LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

LUT School of Energy Science

Master's Degree Programme in Electrical Engineering

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CONTROL SYSTEM OF BATTERY ENERGY STORAGE TECHNOLOGY – CASE GREEN CAMPUS

Examiners: Professor Samuli Honkapuro.

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ABSTRACT

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The application of renewable energy sources is hindered by their intermittent production behaviour and discrepancy of production hours with periods of high energy demand. One of the solutions is the storing of produced energy to the Battery Energy Storage System (BESS). Afterwards, the present technology ensures the stable supply of energy to the grid and can be used by either Transmission System Operator (TSO) or Distribution System Opertator (DSO) for their purposes

The present Master's thesis introduces the simulation tool allowing to exam artificial multifunctional operation of the battery energy storage system (BESS) in combination with an energy source. The tool was created by use of Python. The conducted test researched work of BESS on the day-ahead and hourly markets and frequency stabilization in the grid. The priority tasks for the system were work on Elspot market and on the market of ancillary services. The working schedule was based on an analysis of peak hours in 2016 on Elspot and Frequency Containment Reserve (FCR) markets. The program did not take into account the battery degradation. In the end, the validation of obtained results with a real setup was conducted

The simulation tool demonstrated the ability of BESS to implement multifunctional work. The chosen SOC range was sufficient to perform tasks on the priority markets during the day. The battery was charging either from the solar power plants or Elbas market.

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My parents deserve separate words of gratitude. You are those people who motivate me to move forward and never get down. Without your support and faith, my dream could never become true.

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I would like to thank all those friends that I found here, in Lappeenranta. My memory is full of warm moments that were shared with you. I appreciate all of you and hope that we will stay in touch in the future.

The last thing that came into my mind is a phrase from one of my favorite books "Alice in Wonderland" by Lewis Carroll: "…Sooner or later everything becomes clear, everything will fall into place and build a single beautiful circuit as lace. It will become clear why it was needed, because everything would be right".

Nelli Nigmatulina

December, 2018

TABLE OF CONTENT

TABLE OF CONTENT 4

LIST OF ABBREVIATIONS 6

1. INTRODUCTION 7

1.1. Motivation and problem-setting 8

1.2. Literature review 11

1.3. Barriers to the BESS inclusion to the work of Finnish electricity market 12

1.4. Objectives and delimitations 13

1.5. Research method and tools 14

1.6. Practical significance 14

1.7. Outline of the thesis 14

2. PV PANELS 16

2.1. History of PV panels 16

2.2. Categories of PV panels 16

2.3. PV panel's structure and principle of work 17

2.4. Weather prediction 18

3. BATTERY TECHNOLOGY 20

3.1. History of battery technology 20

3.2. Structure and working principle 20

3.3. Energy storage technologies 22

3.4. LiFePO4 battery 23

3.5. Application of the Li-ion batteries 25

3.6. Examples of BESS 25

3.6.1. "Suvilahti" (Finland) 26

3.6.2. “Batcave” (Finland) 26
3.6.3. “Enspire ME” (Germany) 26
4. ELECTRICITY MARKET 27
4.1. Nord Pool history 27
4.2. Nord Pool 27
4.2.1. Price formation 28
4.3. The market of ancillary services 29
4.4. Price forecast 31
5. SIMULATION TOOL 33
5.1. The Green Campus 33
5.2. Production vs. consumption of the Green Campus 34
5.3. Formation of the work schedule 35
5.4. Description of the simulation tool work 36
6. VALIDATION OF THE RESULTS 39
6.1 Control model 39
6.2 Work on the markets 40
6.2.1 Charging and discharging characteristics 41
6.2.2 Work on FCR-N market 43
6.3 Profitability calculation 44
7. CONCLUSION 48
REFERENCES 50
Appendix A. The reserves products [38] 56
Appendix B. Flow chart 57
Appendix C. Proposed scenario of act 58

LIST OF ABBREVIATIONS

ANN	artificial neural network
ARMA	autoregressive moving-average model
COP	conference of parties
DG	distributed generation
DOD	depth of discharge
DSO	distribution system operator
EPF	electricity price forecast
EV	electrical vehicles
FEC	full equivalent cycles
FCR	frequency containment reserve
FRR	frequency restoration reserve
FCR-N	frequency containment reserve for normal operation
FCR-D	frequency containment reserve for disturbances
GHG	greenhouse has
LAM	limited area models
LUT	Lappeenranta University of Technology
NEMO	nominated electricity market operator
TSO	transmission system operator
SOC	state of charge
SPP	solar power plant
PV	photovoltaic
RE	renewable energy
RES	renewable energy sources

1. INTRODUCTION

For the last decades, increased attention to the climate change problem affected the development of every life sector. The energy industry has been puzzled by the solution of Energy trilemma. It implies granting of secure, equitable and sustainable energy for everyone. For its solution, in 2011 European Commission claimed to enhance the share of renewable energy in gross final energy consumption up to 55% as minimum by 2050 [1]. Every European country had faced its own target of RES share. In 2017, the first results were summed up. It was oriented out that Green energy consumption increased up to 17%. (Figure 1) [2]. Moreover, several states exceeded their 2020 targets beforehand. Finland was one of them.

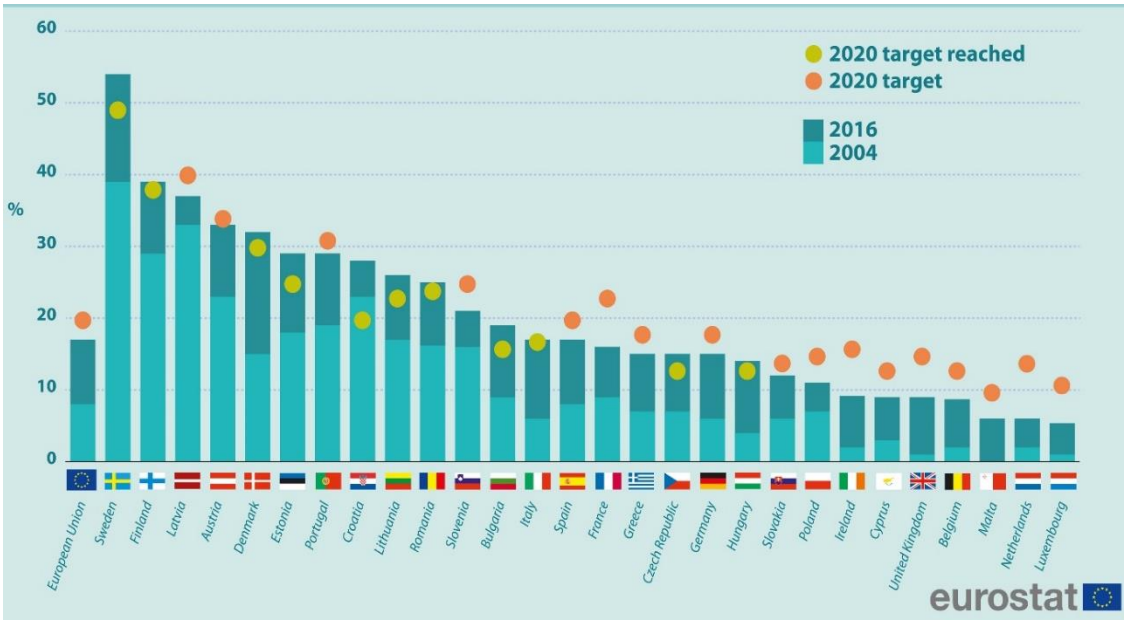

Figure 1. Share of energy from renewable sources in the EU Member States [2]

The quarter of energy in Finland is produced by hydro power plants [3]. However, further growth of this sort of energy is not expected anymore. Major hydro sites are already cycling. As a result, new energy sources are in demand.

One of the most promising energy source on Earth is solar. The difference in quality of solar irradiance on various parts of the planet is about a factor of two [4]. Child et. al. [5] noted that the northern part of Germany and the southern part of Finland does not have significant difference in solar irradiation. Therefore, solar energy can be considered as a new energy resource.

However, production of solar energy in Finland is complicated by its location. During the winter, solar irradiation is much less than during the summer. Eventually, it results in insignificant amount of produced energy. Additionally, hours of solar energy production do not match peak hours of the energy system. Furthermore, it is rule of thumb that production of renewable energy is accompanied by intermittent behaviour. With due regard of increasing electricity consumption, unstable energy generation is destructive to the work of electrical grid. One of the solutions is installation of the renewable-energy power plant in combination with energy storage systems (ESS). Currently, there are several types of them: thermal, chemical, electrochemical, mechanical, thermochemical and electrical. Selection of the appropriate storage depends from its features and type tasks [6]. Current Master's thesis focuses on electrochemical ESS that implies battery technology. Eventually, the combination of "RES + BESS" contributes towards energy security, energy equity and environmental sustainability.

1.1. Motivation and problem-setting

The "PV-panel – BESS" system has a great potential for the future grid operation in Finland. Despite this fact, a number of issues inhibits their wide spreading.

It is common knowledge that the battery cost is rather expensive. According to [7], the cost of the lithium ion battery used for residential installation was currently around 1200€/kWh. Auvinen. K studied the perspective of the solar energy development in Finland [8]. It was noted that the cost of the offgrid system that includes the PV panels with a power of more than 1 kW and a battery will cost around 3500€/kWp. The installation of the batteries together with PV panels increases the cost of the system a lot.

Another issue is connected with recycling of Li-ion batteries. Gaines et.al. analyzed three methods that are currently applied for recycling of Li-ion batteries – pyrometallurgical, hydrometallurgical and direct. It was highlighted that not all the methods are suitable for every type of the battery. For instance, two of those methods could not be applied for LFP batteries. Both results in value reduction of final product. Eventually, all approaches have disadvantages that limit their wide-spreading and needs to be improved [9].

Besides it, consumers possess the low level of knowledge about correct use of the battery. There is a dozen of factors affecting the battery's State-of-Health (SOH). Deep discharging, frequent charging and discharging, temperature criteria play significant role in the battery's

life expectancy. Consequently, it leads to disruptive consequences resulting in earlier battery replacement.

However, in recent years a number of positive events have been happening and enhancing attractiveness of "PV + Battery" system. First of all, Figure 2 clearly shows accelerated growth of the panel's efficiency from 2012 to 2016 for 15%.

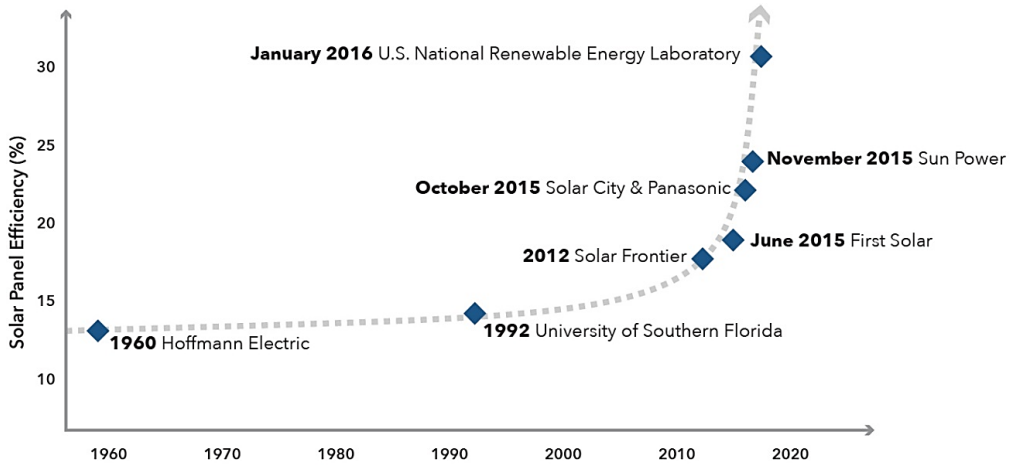

Figure 2. Revolution of the solar power efficiency [10]

Its improvements have led to increased numbers of installations and entailed a price reduction (Figure 3). The graph below demonstrates radical price diminution for over than 100$/W for 40 years.

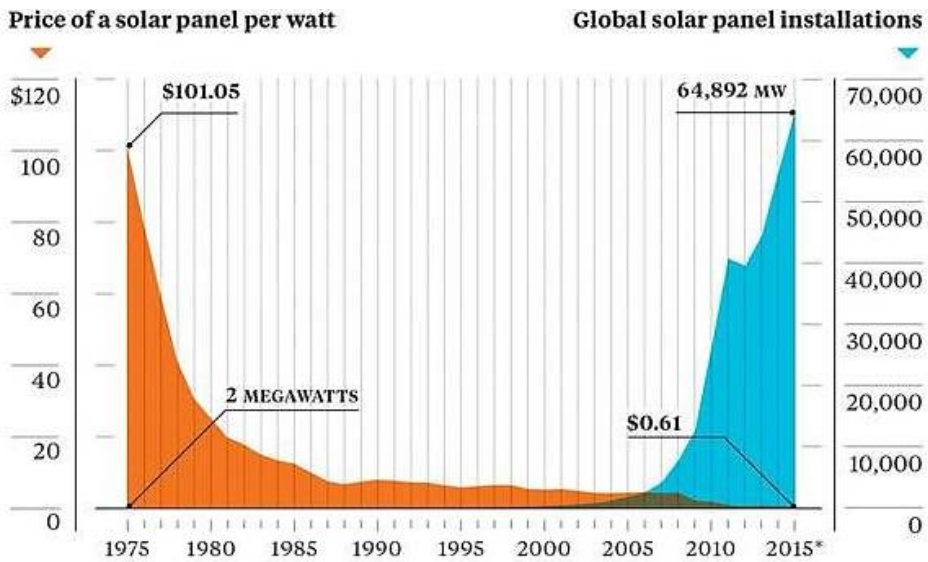

Figure 3. Correlation of the price per PV panel [11]

In addition, recently, a huge leap was performed in development of the waste management in solar industry. This year France claimed about opening of the first facility dedicated to

recycling of the PV panels [12]. Subsequently, a high technology growth and advancements in the recycling question impact towards application of PV panels by various kind of customers.

Among other things, with accumulation of experience and growing demand, the battery cost has been decreasing since their first emergence on the market. Figure 4 depicts the cost forecast for different kind of the batteries for the next 20 years. The symbols on the lines mean the point of achievement of 1 TWh of cumulative capacity. The lines without any symbols indicate nonfulfillment of 1 TWh of cumulative capacity within the given timeline. For pumped hydro storages this value was achieved in 2000, for lead-acid modules in 1970, NiMH: 2046. The graph clearly shows that the cost for all almost all kind of batteries will decrease in the future. For instance, in 2015 the li-ion battery cost was almost 2000$/kWh. However, in 2040 the price of li-ion batteries used for residential installations is expecting to be less than 500$/kWh. With reduction of fossil fuel use, the battery technology is taken into account all over the world. Thus, improvement of current techniques will lead to market growth and subsequent cost reduction.

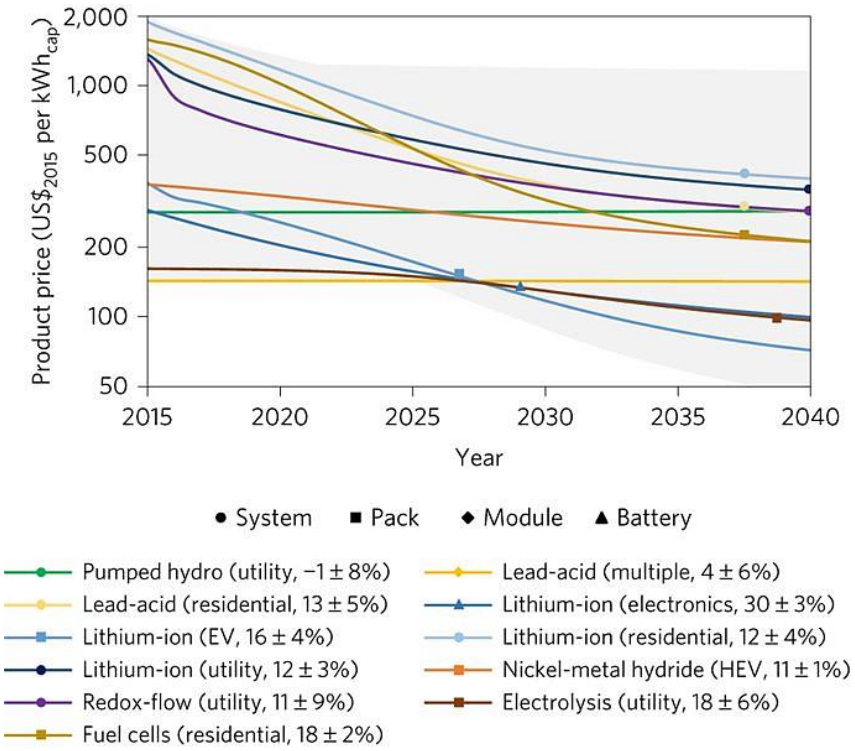

Figure 4. Cost projection of various battery types for the next 20 years [13]

The Finland's target is to become one of the biggest producers of battery technology in Europe. The reason for it is location of all branches of production chain in the country. The

growth of EVs and BESSs use form a ground for growth of battery sector in Finland [14]. Taking into account benefits of BESS and PV panels, their combination makes them one of the advantageous energy suppliers for any customer.

1.2. Literature review

The inclusion of BESS into the work of electricity markets is highly discussed at the current moment. There are many researches considering scenarios of their possible work. In addition, for optimization of their work schedule, methods of price predictions on the markets are also taken into account.

W Gürtler et al. [15] studied models for electricity spot price forecast from eighty-six articles since 2000 to 2015. According to the results, ARMA models are the most used. Wang et al. [16] researched cost prediction on the regulating market with use of two practical approaches. Authors noted substantial price change in the market of ancillary services in contrast with Elspot market. However, it is worth to note that the prices on the regulating market are higher than Elspot prices. It appears more frequently and manifests in significant enhancing of the cost.

Recent studies investigated role of the battery storage systems on the framework of their work on balancing and regulating markets. Tikka et al. [17] considered different aspects of the multipurpose work of BESS. In the framework of this research, simulation tool was implemented for test of different scenarios of BESS work. It was emphasized that the batteries must be used for several tasks for profit increase. In addition, priority of tasks hast to be established to avoid conflicts. Hellman et al. [18] analyzed benefits of BESS for system, market and distribution network on Helsinki example. This study includes first operational results of one of the biggest BESS in Finland – “Suvilahti”. Its work included such tasks as parallel frequency, reactive power and voltage maintenance by the demand of the TSO and DSO. The research showed successful realization of all tasks and brought valuable experience for further researches. Saulny N. studied the results of the joint activity of BESS alongside with the hydropower plant on the hourly regulating market [19]. On the base of “Batcave” model, two scenarios were implemented: All-scenario and Hydro-scenario. In All-scenario battery operated in all possible hours, that might bring profit. Bid assumed to have the lowest price and to provide at least 2 MW of power. For these reasons, every bid in All-scenario was accepted by TSO. In contrast, Hydro-Scenario implied participation only

in hours of HPP involvement. Consequently, it was noted that All-scenario is more advantageous than Hydro-scenario. However, author noted that battery degradation during the work on the markets should be considered in the future.

Some researches highlighted absent of sufficient rules and legislation for correct work of some RES and storages on the market. Huvilinna J. analyzed significance of BESS on the regulating market [20]. It was pointed out that FCR-N with hourly contracts is beneficial for battery's work. In addition, researcher noted that current rules of TSO should be reconsidered for BESS inclusion. Auvinen K. considered the main barriers on the way of development solar energy in Finland [8]. It was highlighted that Finnish Energy sector does not put attention on opportunities for DG implementation.

1.3. Barriers to the BESS inclusion to the work of Finnish electricity market

Both PV panels and BESS have benefits. Their technological growth for the last years demonstrates high interests in them. Its combination makes an impact towards stable and eco-friendly energy supply in Finland. It is easy to install, comparing with other energy resources. These technologies do not produce high-frequency or harmful for life noise. Moreover, the flicker effect is not presented as for wind turbines. However, inclusion both PV panels and BESS in the energy system of Finland is inhibited by some reasons.

Historically, the main energy sources in the country were water, nuclear fuel, gas, coal and wood. Figure 5 illustrates energy sources used for electricity production in 2015.

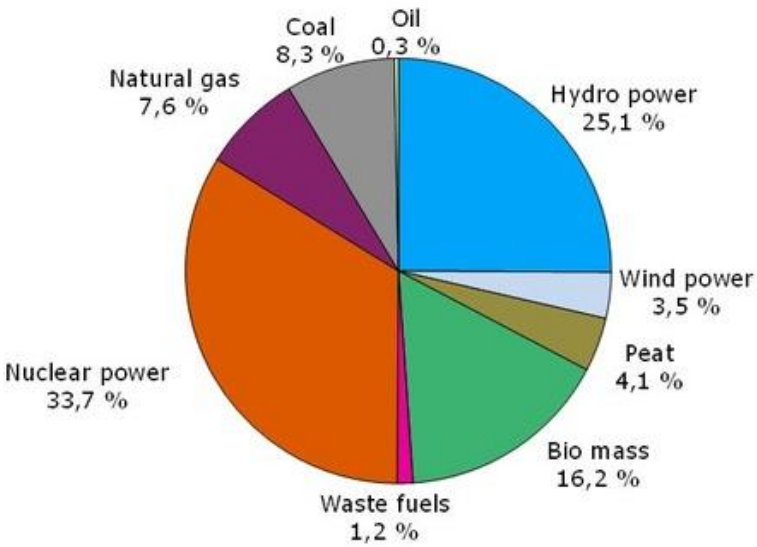

Figure 5. Electricity production by energy sources, 2015 [3]

In 2015, Haukkala [21] noted that the main problem of new energy sources development in Finland is behavioural. The researcher interviewed number of people related to development of solar energy in Finland. The presenters of energy companies and related industries were questioned about necessity of new energy sources involvement in a market. After analysing of all results, it was concluded that promotion of solar energy depends from the actors interests. More than half of power plants working in Finland are hydropower. It is worth to note that HPP participate in the market of ancillary services. With inclusion of new energy sources, owners of power plants, working for many years on the market will suffer economical losses. Therefore, its supporters will barely promote inclusion of new resources in a market.

Next problems arose from the above mentioned. The current feed-in tariff system does not include solar energy. The net-metering system is not legitimized in a country [8]. Besides it, till recently the country had insufficient tax system regarding the work of the BESS. In the Finnish electricity market, batteries were still considered as a customer. At the beginning, the storage owner payed the tax for the electricity when the battery was charging. Then, analogically consumer pays tax, when the battery was discharging. Therefore, role of the batteries on the electricity markets needed to be reconsidered [22].

However, in recent times many positive changes have been happening, Nowadays, Fortum Oyj provides services for installation and follow maintenance of SPP for both private individuals and commercial customers. Recently, Finnish government made first steps towards changing of the current taxation system regarding the BESS. Since the beginning of 2019, the electrochemical ESS will be considered as a part of the grid or a power plant and become duty free. Moreover, the BESS will become under the TSO and DSO ownership only if no party will show its interest or in places where the storage facility is needful for implementation of the operators' commitments [23].

1.4. Objectives and delimitations

The main objective of the work is to create simulation tool implementing decision-making process on the base of several criteria for multi-purpose utilization of BESS with maximization of the economic benefit. Also, the objective includes validation of the tool work with a real battery.

To achieve the objective, next tasks were set:

1. To explore production behaviour of SPP located in Green Campus
2. To examine the work of electricity markets for choice of appropriate working spots.
3. To study Li-ion batteries and their working characteristics
4. To design battery's operation schedule.
5. To develop simulation tool to test and validate with real resources.
6. To analyse results of working scenarios and define their efficiency

There are several delimitations applied during the work. Three working markets were considered: Elspot, Elbas and FCR-N. In priority, work on Elspot and FCR-N was realized. Hours of battery's work were established as permanent for every day. In real life, this value depends from the number of factors such as battery's capacity, the amount of supplied or absorbed energy, battery's ageing effect and etc.

1.5. Research method and tools

For achievement of the determined targets, knowledge about the work of the Li-ion batteries, solar panels and electricity markets were applied.

The object of the research is the solar power plant and BESS located in Lappeenranta University of Technology. The subject of the research is a simulation tool realizing automatic decision-making process.

1.6. Practical significance

Within the current Master's thesis, next key outcomes were derived:

1. Definition of the battery SOC band by two criteria: less destructive for the battery and allowing implementation of its work during the day.
2. Optimization of BESS work on the markets on the base of historical data.
3. Development of the automatically decision-making simulation tool

1.7. Outline of the thesis

Chapter 2 contains information about the work of PV panels. It includes short historical reference, data about variety of solar panels, their structure and mechanism of work. Moreover, it provides information about weather parameters influencing work of the panels and their forecast. In addition, description of the SPP located in LUT is provided.

Chapter 3 provides information about battery technologies: history of their development, kinds, model, work and application. Additionally, the advantages of the LiFePO4 batteries are considered especially. Furthermore, chapter presents examples of BESSs working with the electrical grids in test conditions.

Chapter 4 is dedicated to the analysis of various electricity markets in Finland. Besides, it describes the formation of prices on the markets, factors that impact their development and variants of its prediction.

Chapter 5 is dedicated to the description of the simulation model and strategy choice. Furthermore, it describes the method of the schedule formation and presents the summary of the program work.

Chapter 6 is dedicated to validation of the results with a real battery. It contains description of control model applied for BESS. In addition, it outlined its specific features noted during the tests. Besides it , the chapter provides calculation of the revenue that were derived during the test day.

2. PV PANELS

This chapter introduces one of the technologies used for conversion of solar energy to electricity – PV panels. Historical facts, types of panels, structure and working principle are presented.

2.1. History of PV panels

People began to use solar energy for their own needs in 7th century B.C. Ancient nations applied sun for kindling the fire with subsequent use of it for different purposes. Then, in 1767, Horace de Saussure created the first solar oven. This invention afforded to prepare their food faster and by the safer way [24].

First mention about the conversion of solar energy to electricity is related to 1839 year. Edmund Becquerel noticed the creation of voltage when the light went through the specific material. This opening became a tipping point for the solar energy use. Since that moment, there were plenty openings in physics, allowed people to understand and to use better Becquerel's discovery [24].

The first design of photovoltaic cell was done by Charles Fritts in 1883. It was made of selenium wafers and installed on one of the New York City rooftops. However, the first practical solar cell was invented and presented to the world 70 years later. It was done by three scientists: David Chapin, Calvin Fuller and Gerald Pearson. At the beginning, its conversion efficiency was only 4%. Later, the same three researchers increased it up to 11% [24].

2.2. Categories of PV panels

Solar panels have different modifications, which let them be installed in various places: on a field, on a roof, on a yard. The multiple materials are applied in their manufacture, but the mainly used is silicon. There are three groups of solar panels that are the most commonly used:

- Monocrystalline Silicone (mono-Si)
- Polycrystalline (poly-Si)
- Thin-Film Solar cells

The difference between the types is the purity of the material. Eventually, it affects the efficiency percentage of the PV cells [25].

Monocrystalline technologies are more beneficial than others. They are more advantageous due to manufacturing from the highest-class silicone. Its efficiency fluctuates in the range from 15% to 20%. It makes them space-efficient and provide high output. Consequently, this type of panels requires less space in contrast with others. In addition, their warranty period is 30 years [25].

Polycrystalline solar cell are easier in production and cost less respectively. However, their resulting power output decreases with increasing of the temperature. Consequently, the value of their efficiency is slightly less than for monocrystalline PV panels. In addition, due to low performance, poly-Si panels take more space for installation to produce the same power as mono-Si panels [25].

The efficiency rate of the Thin-Film solar cells is the lowest among all. It varies in a range from 7% to 10%. In contrast with polycrystalline panels, this type of cells is not vulnerable to high temperatures. Their production cost is low as well. However, due to low efficiency rate, they occupy lots of space. Eventually, Thin-Film solar panels become not appropriate for residential building installation [25].

2.3. PV panel's structure and principle of work

Solar panels consist of numerous small sections, which are called photovoltaic cells. These cells covered by glass from the front side and by plastic from the back. Additionally, solar module is sealed in a transparent polymer material. Figure 6 illustrates structure of the PV panel. Insulating back sheet is used to increase reliability and protection from negative weather factors. The last but not the least thing is a junction box that performs a transfer function. It passes produced current further to inverter [26].

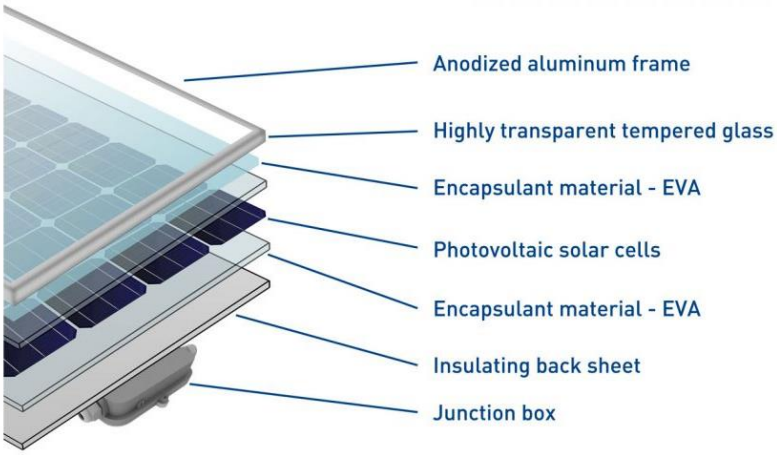

Figure 6 Structure of the photovoltaic panel [26]

Work of the PV panels is conditioned by absorbing of sunlight by photovoltaic cells. Elements of photons knock electrons from the atoms, creating direct current (DC). Then, thanks to the work of inverter, current is converted to the alternating current (AC) and supplied for the regular use [26].

2.4. Weather prediction

Production of solar panels depends a lot from the weather conditions. Figure 7 depicts a daily energy production for February 2018 with respect to the cloudiness and solar irradiance. As it can be seen, energy production has a direct dependence from the correlation of weather parameters. Clear sky and high solar irradiance create auspicious conditions for high energy production.

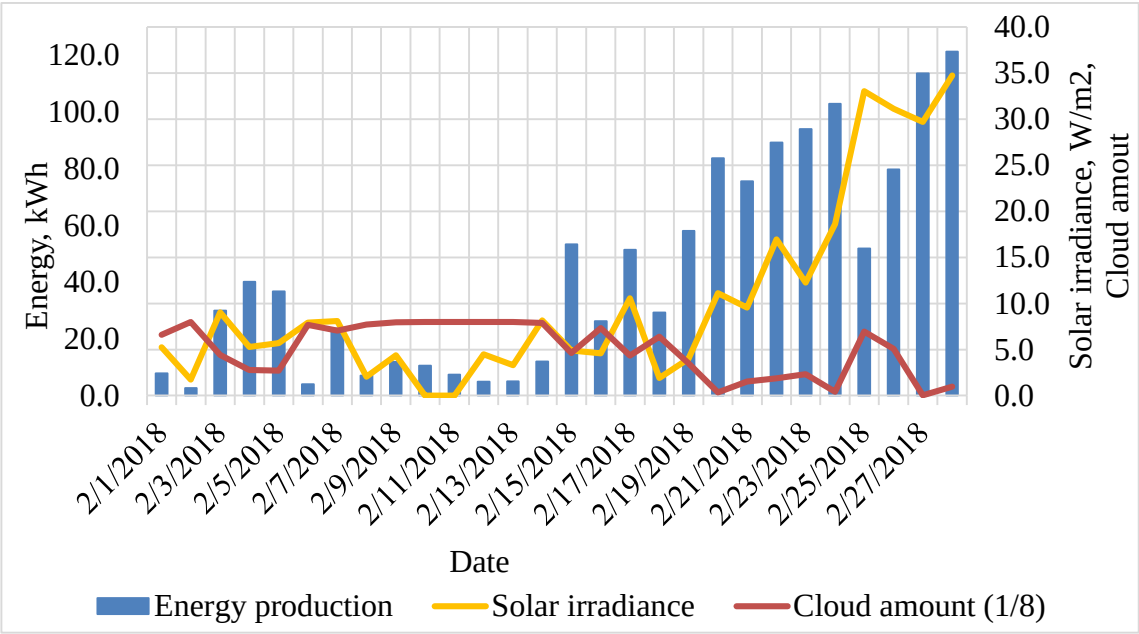

Figure 7. Correlation of energy production from solar irradiation and cloudiness in LUT

With increased penetration of non-traditional energy sources, the weather prognostication became an essential detail for generation companies. It is done by gathering quantitative information about the present state at certain locations and forecasting of its modification by use of meteorology. Moreover, it might be prognosticated for different periods and corrected by new data during the day [27].

For compilation of forecast, different equipment is used: radars, balloon soundings and data from ships and planes. In addition, information from the international networks is handled for a more proper forecast. Another used application are the satellites. They allow obtaining

of information about cloudiness, humidity, temperature, wind speed, directions and lightning. All of it affords to create a highly accurate forecast with difference with real observation of 1-2°C [27].

Besides it, generation companies use weather prognostication for development of the precise working plan. By use of artificial neural network, it could be done for several weeks in advance. ANN uses historical data and weather prediction to obtain forecast of the PV panel output. Historical data includes a combination of the weather parameter and solar power output. Thanks to it, approximate power output can be derived and applied for the current prognostication.

3. BATTERY TECHNOLOGY

The present chapter is dedicated to the battery technologies. During the chapter, specific emphasis will be put on Li-ion battery and LiFePO4 batteries installed in LUT precisely. First of all, the history of the battery technology is presented. Then, structure and working principle of the Li-ion battery are outlined. At the completion, the batteries application and examples of BESS will be described.

3.1. History of battery technology

The history of the battery technology started a long time ago. Alessandro Volta is considered as a person, who innovated the first battery. It was created in 1799 and was done as a system of stacked alternating layers of zinc, brine-soaked pasteboard or cloth, and silver. The main disadvantage of this novelty was "Hydrogen bubble" created at the bottom of the zinc electrodes. Eventually, it shorted battery's application and lifespan [28].

The "Hydrogen bubble" problem was solved in 1836 by John Frederick Daniell. He invented a so-called "Daniell cell" - copper pot filled with copper sulfate solution, immersed in an earthenware pot tank filled with sulfuric acid and a zinc electrode. The electrical potential used in "Daniell cell" became the basis unit for voltage – one volt [28].

The epoch of rechargeable batteries had begun in1859 with Gaston Planté. He was a person who introduced the first lead-acid battery. At the present moment, lead-acid batteries are still one of the most popular solutions for many applications [28].

For the next 150 years, scientists brought to the world many other kinds of batteries such as alkaline, nickel-metal hydride, nickel-cadmium and others. In 1991 Sony performed the major innovation in the battery world - the Li-ion battery. Its success is determined by high capacity, potential and low density. For the last thirty years, huge leap was done to improve initial characteristics of the lithium and decrease its cost [28].

3.2. Structure and working principle

The patterns of battery technology are similar to each other. The differences are in a material chosen for the cathode, anode, electrolyte and separator. Basically, for the Li-ion batteries, metal oxide is used as a cathode. On its base, decision about the battery's performance and further battery's design is derived. Depending from the content, it might be high energy or high power batteries. Currently, there are several main cathode materials: lithium-

manganese, lithium-cobalt, lithium phosphate and lithium nickel manganese cobalt (or NMC). In Li-ion batteries the main material for anode performs graphite. Its porous structure and high inner surface allow storing of ions [29].

The choice of the material for the electrolyte depends from the final application of the battery. Mainly, there are two types of electrolyte used for Li-ion batteries: liquid and polymer. The main substance for the liquid electrolyte is an organic solvent with the mixture of lithium salts. Eventually, these batteries are applied for electric vehicle and hybrid-electrical vehicles. In contrast, technology with the polymer electrolyte uses polyethylene oxide with lithium salt. However, this type of electrolyte has poor conductivity and can be utilized only at high temperatures. Subsequently, application of these batteries is low. Figure 8 below demonstrates the structure of the Li-ion battery and working principle [29].

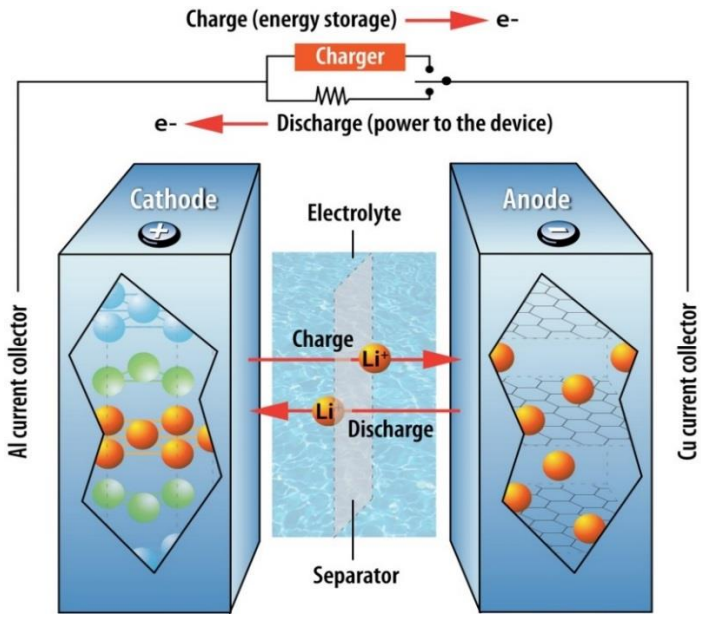

Figure 8. Working principle of the li-ion battery [29]

Lithium ion battery operates on the base of electrochemical reactions which undergoing inside the battery. During the charging positively charged ions flow from the cathode to the anode thorough the electrolyte and separator and intercalate in the porous structure of the anode. During discharging, ions flow from the anode other way around. The electrolyte does not participate in the process chemically and appear as a conductive element for the ions. During the process of charging or discharging no electrons pass inside the battery. Otherwise it will result in short-circuit. Electric charges move the same way as ions, but through the

external circuit. Eventually, they unite with ions in the electrodes and accumulate lithium there [29].

3.3. Energy storage technologies

Battery storage technologies represents one group of energy storages used in the grid work.

There are several techniques applied for energy accumulation for different periods of time. They differ in dependence of the energy type employed for the storage. Energy storages are subdivided as:

- Electrical (capacitor, supercapacitor, superconducting magnetic energy storage)
- Mechanical (pumped hydro, compressed air (CAES), flywheel)
- Electrochemical (secondary battery (lead-acid, li-ion and others) and flow battery (redox flow, hybrid flow-ZnBr)
- Chemical (hydrogen fuel cell)
- Thermal (cryogenic, high temperature thermal and others) [6]

Application of one or another energy storage depends from the functionalities that are established for the device. Figure 9 illustrates ESS applied for the power grid. The figure shows amount of power, time and sort of task that equipment can implement.

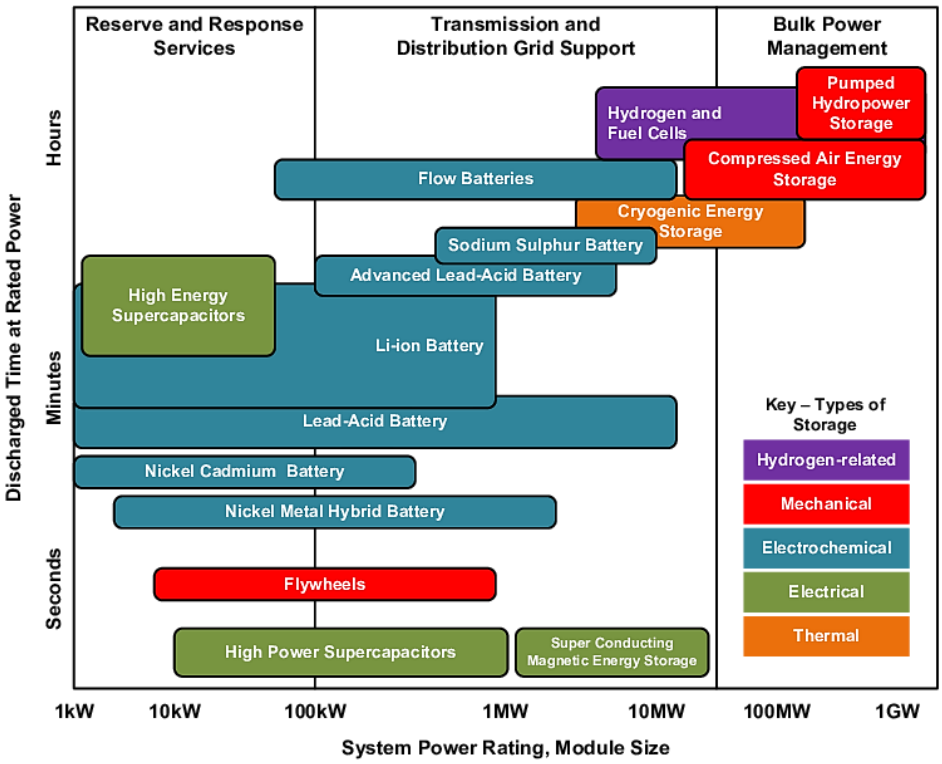

Figure 9. Energy storage technologies applied for the grid work [30]

Basically, ESS are used for the three types of tasks. Every of them implies list of functionalities that the battery might provide for the grid. The first task is maintenance of the power quality. It implies stabilization of the grid technical parameters such as voltage and frequency. The next task is grid support. This term includes load shifting and power bridging. Thanks to ESS, energy consumption could be shifted from the peak hours to another time period. Eventually, it contributes towards electricity price reduction and decreases chances of the grid overloading. Power bridging implies provision of the energy resource for the transition period: switching of one power resource to another. The third term, “bulk power systems”, contains maintenance of the grid’s work in overall. Practically, there is always a long term energy storage of significant power amount that is ready to restore work of the grid in case of substantial grid failure.

As it can be seen from the figure above, electrochemical storages are convenient for many tasks. It can be utilized for either power quality or transmission and distribution grid support. Mechanical and hydrogen-related storages are used as long-term storages and are kept for the significant power fail.

3.4. LiFePO4 battery

LiFePO4 battery is also known as LFP. In a process of design, every battery must follow six main requirements: specific energy density, specific power density, safety, cost, cycle and calendric lifetime. Figure 10 shows performance of this technology for above mentioned criteria. As it can be seen, $LiFePO_4$ family is related to the class of specific power batteries. Hence, the thickness of the electrodes is much lower comparing with high energy batteries. As a result, travelling distance for ions is much shorter, that accelerates charging and discharging processes [31].

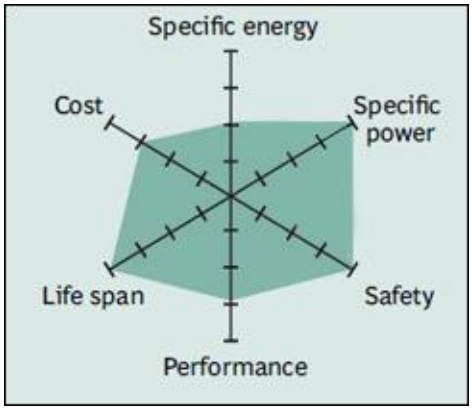

Figure 10. Characteristics of the LiFePO4 battery [32]

The lifetime of the battery depends from the operation mode. Current rating, DOD, overcharging and many other factors entail in the duration exploitation. The main factors limiting the work of the battery are capacity fades and internal resistance growth. A recent study [33] analysed cycling ageing of the LiFePO4 battery. The authors of article conducted the line of experiments and on its base created a Wöhler curve (Figure 11). The graph displays the number of Equivalent Full Cycles (FEC) that the battery can provide with different level of Depth of Discharge (DOD) till it will reach the End of Life (EoL) point. The authors of the present article [34] defined the number of FEC by the next equation:

$$\mathrm{N}_{FEC} = DOD(\%) \cdot N_{cycles} \tag{1}$$

where N_{cycles} - number of cycles the battery will reach EoL

After EoL point the battery can keep only some percentage from its initial capacity. Figure 11 shows the number of FEC till the battery will reach 90% SOH.

Consequently, the study showed absence of linear dependence between the FEC and DOD for this type of the battery. With DOD in a range from 10% to 50%, the number of FEC is the lowest. The battery with 5% DOD has the highest number of cycles. In a range from 60% till 100% the battery keeps the one value of FEC. It is rule of thumb that deep discharge is detrimental for all the batteries. It results in high mechanical stress and material's volume changes that lead to capacity loss. However, the results of experiments showed that for LiFePO4 batteries the most detrimental DOD from 10% till 50%.

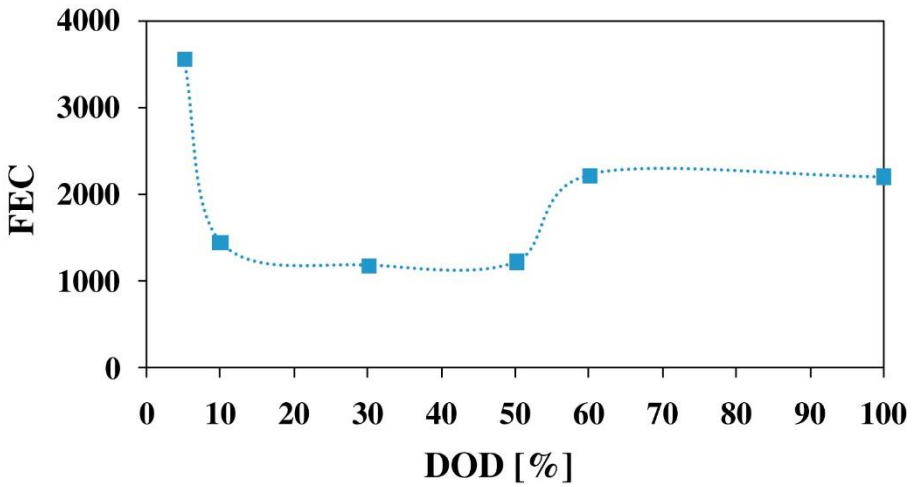

Figure 11. Wöhler curve for the LiFePO4 battery [33]

3.5. Application of the Li-ion batteries

Nowadays, batteries are used in different spheres of life. In a framework of Smart Grid System, their application has been divided into the 5 groups:

- Generation
- Ancillary services
- Transmission and Distribution (T&D) Infrastructure Service
- Renewable Integration
- Customer Energy Management [35]

Under Generation implies that energy stored in a period of low price and demand is used in a peak period. Eventually, this time-shift contributes to the reduction of energy generation cost during hours with high prices. The concept of Ancillary services includes many terms such as Black Start, Frequency Reserve (FR), Voltage Support and Operating Reserve. All these tools are aimed on support of the most secure and trustworthy grid work. In case of Transmission and Distribution Infrastructure Services, BESS offer an opportunity to delay upgrading grids of different voltage for raising of their handling capacity. In addition, due to the high penetration of RES, there is a possibility of congestion charges raise. For this reason, BESS promotes decline of charges at occurrence of congestions. The Renewable Integration term assumes enhancing of renewable energy sources into the work of the grid. In this situation, BESS can smooth short-term and long-term intermittences in energy supply caused by unstable weather conditions. Last, but not the least is Customer Energy Management. This point supposes freedom of customers in handling their energy use, for example, by the maintenance of house's equipment security thanks to avoiding of voltage fluctuation. Additionally, it means the preservation of energy charges by energy storing on time of low price and its use when the price is high [35].

3.6. Examples of BESS

The present subchapter is dedicated to the description of existing BESS located in Europe. All of the units are installed in pair with renewable energy sources: solar power plant, hydro power plant and wind farm. At the current moment all BESS are used in a testing regime.

3.6.1. “Suvilahti” (Finland)

In 2016, Helen Ltd. placed “Suvilahti” electricity storage in operation. It has a power of 1.2 MW and a capacity of 600 kWh. First tests were handled to examine the work of the batteries in voltage, frequency and reactive power at once by demand of DSO and TSO. Eventually, tests showed prosperous results and provided valuable knowledge regarding the energy capacity limits of the installation. Further tests will be continued to find the most advantageous way of the battery use and to determine the limits of their versatility [18].

3.6.2. “Batcave” (Finland)

A year later Fortum Oyj launched its battery project called “Batcave”. On the territory of the Nordic countries, this installation is the biggest for the current moment. It has 2 MW power and 1 MWh energy capacity. “Batcave” was aimed to test the work of BESS in cooperation with hydro power plant. During the first trials, effective work of the battery was highlighted throughout all working hours. In addition, prosperous energy delivery by HPP was pointed out in case of inability of battery work [19].

3.6.3. “Enspire ME” (Germany)

This project is located in Germany near the border with Denmark. At the present moment, this is the largest BESS in Europe – 48 MW system with capacity of 50 MWh. It consists of 10 000 lithium-ion batteries and will be connected to the local wind turbines. After the start of actual work, the battery will supply energy to the primary reserve market – provision of reactive power to the grid. Currently, the main providers for the reserve market are power plants based on coal or gas. Launching of “Enspire ME” will replace those power plants and dramatically reduce amount of CO2 emissions [36].

4. ELECTRICITY MARKET

Present chapter is dedicated to the description of the work of electricity markets in Finland. It consists of short historical information about establishing of the market in the country, information about operation and price formation. In addition, it provides information about current methods, used for prediction of the price.

4.1. Nord Pool history

After the adoption of the Electricity Market Act in 1995, the Finnish energy market was open for the competition. Then, in 1998 it became a part of Nord Pool, established for providing efficient exchange of energy between the Nordic countries and to increase security of supply. Its history started in 1990, when Norway deregulated their electricity market and started to trade electricity between its regions. Year by year, the procedure was repeated in other Scandinavian and Baltic countries, UK and Germany. Nowadays, Nordic market of energy is the leading market in Europe, which operates in nine countries and determined as a Nominated Electricity Market Operator (NEMO) in 15 European countries [37].

4.2. Nord Pool

The Nord Pool electricity market is a market for physical trading. It is deviated onto the several: Elspot (day-ahead) and Elbas (Intraday) markets. .

Table 1 illustrates used in the thesis market places and their features [38].

Table 1. Nord Pool market [38]

Market place	Contract type	Minimum bid size	Market gate closure
Elspot market	Hourly market	0,1 MW	Day before at 13:00
Elbas market	Hourly market	0,1 MW	30 minutes before each hour

Work on Elspot market follows the next principle. At the beginning, purchasers of energy conclude a contract with the suppliers for trading energy in the agreed amount for the next day. There are four types of orders:

- single hourly order
- block orders
- exclusive groups
- flexi orders.

All bids are stated until 12:00 and volumes are pointed in MW per hour. Then, at 13:00 prices for the next day are announced. The actual delivery starts at 00:00 [39].

The work of the Intraday market is performed to balance supply and demand in real time. The agreement for delivery is conducted one hour in advance [40].

4.2.1. Price formation

Trade of energy on Elbas market is realized by the principle “first come-first served”: sell with the lowest prices and purchase with the highest prices are first in order [40].

The electricity price on Elspot market is determined on the base of the supply and demand intersection. Figure 12 below graphically displays the principle. If energy supply cannot cover the demand, the price for commodity is higher than average. On the contrary, if the supply of energy is sufficient or even higher than needed, the price is average or lower [39].

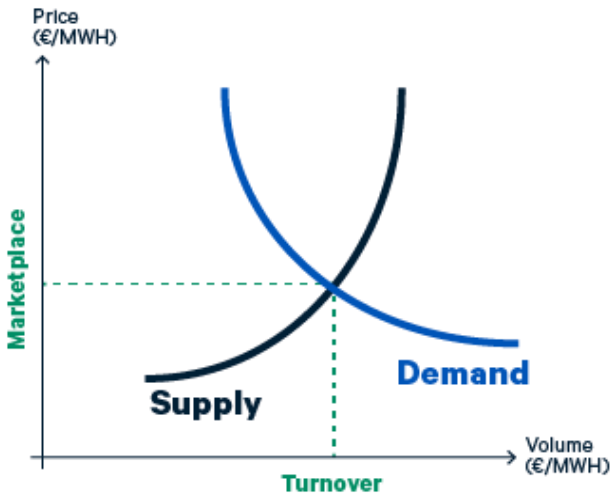

Figure 12. The principle of the price determination on Elspot market [39]

Figure 13 illustrates the price behavior on Elspot market on several days. There are two visible peaks on 20th of January and 28th of April. It is worth to note that these days were working days. Therefore, at the morning people are get ready for work and at the evening do necessary housework. On the contrary, 21st of January was Saturday. Usually, at the day-offs the electricity demand significantly decrease that entails lower electricity prices.

Nevertheless, the slight increase of demand with the next rise of price is also presented - at 18:00. However, the price rise is not comparable with its growth at workdays.

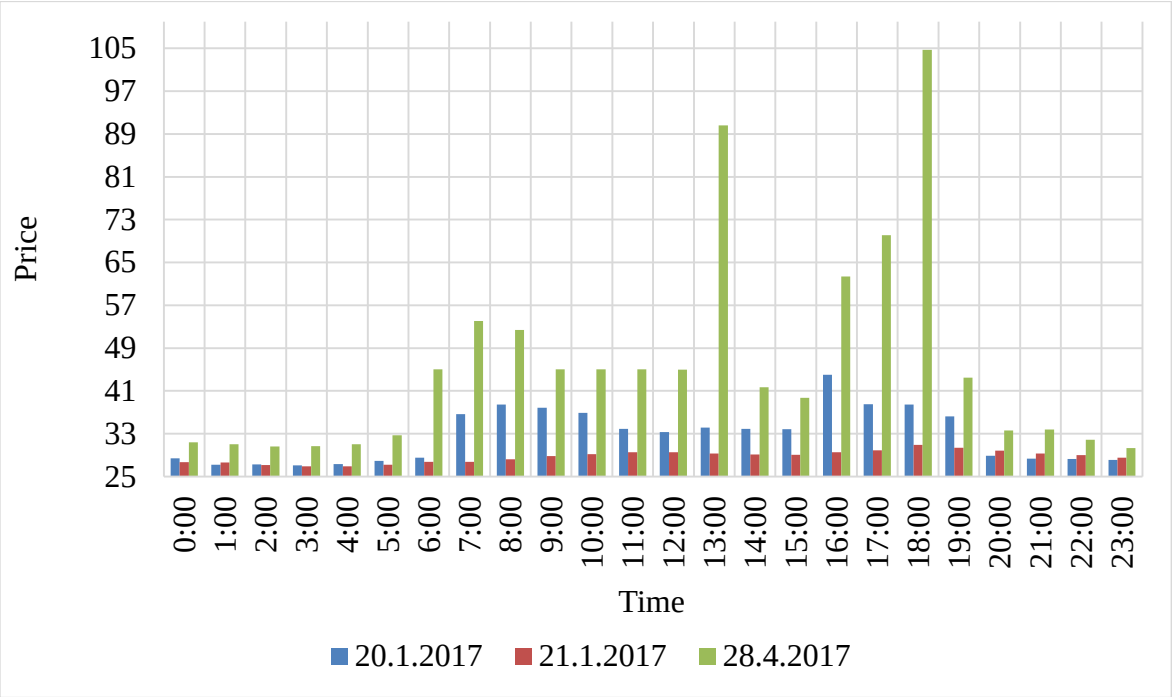

Figure 13. Price behavior on Elspot market

The behaviour of the price on 28th of April differs comparing with other days. The cost change is more sharp and significant. For 1 hour the price has grown in 2 times: from 45€ to 90€. The same was repeated at the evening: the price rise from 40€ to 105€. There are a number of factors affecting the price formation:

- Technical (bottlenecks in the grid, major power plant fails, grid failure and others);
- Climatic (impact of the weather conditions on the output of the renewable sources of energy, temperature rise/fall, fullness of the hydro reservoirs and others);
- Economical (influence of the world economy, increasing/decreasing price of the fuel);
- Political

Depending from these criteria, the price for the energy can increase or decrease significantly.

4.3. The market of ancillary services

For normal grid operation, market operators should submit plan of energy production and consumption in advance. However, in a real-time mode, there are always deviations from that plan. It results in a variation of grid characteristics and lead to irreversible consequences.

Therefore, there are some market mechanisms aimed to stabilize regular operation of the energy system.

For retention of the frequency within the dead band, there is a reserve market, which is operated by the TSO of every country. In Finland, it is Fingrid. In case of necessity, capacity is obtained from the reserves within the country or from Russian or Nordic electricity markets [41].

Frequency reserves are distinguished to several, which are determined for various situations. Some of them works automatically, others from the TSO's signal. Figure 14 illustrates reserve products used by Fingrid Oyj. For constant frequency control, frequency containment reserve (FCR) is considered. In its turn, it is categorized as reserves for normal (FCR-N) and disturbance (FCR-D) operation. FCR-N is applied to maintain frequency within the dead band in its regular state. In contrast, FCR-D works if one of the major suppliers switched off and frequency drops significantly. In such cases, FCR-D will be used to avoid noticeable reduction and for further inclusion of the FCR-N. Frequency Restoration Reserve (FRR) is maintained for recovering frequency to its regular meaning and further inclusion of the FCR. These sources are used very rarely and upon the request of the Fingrid [42].

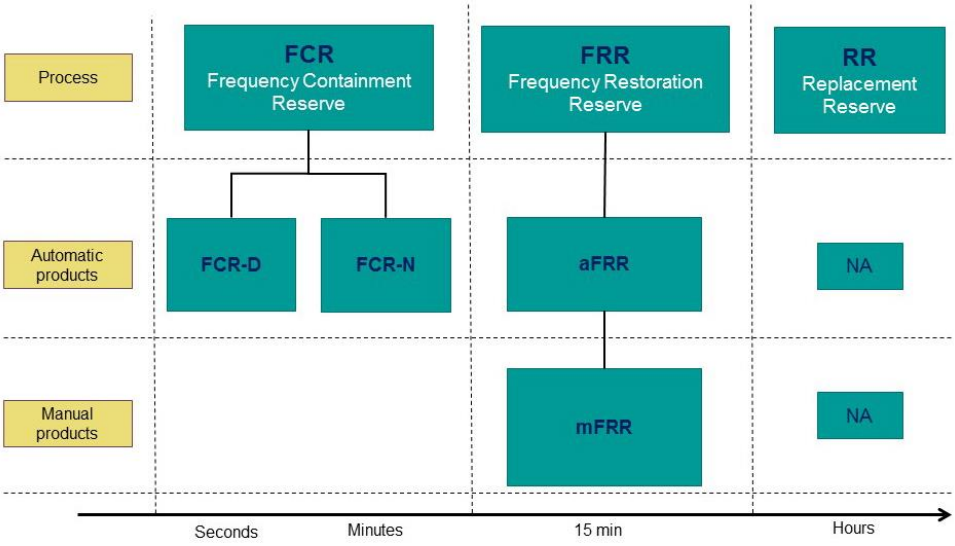

Figure 14 Reserve products of Fingrid Oyj [42]

To participate in the market, company-supplier must make an agreement with the TSO. There are two types of the contract: yearly and hourly contracts. These contracts are independent for both FCR-N and FCR-D markets. Yearly agreement is concluded once per

year at the certain time and involvement in the market out of this time is impossible. In contrast, hourly agreement can be signed in any moment before market gate closure. Furthermore, the requirement of the minimum capacity size of the reserve should be fulfilled. Appendix A illustrates the list of reserve products presented by Fingrid with their main characteristics.

4.4. Price forecast

The theme of electricity price forecast (EPF) is crucial for all market players. There are many factors which cannot be predicted forward and complicate the price forecast on the market. Moreover, estimation of the price modification is difficult in the case of any disturbances. Ultimately, it becomes necessary for market players to hedge themselves against financial losses and volume risks.

Price forecasting is distinguished according to the applied approach and period. Prognostication of the electricity cost can be short-term (STPF), medium-term (MTPF) and long-term (LTPF). Various time ranges have different purposes. For instance, LTPF is employed in researching of investment profitability and for determining of the oncoming work. MTPF is used for defining risks, determination of the derivatives' cost and for balancing sheet calculations [43].

Weron [43] distinguished modelling approaches used for price forecasting into six groups:

- Production cost models (imitate the work of the generation power plants with the idea of matching demand at the least cost).
- Equilibrium approaches (creation of the price processes with help of equilibrium models).
- Fundamental methods (specification of the price dynamics with modeling the impact of important physical and economic factors on the price of electricity).
- Quantitative models (description of the statistical properties of electricity cost though the period of time, with the ultimate objective of derivatives evaluation and risk management)
- Statistical approaches (use of statistical methods for prognostication either load or power market realization of the econometric techniques)
- Artificial intelligence-based techniques (work of the neural network and other approaches for creation of the price processes).

Within the current Master's thesis, price behaviour on Elspot market in 2017 was investigated. According to the data, cost changing on Elspot market is cyclical. In majority during the weekdays, the electricity cost was the highest during morning hours – from 7 till 9 a.m. On the weekends peak hours were shifted to the evening – from 6 till 8 p.m. Moreover, it is worth to note that the cheapest cost of electricity is constantly located every day during night hours – from 1 till 3 a.m. However, a slight change of time cannot be excluded. In contrast, modification of the price on the regulating market happens unpredictably and dramatically. Moreover, there is always uncertainty of the future action on the FCR-N market. Reserve providers must be prepared to obtain capacity or to provide it.

5. SIMULATION TOOL

Chapter 5 is dedicated to the description of the simulation tool implementation. The strategy choice, work schedule, description of the control of BESS and other program features are provided.

5.1. The Green Campus

Lappeenranta University of Technology is famous by its Green Campus. On its base, there are 835 of installed panels in total that takes 1500 square meters. The mounted panels are monocrystalline silicone and polycrystalline. In majority, the panels located on the walls and roofs of the university. Some of the PV panels are single and complemented by turning devices. One of the substations constitutes the carport roof. Ultimately, all the panels are divided into seven substations:

- Carport
- Flatroof
- Wall (south)
- Wall (west)
- Tracker
- Fixed installation
- Single panel

The produced energy is converted from DC to AC by power converter and supplied to the university. Eventually, the rated peak power of the Green Campus SPP is 208.5 kW. The produced electricity can replace bought share of energy from the electricity markets [44].

In addition, the Green Campus is equipped by two hundred thirty units of the LiFePO4 batteries. Their summary capacity is 132 kWh and power is 188 kW. Combination of installed PV panels and batteries allows performing of various tests to analyze and follow work and behaviour of the Smart Grid system [17]. Figure 15 illustrates the approximate model of Green Campus.

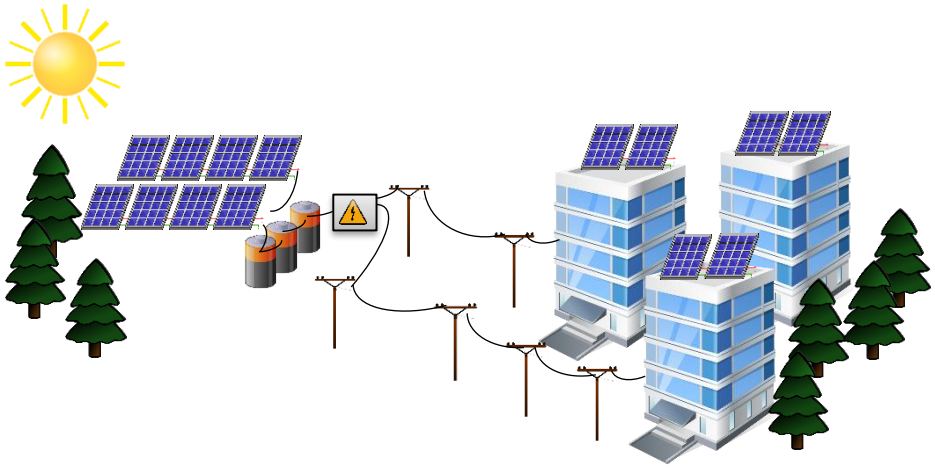

Figure 15. The approximate model of Green Campus

5.2. Production vs. consumption of the Green Campus

Decision about batteries participation on the markets depends from the excess energy. First of all, consumption and production of Green Campus needs to be studied.

Figure 16 depicts daily energy consumption of the university and daily energy production of the solar power plant in 2017. It is clearly seen that for the current moment energy consumption of LUT is much higher than production of the SPP. In coming years, the size of the solar power plant will be enhanced by two times. The amount of new capacity still will not be enough to cover the consumption. However, enhancing the technology's efficiencies, use of demand response and application of the BESS for the university needs will bring a positive effect to the educational institution.

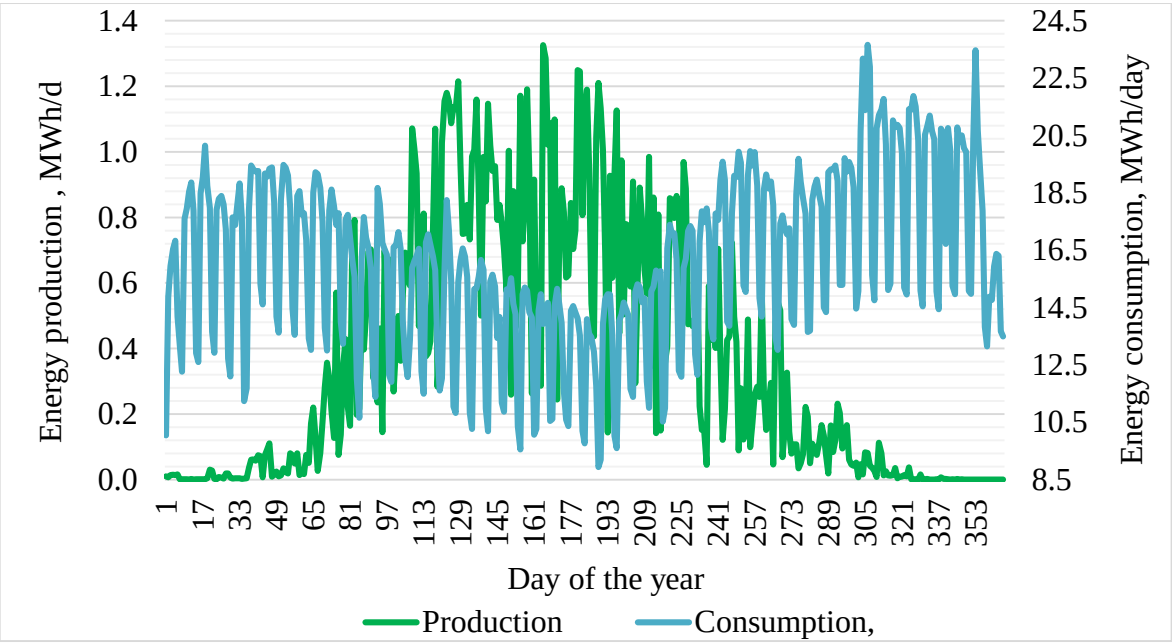

Figure 16. Consumption of the 4th building vs. production of the SPP in 2017

Nowadays, artificial intelligence technologies are utilized for reception of accurate data about production and consumption. Ivan Osipov [45] in its research had used regression-based methods and machine learning based methods for definition of energy balance in Green Campus. In was concluded that production and consumption of the building can be predicted with quite high precision. Afterwards, these data and outcomes of the present research might be used for the future studies.

5.3. Formation of the work schedule

As it was mentioned before, there are three markets that are considered for work: Elspot, Elbas and FCR-N. The Elbas market is used for sell and purchase of energy for the battery charging. The Elspot and FCR-N markets are utilized only for energy and capacity sell. Hours of participation on Elspot and FCR-N markets were chosen according to the analysis of peak hours regarding the price for 2017 (Figure 17). As it can be seen, there are 2 hours during the morning and evening when the price was the highest.

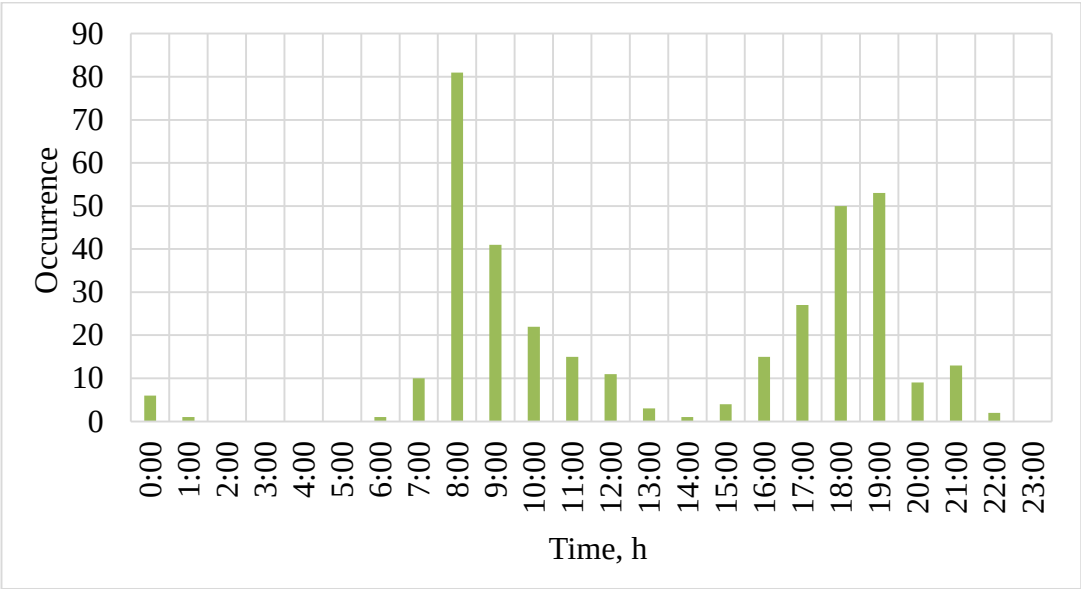

Figure 17. Occurrences of peak hours, Elspot market 2017

The same procedure was repeated for FCR-N market (Figure 18). The peak hours for the FCR-N market were mostly located at night and early morning. Hence, hours with the highest occurrence of peak prices were selected.

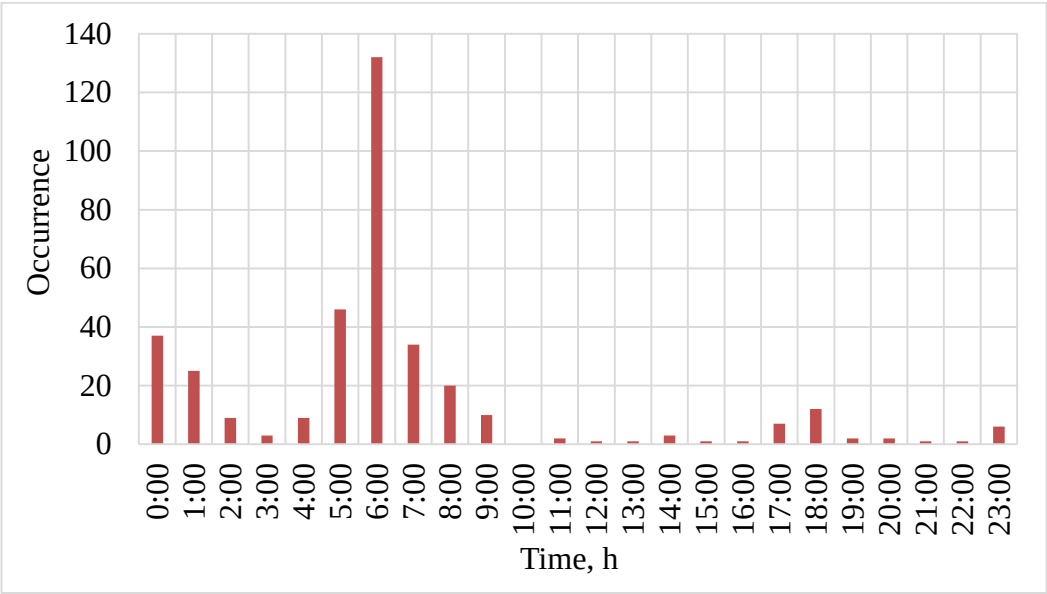

Figure 18. Occurrences of peak hours, FCR-N, market, 2017

Hours of work on Elbas market and for charging of the battery are floating. It depends from SOC that was left after work on FCR-N and Elspot markets.

5.4. Description of the simulation tool work

After adoption of all assumptions and creation of the work schedule, the program was built. The next flow chart was drawn for illustration of the operation algorithm (Appendix B. **Flow chart**). The program was performed by one of the most wide-spread programming languages – Python. This is a high-level programming language that might be used for any purpose. Figure 19 illustrates example of the battery work on the market.

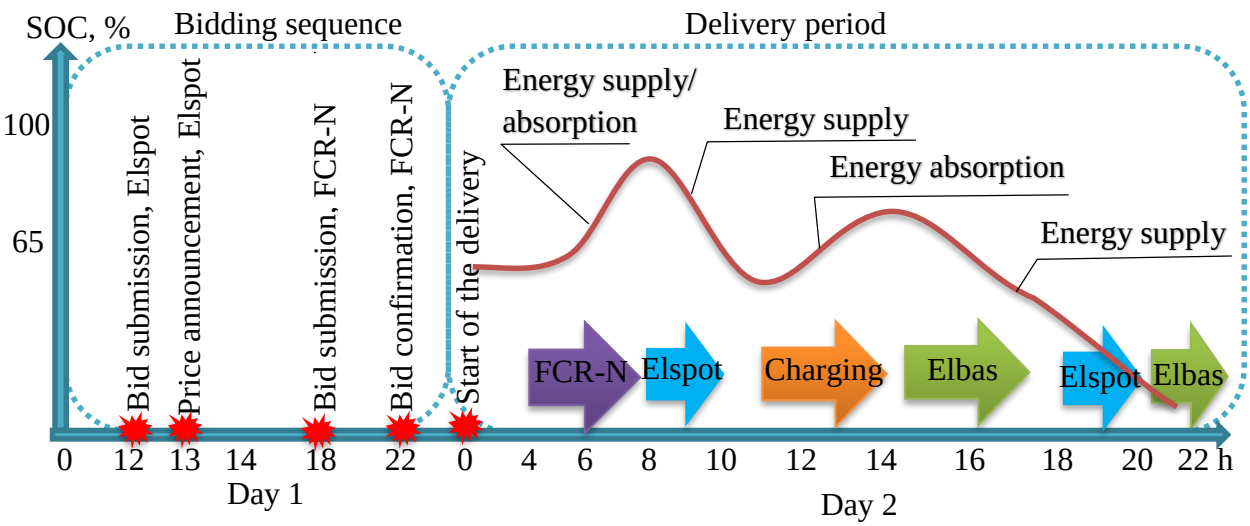

Figure 19. Bidding sequence and actual work

Every decision-making process occurs after definition of the battery's SOC. The starting point for the battery work was determined as 65%. The charging process goes till this value.

The SOC range from 20% till 80% is determined for work on Elspot market and FCR-N. The band was defined as less destructive for the battery's SOH. The main emphasize of the program are FCR-N and Elspot market. Work on the regulating market is planned once per day - at the early morning. Operation on the Elspot is scheduled twice per day: at the morning after FCR-N and at the evening from 6 p.m. till 7 p.m.

If the battery's SOC is less than 20%, the charging process begins. The program checks power output of the PV panels at the current moment. On the base of the threshold determined as sufficient for the charging, program makes a decision about energy source: PV panels or Elbas market. The threshold value was defined as the sum of the average power output of the SPPs. Since the main production occurs from April till September, the value was defined on the base of the summer month. Next pie chart (Figure 20) clearly shows difference of energy generation between SPPs in July. As it can be noted, the highest power output is produced by carport, flatroof and south wall.

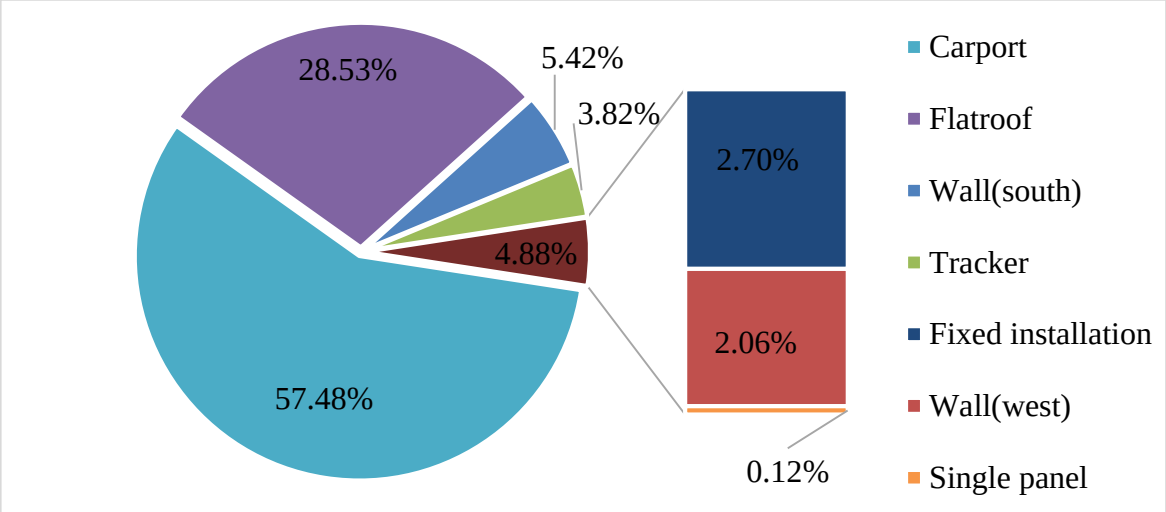

Figure 20. Average power production by PV panels, July 2017

Further, average production of every power plant was defined. Table 2 illustrates the number of generated power by each SPP and their sum. Eventually, this value was specified in a program as a minimum threshold for charging from the SPP. The process proceeds till the battery will reach 65% SOC. During the process, program checks every hour power output of the SPPs for further decision about energy source for the next hour.

Table 2. Average production of power plant from April till November, 2017

Name of the SPP	Average production, kW
Carport	13,5
Flatroof	6,6
Wall (south)	1,5
Sum	21,6

If the present power output of the panels is less than the minimum threshold, battery will be charged from Elbas market. Purchase of energy from the market should be planned one hour in advance. Therefore, actual charging procedure starts one hour after the low SOC was stated. The process continues for the next several hours till it will reach the value of 65%.

If the battery's SOC is more than 80%, program checks working schedule and determines necessity of discharging. If the work on the FCR-N market is planned in the next several hours, the battery should be discharged immediately. Local appliances such as EVs, PHEVs, and bicycles can be used for this purpose. Another option is sell of energy to the Elbas market.

In the framework of the current thesis, this function is not implemented in the program. The 80% SOC might be crossed, if the battery was charged both times from the FCR-N. These hours are scheduled at the morning. However, work on Elspot market is planned to happen after that. Therefore, immediate battery discharge is unnecessary because of the next operation on Elspot market.

Finally, the energy sell on Elbas market is considered during the day on the base of the battery's SOC. If the capacity level is more than 30% and no market work is planned for the next hour, battery can provide energy to the Elbas market.

6. VALIDATION OF THE RESULTS

This chapter is dedicated to the validation of the results of the simulation tool with a real battery. At the beginning, the description of BESS control will be introduced. Then, the charging and discharging processes will be outlined. Furthermore, the operation of the battery during the day will be described. Finally, the profitability of battery work for one day will be calculated.

6.1 Control model

For conduction of the studies researching the BESS's capabilities, the control system was developed. The model was built on the principle of Open Systems Interconnection (OSI) model. There are several levels that use its own input parameters and handle tasks. In such hierarchy, each level serves the layer above it. Consequently, the flow of information is passing across the network. Figure 21 below represents a model of the control system of BESS located in LUT.

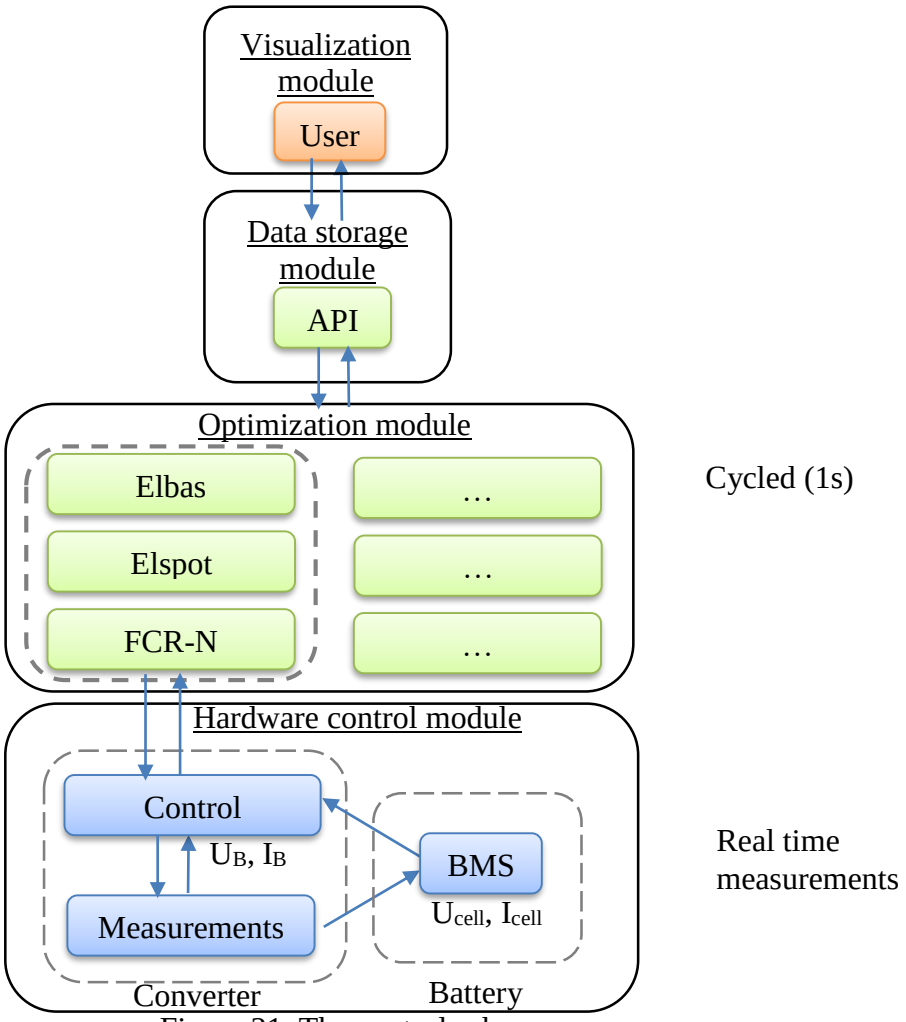

Figure 21. The control scheme

The bottom level is a hardware control module. It is presented by hardware control on site: a converter and Battery Management System (BMS) of the battery. The BMS send to control part in the converter the value of cell's voltage and current. In its turn, the control sends these numbers to the measurement system that indicate the voltage and current value of the whole battery. Then, the value is sent back to the control part and further to optimization module for making of the decision about the next task. Also, the value of the battery voltage and current is sent back to BMS.

The second level is an optimization module. At this level the execution of the decision-making function is carried out on the base of accepted command and other input data. These metrics are local grid status, battery values and other observed data.

The third level is a data storage module. This part is represented by centralized data center that includes tasks for the next several hours. These commands are sent to the optimization module that creates decisions regarding them and performs it. Besides it, the data storage module ensures data interface used for visualization and exporting by the last level – visualization module.

The last level provides graphical interface for visualisation of the battery work. In addition, the module has alerting tools that could be sent to the user in case of stipulated events.

The connection between the modules is established via the TCP/IP connections. The IEC 104 protocol is used for obtaining the measurements in the communication module.

6.2 Work on the markets

Figure 22 below illustrates one of the days during the test of the real battery. As it can be seen the battery implemented all the necessary tasks successfully.

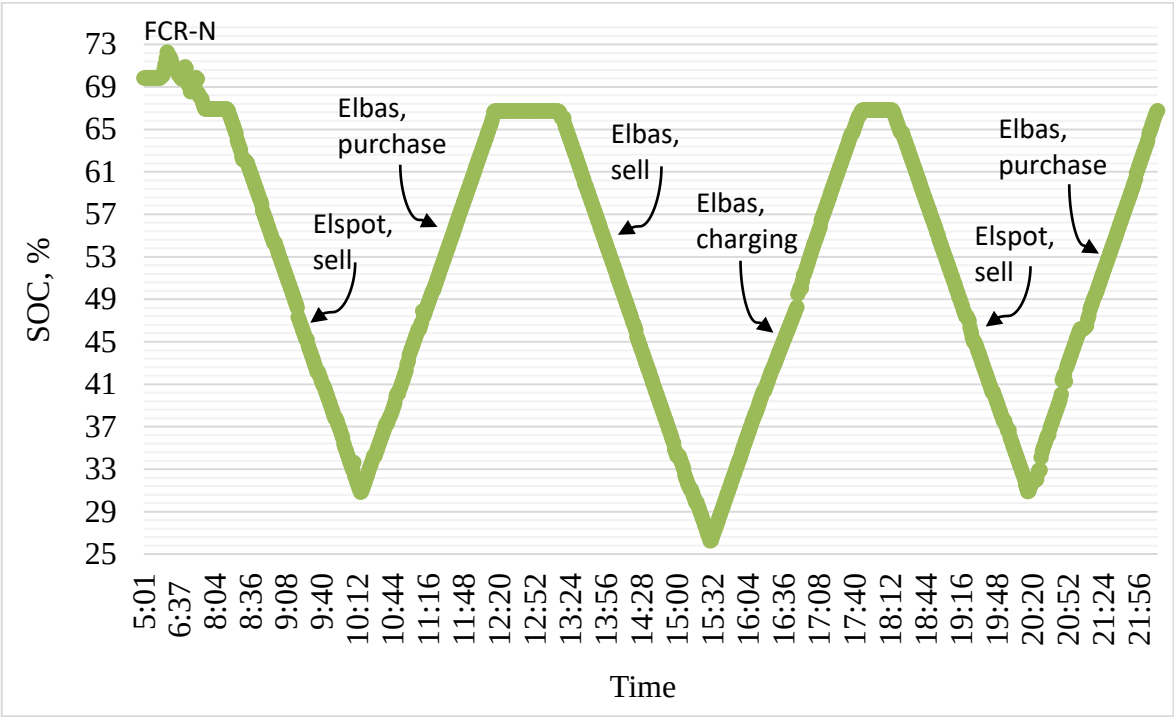

Figure 22. Work of the battery during the day, 22.11.2018

The initial SOC for the battery was defined as 65%. However, Figure 22 displays that the initial SOC was higher than the assumed value. It is happened because of the signal delay between the battery and server. During the tests, the value of battery's SOC was coming to the server with 15 minutes delay. Consequently, almost all the needed values are slightly higher than they should be.

According to the results of the simulation, the assumed schedule of the battery work almost matched the schedule derived during the tests. The deviations were noted in the period from 12:00 till 18:00. The results showed variation of hours of work on Elbas market. It depends from the work of the BESS on FCR-N. It is hard to predict to in advance what kind of task the battery will implement and for how long: either discharging or charging. Eventually, it effects on the start of charging after realization of work on Elspot market and left SOC.

6.2.1 Charging and discharging characteristics

Figure 23 below displays the process of discharging the BESS on Elspot market. During realization of the simulation tool, it was assumed that the battery's SOC change is 15% for one hour. In the process of the real battery test, this value was verified. It is clearly seen that from 8 a.m. till 9 a.m. the battery was discharged for 14%. However, for the next hour SOC decreased for 16%. In addition, it is worth to note that for the first 15 minutes the battery was discharged for only 2%. On contrast, for the next 15 minutes SOC has decreased for

4%. This deviation could be explained by many reasons. The number of cycles, losses, fluctuation of the applied voltage can result in variation of SOC change.

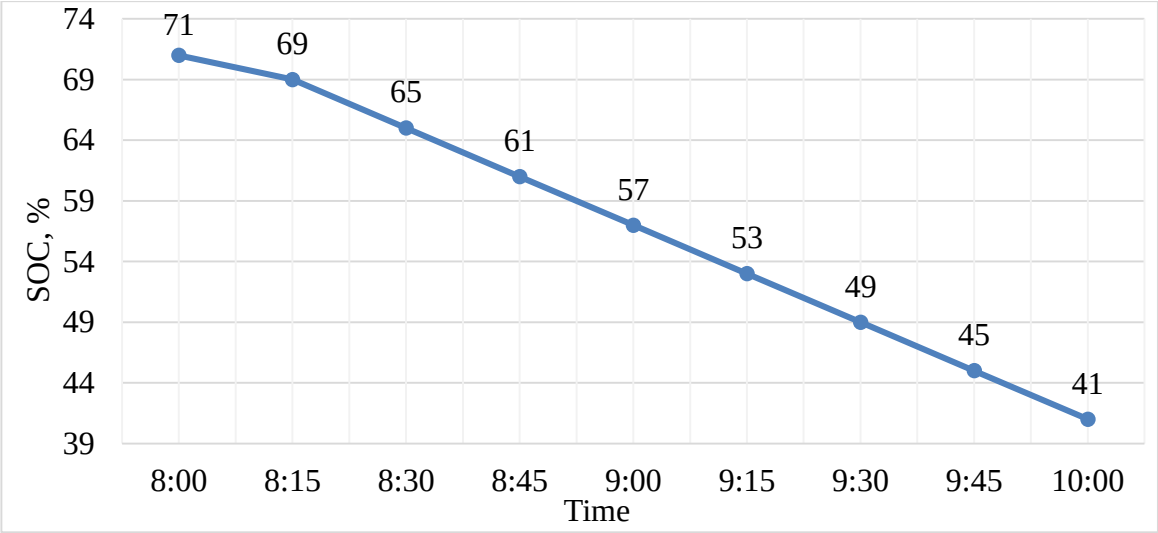

Figure 23. Work on Elspot market, 7.11.2018

Figure 24 displays the process of battery charging during the day. At this day the solar power output was low to charge the battery. Therefore, the unit was charged from Elbas market. As it can be seen, for one hour the battery's SOC increased for 16%. This number almost matches the assumed one. Also, the process of charging the battery is characterized by the same feature as discharging process. In the period from 11:45 to 12:00 the battery's SOC has changed for 2%. However, before this moment, SOC was increasing for 4% every 15 minutes.

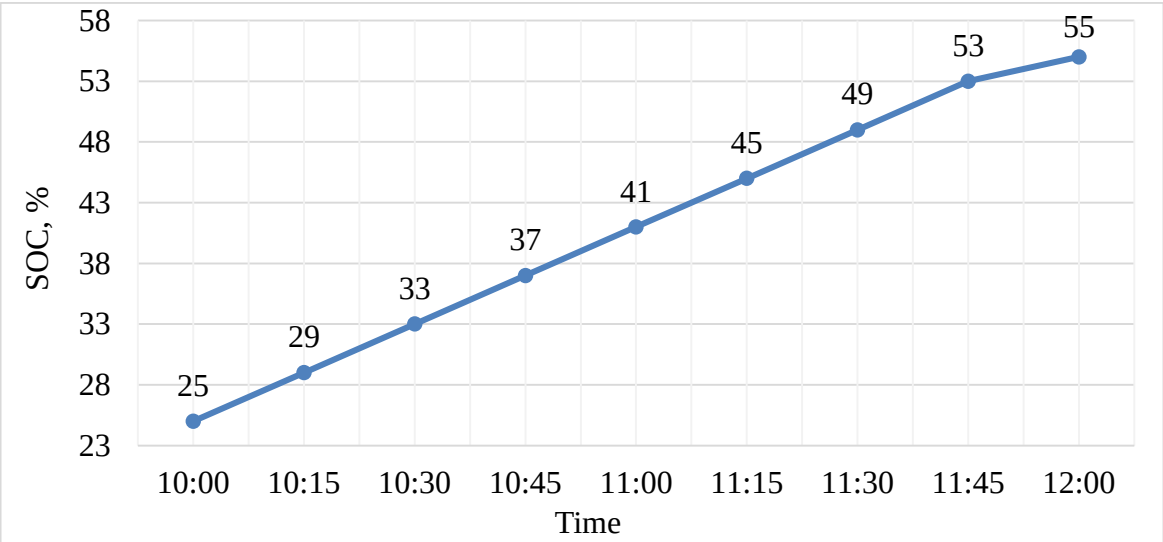

Figure 24. The charging process, 7.11.2018

During the tests the problem of balancing of cells voltage emerged. The test battery had an installed passive balancing system. If the voltage of one cell in the battery pack will reach the minimum value or lower, all the battery cells will look like the weakest one. In that case, the dissipative technique finds the cell with the highest voltage and start to dissipate the energy from it till the cell will reach the voltage of the weakest cell. Unfortunately, the balancing system installed in the test battery could not manage it sufficiently. In majority, the problem was emerging during the processes of charging. In reply to it, the controller significantly decreased amount of the incoming energy from 20 kWh to 6 kWh or 3 kWh. One of the solutions for the problem was reduction of the range of used capacity and scale it till the necessary values. Therefore, for continuation of the tests, the effective battery capacity was 70 kWh instead of 140 kWh. The amount of charging or discharging energy was also decreased from 19 kWh till 10 kWh.

6.2.2 Work on FCR-N market

Figure 25 displays in detail the work of the battery on FCR-N market at one of the days. The frequency values are 3 minute moving average values. From 5:00 till 6:00 the frequency behavior was more stable in comparison with the next hour. Therefore, the battery's SOC was more or less stable during the first hour. At 5:43 the battery started to react to the sharp increase of the frequency by absorbing the energy from the grid. Then, with steep reduction of the frequency, the battery started the discharging process.

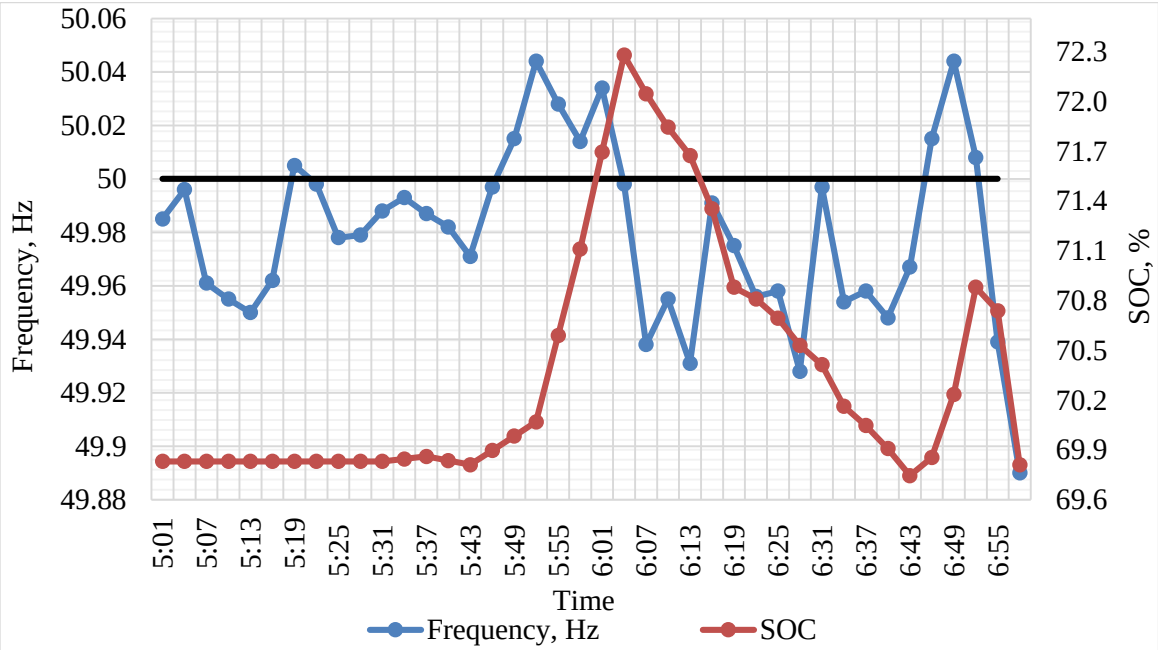

Figure 25. Work on the battery on FCR-N market, 6.12.2018

Figure 26 shows another test of the battery for its ability to react on fluctuation frequency on the grid. From 5:00 till 6:00 the frequency value varied on the threshold of the minimum value of the deadband. During this hour the BESS was discharging all the time for provision of necessary absent energy in the grid. From 6:00 till 7:00 the frequency behavior entered the deadband and the battery stopped the process of radical discharging. The further slight fluctuation of the frequency correlate with small batteries discharges.

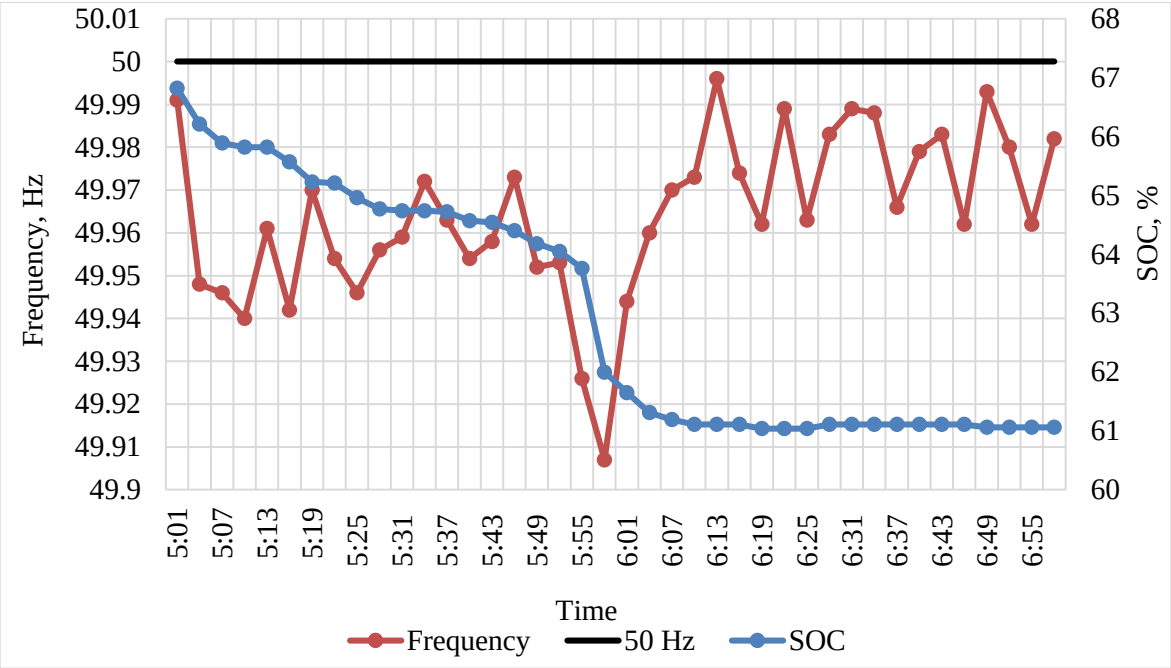

Figure 26. Work of the battery on FCR-N market, 8.12.2018

During the realization of the work on FCR-N market, the battery immediately reacted to any frequency change. Once again, it highlights the advantage of the battery's application for provision of ancillary services to the grid. In the future, the tests regarding other ancillary services are needed to be conducted.

6.3 Profitability calculation

The appropriateness of the established schedule can be estimated by calculation of its profitability. First of all, it is necessary to calculate the cost of the battery work per cycle. According to [33], the LiFePO4 battery will reach 80% SOH after approximately 3000 FEC with 100% DOD. In [46] it was pointed out that the round trip efficiency of LiFePO4 battery is 98%. In addition, the authors noted the variable battery price is 752 €/kWh.

Therefore, the total amount of cycles over the lifetime is:

$$2 \cdot \eta_{RT} \cdot C_{DoD(100\%)} \cdot N_{av,cycles} = Total\ stored\ energy \tag{2}$$

The investment cost of the BESS is calculated by the next formula:

$$Cost_{battery} \cdot C_{battery} = Capex_{battery}\ € \tag{3}$$

The price of the battery work per 1 kWh is

$$Cost_{1kWh} = \frac{Capex_{battery}\ €}{Total\ stored\ Energy} = 0.13 \frac{c€}{kWh}, \tag{4}$$

where

η_{RT}	round trip efficiency
$C_{DOD(100\%)}$	capacity with a DOD = 100%,
$N_{av.cycles}$	the average number of cycles
$Cost_{battery}$	cost of the battery
$C_{battery}$	battery capacity

Since the amount of charging or discharging energy was assumed as permanent for Elspot and Elbas market, it is necessary to calculate the cost of one discharge or charge event:

$$19.8\ kWh \cdot \frac{0{,}13€}{kWh} = 2.57€$$

For FCR-N market, the battery cost is calculated by other way. Firstly, the changing of battery's SOC needs to be defined:

$$SOC_t - SOC_{t+n} = \Delta SOC \tag{5}$$

Secondly, changing of capacity regarding every change of SOC is calculated:

$$\frac{|\Delta SOC \cdot C_{battery}|}{100} = \Delta C \tag{6}$$

Then, sum of the capacity change for one hour is considered:

$$\sum \Delta C = \Delta C_{1\ hour} \tag{7}$$

Finally, the operation cost of one hour of work on FCR-N market is defined as:

$$\Delta C_{1\ hour} \cdot Cost_{1kWh} = Cost_{1h} \tag{8}$$

where

SOC_t SOC of the battery at t point of time

SOC_{t+1} SOC of the battery at the next point of time

ΔSOC SOC change

ΔC change of capacity

Consequently, the revenue from all the markets was calculated and presented at Table 3.

Table 3. Calculation of the revenue flow during the battery operation, 6.12.2018

Time	Type of the market	Allocated capacity, kW; kWh	Market price, €/MWh; €/MW	Battery cost, €	Market revenue, €	Revenue, €
5:00	FCR-N	20	11	-0.17	0.22	0.05
6:00		20	30	-0.54	0.6	0.06
8:00	Elspot	20	58.06	-2.57	1.16	-1.41
9:00		20	57.98	-2.57	1.15	-1.42
10:00	Elbas	20	-55.42	-2.57	-1.11	-3.68
11:00		20	-51.52	-2.57	-1.03	-3.6
13:00	Elbas	20	51.1	-2.57	1.02	-1.55
14:00		20	51.09	-2.57	1.02	-1.55
15:00		20	53.75	-2.57	1.07	-1.5
16:00	Elbas	20	-62.55	-2.57	-1.25	-3.82
17:00		20	-66.70	-2.57	-1.33	-3.9
18:00	Elspot	20	63.09	-2.57	1.26	1.31
19:00		20	51.91	-2.57	1.03	-1.54
20:00	Elbas	20	-47.94	-2.57	-0.96	-1,61
21:00		20	-46.13	-2.57	-0.92	-3,49
Sum						-30,27

As it can be seen from the table, the revenue for one day of battery work amounts -30.27€. Further, the same calculation was conducted for another two days (Table 4).

Table 4. Calculation of the revenue

Date	Revenue, €
7.12.2018	-38
8.12.2018	-30.71

Eventually, according to the results of the tests all three days brought a negative profit. It is worth to note that the chosen hours of work on Elspot and FCR-N market in majority were the most profitable. During three days, 8:00 and 9:00 on Elspot market were the most profitable during the morning or even during the all day. In the future, the chosen hours are needed to be selected every day with accounting of various details.

It is worth to note that during the calculation, the cost of the contracts concluded with TSO and Nord Pool were not considered. Furthermore, the tests with a real battery were conducted in November and December of 2018. The profitability of the battery will drastically increase at the period from April till September. The growth of power output of the PV panels will lead to reduction of Elbas market as energy source for charging the battery.

7. CONCLUSION

The Master's thesis presents the decision-making simulation tool imitating artificial work of the BESS on the electricity markets. The battery implements several tasks: supply of energy to Elspot and Elbas markets and work for the market of ancillary services – maintenance of frequency stability. For the battery charging, SPPs installed on the university base were used as a main energy source. If the power production of the PV panels is low, Elbas market was applied for the battery charging. The battery operational schedule was settled on the base of historical data. Coincidence of peak hours for the last year was calculated for Elspot market and FCR-N market. Then, these hours were settled for the operating schedule. Left hours were established for work on Elbas market. The simulation tool was developed by use of Python.

Operation of BESS implies many parameters that cannot be predicted or calculated in advance. For this reasons, parameters such as battery degradation were neglected. The amount of provided or absorbed power was established as permanent.

Eventually, the simulation tool demonstrated its efficiency and proved the ability of BESS to work during the day. The energy was supplied to the priority markets at the morning and at the evening. In addition, the energy was also provided to the hourly market. During the day the battery was successfully charged either from the SPPs or from Elbas market.

After the tests of artificial battery, validation of obtained results was done with a real LiFePO4 battery. The line of the tests approved determined operational schedule. Also, it is shown that the estimated value of SOC change for 1 hour approximately matched the real one. The slight deviation could be explained by a number of terms such as battery degradation rate, number of cycles, temperature and others. Therefore, in further studies battery's SOH is needed to be taken into account. In addition, the yield of the project for the owner was calculated. The calculation did not consider cost of the contracts concluded with Nord Pool and TSO. Eventually, according to the results, work of the battery in the framework of the chosen strategy is not profitable. It is worth to note that the tests were conducted in November and December. During the summer period the profitability will increase due to replacement of charging from Elbas market by use of SPPs.

There are a lot of open questions regarding the use of BESS as energy source. Besides it, BESS installed in the residential sector can also be used for the grid needs. At the current

moment, the cost of the BESS is one of the main issues that inhibits their high penetration to the market due to absent of profitability. It is worth to note that the cost reduction and sufficient support from the government will positively effect on their distribution. Their application for both – the owner and the grid – will impact towards sustainable work of the electrical grid, increasing of owner's profit, penetration of renewable energy sources and development of distribution generation.

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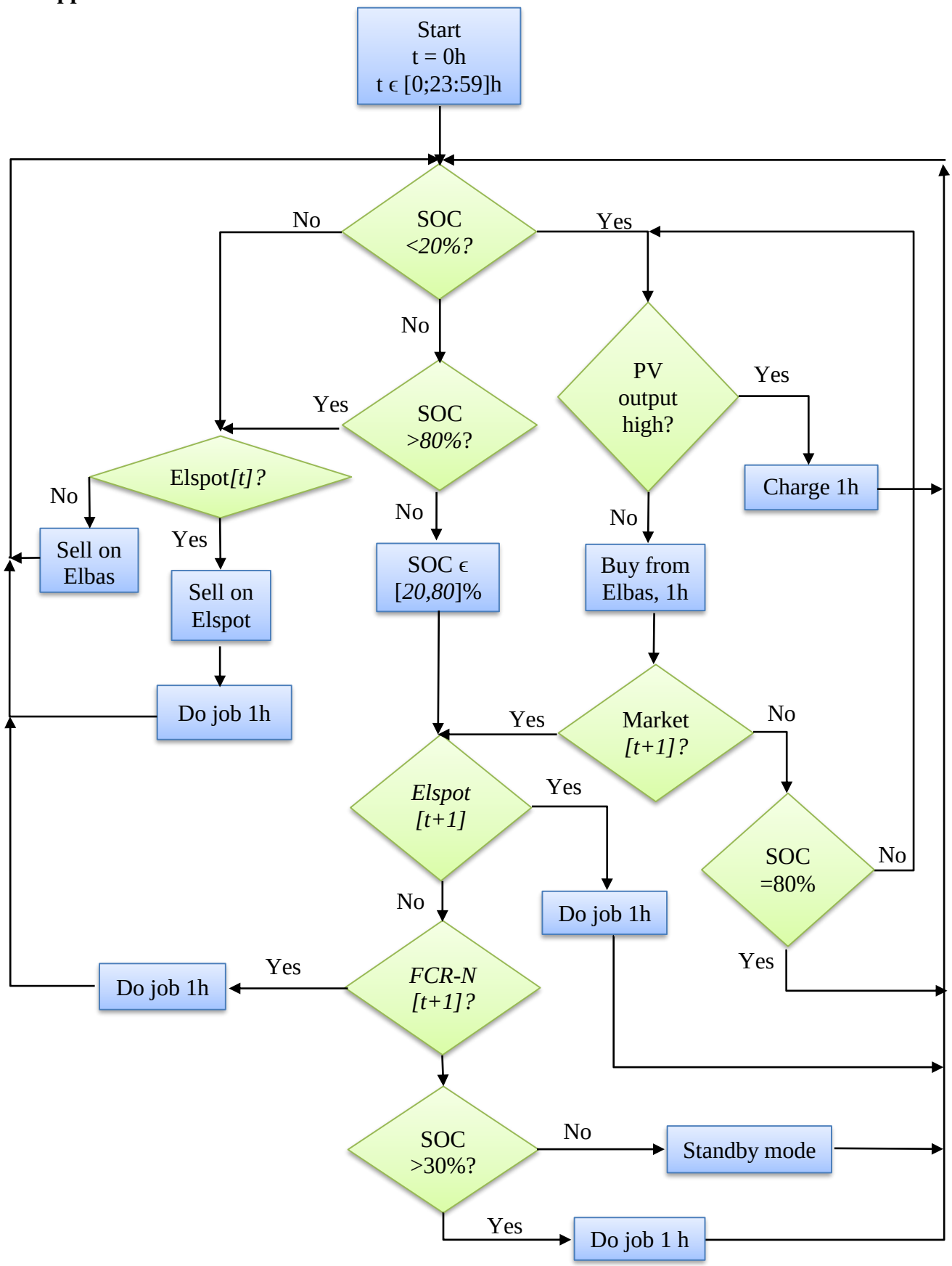
Appendix A. The reserves products [38]

Market place	Contract type	Minimum bid size	Market gate closure	Frequency of use	Price level 2018
FCR-N	Hourly market	0,1 MW	Yearly market previous autumn, hourly market day before at 18:30	Several times a day	14 €/MW,h (yearly market)
FCR-D	Yearly and hourly markets	1 MW	Yearly market previous autumn, hourly market day before at 18:30	Several times per day - per year	2,8 €/MW,h (yearly market)
aFRR	Hourly market	5 MW	Day before at 17:00	Several times a day	Hourly market price + balancing energy price
Balancing power market (mFRR)	Hourly market	5 MW	45 min before each hour	According to the bids, several times/day - per year	Market price
Balancing capacity market (mFRR)	Weekly auctions	5 MW	Week before on Tuesday at 12:00	According to the bids, several times/day - per year	~3 €/MW,h

Appendix B. Flow chart



Appendix C. Proposed scenario of act

Time	Market 1	SOC1, %	Action 1	Market 2	SOC2, %	Action 2
00:00		65	Standby mode		65	Standby mode
01:00		65	Standby mode		65	Standby mode
02:00		65	Standby mode		65	Standby mode
03:00		65	Standby mode		65	Standby mode
04:00		65	Standby mode		65	Standby mode
05:00	FCR-N	65	Discharge	FCR-N	65	Charge
06:00	FCR-N	50	Discharge	FCR-N	80	Charge
07:00		35	Standby mode		95	Standby mode
08:00	Elspot	35	Discharge	Elspot	95	Discharge
09:00	Elspot	20	Discharge	Elspot	80	Discharge
10:00	PV/Elbas	5	Charge		65	Standby mode
11:00	PV/Elbas	20	Charge	Elbas	65	Discharge
12:00	PV/Elbas	35	Charge		50	Standby mode
13:00	PV/Elbas	50	Charge	Elbas	50	Discharge
14:00		65	Standby mode		35	Standby mode
15:00	Elbas	65	Discharge	Elbas	35	Discharge
16:00		50	Discharge		20	Standby mode
17:00	Elbas	50	Standby mode	Elbas	20	Discharge
18:00	Elspot	35	Discharge	Elspot Penalty	5	Standby mode
19:00	Elspot	20	Discharge	Elspot Penalty	5	Charge from Elbas
20:00	Elbas	5	Charge	Elbas	20	Charge
21:00	Elbas	20	Charge	Elbas	35	Charge
22:00	Elbas	35	Charge	Elbas	50	Charge
23:00	Elbas	50	Charge	Elbas	65	Charge