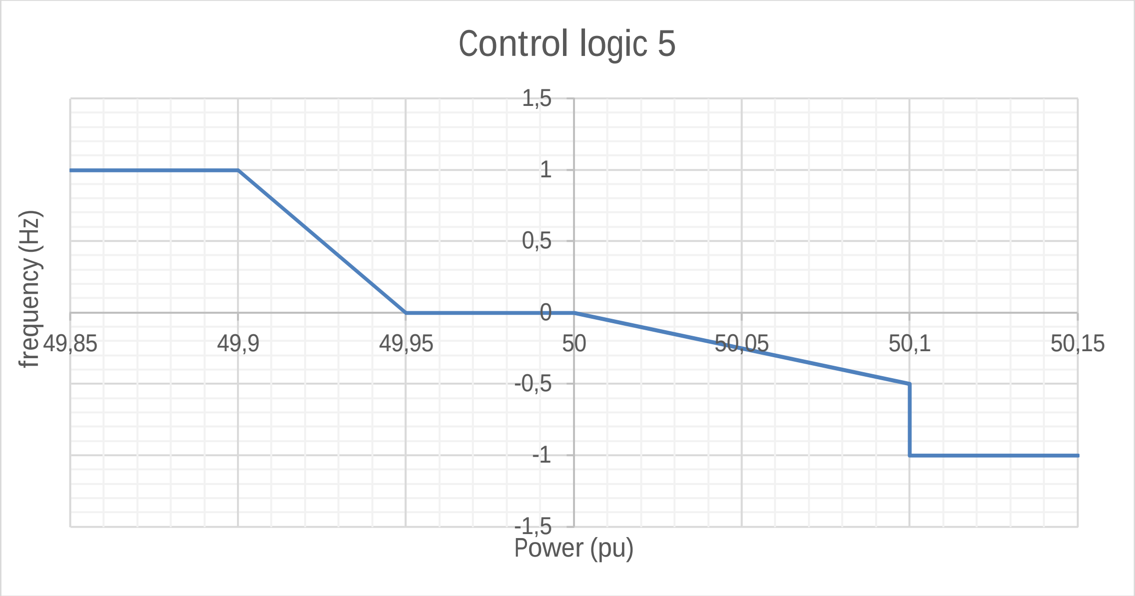

Figure 20: Control logic 5

Results of the simulation is in Table 14. Full monthly results are in Appendix 6. Conservative approximation of total charge-discharge cycles are counted as discharged energy divided by nominal capacity:

$$Cycles = \frac{347111kWh}{500kWh} \approx 694$$

The ratio of discharged energy and undelivered discharged energy is:

$$Ratio = \frac{347.111MWh}{59.665MWh} \approx 5.82$$

The ratio of charged energy and undelivered charged energy is:

$$Ratio = \frac{349.072MWh}{443.758MWh} \approx 0.79$$

Table 14: Results of control logic 5

Logic 5 (2013)	Monthly mean	Total
Up_E	27.825 MWh	347.111 MWh
Down_E	28.029 MWh	349.072 MWh
F_up_E	3.465 MWh	59.665 MWh
F_down_E	85.347 MWh	443.758 MWh
Avg F_up_B	1.3 %	
Avg F_down_B	22.0 %	
Avg up_B	9.5 %	
Avg down_B	23.1 %	
Avg idle_B	67.4 %	

6.1.6 Control logic 6, SOC optimization inside deadband

The control logic 6, in Figure 21 is very similar with control logic 1. It has an additional SOC optimization routine, which is used to improve availability of the BESS. Many lithium battery manufacturer recommends charging at 0.5C rate, which correlates with constant power of 0.25 pu. Hence, the constant power of 0.25 pu was chosen.

The control logic 6 can be expressed using linear equations:

$P = -20f + 999$, while $f = [49.90; 49.95]$. (Power injected)

$P = 20f - 1001$, while $f = [50.05; 50.10]$. (Power consumed)

Constant power areas are:

$P = 1$, while $f < 49.90$. (Power injected)

$P = 0$, while $f = [49.95; 50.05]$. (Idle)

$P = -1$, while $f > 50.10$. (Power consumed)

Additional SOC optimization is:

P = -0.25, while the SOC is lower than 50 % and f = [50; 50.05].

P = 0.25, while the SOC is higher than 50 % and f = [49.95; 50].

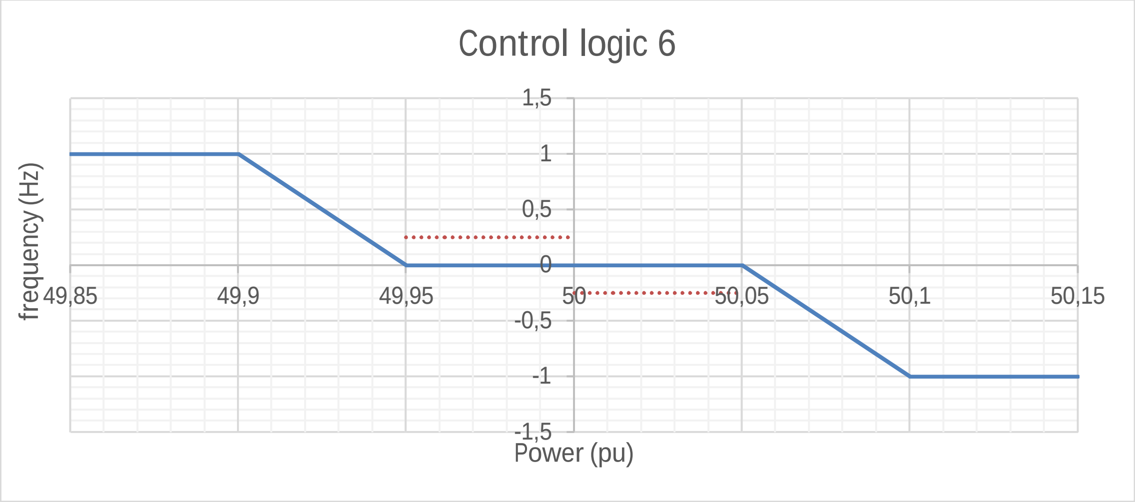

Figure 21: Control logic 6

Results of the simulation is in Table 15. Full monthly results are in Appendix 6. Conservative approximation of total charge-discharge cycles are counted as discharged energy divided by nominal capacity:

$$Cycles = \frac{511110kWh}{500kWh} \approx 1022$$

The ratio of discharged energy and undelivered discharged energy is:

$$Ratio = \frac{511.110MWh}{95.677MWh} \approx 5.34$$

The ratio of charged energy and undelivered charged energy is:

$$Ratio = \frac{511.381MWh}{141.285MWh} \approx 3.62$$

Table 15: Results of control logic 6

Logic 6 (2013)	Monthly mean	Total
Up_E	39.316 MWh	511.110 MWh
Down_E	39.337 MWh	511.381 MWh
F_up_E	7.360 MWh	95.677 MWh
F_down_E	10.868 MWh	141.285 MWh
Avg F_up_B	2.1 %	
Avg F_down_B	2.7 %	
Avg up_B	17.1 %	
Avg down_B	16.7 %	
Avg idle_B	66.2 %	

6.2 Simulation results

Six different control logics were simulated by a lossless model of the BESS. The control logic 1 is the current control curve in FCR-N market in use. It has the lowest total discharged energy and charged energy – denoted in battery cycles, which can be seen beneficiary for the BESS operator due to the fact that the lifetime of the batteries is in relation to the battery cycles.

Control logics 2 and 3 have much more demanding deadband requirement, which causes the BESS to operate at much higher utilization rate. The difference of deadband between control logic 1 and 2 has a huge effect to utilization of the BESS. In control logic 2, the BESS does 1345 cycles, which is 2.5 times more than in control logic 1. However, higher utilization rate is only logical due to the higher operational requirement, which can be seen as a larger area of power generation in control curve. Control logic 3 has no deadband, which makes the BESS being active constantly, thus the amount of cycles is the highest of all the studied control logics. Consequently, market rule change in deadband possess a high risk for the profitability of the BESS, unless monetary compensation changes accordingly as well.

Control logics 4 and 5 have an asymmetric control curves, which have a tendency to charge the BESS to a higher SOC level. The average SOC level for the control logic 4 is 81.8 % and for the control logic 5 is 73.8 % respectively, see Appendix 6. Asymmetric control curve emphasizes up-regulation in cost of down-regulation. The BESS contributes more to up-regulation than to down-regulation due to the higher average level of SOC, which enable a longer discharging duration in a prolonged low frequency situation. In 2014, Danish west FCR market had an average price of 20.51 EUR/MW for the up-regulation, and an average price of 1.52 EUR/MW for the down-regulation (Energinet, 2015). Therefore up-regulation is much more profitable than down-regulation. This information can be used to optimize the BESS to operate more in the up-regulation. However, control curve of Finnish FCR-N market is symmetric, and explained optimization can't be used.

Control logic 6 is similar to control logic 1, but it has an additional SOC optimization inside the deadband. The SOC optimization is fairly simple, where constant 0.5C charge and discharge is applied if the frequency is inside the deadband and the SOC deviates from 50 %. The idea of SOC optimization is to increase availability of the BESS, and to reduce amount of time spent at 0 % and 100 % state of charge. In Figure 22 is shown, how the control logic 6 outperforms other control logics in terms of SOC distribution density, in which the BESS is less often at 0 % or at 100 % state of charge. However, comparing the difference of time spent in situation, where the BESS should deliver power, but is not able to do so due to SOC being at 0 % is almost nonexistence. Average time of not supplying up-regulation power (Avg F_up_B) of control logic 1 is at 2.8 %, whereas in control logic 6 the same is at 2.1 %. Also, the energies not delivered (F_up_E and F_down_E) closely match each other. Therefore the performance of both logics is very similar. The greatest difference between logics 1 and 6 is the difference in charge-discharge cycles. In control logic 1: 538 cycles. In control logic 6: 1022 cycles.

Figures 23, 24, 25, and 26 illustrates behavior of the BESS in different control logics. In Figures 23 and 24, negative values denotes discharging and positive values charging of the batteries. Figure 23 shows power distribution densities during the July of 2013. In the case of control logic 1, the BESS mostly idles and the power output is mostly low or zero. It is noteworthy, that in asymmetric control logics of 4 and 5, the distribution of power is much higher in charging, but in fact, the BESS contributes more to up-regulation than to down-regulation.

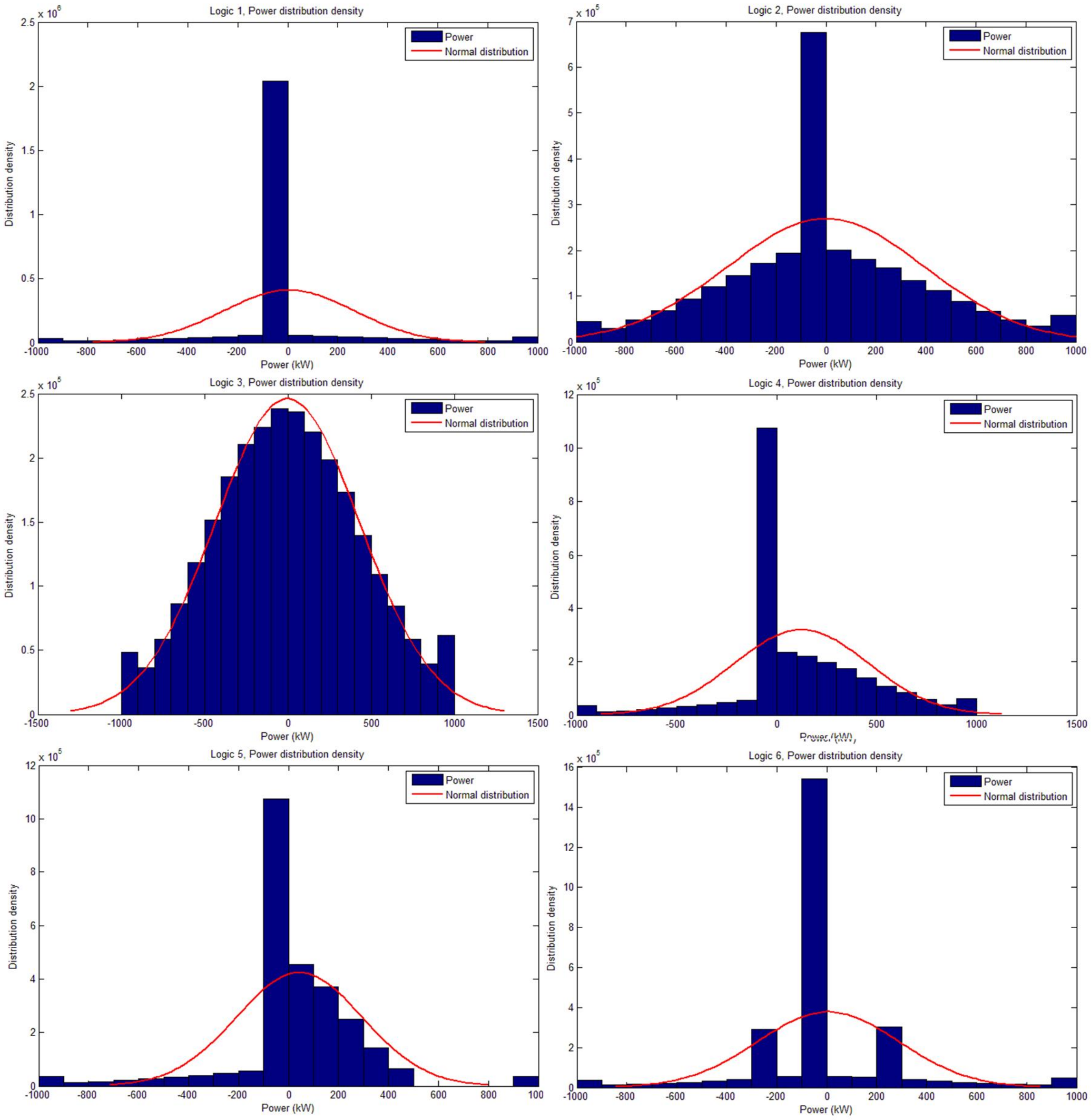

Figure 22: Power distribution densities during July 2013

In Figure 24 is shown the power request of the BESS in one hour. In control logic 3, the BESS is constantly following the frequency. This might be the best and the most utilizing control logic, but constant operation would stress the system and the batteries significantly. In this operation, energy losses and battery degradation would be significant.

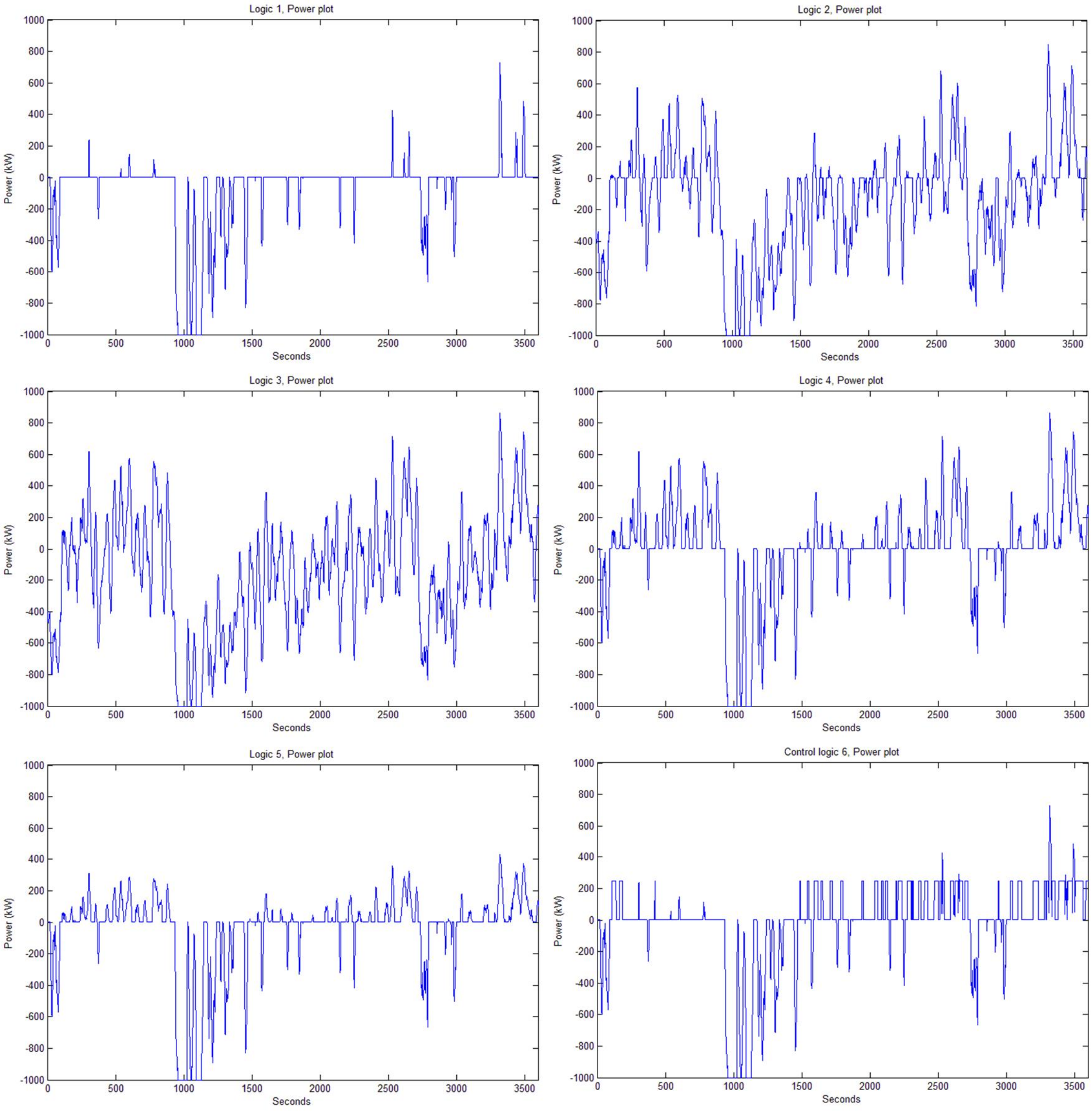

Figure 23: Power plots during the first hour of 1st of July 2013

In Figure 25, distribution densities of state of charge is shown. In symmetric control logics, the SOC is most of the time at fully charged or at fully discharged states. In asymmetric control logics, the SOC is mostly fully charged and rarely fully discharged. This confirms the earlier statement, that the asymmetric control emphasis up-regulation due to higher average level of SOC. The SOC optimization of control logic 6 in Figure 25 shows how the SOC stays mostly at around SOC 50 %.

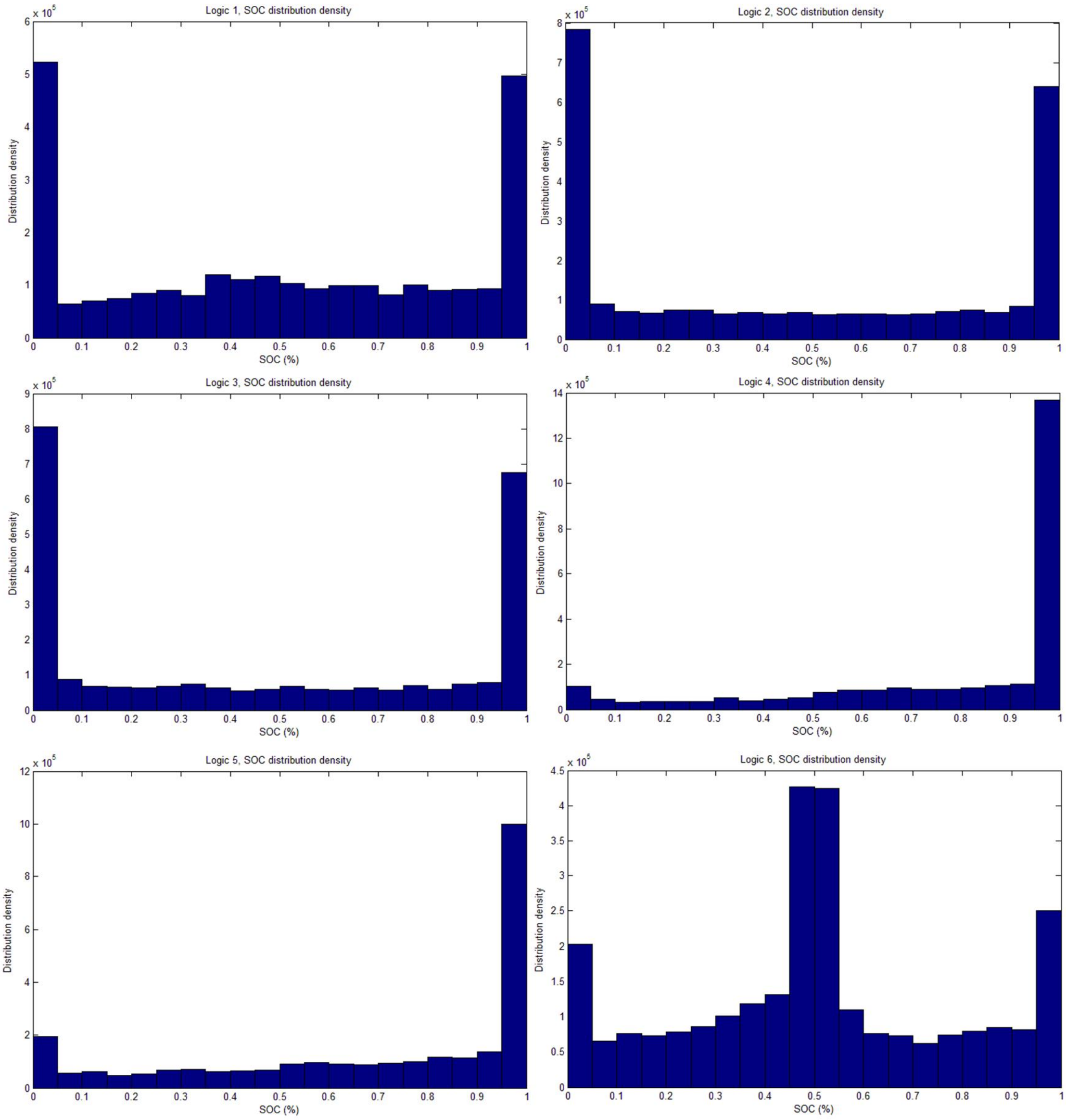

Figure 24: SOC distribution densities during July 2013

Figure 26 show the SOC plots of the simulations during the 1st and 3rd of July. It is clear, that control logics 2 and 3 have considerably higher amount of full charge-discharge cycles than other control logics. It is also surprising, how many partial cycles control logic 6 generates. From the Figure 26, control logics 1, 4, and 5 are the least battery degrading logics.

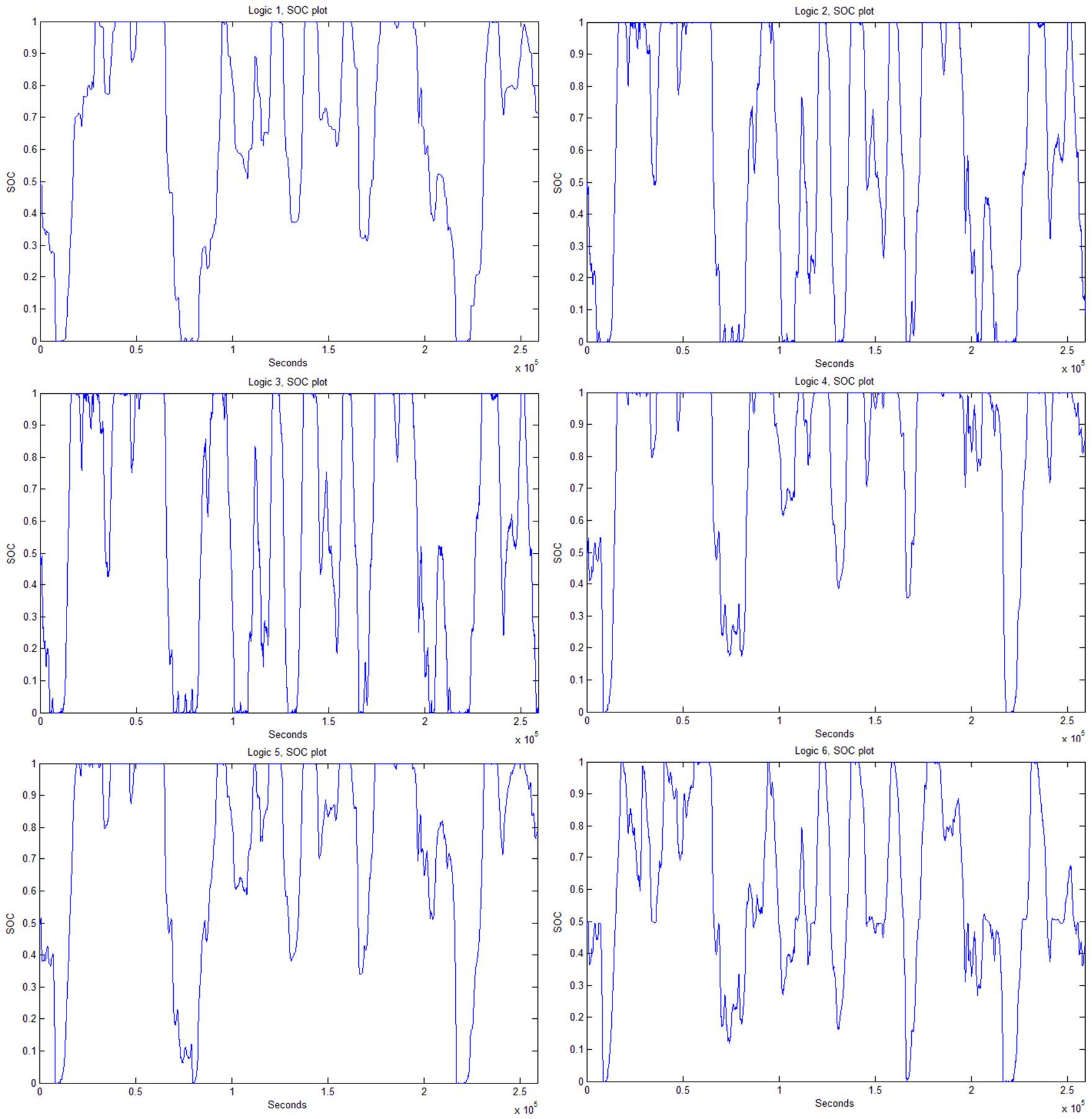

Figure 25: SOC plots during 1st of July 2013 to 3rd of July 2013

Control logics 2 and 3 charge and discharge rapidly to full or empty as a result of a small frequency deviation. Consequently a BESS would spend most of the time at either full or empty SOC.

If the market model would be asymmetric, control logics 4 and 5 would fare much better than control logic 1. The ratio of discharged energy and undelivered discharged energy in control logic 5 is 5.82 compared to 2.52 of control logic 1. However, control logics 4 and 5 cycles more than control logic 1.

Having the extra SOC optimization routine in control logic 6 doesn’t seem to give much added value compared to control logic 1. Even though control logic 6 generates twice as much energy as control logic 1, the energy not delivered is similar in both logics.

Control logic 1 generates conservative amount of regulation energy compared to other control logics, however it delivers power fairly well. It has the least amount of battery degrading cycles.

7 Profit and cost models

A BESS is generally profitable, if marginal cost of electricity is greater than storing costs. To be more precise, the requirements of different applications define applicable technology, see section 3.2. In Figure 27 is presented different factors affecting costs for storing energy (Fuchs et al. 2012: 49). This annuity methodology is used in simplified form in section 7.1 calculating BESS cash flow and net present value at ancillary service market.

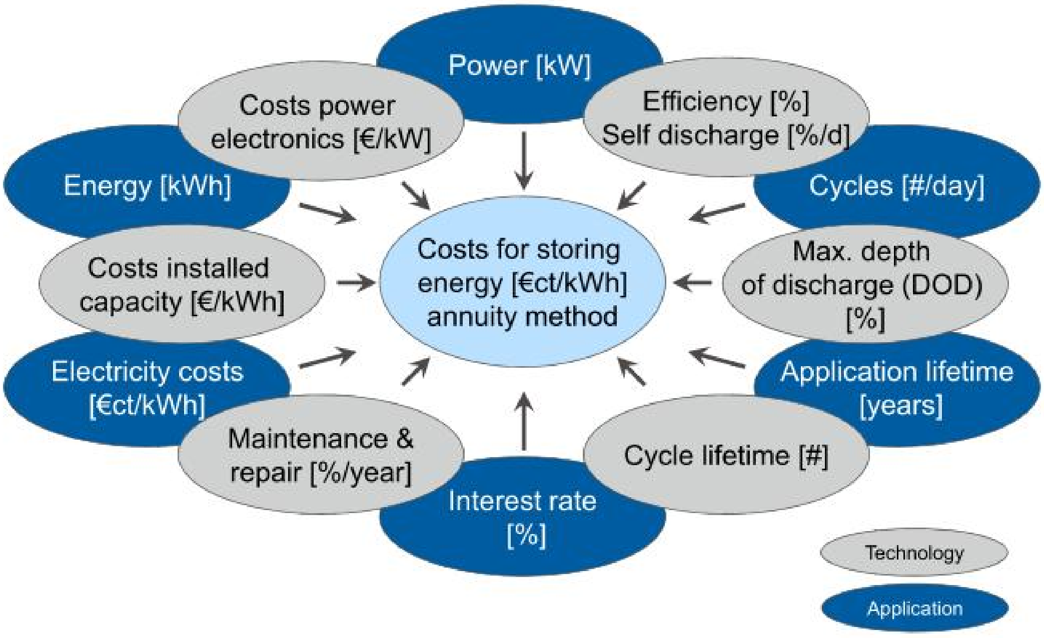

Figure 26: Calculating cost of storing energy (Fuchs et al. 2012: 49)

7.1 Calculating BESS cash flow and net present value at ancillary service market

Economic viability of an investment can be approximated by calculating net present value. The net present value (NPV) of an investment is calculated in Equation 3.

$$NPV = \sum_{i=1}^{n} \frac{C_t}{(1+i)^t} - C_0 \qquad (3)$$

t	The time of cash flow
i	The discount rate
C_t	The net cash flow, EUR
C_0	The initial investment, EUR

Assume a 1 MVA and 500 kWh BESS has subsequent yearly costs and yearly income. Lifetime of the BESS can be assumed to be 10 years. The BESS is operating 70 % of the time. Daily electricity consumption is 120 kWh (Schmutz, 2013: 36). The discount rate is set to 7 %. Annual income is assumed to be equal to income in 2014. Annual maintenance, repair, and battery replacement costs are estimated to be 10 % of the initial investment cost. In the NPV calculation, values are rounded and represent approximate values.

Costs:

- Estimated onetime investment cost of 1.5 million euros
- Estimated annual maintenance and repair including battery replacement after 10 years 150 000 EUR
- Electricity costs 50 EUR/MWh, therefore cost of electricity can be calculated:

$$Cost\ of\ electricity = 0.7 \times 365d \times 0.12\,MWh \times 50\,\frac{EUR}{MWh} = 1533\text{EUR}/a \quad (4)$$

Income:

- Annual income from Fingrid Oyj’s hourly FCR-N market in 2014 was 279 670 EUR/MW, see Appendix 2
- Total yearly income of FCR-N and voltage support is rounded to 300 000 EUR

In Table 16 and in Figure 28 is presented yearly cumulative net present value of the BESS. Payback time is 15 years and net present value after 20 years is 200 339 euros.

Table 16: BESS costs and net present value yearly

Year	Investment, EUR	Income, EUR	Costs, EUR	NPV yearly, EUR	NPV cumulative, EUR
2015	-1500000	300000	-150000	-1350000	-1350000
2016	0	300000	-150000	140187	-1209813
2017	0	300000	-150000	131016	-1078797
2018	0	300000	-150000	122445	-956353
2019	0	300000	-150000	114434	-841918
2020	0	300000	-150000	106948	-734970
2021	0	300000	-150000	99951	-635019
2022	0	300000	-150000	93412	-541607
2023	0	300000	-150000	87301	-454305
2024	0	300000	-150000	81590	-372715
2025	0	300000	-150000	76252	-296463
2026	0	300000	-150000	71264	-225199
2027	0	300000	-150000	66602	-158597
2028	0	300000	-150000	62245	-96352
2029	0	300000	-150000	58173	-38180
2030	0	300000	-150000	54367	16187
2031	0	300000	-150000	50810	66997
2032	0	300000	-150000	47486	114483
2033	0	300000	-150000	44380	158863
2034	0	300000	-150000	41476	200339

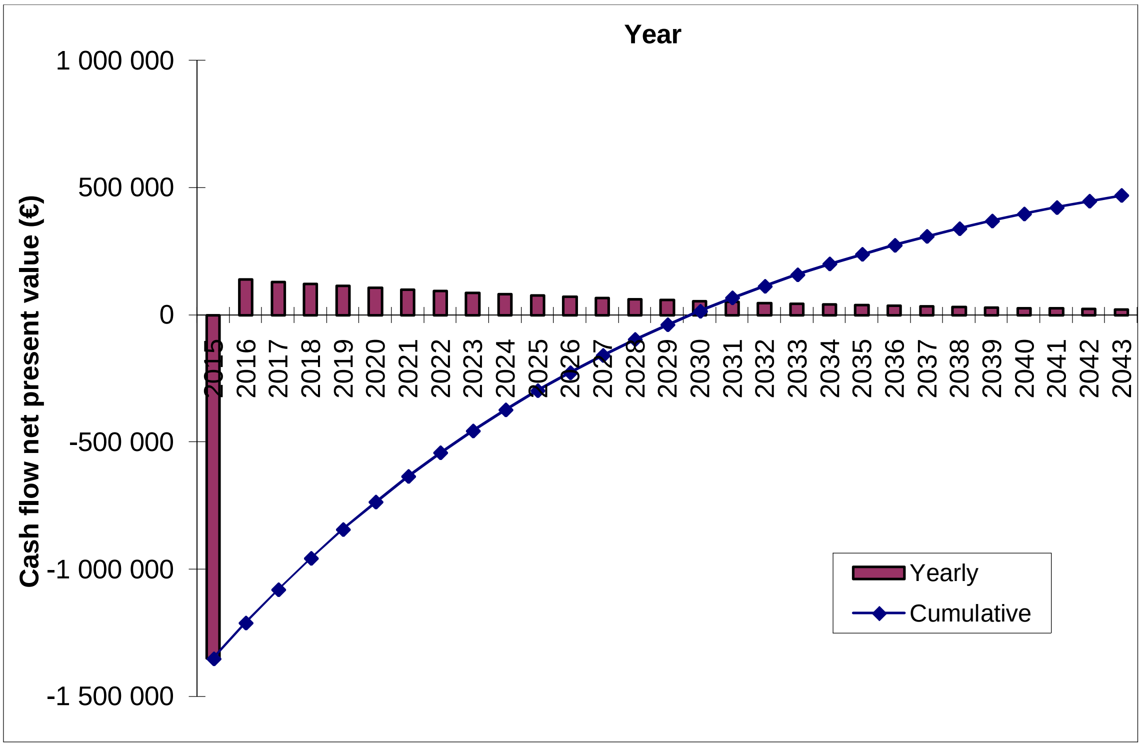

Figure 27: BESS yearly cumulative net present value

Calculating payback time more detailed can be difficult due to uncertainties involved. Battery lifetime can be less than planned, and the market value of FCR-N market can increase or decrease. A BESS investment with given uncertainties and a long payback time of 15 years can be hard to justify. However, there are investment subsidy mechanics in Finland, which can improve viability of the investment significantly. One such subsidy is the energy subsidy for the energy efficiency improvement projects, granted by the ministry of employment and the economy in Finland. Furthermore, the technology involved in energy storing can improve considerably in the future by new innovations, thus making the BESS investment economically more viable.

8 Conclusions

In this chapter, the FCR-N simulations and ancillary service markets are summarized. Finally, the importance of market regulation for a BESS in frequency control is discussed.

8.1 Summary of control logic simulations in FCR-N

Strictly from the point of view of the BESS operator, control logic 1 is the preferred logic due to the least amount of charging and discharging of the batteries. Therefore control logic 1 has the least amount of battery degradation and energy purchases. Narrower frequency deadband in control logics 2 and 3 increase the operational time of the BESS significantly, hence increasing battery degradation. Asymmetric control curves in control logics 4 and 5 increase up-regulation output in cost of down-regulation output. In addition, up-regulation can be seen much more valuable for the power system than the down-regulation. Control logic 6 has an additional SOC optimization routine to increase availability of the BESS, but this increases charge-discharge cycles of the batteries considerably decreasing profitability.

One common factor can be seen from the simulations. If the area of power output in the power to frequency diagram is increased, the utilization of BESS increases almost proportionally. It is important to notice, that even though control logic 1 generates the least amount of regulation energy, during only 2.8 % of the total time it is not able to deliver up-regulation power.

8.2 Summary of ancillary service markets

Ancillary service markets in Finland consists of Fingrid Oyj held reserve markets. Fingrid Oyj is also responsible for the up keep of black-start capability and balancing reactive power flow in the power system, which both are classified as ancillary services.

The most profitable reserve market for a BESS was found to be the hourly market of the frequency containment reserve for normal operation (FCR-N). However, the market size of the FCR-N hourly market is very limited – only averaging 15 MW each hour of the year in 2014. The limited size of the market involves a definite market risk. The theoretical value of 1 MW in the FCR-N hourly market in the year 2014 was approximately 280 000 EUR. The value of frequency containment reserve in disturbance (FCR-D) is far too low to be a viable market place for an expensive BESS.

The investment value of reactive power compensation is approximately 70 000 EUR for 1 MVAr. Reactive power compensation can be provided simultaneously with reserve power generation.

The black-start capability was left outside of the scope of this thesis, but a BESS could provide black-start service, however the value of black-start should have to be higher than the value of FCR-N to be economically viable. This is due to the capacity requirement, which the black-start capability requires.

The payback time of a BESS participating to an FCR-N hourly market and providing reactive power compensation was calculated to be approximately 15 years, and having an approximate net present value of 200 000 EUR after 20 years.

8.3 Discussion

Battery energy storages offer a fast and reliable frequency control, superior to traditional hydro and gas turbine power. However, current frequency regulation markets can be unjust for BESS operators due to the unreasonable remuneration, which doesn’t take account of the fast ramping capability. In 2011, the Federal Energy Regulatory Commission (FERC) in the USA issued new rules (FERC order 755) for performance based pricing of frequency regulation service markets. These new rules take into account the speed and accuracy of the delivered frequency regulation power. Therefore, FERC order 755 is making energy storage economically more viable by increasing its remuneration.

8.4 Market regulation of frequency control as a market enabler

Risks of a BESS are mostly related to market risks, and to a lesser extent also to operational risks. Changes in market regulation rules e.g. deadband of FCR-N can lead to a higher operational time of a BESS. Higher operational time and power output cause higher energy losses, energy costs, and higher battery degradation. Also, increasing operational time requirement increases battery capacity, which has a direct effect on the investment cost of a BESS. Another market risk is related to the FCR markets themselves. The market value and size of hourly FCR-N market fluctuates, thus causing uncertainty of the payback time.

Today’s frequency regulation markets are not designed to take into account the strengths and weaknesses of battery energy storages systems. As a relatively new and rare resource, regulators globally have not set much weight or interest to facilitate regulatory rules concerning energy storages.

It is however the choice of the TSO’s if they want clean, faster, and more capable frequency control. There are a few market model improvements that TSO’s could consider to increase viability of energy storages. First of all, it would be important to implement an official and functioning grid code to support energy storage investments. Increasing the value of up-regulation by implementing an asymmetric market model would employ full potential of a BESS, as the value of up-regulation power is higher than down-regulation power. Rewarding fast ramping capability by implementing performance based remuneration would also be advisable. And finally, dedicating a portion of the market share of frequency control explicitly to energy storages would promote clean energy industry.

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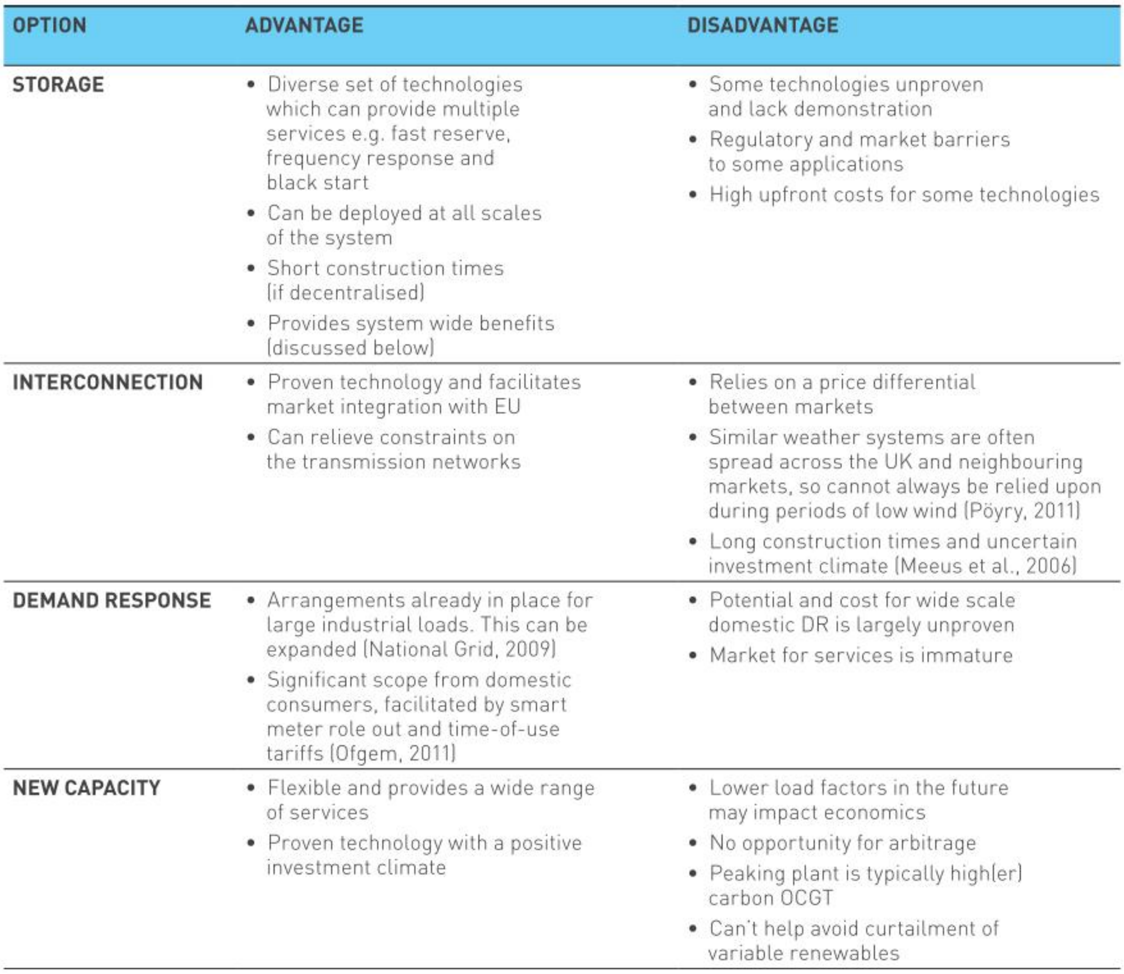
Appendixes

Appendix 1. Characteristics of different balancing options (Bolton et al, 2012: 29)
Appendix 2. FCR hourly market compensation for 1 MW in 2011 – 2014
Appendix 3. Comparison of battery technologies (Bolton et al, 2012: 21)
Appendix 4. Matlab code for simulating BESS in frequency regulation
Appendix 5. Control block diagram of Apros BESS model
Appendix 6. Simulation results

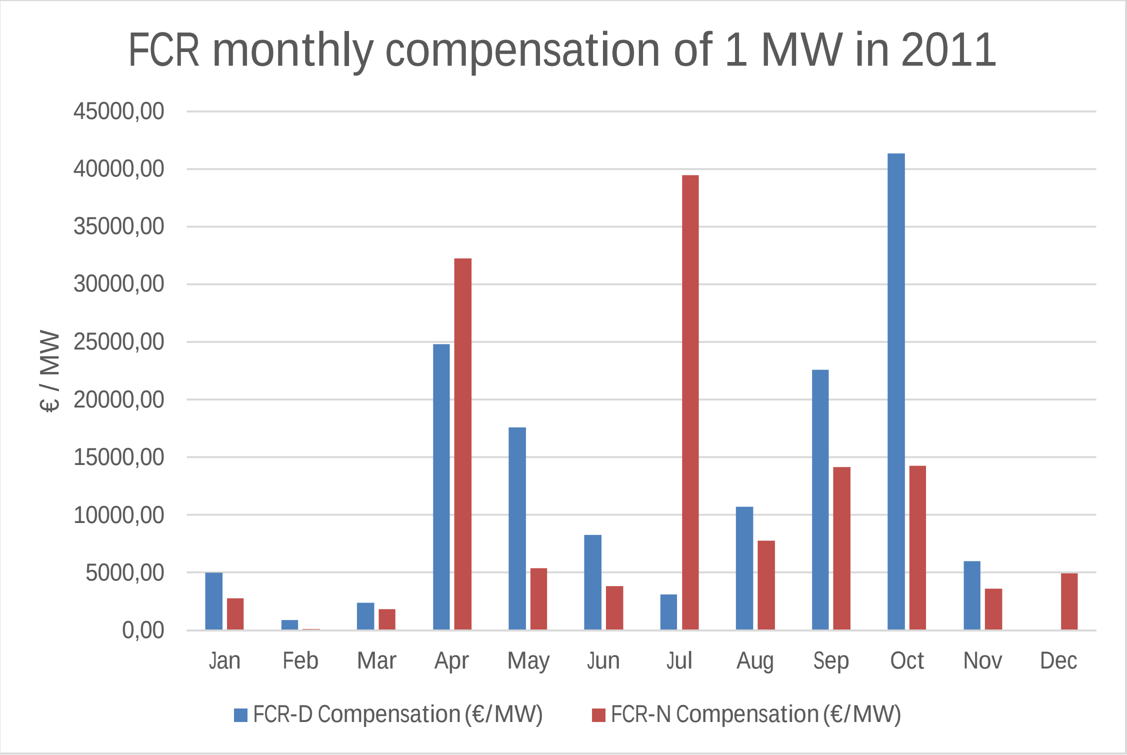
Appendix 1. Characteristics of different balancing options (Bolton et al, 2012: 29)



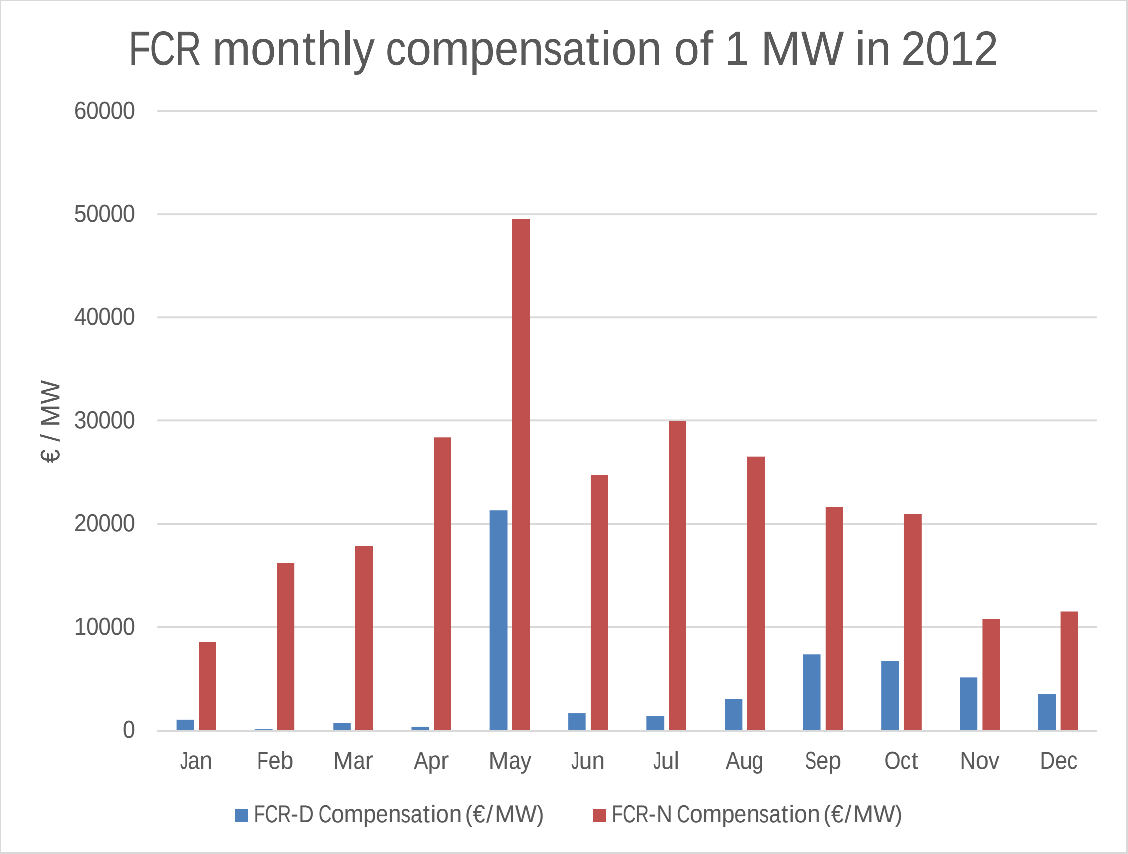
OPTION	ADVANTAGE	DISADVANTAGE
STORAGE	• Diverse set of technologies which can provide multiple services e.g. fast reserve, frequency response and black start • Can be deployed at all scales of the system • Short construction times (if decentralised) • Provides system wide benefits (discussed below)	• Some technologies unproven and lack demonstration • Regulatory and market barriers to some applications • High upfront costs for some technologies
INTERCONNECTION	• Proven technology and facilitates market integration with EU • Can relieve constraints on the transmission networks	• Relies on a price differential between markets • Similar weather systems are often spread across the UK and neighbouring markets, so cannot always be relied upon during periods of low wind (Pöyry, 2011) • Long construction times and uncertain investment climate (Meeus et al., 2006)
DEMAND RESPONSE	• Arrangements already in place for large industrial loads. This can be expanded (National Grid, 2009) • Significant scope from domestic consumers, facilitated by smart meter role out and time-of-use tariffs (Ofgem, 2011)	• Potential and cost for wide scale domestic DR is largely unproven • Market for services is immature
NEW CAPACITY	• Flexible and provides a wide range of services • Proven technology with a positive investment climate	• Lower load factors in the future may impact economics • No opportunity for arbitrage • Peaking plant is typically high(er) carbon OCGT • Can't help avoid curtailment of variable renewables

Appendix 2. FCR hourly market compensation for 1 MW in 2011 – 2014 (Data: Fingrid)

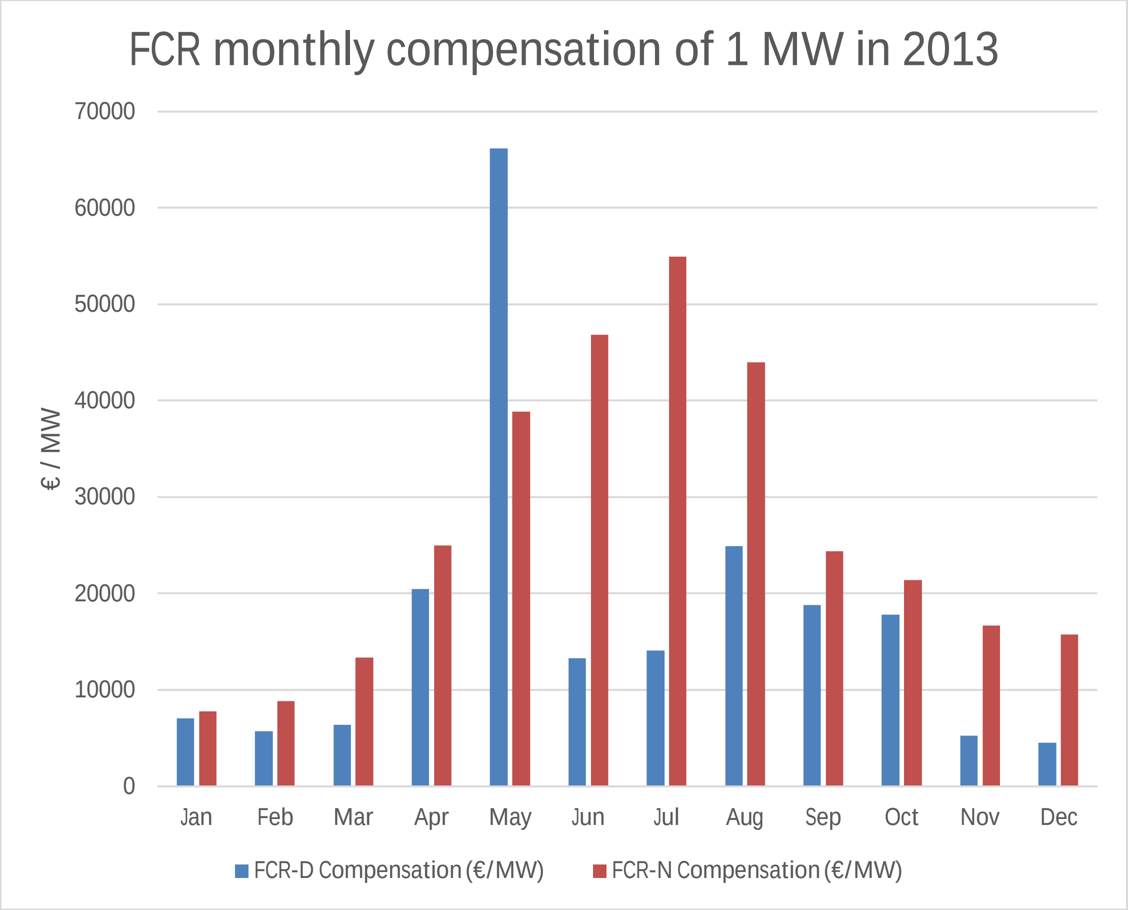
2011	FCR-D value (EUR/MW)	FCR-N value (EUR/MW)
Jan	5 021.17	2 781.87
Feb	941.09	146.94
Mar	2 401.53	1 882.64
Apr	24 882.60	32 316.49
May	17 627.06	5 405.94
Jun	8 327.30	3 835.7
Jul	3 140.15	39 491.6
Aug	10 745.63	7 825.1
Sep	22 644.97	14 218.3
Oct	41 420.90	14 323.7
Nov	6 023.39	3 620.3
Dec	5 192.81	4 999.2
TOT	148 368.6	130 847.78



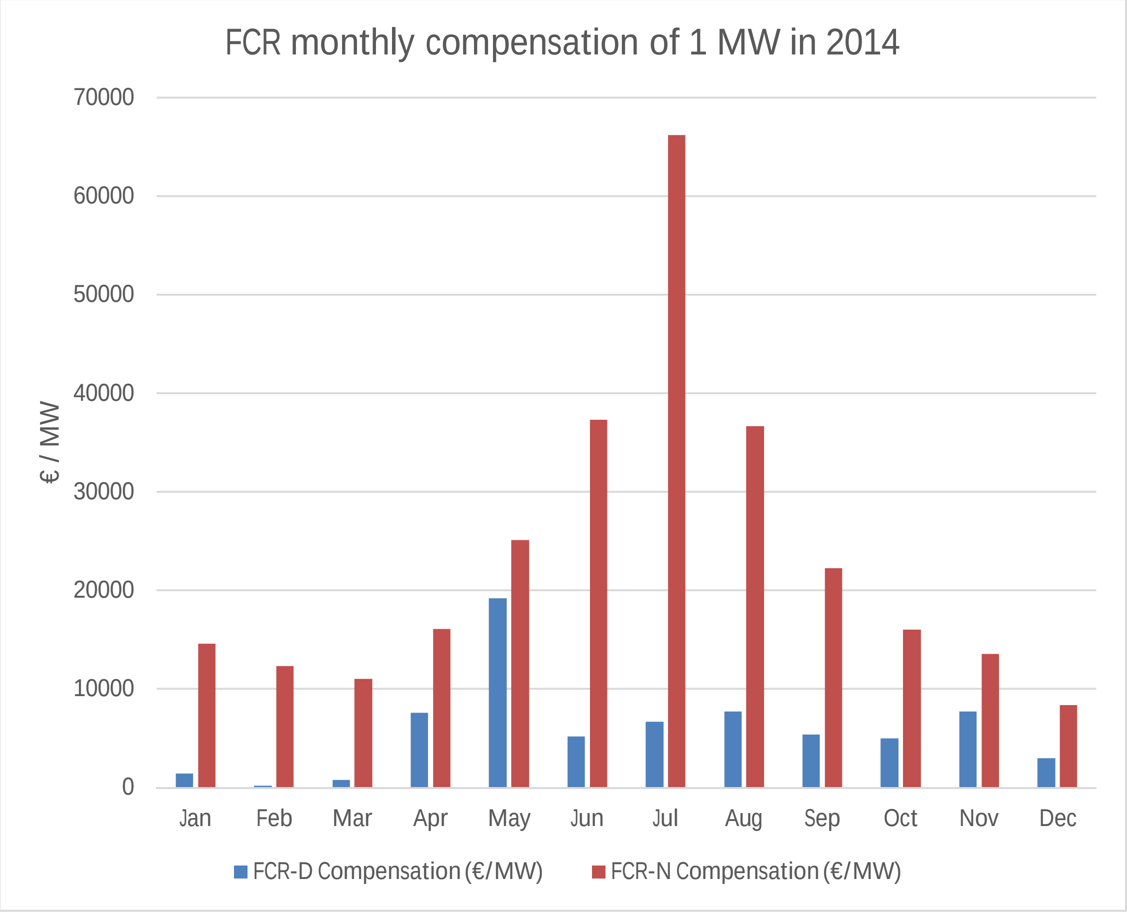
2012	FCR-D value (EUR/MW)	FCR-N value (EUR/MW)
Jan	1 059.3	8 559.57
Feb	140.25	16 285.62
Mar	715.14	17 853.95
Apr	399	28 415.9
May	21 346.6	49 547.2
Jun	1 690.66	24 756.5
Jul	1 456.06	30 023.85
Aug	3 061.41	26 535.5
Sep	7 400.55	21 671.94
Oct	6 750.59	20 968.5
Nov	5 180.22	10 785.5
Dec	3 549.06	11 538.8
TOT	52 748.84	266 942.83



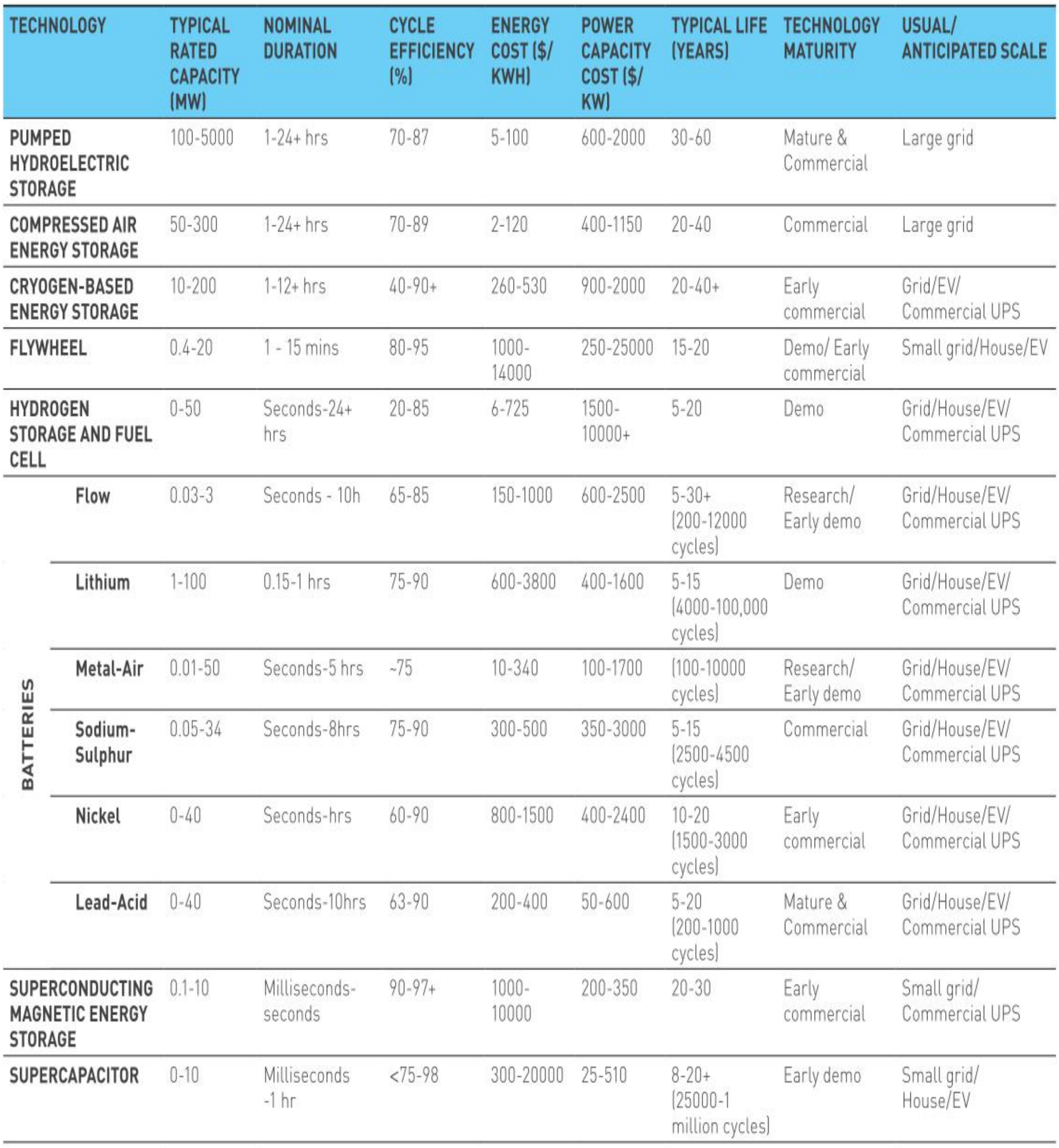
2013	FCR-D value (EUR/MW)	FCR-N value (EUR/MW)
Jan	7 086.07	7 819.36
Feb	5 743.93	8 860.05
Mar	6 402.46	13 407.75
Apr	20 498.84	25 040.61
May	66 225.31	38 932.94
Jun	13 311.32	46 854.8
Jul	14 140.1	54 969.5
Aug	24 957.51	44 039.7
Sep	18 803.44	24 427.34
Oct	17 851.9	21 401.32
Nov	5 272.7	16 716.1
Dec	4 538.3	15 757.3
TOT	204 831.88	318 226.77



2014	FCR-D value (EUR/MW)	FCR-N value (EUR/MW)
Jan	1 429.39	14 575.97
Feb	228.9	12 333.42
Mar	777	11 043.9
Apr	7 630.3	16 131.28
May	19 197.7	25 099.05
Jun	5 176.4	37 334.3
Jul	6 672.6	66 199.9
Aug	7 707.45	36 688.25
Sep	5 374.6	22 275.55
Oct	5 024.3	16 022.64
Nov	7 727.4	13 573.85
Dec	2 983.4	8 392.1
TOT	69 929.44	279 670.21



Appendix 3. Comparison of battery technologies (Bolton et al, 2012: 21)



TECHNOLOGY		TYPICAL RATED CAPACITY (MW)	NOMINAL DURATION	CYCLE EFFICIENCY (%)	ENERGY COST ($/ KWH)	POWER CAPACITY COST ($/ KW)	TYPICAL LIFE (YEARS)	TECHNOLOGY MATURITY	USUAL/ ANTICIPATED SCALE
PUMPED HYDROELECTRIC STORAGE		100-5000	1-24+ hrs	70-87	5-100	600-2000	30-60	Mature & Commercial	Large grid
COMPRESSED AIR ENERGY STORAGE		50-300	1-24+ hrs	70-89	2-120	400-1150	20-40	Commercial	Large grid
CRYOGEN-BASED ENERGY STORAGE		10-200	1-12+ hrs	40-90+	260-530	900-2000	20-40+	Early commercial	Grid/EV/ Commercial UPS
FLYWHEEL		0.4-20	1 - 15 mins	80-95	1000-14000	250-25000	15-20	Demo/ Early commercial	Small grid/House/EV
HYDROGEN STORAGE AND FUEL CELL		0-50	Seconds-24+ hrs	20-85	6-725	1500-10000+	5-20	Demo	Grid/House/EV/ Commercial UPS
BATTERIES	**Flow**	0.03-3	Seconds - 10h	65-85	150-1000	600-2500	5-30+ (200-12000 cycles)	Research/ Early demo	Grid/House/EV/ Commercial UPS
	Lithium	1-100	0.15-1 hrs	75-90	600-3800	400-1600	5-15 (4000-100,000 cycles)	Demo	Grid/House/EV/ Commercial UPS
	Metal-Air	0.01-50	Seconds-5 hrs	~75	10-340	100-1700	(100-10000 cycles)	Research/ Early demo	Grid/House/EV/ Commercial UPS
	Sodium-Sulphur	0.05-34	Seconds-8hrs	75-90	300-500	350-3000	5-15 (2500-4500 cycles)	Commercial	Grid/House/EV/ Commercial UPS
	Nickel	0-40	Seconds-hrs	60-90	800-1500	400-2400	10-20 (1500-3000 cycles)	Early commercial	Grid/House/EV/ Commercial UPS
	Lead-Acid	0-40	Seconds-10hrs	63-90	200-400	50-600	5-20 (200-1000 cycles)	Mature & Commercial	Grid/House/EV/ Commercial UPS
SUPERCONDUCTING MAGNETIC ENERGY STORAGE		0.1-10	Milliseconds-seconds	90-97+	1000-10000	200-350	20-30	Early commercial	Small grid/ Commercial UPS
SUPERCAPACITOR		0-10	Milliseconds -1 hr	<75-98	300-20000	25-510	8-20+ (25000-1 million cycles)	Early demo	Small grid/ House/EV

Appendix 4. Matlab code for simulating BESS in frequency regulation

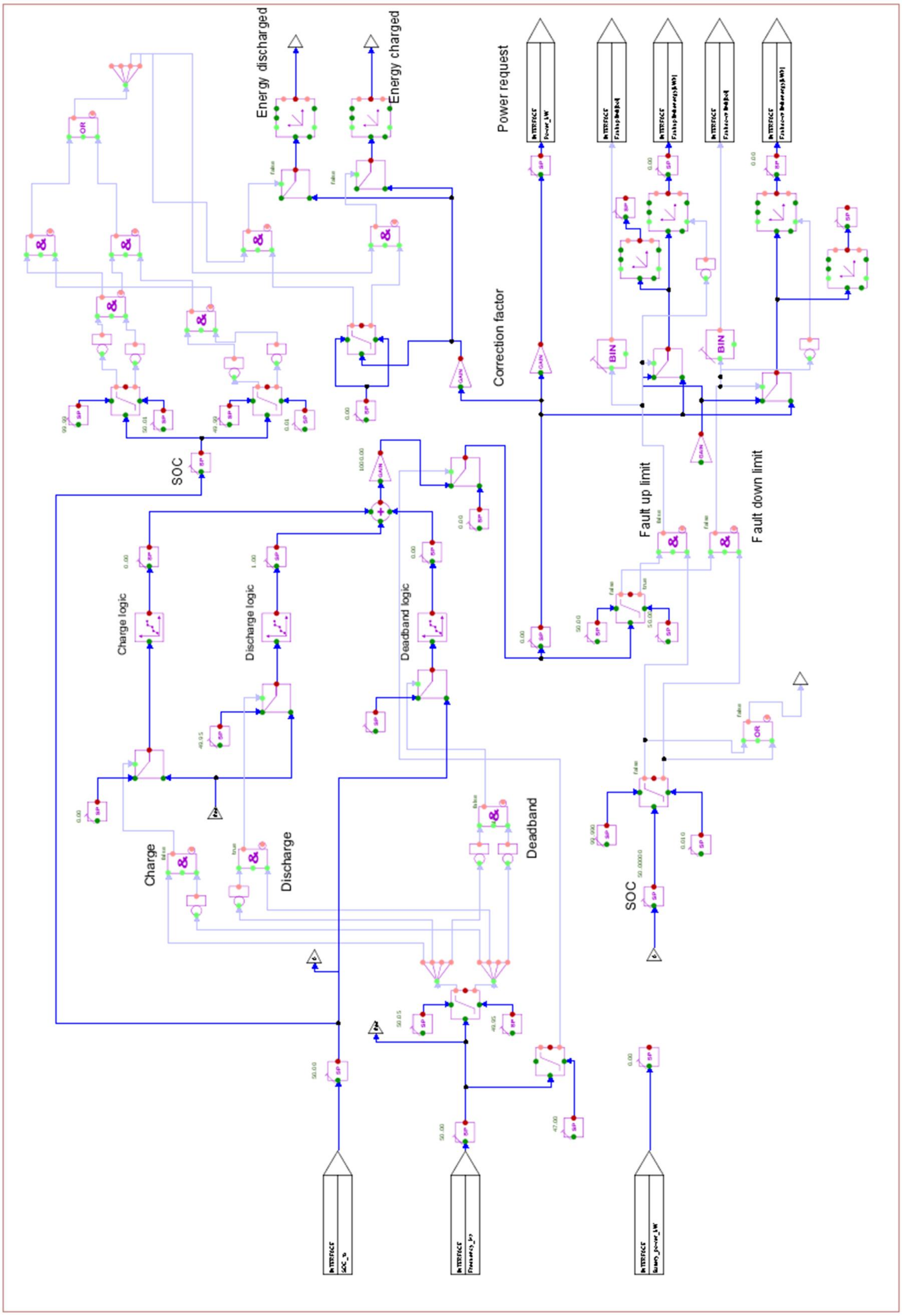
```
% Program to simulate a BESS at FCR market
% Author: Janne Huvilinna, 2015
% This program simulates one month using one second fre-
quency data
% All rights reserved :)

data = importdata('monthly_frequnecy_data.txt');

%% Initialize BESS
dispstat('','init'); % Progress information due to long
simulation time
dispstat(sprintf('Beginning the simula-
tion...'),'keepthis','timestamp');

Power_max = 1000; % Maximum power in kW
P = 0; % Instantaneous power request in kW
Capacity_max = 500; % Maximum energy capacity in kWh
Capacity = 250; % Instantaneous capacity in kWh
SOC = Capacity/Capacity_max; % State of charge
results = zeros(2678400,14); % Data logging
final_results = zeros(11,1); % Final results
up_E = 0; % Delivered up regulation energy
up_B = 0; % Delivered up regulation boolean
down_E = 0; % Delivered down regulation energy
down_B = 0; % Delivered down regulation boolean
F_up_E = 0; % Undelivered up regulation energy
F_up_B = 0; % Undelivered up regulation boolean
F_down_E = 0; % Undelivered down regulation energy
F_down_B = 0; % Undelivered down regulation boolean
idle = 0; % Idle time

% Example script for control logic 1
for i=1:2678400
    %% f < 47Hz
    if (data(i,1) <= 47)
       P = 0;
    end

    %% 47Hz < f < 49.90Hz
    if (data(i,1) > 47 && data(i,1) < 49.90)
       P = -Power_max;
    end

    %% 49.90Hz <= f <= 49.95Hz
    if (data(i,1) >= 49.90 && data(i,1) <= 49.95)
       P = -Power_max * ((-20) * (data(i,1)) + 999);
```

```
    end

    %% 49.95Hz < f < 50.05Hz
    if (data(i,1) > 49.95 && data(i,1) < 50.05)
       P = 0;
    end

    %% 50.05Hz <= f <= 50.10Hz
    if (data(i,1) >= 50.05 && data(i,1) <= 50.10)
       P = Power_max * (20 * (data(i,1)) - 1001);
    end

    %% f > 50.10Hz
    if (data(i,1) > 50.10)
       P = Power_max;
    end

    %% BESS in operation
    if (Capacity <= 0)
        if (P < 0)
           F_up_E = F_up_E + P * (1/3600);
           F_up_B = 1;
           up_B = 0;
           Capacity = 0;
           SOC = 0;
        end

        if (P > 0)
            Capacity = Capacity + (P * (1/3600));
            SOC = Capacity/Capacity_max;
            F_up_B = 0;
            up_B = 1;
        end

        if (P == 0)
            F_up_B = 0;
            up_B = 0;
        end
    end

%%
    if (Capacity >= Capacity_max)
        if (P > 0)
           F_down_E = F_down_E + P * (1/3600);
           F_down_B = 1;
           down_B = 0;
           Capacity = Capacity_max;
           SOC = 1;
        end

        if (P < 0)
           F_down_B = 0;
```

```
           down_B = 1;
           Capacity = Capacity + (P * (1/3600));
           SOC = Capacity/Capacity_max;
        end

        if (P == 0)
            F_down_B = 0;
            down_B = 0;
        end
    end

%%
    if (Capacity > 0 && Capacity < Capacity_max)
        Capacity = Capacity + (P * (1/3600));
        SOC = Capacity/Capacity_max;

        if (Capacity < 0)
           Capacity = 0;
           SOC = 0;
        end

        if (Capacity > Capacity_max)
           Capacity = Capacity_max;
           SOC = 1;
        end

        if (P > 0)
            down_B = 1;
            up_B = 0;
            down_E = down_E + (P * (1/3600));
        end

        if (P < 0)
            up_B = 1;
            down_B = 0;
            up_E = up_E + (P * (1/3600));
        end

        if (P == 0)
            up_B = 0;
            down_B = 0;
        end
    end

    if (up_B == 0 && down_B == 0)
        idle = 1;
    else
        idle = 0;
    end
%%
    results(i,1) = i; % Time step of one second
    results(i,2) = data(i,1); % Frequency
```

```
    results(i,3) = P; % Instantaneous power request
    results(i,4) = Capacity; % Instantaneous capacity
    results(i,5) = SOC; % Instantaneous SOC
    results(i,6) = up_B; % Up regulation activated
    results(i,7) = up_E; % Up regulation energy
    results(i,8) = down_B; % Down regulation energy
    results(i,9) = down_E; % Down regulation activated
    results(i,10) = F_up_B; % Undelivered up regulation ac-
tive
    results(i,11) = F_up_E; % Undelivered up regulation en-
ergy
    results(i,12) = F_down_B; % Undelivered down regulation
active
    results(i,13) = F_down_E; % Undelivered down regulation
energy
    results(i,14) = idle; % Idle time

    dispstat(sprintf('Calculating
%2.0f%%',i/2678400*100),'timestamp');
end
dispstat('Finished.','keepprev'); % Simulation ended

%% Final results in one table
M = mean(results);
final_results(1,1) = M(1,5); % Avg SOC
final_results(2,1) = M(1,3); % Avg Power
final_results(3,1) = results(end,7); % up_E
final_results(4,1) = results(end,9); % down_E
final_results(5,1) = results(end,11); % F_up_E
final_results(6,1) = results(end,13); % F_down_E
final_results(7,1) = M(1,10); % Avg F_up_B
final_results(8,1) = M(1,12); % Avg F_down_B
final_results(9,1) = M(1,6); % Avg up_B
final_results(10,1) = M(1,8); % Avg down_B
final_results(11,1) = M(1,14); % Avg idle_B
```

Appendix 5. Control block diagram of Apros BESS model



Appendix 6. Simulation results

Logic 1 (2013)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	TOT	Ratio
Avg SOC (%)	0,526	0,582	0,520	0,578	0,434	0,534	0,505	0,550	0,511	0,510	0,518	0,519	0,524		
Avg Power (kW)	11,262	-0,100	2,070	7,934	-3,561	2,042	5,358	8,810	7,373	10,703	5,823	7,032	5,395		
up_E (kWh)	-20506	-7793	-19052	-22117	-28143	-18073	-26853	-31815	-25377	-27861	-18933	-22239	-22397	-268762	2,518296
down_E (kWh)	20529	7913	19241	22008	28211	17876	26607	32069	25622	27654	19184	22478	22449	269392	1,75256
F_up_E (kWh)	-7440	-3866	-10351	-5563	-10369	-7371	-10997	-11489	-14850	-10141	-6444	-7843	-8894	-106724	0,397
F_down_E (kWh)	15796	3678	11701	11384	7652	9038	15229	17789	19913	18311	10385	12836	12809	153714	0,571
Avg F_up_B	0,024	0,014	0,030	0,018	0,031	0,025	0,036	0,035	0,044	0,031	0,021	0,027	0,028		
Avg F_down_B	0,044	0,013	0,033	0,033	0,021	0,024	0,043	0,049	0,055	0,044	0,032	0,040	0,036		
Avg up_B	0,078	0,032	0,068	0,081	0,090	0,063	0,094	0,108	0,091	0,095	0,077	0,081	0,080		
Avg down_B	0,073	0,033	0,066	0,072	0,097	0,064	0,089	0,101	0,086	0,089	0,073	0,076	0,077		
Avg idle_B	0,848	0,935	0,865	0,847	0,813	0,873	0,817	0,791	0,823	0,816	0,850	0,843	0,844		
Logic 2 (2013)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	TOT	
Avg SOC	0,505	0,652	0,507	0,520	0,499	0,377	0,471	0,512	0,509	0,491	0,491	0,474	0,501		
Avg Power	4,753	0,891	-0,667	2,401	-4,766	-1,310	0,033	4,393	0,711	-0,763	2,263	1,907	0,820		
up_E	-51407	-20043	-51120	-50887	-64209	-42332	-59082	-61427	-55819	-58055	-51438	-54808	-51719	-672345	1,282014
down_E	51540	20298	51349	50625	64129	42071	58846	61681	56071	57930	51684	54987	51768	672978	1,266017
F_up_E	-42640	-17292	-39547	-34991	-41081	-28256	-48471	-52675	-52344	-48584	-36437	-41785	-40342	-524444	0,780
F_down_E	46044	17636	38821	36981	37614	27574	48732	55690	52604	48142	37819	43025	40890	531571	0,790
Avg F_up_B	0,152	0,066	0,132	0,119	0,129	0,095	0,162	0,161	0,170	0,158	0,135	0,146	0,136		
Avg F_down_B	0,137	0,069	0,124	0,115	0,125	0,083	0,146	0,164	0,156	0,132	0,126	0,135	0,126		
Avg up_B	0,251	0,113	0,263	0,258	0,274	0,187	0,256	0,259	0,254	0,258	0,267	0,263	0,242		
Avg down_B	0,242	0,116	0,263	0,247	0,283	0,191	0,259	0,250	0,250	0,251	0,264	0,258	0,239		
Avg idle_B	0,507	0,771	0,474	0,495	0,443	0,622	0,485	0,490	0,497	0,492	0,469	0,479	0,519		
Logic 3 (2013)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	TOT	
Avg SOC	0,498	0,665	0,516	0,511	0,504	0,364	0,474	0,509	0,511	0,488	0,489	0,474	0,500		
Avg Power	1,683	1,305	-1,413	0,340	-3,701	-2,051	-1,316	3,361	-1,338	-4,165	0,795	-0,023	-0,544		
up_E	-63860	-26143	-66094	-64345	-78478	-51480	-71673	-72989	-67724	-70032	-65733	-68539	-63924	-831015	1,281887
down_E	63971	26402	66323	64074	78347	51203	71435	73242	67977	69927	65968	68702	63964	831535	1,294312
F_up_E	-54347	-21201	-48966	-43657	-49814	-34624	-59549	-64075	-63283	-60222	-46072	-52597	-49867	-648274	0,780
F_down_E	55488	21819	47685	44173	47191	33425	58808	66323	62067	57228	46409	52418	49419	642453	0,773
Avg F_up_B	0,177	0,074	0,152	0,139	0,147	0,108	0,183	0,182	0,190	0,181	0,156	0,169	0,155		
Avg F_down_B	0,157	0,078	0,143	0,128	0,146	0,096	0,165	0,184	0,174	0,150	0,144	0,153	0,143		
Avg up_B	0,321	0,155	0,352	0,336	0,351	0,236	0,323	0,321	0,320	0,324	0,351	0,341	0,311		
Avg down_B	0,312	0,156	0,352	0,327	0,357	0,239	0,328	0,313	0,315	0,319	0,349	0,337	0,309		
Avg idle_B	0,367	0,689	0,296	0,338	0,293	0,525	0,349	0,365	0,365	0,358	0,300	0,322	0,381		
Logic 4 (2013)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	TOT	
Avg SOC	0,834	0,868	0,834	0,857	0,814	0,783	0,780	0,780	0,788	0,795	0,859	0,824	0,818		
Avg Power	122,993	54,404	113,706	111,888	116,947	82,191	124,175	129,372	124,736	119,821	120,823	122,353	111,951		
up_E	-25046	-10627	-24356	-26212	-36070	-22940	-34650	-37120	-32682	-33388	-23756	-27060	-27825,429	-361731	8,030382
down_E	25315	10886	24636	26169	36304	23158	34497	37399	32956	33660	24037	27331	28029,061	364378	0,328413
F_up_E	-2901	-1032	-5047	-1468	-2443	-2504	-3199	-6184	-7546	-4614	-1621	-3022	-3465,019	-45045	0,124527
F_down_E	94138	37332	89364	82070	89217	61464	95738	102158	97081	93488	88333	93782	85347,093	1109512	3,04495
Avg F_up_B	0,008	0,003	0,014	0,004	0,007	0,008	0,009	0,018	0,021	0,013	0,005	0,010	0,010		
Avg F_down_B	0,335	0,165	0,363	0,309	0,325	0,212	0,319	0,330	0,332	0,305	0,348	0,338	0,307		
Avg up_B	0,095	0,043	0,085	0,095	0,115	0,080	0,120	0,126	0,114	0,113	0,094	0,098	0,098		
Avg down_B	0,134	0,069	0,131	0,145	0,176	0,122	0,174	0,167	0,157	0,163	0,144	0,152	0,144		
Avg idle_B	0,772	0,888	0,784	0,760	0,709	0,798	0,706	0,708	0,728	0,724	0,762	0,750	0,757		
Logic 5 (2013)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	TOT	
Avg SOC	0,764	0,799	0,779	0,776	0,714	0,699	0,689	0,704	0,699	0,708	0,781	0,739	0,738		
Avg Power	48,539	20,041	42,140	42,850	37,817	27,851	43,338	44,645	42,782	43,870	46,543	45,660	40,506		
up_E	-24178	-10170	-23452	-25248	-34833	-21948	-32899	-35776	-30948	-31893	-22551	-26514	-26701	-347111	5,817652
down_E	24434	10425	23713	25171	35028	21951	32689	36033	31202	31989	22815	26771	26852	349072	0,786627
F_up_E	-3769	-1489	-5950	-2431	-3680	-3495	-4951	-7528	-9280	-6109	-2825	-3568	-4590	-59665	0,171891
F_down_E	39625	14702	37042	33361	31620	23546	37404	40487	39828	38652	36073	37282	34135	443758	1,271251
Avg F_up_B	0,011	0,005	0,016	0,007	0,010	0,012	0,014	0,022	0,026	0,017	0,008	0,012	0,013		
Avg F_down_B	0,249	0,123	0,277	0,228	0,212	0,144	0,219	0,234	0,240	0,215	0,255	0,246	0,220		
Avg up_B	0,092	0,042	0,082	0,092	0,111	0,076	0,115	0,121	0,110	0,109	0,091	0,096	0,095		
Avg down_B	0,221	0,111	0,217	0,226	0,289	0,191	0,273	0,262	0,249	0,253	0,237	0,244	0,231		
Avg idle_B	0,688	0,847	0,701	0,682	0,600	0,733	0,612	0,616	0,641	0,638	0,672	0,660	0,674		
Logic 6 (2013)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	TOT	
Avg SOC	0,511	0,521	0,494	0,525	0,487	0,448	0,507	0,515	0,507	0,506	0,517	0,507	0,504		
Avg Power	8,520	-1,275	0,652	7,895	-0,281	3,785	6,479	5,906	5,194	12,186	3,357	5,034	4,788		
up_E	-36948	-15248	-34736	-38760	-48472	-32435	-47217	-51028	-44517	-44605	-37206	-40622	-39316	-511110	5,342068
down_E	36955	15293	34740	38536	48431	32376	47041	51288	44562	44618	37462	40742	39337	511381	3,619508
F_up_E	-6668	-2896	-9125	-4565	-7380	-4852	-7592	-12107	-13091	-9227	-4471	-6344	-7360	-95677	0,187193
F_down_E	13000	1994	9606	10473	7212	7636	12589	16241	16785	18280	6633	9969	10868	141285	0,276281
Avg F_up_B	0,021	0,010	0,024	0,013	0,019	0,014	0,021	0,033	0,035	0,026	0,013	0,020	0,021		
Avg F_down_B	0,034	0,007	0,023	0,026	0,018	0,019	0,032	0,039	0,041	0,040	0,018	0,027	0,027		
Avg up_B	0,166	0,075	0,152	0,174	0,195	0,140	0,199	0,217	0,197	0,185	0,176	0,179	0,171		
Avg down_B	0,157	0,074	0,148	0,166	0,207	0,142	0,195	0,206	0,188	0,183	0,168	0,172	0,167		
Avg idle_B	0,677	0,851	0,699	0,660	0,598	0,719	0,605	0,578	0,615	0,632	0,656	0,650	0,662		