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Electrical Engineering

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MULTI-OBJECTIVE OPTIMISATION OF COMMUNITY BATTERY ENERGY STORAGE CAPACITY EXPLOITATION

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ABSTRACT

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Utilizing battery energy storage systems (BESS) in power systems can elevate the efficiency, reliability, stability and security of the system, and simultaneously can provide economic benefits for the battery operator. Profitability of allocating battery capacity to different electricity markets is a critical factor which should be evaluated precisely. Determining of the optimal battery capacity via an optimal bidding strategy for allocation to different electricity markets in Finland, i.e. Nord Pool day-ahead and intra-day markets and Fingrid frequency containment reserve markets is investigated in this thesis.

The bidding model for the Nord Pool day-ahead and intra-day markets are developed as a stochastic profit maximization model. The optimization problem is formulated with the objective of maximizing the total expected value of battery system's profit subjected to various technical linear and non-linear constraints. Two Matlab® optimization algorithms are examined to solve the optimization problem effectively: interior-point algorithm and genetic algorithm. The optimization results indicate that employing the battery system in Elspot day-ahead and Elbas intraday markets is not profitable for battery owner due to high amount of battery costs.

The capacity allocation of battery system to Fingrid frequency containment reserve markets for normal operation (FCR-N) and disturbances (FCR-D) are studied by applying two methods: optimization method and fixed power method. In the optimization method, an optimal model for battery system is formulated and solved by Matlab®. The purpose of optimization is to maximize the profit with observing the market prices, battery costs, technical constraints of battery system and requirements of market. The optimization results show that the battery system is profitable in both FCR-N and FCR-D markets. In the fixed-power method a constant amount of battery power is supposed to be dedicated to Fingrid frequency markets for all hours of the day. The results of applying fixed-power method show that utilizing the battery system in FCR-N market is not profitable due to the high amount of battery costs and the penalty that should be paid to Fingrid for the hours that the declared power could not be provided to market. On the other hand, the results of applying this method show that utilizing the battery system in FCR-D market is profitable with considering the battery costs and penalty payments. The results are based on the frequency data of May 2016.

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Table of Contents

ABSTRACT

ACKNOWLEDGMENT

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

1 INTRODUCTION 12
  1.1 Objectives and scope of thesis 12
  1.2 Structure of thesis 13
2 LITERATURE REVIEW 15
3 ELECTRICITY MARKETS IN FINLAND 19
  3.1 Nord Pool spot markets 20
    3.1.1 Elspot day-ahead market 21
    3.1.2 Elbas intraday market 22
  3.2 Balancing power market 23
  3.3 Fingrid ancillary service markets 23
    3.3.1 Frequency control 24
    3.3.2 Power reserve markets 24
4 BATTERY ENERGY STORAGE SYSTEM (BESS) 26
  4.1 Operation technology 26
  4.2 Applications and benefit analysis 26
  4.3 BESS research facility 28
5 OPERATIONAL PLANNING FOR UTILIZING BESS IN ELECTRICITY MARKETS 30
  5.1 Bidding strategy 30
  5.2 Trading in Finnish electricity markets 30
6 OPTIMIZING THE EXPLOITATION OF BATTERY CAPACITY FOR NORD POOL SPOT MARKET 35
  6.1 Mathematical modeling of BESS optimization problem 35
    6.1.1 Revenue obtained from selling energy of the battery system 37
    6.1.2 Cost aroused for purchasing energy for the battery system 38

6.1.3 Objective function of the optimization problem ... 39
6.2 Optimization problem solving method ... 39
6.2.1 Optimal bidding solution ... 40
6.2.2 Impacts of electricity markets uncertainties on optimal solution ... 42
6.3 Constraints ... 43
6.4 Algorithms utilized for solving the optimization problem ... 46
6.4.1 Interior-point algorithm ... 47
6.4.1.1 Optimization results using Interior-point algorithm ... 49
6.4.2 Genetic algorithm ... 52
6.4.2.1 Optimization results using genetic algorithm ... 56
6.5 Battery system costs ... 61
7 OPTIMIZING THE EXPLOITATION OF BATTERY CAPACITY FOR FINGRID FREQUENCY MARKETS ... 63
7.1 Fingrid frequency price analysis ... 63
7.2 Data analysis of frequency deviations of May 2016 on average hourly basis ... 69
7.2.1 Data analysis of frequency deviations of FCR-N market ... 69
7.2.2 Data analysis of frequency deviations of FCR-D market ... 72
7.3 Data analysis of frequency deviations of first week of May 2016 ... 74
7.4 Capacity allocation of BESS to Fingrid frequency markets ... 76
7.4.1 Capacity optimization of BESS for FCR-N and FCR-D markets ... 82
7.4.1.1 Mathematical modeling of BESS optimization problem ... 82
7.4.1.2 Objective function of the optimization problem ... 83
7.4.1.3 Optimal bidding solution ... 84
7.4.1.4 Constraints ... 85
7.4.1.5 Optimization results for FCR-N market ... 87
7.4.1.6 Optimization results for FCR-D market ... 90
7.4.2 Constant capacity allocation of BESS to FCR-N and FCR-D markets ... 95
7.4.2.1 Results of constant capacity allocation of BESS to FCR-N market ... 95
7.4.2.2 Results of constant capacity allocation of BESS to FCR-D market ... 97
8 KEY RESULTS AND DISCUSSION ... 100
9 CONCLUSION ... 102
REFERENCES ... 104
Appendix A: Fmincon solution process ... 108

Appendix B: Time duration of frequency deviations – first week of May 2016 110

Appendix C: Battery charging/discharging time (% hour) – first week of May 2016 117

Appendix D: Optimal hourly power for FCR-N market by using optimization method - first week of May 2016.. 124

Appendix E: Optimal hourly power for FCR-D market by using optimization method - first week of May 2016.. 131

Appendix F: Results of utilizing battery system in FCR-N market by using fixed power allocation method - first week of May 2016.. 138

Appendix G: Results of utilizing battery system in FCR-D market by using fixed power allocation method - first week of May 2016.. 145

LIST OF FIGURES

Figure 1 Development of the Finnish electricity markets (Jarmo Partanen, Satu Viljainen, Jukka Lassila, Samuli Honkapuro, Kaisa Salovaara, Hanna Niemelä, Salla Annala, Mari Makkonen, 2017) 19
Figure 2 Reserve products used in Finland (Fingrid, 2017) 25
Figure 3 Electricity retailer's operation in the smart grid environment (Valtonen, 2015) 32
Figure 4 Time-limits for operations in Finnish electricity markets 33
Figure 5 Elspot hourly prices - Average 2016 40
Figure 6 Elbas hourly prices - Average 2016 41
Figure 7 Elbas hourly prices - January 2016 41
Figure 8 Comparison between Elbas January and average prices 42
Figure 9 Optimal hourly supply and demand energies using interior-point algorithm 50
Figure 10 Objective function value 51
Figure 11 Creating a random initial population (Mathworks, 2017) 54
Figure 12 Three types of children (Mathworks, 2017) 54
Figure 13 Population at the second generation which are elite, crossover, or mutation children (Mathworks, 2017) 54
Figure 14 Populations at iterations 60 (Mathworks, 2017) 55
Figure 15 Populations at iterations 80 (Mathworks, 2017) 55
Figure 16 Populations at iterations 100 (Mathworks, 2017) 55
Figure 17 Optimal hourly supply and demand energies using genetic algorithm 57
Figure 18 Penalty function value 58
Figure 19 Best penalty function value 59
Figure 20 Stopping criteria 60
Figure 21 FCR-N hourly prices – Year 2016 64
Figure 22 FCR-D hourly prices – Year 2016 64
Figure 23 FCR-N & FCR-D hourly prices – Average year 2016 65
Figure 24 FCR-N & FCR-D hourly prices – Average May 2016 66
Figure 25 FCR-N zero/non-zero value hours – Year 2016 67
Figure 26 FCR-D zero/non-zero value hours – Year 2016 67
Figure 27 FCR-N zero/non-zero value hours – May 2016 68
Figure 28 FCR-D zero/non-zero value hours – May 2016 68
Figure 29 Time duration frequency ≤ 49.95 or ≥ 50.05 Hz – Average May 2016 70
Figure 30 Total time duration frequency ≤ 49.95 or ≥ 50.05 Hz – Average May 2016 71
Figure 31 Longest time duration frequency ≤ 49.95 Hz – May 2016 71
Figure 32 Longest time duration frequency ≥ 50.05 Hz – May 2016 72
Figure 33 Time duration frequency < 49.90 Hz – Average May 2016 73
Figure 34 Longest time duration frequency < 49.90 Hz – May 2016 73
Figure 35 Probability distribution of battery occupation in FCR-N market 77
Figure 36 Optimal hourly power for FCR-N market - Average May 2016 87
Figure 37 Objective function value 88
Figure 38 Hourly SOC changes of battery system in FCR-N market - Average May 2016 88

Figure 39 Hourly SOC changes of battery system in FCR-N market - first week of May 2016.. 89
Figure 40 Profit in FCR-N market by using optimization method – May 2016........................... 90
Figure 41 Optimal hourly power in FCR-D market - Average May 2016 91
Figure 42 Objective function value.. 92
Figure 43 Hourly SOC changes of battery system in FCR-D market - Average May 2016 92
Figure 44 Profit in FCR-D market by using optimization method – May 2016........................... 94
Figure 45 Profit in FCR-D market by using fixed power allocation method – May 2016........... 98
Figure 46 Comparison between the profitability of utilizing the battery system in different markets - May 2016 102

LIST OF TABLES

Table 1 Optimal hourly supply energies by using interior-point algorithm 49
Table 2 Optimal hourly demand energies by using interior-point algorithm 49
Table 3 Profit value using Matlab fmincon function 52
Table 4 Optimal hourly supply energies by using genetic algorithm 56
Table 5 Optimal hourly demand energies by using genetic algorithm 57
Table 6 Profit value using Matlab ga function.. 61
Table 7 Longest duration 49.90 ≤frequency ≤ 49.95 Hz 75
Table 8 Longest duration frequency ≥ 50.05 Hz 75
Table 9 Longest duration frequency < 49.90 Hz 76
Table 10 Duration of battery charging/discharging (%) in FCR-N market – Average May 2016 79
Table 11 Duration of battery charging/discharging (%) in FCR-D market – Average May 2016 80
Table 12 Optimal hourly power for FCR-N market – Average May 2016 87
Table 13 Optimal hourly power for FCR-D market - Average May 2016 91
Table 14 Final profit of utilizing battery system in FCR-D market by using optimization method – May 2016 93
Table 15 Results of utilizing battery system in FCR-N market by using fixed power allocation method - Average May 2016 96
Table 16 Results of utilizing battery system in FCR-D market by using fixed power allocation method – Average May 2016.. 99

LIST OF SYMBOLS/ABBREVIATIONS

BESS	Battery Energy Storage System
BMS	Battery Management System
CET	Central European Time
EET	East European Time
ESS	Energy Storage System
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve for Normal Operation
FRR	Frequency Restoration Reserve
FRR-A	Automatic Frequency Restoration Reserve
FRR-M	Manual Frequency Restoration Reserve
GA	Genetic Algorithm
kW	Kilowatt
kWh	Kilowatt hour
LiCoO2	Lithium cobalt oxide
Li-ion	Lithium-ion
LiFePO4	Lithium iron phosphate
MG	Micro grid
MW	Megawatt
MWh	Megawatt hour
SOC	State of charge
TSO	Transmission System Operator

1 INTRODUCTION

The role of stationary and mobile energy storages in modern smart grid environments is more significant than before. Storages are needed to fully exploit the potential advantages of renewable energies, distributed generation, energy storages and demand response techniques. Profitability is a vital factor when battery systems, combined with other energy resources or as an independent market player, participate in different electricity trade markets. Determining of the optimal battery capacity via an optimal bidding strategy for allocation to different electricity markets provides the higher economic profitability for the battery operator. This may mean, operating in electricity markets in frequency control, electricity traded in day-ahead and intra-day markets. Each market has its own requirements and obligations that should be observed by the participants. Moreover, technical constraints of the battery energy storage system should be fulfilled when utilized in electricity markets. Potential application and optimal scheduling of the BESS for attending in different electricity markets in Finland, i.e. energy markets of Nord Pool Spot and frequency control markets of transmission system operator (Fingrid Oyj), is investigated in this thesis. The obtained results are based on historical data of real markets and existing BESS resources in real-life pilot sites.

1.1 Objectives and scope of thesis

The objective of this thesis is to establish an operation strategy for determining an optimal capacity of the battery system on each hour for dedicating to electricity market players in Finland. The strategy is aimed to provide an optimized solution that is in compliance with the technical requirements of battery system and meets the obligations of markets. The profitability of utilizing the battery system in each market is intended to be evaluated. The results of this work provide a realistic vision for the battery owner to decide about participating in electricity markets. The scope of the thesis is to develop a methodology for optimizing the exploitation of battery capacity for allocation to Nord Pool day-ahead and intra-day markets, in addition to Fingrid frequency containment reserve markets.

The bidding model for the Nord Pool day-ahead and intra-day markets will be developed as a stochastic profit maximization model. The optimization problem is formulated with the objective of maximizing the total expected value of battery system's profit subjected to various technical linear and non-linear constraints. Constraints regarding battery energy capacity, state of charge, charging and discharging power limitations are considered in order to find the optimal solution of the formulated optimization problem. Two Matlab® optimization algorithms will be examined to solve the optimization problem effectively: interior-point algorithm and genetic algorithm. The results of applying mentioned algorithms will be presented, evaluated and compared together.

The capacity allocation of battery system to Fingrid frequency containment reserve markets for normal operation (FCR-N) and disturbances (FCR-D) will also be studied. Firstly, an optimization method will be investigated by formulating an optimization problem with objective of maximizing the profit and with considering the technical constraints. The optimization problem will be solved by Matlab® to determine the optimal battery capacity allocation to each FCR-N and FCR-D markets. The real historical data of frequency deviations will be used for this purpose. The profitability of participating in frequency markets with attention to involved risks will be discussed. Secondly, due to the unknown frequency deviations in real-time applications another method will be also studied to analyze the feasible scheduling of battery capacity allocation to Fingrid frequency markets without performing any optimization.

Applying each method, the profitability of battery system will be evaluated for each market and the challenges and risks will be discussed.

1.2 Structure of thesis

This thesis is organized in 9 chapters as follows:

Chapter 1 of the thesis includes an introduction to the topic and objective and scope of the thesis.

Chapter 2 presents a literature review about the prior studies that have been done in the same field.

Chapter 3 gives an illustrative explanations about the electricity markets in Finland including Nord Pool Spot market that has places for day-ahead and intra-day trading and Fingrid that holds ancillary service markets.

Chapter 4 is focused on the application and operating technology of Battery Energy Storage System (BESS). The benefits of BESS is also discussed in this chapter. The BESS research facility of this thesis is also introduced in this chapter.

Chapter 5 is mainly aimed to describe operational planning for utilizing BESS in electricity markets. The bidding strategy and trading in Finnish electricity markets are discussed in this chapter. Also, the time ordered flow-chart of operating in Finnish electricity markets is presented.

Chapter 6 seeks to investigate optimizing the exploitation of battery capacity for Nord Pool Spot market. The mathematical modeling of the BESS optimization problem and the relevant objective function is presented in this chapter. The applied constraints are characterized and the solving method is introduced. Two Matlab® functions and the utilized algorithms for solving the optimization problems are proposed and the optimization results of applying each function are presented separately. The battery costs are also addressed in this chapter and the calculated values are displayed.

Chapter 7 seeks to investigate optimizing the exploitation of battery capacity for Fingrid frequency markets. This chapter starts with an analysis on the prices of Fingrid frequency markets including frequency containment reserve market for normal operation (FCR-N) and frequency containment reserve market for disturbances (FCR-D). Data analysis of frequency deviations of May 2016 on average hourly basis and for the first week of May 2016 day by day for both frequency markets is presented in this chapter. The analysis performed for the battery capacity allocation to Fingrid frequency markets based on the time durations of frequency deviations is described, and the methods that are investigated to determine the hourly battery schedule for attending in Fingrid frequency markets are presented in this chapter. The first method is characterized by defining and formulating an optimization problem. The objective function and relevant constraints are addressed and the Matlab® function which solves the optimization problem is introduced. The optimization results for both FCR-N and FCR-D markets are presented for May 2016 in average besides for the first week of May 2016 day by day. Another method for scheduling the battery system without conducting any optimization program is also proposed in this chapter and the calculated revenues and costs are presented. The achieved results and the challenges of applying each method are discussed in this chapter.

Chapter 8 is the summary of the thesis and provides a discussion on the key results. The main outcomes of the thesis is presented in this chapter.

Chapter 9 is the final conclusion and the important outcomes.

2 LITERATURE REVIEW

Utilizing energy storages in power systems can elevate the reliability, stability and security of the system. The efficiency is improved when energy storage systems are exploited in smart grids or in microgrids. Energy storage systems can reinforce the balance of the power system and can contribute in better frequency regulations.

Plenty of studies have been carried out to evaluate the benefits of energy storages on the quality of power systems. Some studies also investigated the economic benefits that the energy storage systems can provide when utilized in power systems. Eyer and Corey [29] in Sandia report assessed the benefits of energy storage for the electricity grid. They showed the benefits and value propositions characterized provide an important indication of storage system cost targets for system and subsystem developers, vendors, and prospective users. Haddadian *et al.* [27] studied optimal scheduling of distributed battery storage for enhancing the security and the economics of electric power systems. Economic, social, and environmental challenges of the constrained electricity generation are addressed in the research. Sunde [11] investigated the impact of the optimal scheduling of the battery storages on the Norwegian power system. It was showed that the developed optimization model for battery dispatch gives reasonable results regarding power production, power flows, and battery dispatch. Also, it was shown that the total system operating cost is decreased when battery was included in the system. Khani [12] studied the optimal scheduling of energy storage for energy shifting and ancillary services to the grid in Ontario’s power system. Hussein *et al.* [30] investigated some design and operation aspects of distributed battery micro-storage systems in a deregulated electricity market system. Design aspects such as system architecture, system sizing, power stage design, battery management system (BMS), economic aspects and operation in a deregulated electricity market with and without renewable DGs were covered in the research. The economic benefits of BESS in electric distribution system was investigated by Zhang [18]. Three major battery energy storage system application topics were considered in his research: energy purchases shifting, distribution feeder deferral and outage avoidance. Chen *et al.* [32] analyzed the cost benefit of optimal sizing of an energy storage system in a microgrid (MG). Lamont [31] developed a theoretical framework to evaluate the marginal values of the components of a storage system, and to characterize the impact of storage on the price patterns in the system. His research was focused on assessing the economic value and optimal structure of large scale electricity storage.

Several studies have been focused on profitability by participating in electricity markets in order to provide energy, reserve and ancillary services. Some of the studies were only investigated participation of energy storage in energy markets and some address participation in ancillary service markets as well. Lampropoulos *et al.* [17] studied the day-ahead economic optimisation of energy storage systems within the setting of electricity spot markets. The case study was about a lithium-ion battery system integrated in a low voltage distribution grid with residential customers and photovoltaic generation in the Netherlands. Herranz *et al.* [19] proposed a methodology for determining the optimal bidding strategy of a retailer who supplies electricity to end-users in the short-term Spanish electricity market, although, the energy storage owners were not distinguished in the study. Fampa and Pimentel [20] presented the problem of strategic bidding under uncertainty in a wholesale electricity market by applying genetic algorithm. Kefayati and Baldick [22] studied the optimal operation of storage assets in response to pricing signals from the market. It was shown that under certain conditions, the optimal policy for operating the storage asset follows an extended threshold form and can be obtained in a computationally efficient manner. Oudalov *et al.* [50] presented a method for the dimensioning of a battery energy storage system (BESS) to provide a primary frequency reserve. A control algorithm with adjustable state of charge limits and the application of emergency resistors was implemented. It was shown that an optimized lead-acid BESS can be a profitable utility solution for the primary frequency control. A similar study by Mercier *et al.* [49] presents a method for optimal sizing and operation of a battery energy storage system (BESS) used for spinning reserve in a small isolated power system in order to achieve highest expected profitability of the device. Shi *et al.* [45] considered using a battery storage system simultaneously for peak shaving and frequency regulation through a joint optimization framework which captures battery degradation, operational constraints and uncertainties in customer load and regulation signals. It was shown that the electricity bill of users can be reduced by up to 15%. Huvilinna [10] studied applicability and economic viability of a BESS in the Finnish national transmission system operator, Fingrid Oyj. He stated that 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. Aghamohammadi and Abdolahinia [48] presented a method for determining optimal size of a battery energy storage system (BESS) for primary frequency control of a Microgrid. Pan *et al.* [47] investigated the capacity optimization of BESS for frequency regulation. A hybrid frequency regulation system consisting of BESS and generators was studied. An optimal allocation method was proposed and the regulation capacity of BESS was optimized. It was indicated that the hybrid regulation system can better reduce frequency deviations at a lower cost. Bradbury *et al.* [28] studied the economic viability and potential of energy storages' arbitraging in power markets. Cheng and Powell [46] studied optimizing the use of battery storage for multiple applications, in particular energy arbitrage and frequency regulation. A dynamic programming approach over different time scales was proposed. Research conducted by Udegbe [15] focuses on modeling the energy management system (EMS) for a commercial building microgrid capable of performing peak-shaving and providing backup reserve power, while participating in the PJM frequency regulation market.

In many studies the energy storage systems are combined with other energy resources such as solar or wind. Shu and Jirutitijaroen [24] proposed an adaptive optimal policy for hourly operation of an energy storage system (ESS) in a grid connected wind power company. Their purpose was to time shifting the wind energy to maximize the expected daily profit following uncertainties in wind generation and electricity price. Akhavan-Hejazi and Mohsenian-Rad [14] studied the optimal operation of independent storage systems in electricity markets with high wind penetration. The case where a significant portion of the power generated in the grid is from wind and other intermittent renewable energy resources was investigated. Profitability of the private investment on storage units were showed. Ding *et al.* [25] studied the rolling optimization of wind farm and energy storage system in electricity markets and showed using the proposed optimization method can increase the profit for the union prominently. Dicorato *et al.* [21] proposed an approach for planning and operating an energy storage system for a wind farm in the electricity market. An economic feasibility analysis was also carried out. Zou *et al.* [26] proposed an optimising SOC control approach for BESS in wind farm which could regulate wind power fluctuation in a suitable level and maintain SOC in an optimal range by utilising the wind power prediction information. Hill *et al.* [23] presented an overview of the challenges of integrating solar power to the electricity distribution system, a technical overview of battery energy storage systems, and illustrated a variety of modes of operation for battery energy storage systems in grid-tied solar applications. Aggregator's bidding strategy in spot markets is addressed in the research conducted by Ayón *et al.* [16]. An optimization method that produces optimal bidding curves to be submitted by an aggregator to the day-ahead electricity market and the intraday market, considering the flexible demand of his customers (based in time dependent resources such as batteries and shiftable demand) was proposed.

Utilizing battery system as an independent participant in both energy market and ancillary service market by determination of optimal scheduling of the capacity of the battery system for allocation to different markets based on the battery's charge and discharge levels and other technical constraints, and the choice of optimal price for participation in each market using one year of markets' real data, is an approach which was not investigated widely in previous studies. Few studies in the field of battery system as an independent market player that was accomplished recently are characterized here with some differences with this thesis. For instance, in the study carried out by Kefayati and Baldick [22], an optimal operation of the energy storage device as an independent asset in response to stochastic real-time market prices was proposed. However, the ancillary service markets were not independently addressed in the study. Battery costs were not considered either. Another study by Mohsenian-Rad [13] proposed an optimal supply and demand bidding, scheduling, and deployment design framework for battery system in day-ahead energy market. The battery capacity allocation to ancillary service market was not investigated in the work. Battery costs were not addressed in the profitability calculations either.

3 ELECTRICITY MARKETS IN FINLAND

Since 1990s, the traditional electrical power industry has been deregulated and a competitive environment was established by opening of the electricity market. The reform of the Finnish electricity market in 1995 removed obstacles to competition in the sectors of the market where competition is possible, that is, generation and sales. Now, it was possible for the end-users of electricity to invite tenders from electricity suppliers. Previously, the supplier of electricity had automatically been the local electricity company operating in the area; now the market reform brought new, versatile alternatives to purchasing of electricity also for large-scale consumers and retailers [51].

Below figure illustrates the development of the Finnish electricity markets from a closed to an open market [51]:

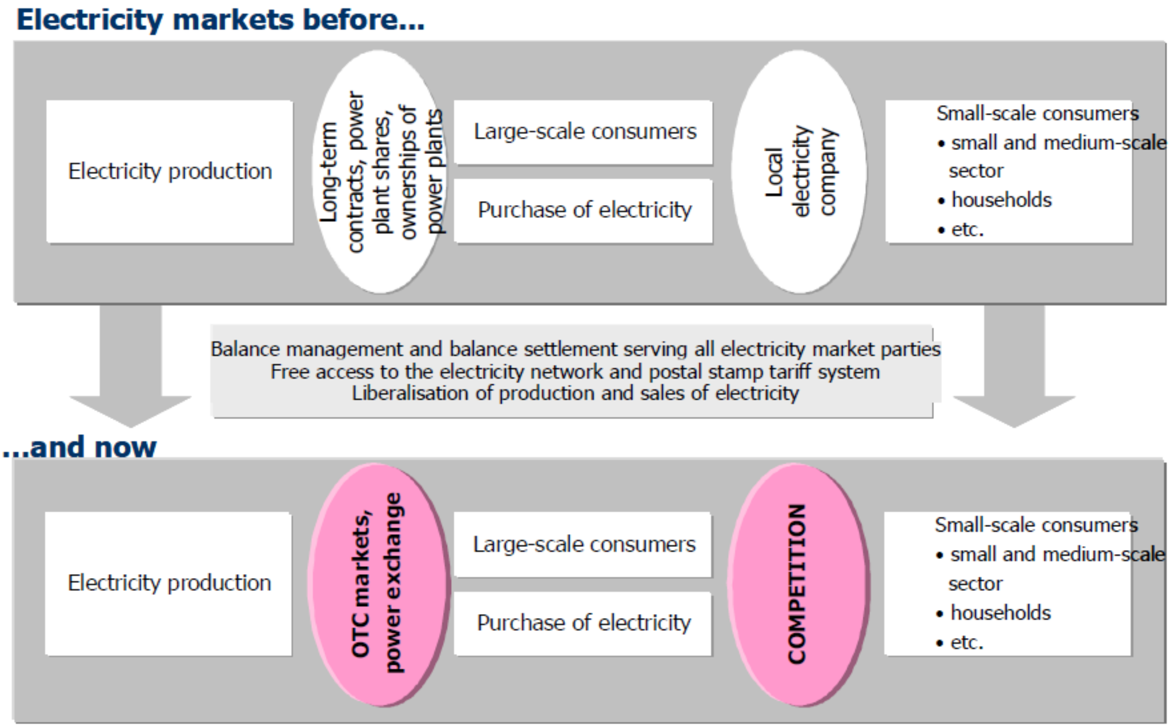


Figure 1 Development of the Finnish electricity markets *(Jarmo Partanen, Satu Viljainen, Jukka Lassila, Samuli Honkapuro, Kaisa Salovaara, Hanna Niemelä, Salla Annala, Mari Makkonen, 2017)*

Electricity trading in Finland is performed through market places, organized by Nord Pool Spot and Fingrid Oyj. Nord Pool spot runs the energy market and offers both day-ahead and intraday markets to its customers, while Fingrid runs ancillary service markets.

Each market has its own trading rules and regulations which should be observed by the market participants. Bids must be proposed by the bidders according to bidding rules and principles of the markets during the tendering time limits.

3.1 Nord Pool spot markets

The electrical grid power system is divided into four main parts: Generation, transmission, distribution and retail.

In Nordic countries, including Finland, it is possible to have competition in generation and retail. However, transmission and distribution have the monopoly nature.

The Finnish power system is part of the inter-Nordic power system. The power system in Finland consists of power plants, nation-wide transmission grid, regional networks, distribution networks and electricity consumers.

Power production and transmissions capacity has been extended over the years. With increasing number of transactions that took place, a new formed competitive structure called power pools were developed. Power pools provide a dynamic market where power can be bought or sold across areas and countries more easily. In power pool market the electricity generating companies can compete to fulfill the customers’ needs. Because of the dynamic nature of the market, each market participant determines its own bidding strategy to respond to the market requirements and maximize its profit simultaneously.

Nord Pool is Europe’s leading power market, and offers trading, clearing, settlement and associated services in both day-ahead and intraday markets across nine European countries, including Finland [1].

Nord Pool is owned by the Nordic transmission system operators. It is appointed as one of the most efficient electricity markets in the world with high security level of supply.

Entities willing to participate in any of the physical markets trading must sign a Participant Agreement with Nord Pool and be qualified as counterparty under the Clearing Rules prior to the initiation of trading.

3.1.1 Elspot day-ahead market

Power trading is mainly performed in day-ahead market of Nord Pool spot, named Elspot market. Elspot was established in 1993 and play an important role in electricity trading in Nordic countries. Trading in the day-ahead market is conducted by means of day-ahead auction for the following day, considering all orders received prior to gate closure [2].

Participants must submit their bids in accordance with the rules and regulations of the market. In the Nord Pool market the bids are quantity-price pairs. The bids must contain the volume of energy (MWh) that is aimed to be sold or purchased in each hour of the following day and the desired trading price. When all members have submitted their bids, equilibrium between the aggregated supply and demand curves is established for all bidding areas. Afterwards, the system and area prices are calculated and published. The power price is determined by the balance between supply and demand. Factors like weather can change the supply and demand, and consequently can impact on prices [2].

The system price is calculated based on the sale and purchase orders disregarding the available transmission capacity between the bidding areas in the Nordic market. The system price is the Nordic reference price for trading and clearing of most financial contracts.

Sellers and buyers should submit their bids for the following day delivery by 12:00 CET. An advanced algorithm calculates the price based on selling and buying curves by equilibrium point trading method. Selling and buying curves are formed by taking into account all submitted bids. The intersection point of selling and buying curves determines the system price for each hour. Grid capacities and congestion problems are not taken into account in the system price calculation. Around 12:45 CET hourly prices are announced to the market and trades are settled. The physical delivery of power starts from 00:00 CET the next day according to the contracts agreed [2].

Sellers' and buyers' energy capacity and hourly prices that are respectively delivered or needed, are entered in the Nord Pool day-ahead trading system and delivery of power for the following day is agreed between the seller and buyer. All participants are given access to the day-ahead (Elspot) market, although, participants must have a balancing agreement with the respective Transmission System Operator (TSO).

In addition to hourly contracts, block contracts and flexible contracts for the next 24 hours are possible in Elspot market.

3.1.2 Elbas intraday market

In addition to day-ahead market, Nord Pool offers an intraday market named Elbas. The Elbas market was opened in March 1999. Elbas market supports day-ahead market and is a subsequent market after Elspot market which enables continuous trading near the delivery time [3].

Due to the interval between the Elspot price fixing and actual power delivery, imbalances between day-ahead contracts and produced volume may happen which need to be offset. Intraday market enables participants to improve their physical electricity balance.

After closing of the Elspot market, at 14:00 CET, capacities available for Nord Pool's intraday trading are published. Elbas offers continues trading till one hour before the physical delivery time [3]. The bids must specify both the volume and the price for each particular hour. Unlike day-ahead electricity prices that are unchanged after settlement, the prices of the intraday market may vary during the trading period. Prices are set based on a first-come, first-served principle, where best prices come first – highest buy price and lowest sell price [3].

Imbalance in power market can occur due to various reasons, including incidents which may take place between the closing of the day-ahead market at noon CET and delivery of the next day. For instance, unpredictable nature of wind power or a problem in operation of a power plant can endanger the balance of the power.

The existence of uncertainty, which is one of the important characteristics of the energy markets, should always be taken into account. This is so apparent in the Nord Pool market, where wind power is one of the main sources of the electricity production.

Growing of renewable energies can increase the imbalance in the power market, and consequently is making the intraday market more important than before. Elbas market plays a key role in the development of intraday power trading in Europe.

3.2 Balancing power market

Fingrid holds the balancing power market via which it gains regulating capacity for power balance. All producers and load holders can attend in the balancing power market by submitting regulation bids. Power regulation bids are divided into two categories: Up-regulation bids and Down-regulation bids [39].

Up-regulation bids are for increasing the generation or reducing the consumption. In contrast, down-regulation bids are for decreasing the generation or increasing the consumption.

Up-regulation bids should contain the price for a specific volume that the participant can increase generation or reduce consumption. The lowest bid price is the Elspot price.

Down-regulation bids should contain the price that the participant offers to pay to decrease generation or to increase consumption. The highest bid price is the Elspot price.

Regulating power offers should be submitted to Fingrid not later than 45 minutes before the operating hour. The current minimum capacity for balancing power bids is 10 MW and the bidder should be able to activate the resource in 15 minutes. Fingrid plans to reduce the minimum size of the balancing power market bids to 5 MW in future [39].

3.3 Fingrid ancillary service markets

In Finland, the power transmission is conducted by Fingrid. The responsibility of planning and monitoring the operation of the Finnish electricity transmission system is by Fingrid. Fingrid ensures the adequacy and robustness of the system, and is responsible for maintaining and developing the system. Fingrid is also responsible to maintain the instantaneous balance between supply and demand besides providing the security of the power grid in Finland. This is performed via its balancing power market. Moreover, Fingrid organizes ancillary service markets. Ancillary services include frequency control, voltage control, spinning and standing reserve.

3.3.1 Frequency control

The balance between production and consumption is crucial in a power grid. Fingrid ensures that there is a balance between production and consumption of power at all times. Fingrid is responsible to keep the Finnish power system in balance by continuous managing and controlling the power system. If consumption and production are not balanced, the frequency of the grid fluctuates lower or upper the pre-defined range. Frequency should be returned back to normal range by regulating the production and/or consumption. This can be performed by injecting power to the grid or absorbing the excess power from the grid. Balance between consumption and production can be achieved by activating the maintained reserves or by initiating regulating bids from the balancing power markets [36].

3.3.2 Power reserve markets

Nordic Transmission System Operators (TSOs) agree the obligations for maintaining reserves. Two types of reserves are maintained by Fingrid: 1. Frequency Containment Reserves (FCR) and 2. Frequency Restoration Reserves (FRR). Frequency Containment Reserves (FCR) are used for constant control of frequency while Frequency Restoration Reserves (FRR) are used to return frequency back to its normal range to be able to activate the Frequency Containment Reserves once again [37, 38]. Frequency Containment Reserves (FCR) can be activated for normal operation (FCR-N) or disturbances (FCR-D). When changes in frequency occurs in normal operation, that is the frequency falls below 49.95 or rise over 50.05 HZ, FCR-N is activated in 3 minutes to keep the frequency in a normal range of 49.9 to 50.1 Hz [37]. If an unexpected defect happens in operation which causes serious frequency deviation outside standard range, FCR-D is automatically activated. The activation time is determined by the resource type. The reserve unit used in the maintenance of the frequency controlled disturbance reserve shall regulate almost linearly so that the activation begins when the frequency decreases below 49.90 Hz, and the full reserve shall be activated at a frequency of 49.50 Hz. Half of the frequency controlled disturbance reserve shall be activated in five seconds, and it shall be activated in full in 30 seconds at a stepped frequency change of -0.50 Hz [37].

Fingrid has two separate markets for FCR-N and FCR-D. In each market, long term (yearly) and short term (hourly) agreements are possible. Participating in hourly market is independent from participating in yearly market and can take place in the middle of calendar year, while participating in yearly market is not possible in the middle of the year [33].

Bids to Frequency Containment Reserve (FCR) hourly markets must be submitted till 18:30 o'clock (EET). Fingrid processes the submitted bids and prioritize the cheapest bids. The final result of accepted bids is announced by Fingrid at 22:00 o'clock (EET) [43].

Frequency Restoration Reserves (FRR) is divided into automatic (aFRR) and manual (FRR-M) reserves. The aim of Automatic Frequency Restoration Reserve (FRR-A) is to turn back the frequency to 50 Hz automatically, while the purpose of FRR-M is to control power balancing in normal and disturbance situations when activated manually from Fingrid's Main Grid Control Centre. Bids for the FRR-A market must be submitted by 17:00 o'clock (EET). Fingrid announces the accepted bids by 18:05 o'clock (EET) [38].

Frequency reserve obligations for Finland is about 140 MW for normal operation (FCR-N), 220-265 MW for disturbances (FCR-D), 70 MW for automatic restoration (aFRR) which is maintained only in morning and evening hours, and 880-1100 MW for manual restoration (FRR-M).

Below picture shows the frequency control processes conducted by Fingrid [36]:

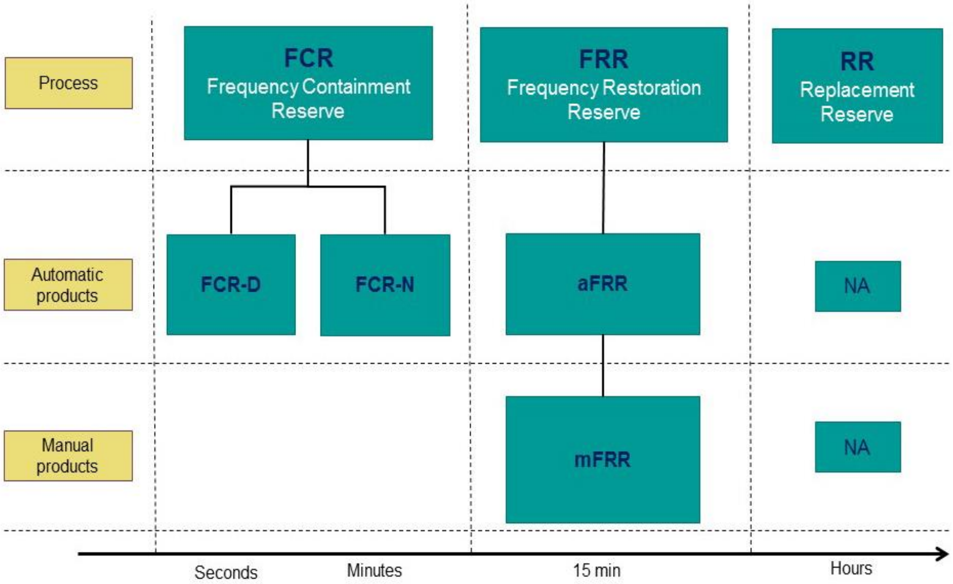


Figure 2 Reserve products used in Finland *(Fingrid, 2017)*

Minimum bid size requirements for FCR-N, FCR-D, a-FRR and FRR-M are 0.1, 1, 5 and 10 MW respectively [37].

4 BATTERY ENERGY STORAGE SYSTEM (BESS)

4.1 Operation technology

Energy storage is the storing of energy to be used at a later time. Different technologies are used to provide short-term or longer term energy storage. According to Energy Storage Association, energy storage technologies are divided into six main categories:

- Solid State Batteries
- Flow Batteries
- Flywheels
- Compressed Air Energy Storage
- Thermal
- Pumped Hydro-Power

Battery energy storages use electrochemical method for storing energy. There are a large range of battery technologies available, including lead-acid batteries, lithium-ion batteries, lithium-iron-phosphate batteries, nickel-cadmium batteries, nickel-metal hydride batteries, sodium-ion batteries, etc. $LiFePO_4$ batteries have lower energy density than the more common lithium cobalt oxide (LiCoO2) type but offer longer lifetimes, better power density and are inherently safer.

In addition to battery, Battery Energy Storage System (BESS) contains other components like power conversion system, monitoring and control systems.

4.2 Applications and benefit analysis

In the past, batteries were not common in grid energy storage, due to some negative aspects like their costs, maintenance needs, short lifetime, etc. However, with improving the technologies used in constructing the batteries, they now more contribute in power systems. BESS, when used in energy chain, can improve the efficiency and power quality and can reduce energy losses of the grid; therefore, can play a significant role in smart grids. It can contribute in better frequency regulations and can provide a reliable source of energy with minimum interruptions. Moreover, BESS can produce and control reactive power generation accurately, and consequently controlling voltage level.

Furthermore, in contrast with some other energy resources like solar, wind, compressed air and pumped hydro resources, geographical restrictions are invalid for battery energy storages. The usage of BESS in electricity distribution networks, domestic and industrial applications are growing. European Commission intends to increase efficiency, flexibility, safety, reliability and quality of the European electricity systems and to fully exploit the potential advantages of renewable energies, distributed generation, energy storages and demand response techniques (European Commission. European Technology Platform SmartGrids. SmartGrids SRA 2035. Strategic Research Agenda, 2012). So, the role of stationary and mobile energy storages in European modern smart grid environments is more significant than before.

BESS is an effective solution to meet the power balancing requirement especially with the rise of variable renewable energies such as wind and solar. BESS improves the power grid stability when distributed energy from renewable resources are integrated into existing distribution networks. BESS can improve the balance of power in a short time by quickly compensating and balancing the fluctuations caused in the network, and by regulating exchange of active and reactive power with the power system.

BESS can also be used for the peak shaving, load leveling, transmission congestion relief and frequency regulation purposes.

Batteries can provide either energy or power for the grid depending on the application and the market that they are intended to be used for. For instance, in frequency regulation application battery should be able to inject/absorb power to/from the grid in a short period, while in the spot markets batteries are used to provide required energy for a longer period of time, for instance, for load leveling of the network.

Battery systems can respond immediately when called. Generally, comparing with generators, battery systems can provide faster and more precise service.

In addition to above-mentioned technical profits for the electricity grids, BESS, if used properly, can provide noticeable economical profit for the battery operators. Optimal scheduling and deployment design framework of battery systems can minimize the costs and maximize the revenue from employing the battery systems. Also, BESS capacity can be allocated to different stakeholders in an appropriate time manner. By defining a suitable methodology for optimal techno-economical sharing of capacity, BESS can participate in different markets for different applications. This may mean, for instance, operating at the same time in electricity markets in frequency control, electricity trade in day-ahead, intraday, and ancillary markets and at the same time offering various services to local network operations and several other stakeholders.

Currently, several battery storage projects are running around the world with different battery capacities from few kWh to hundreds MWh. However, battery energy storage systems (BESS) have not yet spread into the real electricity markets and the number of studies to investigate their profitability in the market, considering their lifetime, energy density and degradation, is not enough yet.

4.3 BESS research facility

The battery energy storage system which has been focused in this thesis belongs to Helen Ltd.

In August 2016 Helen Ltd commissioned the largest Battery Energy Storage System (BESS), "Suvilahden sähkövarasto", in Nordic countries. The BESS, rated 1.2 MW / 600 kWh, was built by Toshiba Transmission and Distribution Europe S.p.A. using Toshiba's state-of-the-art SCIB battery modules and supplied to Helen by Landis + Gyr Ltd. It is located in Suvilahti, an urban district in downtown Helsinki, the capital of Finland. The BESS is installed next to a primary substation of the local DSO, Helen Electricity Network, where Helen commissioned Finland's first large-scale (380 kWp) solar power plant in April 2015. Both the BESS and the solar power plant share the same connection point to the DSO's 10 kV medium voltage network.

- 600 kWh, 1.2 MW nominal ratings, 50% overload capability
- 15 000 Toshiba SCIB Li-ion (LTO) cells
- Integrated system inside 12 m container designed for arctic conditions
- Redundant system with two converters and 22 individual battery strings
- Shares a 10 kV grid connection with Helen's 340 kWp solar power plant in downtown Helsinki
- Commissioned in July 2016
- Programmable control system with multi-use capability and smart grid integration

In this thesis, an optimizing exploitation of low voltage network connected battery (LiFePo4) capacity from the perspectives of the electricity market players in Finland has been investigated and the profitability of employing of battery system in different markets has been studied. BESS is supposed to be a part of the larger aggregated group of energy storage resources, and thus minimum bid sizes in different markets are ignored.

In this thesis battery systems is considered independently without combination with any other energy resource.

The results of this thesis are applicable (at least to some extent) for other battery types as well.

5 OPERATIONAL PLANNING FOR UTILIZING BESS IN ELECTRICITY MARKETS

5.1 Bidding strategy

Accurate knowledge about the nature and structure of Finnish electricity markets are essential for effective planning of battery system utilization in electricity trading. The battery owner should have a comprehensive plan to be able to participate in Finnish electricity markets securely. The major purpose of planning is to determine a strategy to optimize the exploitation of battery capacity and maximizing the profit that can be achieved from employing the battery system in different electricity markets within the boundaries set by the electricity market design and legislation. The volume of battery power or energy that should be allocated to each market and the desired trading price in each market should be determined. The strategy for trading in each market should be planned separately with attention to the characteristics and nature of that market. As the economical objective of planning is to maximize the profit, the planning should clarify from which market the battery energy can be purchased with less price and to which market the battery energy can be sold with more price. In other words, the planning should verify how the battery system capacity should be allocated to different markets and with what price, to earn the maximum profit. Due to the fact that electricity price and consumption involve uncertainties, imposing risks may arise which need to be managed effectively. Developing an optimal plan for using battery system in multi-applications involve different challenges. Important challenges include various constraints that should be taken into account for each application with attention to inherent uncertainty nature of electricity markets and impacts of the plan on the aging and degradation of the battery system.

5.2 Trading in Finnish electricity markets

Trading in Finnish electricity markets can be divided into two main components. The first one is the basic energy markets of Nord Pool, and the second one is the Fingrid ancillary service markets. The mentioned markets consist of sub-markets including Elspot day-ahead market, Elbas intraday market, Fingrid FCR-N and FCR-D markets which were explained in the former chapter 3 by details. Operation of the battery system should be investigated in each of these markets independently to find the best scenario for battery scheduling.

Timeline requirements should be pointed out in the plan along with the technical requirements. Short-term planning to operate in Finnish electricity markets starts with planning to participate in Elspot day-ahead and Elbas intraday markets and continues with planning to participate in Fingrid reserve markets. The deadline for submitting bids to the day-ahead market, Elspot, is 12:00 CET [2]. The battery owner should specify the amount of supply and demand energies for each hour of the next day beside the intended trading price in the submitted bid to Elspot. The amount of energy which should be sold or purchased and the related price are determined by utilizing the optimization program. Although it is logical to purchase energy to charge the battery in the low-price hours and discharge the battery in high-price hours, the constraints regarding keeping the state of charge of the battery in a specific range may make it hardly possible to always purchase energy at low-price hours of the day. The applied optimization solver determines the best scheduling considering all of the limitations. The battery owner receives the declaration of Elspot trades and prices latest on 13:00 CET [2]. Afterwards, the preliminary plan for participation in Elbas market should be drawn-up. One hour later, at 14:00 CET Elbas intraday market opens to receive the bids for the next day intraday trades. Submitting bids in Elbas market is possible until one hour before the start of the physical delivery time [3]. It means, the battery owner has many hours for balancing trades. The Elbas market should be monitored continuously by the battery owner and necessary changes should be applied to the preliminary plan. The Elbas prices are usually higher than the Elspot prices, so the optimal plan is arranged possibly to purchase energy from Elspot while selling energy to Elbas by observing all of the technical constraints.

Depending on the clarified day-ahead hourly traded energies and prices by the Elspot, battery owner should update the available battery capacity and calculate the optimal price and power that can be proposed to Fingrid markets. In other words, the unsuccessful traded capacity to Elspot should be added to the previously allocated capacity for Fingrid for the related hours, and the bidding information should be updated consequently. The bids to Fingrid reserve markets FCR-N and FCR-D should be submitted till 17:30 CET [43]. It means the battery owner has 4.5 hours interval to make the final plan for Fingrid markets after being informed about Elspot result. The bidding strategy and scheduling of battery system for Fingrid markets are remarkably important, as the Fingrid markets are the most profitable markets in Finland and provides the best opportunity for the battery owner to attain significant profit [10]. At 21:00 CET Fingrid declares the capacities and prices [43]. At this time battery owner realizes all of the battery capacities that are accepted for trading in Elspot and Fingrid reserve markets in total and the hours in which the battery should be available for those markets. Afterwards, the remaining capacity of the battery for trading in Elbas market can be updated. The Elbas market is flexible. It means it provides the opportunity to update the bids continuously till one hour before the delivery time.

Below figure from Valtonen doctoral dissertation provides a flow chart of the retailer's operation in the market environment on a timeline [9].

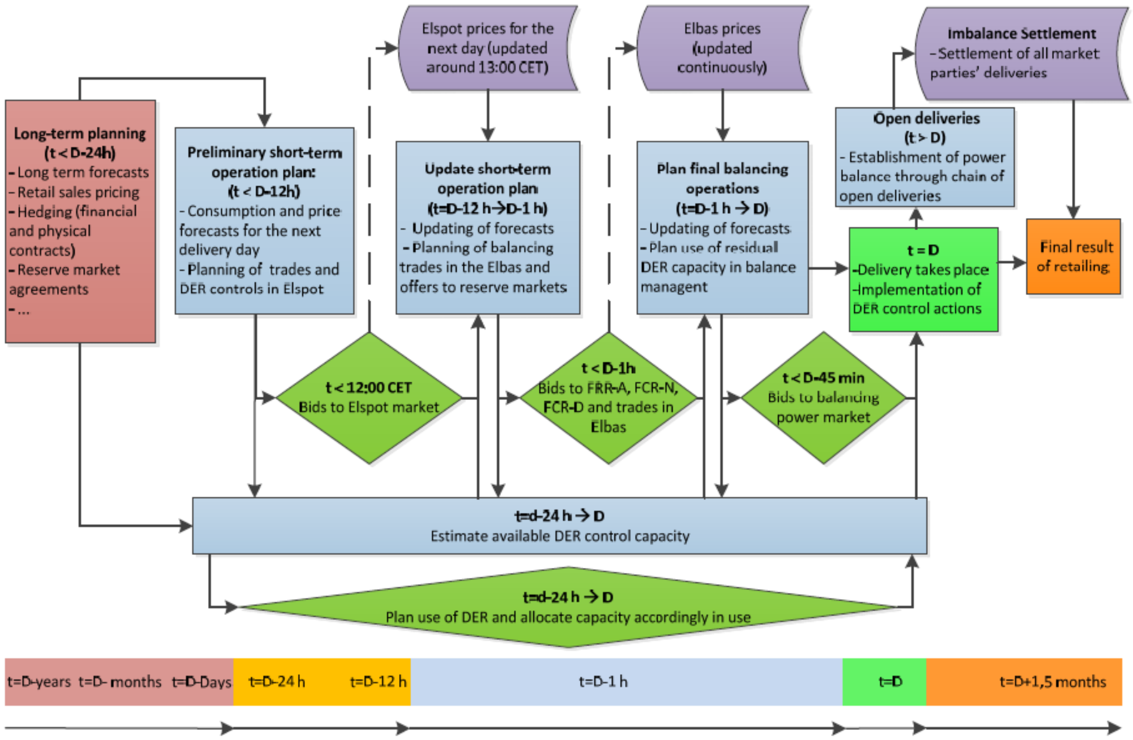


Figure 3 Electricity retailer's operation in the smart grid environment *(Valtonen, 2015)*

Below flow-chart shows the time-limits for operations in Finnish electricity markets:

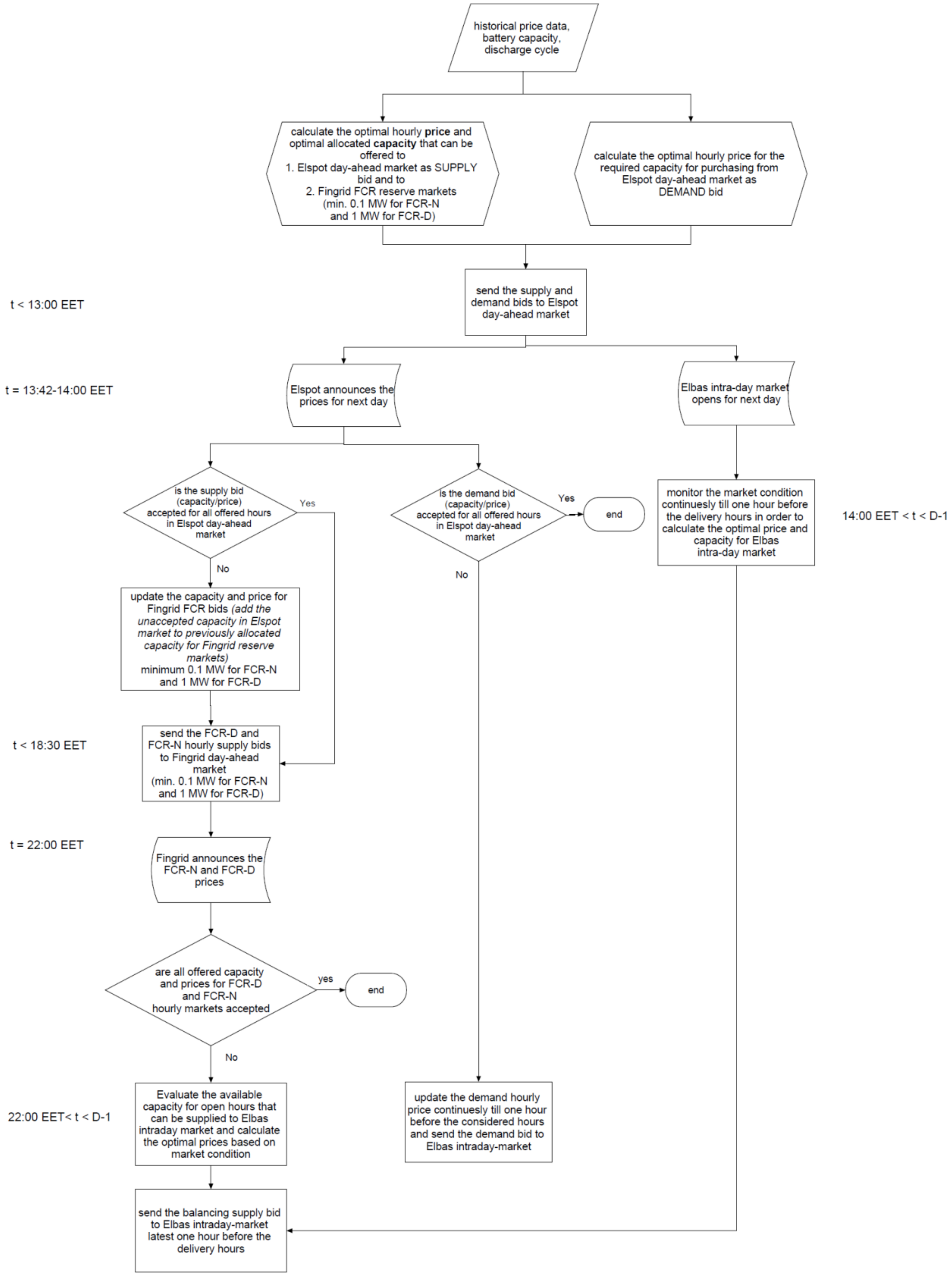


Figure 4 Time-limits for operations in Finnish electricity markets

In this thesis the methodology for allocating the load control capacity to Nord Pool day-ahead market (Elspot), Nord Pool intraday market (Elbas), Fingrid frequency reserve markets (FCR-N and FCR-D) have been studied and the financial profit attained from employing the battery in each market has been calculated.

6 OPTIMIZING THE EXPLOITATION OF BATTERY CAPACITY FOR NORD POOL SPOT MARKET

6.1 Mathematical modeling of BESS optimization problem

The purpose of this section is to mathematically formulate the optimization problem in order to find the optimal scheduling of battery capacity allocation to Nord Pool day-ahead (Elspot) and intraday (Elbas) markets.

In this thesis the battery is supposed to be price taker which means it is not significant enough to influence the market prices.

In order to determine the optimal energy volume of the battery system as supply and demand bids to electricity markets for each hour of the day, it is needed to solve an optimization problem that is formulated based on the gained revenue and aroused costs of employing the battery system in Nord Pool electricity markets.

Nord Pool day-ahead and intraday markets are energy markets, i.e. the participants should specify the energy volume that they tend to sell or buy through these markets.

Energy bids to Nord Pool spot market are categorized as supply bids and demand bids. If the battery owner submits a supply bid, it means battery owner aims to sell energy and consequently the battery system will be discharged at the declared hour. In contrast, if the battery owner submits a demand bid, it means battery owner aims to purchase energy and consequently the battery system will be charged at the declared hour.

The Nord Pool spot market can be splitted into $T = 24$ hourly time slots. Energy components of the bids are denoted by e_s and e_d. $e_s(t)$ is the energy component of supply bid at time slot t and $e_d(t)$ is the energy component of demand bid at time slot t. It should be noted that the battery system cannot submit both supply bid and demand bid for the same hour.

Supply energy $e_s(t)$ should be always less than the maximum discharge rate of the battery and similarly, demand energy $e_d(t)$ should be less than the maximum charge rate of the battery system.

The energy capacity of the battery is the total Watt-hours available when the battery is discharged certain discharge current from 100 percent state-of-charge to the cut-off voltage. The usable battery capacity is defined by the maximum and minimum state of charge limits.

State of Charge $(SOC)(\%)$ is the present battery capacity as a percentage of maximum capacity. SOC is generally calculated using current integration to determine the change in battery capacity over time. For the battery system studied in this thesis, maximum state of charge of the battery system is defined 90% and minimum state of charge is defined 10%.

The minimum and maximum allowed charge level of the battery are defined as C_{max} and C_{min}, which are calculated based on the maximum and minimum values of state of charge of the battery. The battery should always have the minimum amount of charge level after each energy transaction. In this thesis it is assumed that the initial charge level of the battery is around 80% of the battery total capacity and is shown as C_{crt} here. Obviously, the value of C_{crt} is always between the values of C_{min} and C_{max}.

The difference between the total amount of energy which is purchased in the market and the energy which is sold to the market should be in a specific range, as a function of the minimum, maximum and certain values of battery capacity. This ensures that the total stored energy at the battery at each time frame is always within the permitted range.

Submitted bids, in addition to the volume of energy that the battery owner plans to buy or sell for each particular hour, should also include the price that the battery owner wishes to trade the specified amount of energy for that hour. After the deadline for submitting the bids, the Nord Pool trading system calculates the price for each hour of the following day and announces the cleared price to the trade participants. Since the battery system is price-taker, the market cleared price does not depend on the battery charge and discharge variables $e_s(t)$ and $e_d(t)$.

As explained in the chapter 3, the participants should first submit their bids to Nord Pool day-ahead market (Elspot). The day-ahead market (Elspot) is settled sooner than the intraday market (Elbas). The reason is that the trading in Elbas market is possible till one hour before the actual delivery time. Thus, the Elspot prices are approved sooner than the Elbas prices.

If the offered price by the battery owner is less than or equal to the Elspot cleared price, the battery owner can sell the energy volume stated in the submitted supply bid at the day-ahead market, and in contrast, if the offered price by the battery owner is greater than the Elspot cleared price, the battery owner will not be able to sell the energy at the day-ahead Elspot market. In order to formulate the mentioned fact, we define an indicator function $\mathbb{I}$ (.) which switches 0 and 1 based on comparison between the offered price by the battery owner and the cleared price by the day-ahead market (Elspot) [13]. This means, if the declared energy price (λ) by the battery owner be less than or equal to the Elspot price (λ_{elspot}) after the market is cleared, the indicator function $\mathbb{I}$ is 1, Otherwise, $\mathbb{I}$ is 0:

$$\mathbb{I}\ (\lambda_{elspot} |\ \lambda) = \begin{cases} 1,\ \lambda(t) \leq \lambda_{elspot}(t) \\ 0,\ \lambda(t) > \lambda_{elspot}(t) \end{cases} \tag{1}$$

6.1.1 Revenue obtained from selling energy of the battery system

The total energy which is sold at Elspot day-ahead market via the supply bid is calculated as:

$$\sum_{t=1}^{T=24} e_S(t) * \mathbb{I}\ (\lambda_{elspot} |\ \lambda) \tag{2}$$

The total revenue that gained from selling energy to the Elspot day-ahead market is calculated simply as:

$$\sum_{t=1}^{T=24} e_S(t) * \mathbb{I}\ (\lambda_{elspot} |\ \lambda) * \lambda_{elspot} \tag{3}$$

The amount of unsold energy in the Elspot day-ahead market is the difference between the total amount of supply energy and the total energy that sold at the day-ahead market:

$$\sum_{t=1}^{T=24} e_S(t) - \sum_{t=1}^{T=24} e_S(t) * \mathbb{I}\ (\lambda_{elspot} |\ \lambda) \tag{4}$$

It is assumed that the rest of energy which could not be sold at Elspot day-ahead market will be sold later in the Elbas intraday market. This assumption is necessary for calculation of optimal amount of energy which should be sold at each time frame.

It should be noted that Nord Pool intraday market (Elbas) is designed for balancing purpose, and differs from Elspot trading. In Elbas, the prices are set based on a first-come, first-served principle. The lowest sell price and the highest buy price come first, and transactions are matched automatically as soon as concurring. The price of the Elbas intraday market will be cleared after the closing of the market one hour before the physical delivery hour, and is shown as λ_{elbas} here. Similar to Elspot day-ahead market, as the battery system is price taker, the cleared price by Elbas intraday market is not affected by the supply and demand energy bids proposed by battery owner. The total revenue which is obtained from selling the remaining energy at the Elbas intraday market is calculated as:

$$\sum_{t=1}^{T=24}[1-\mathbb{I}\ (\lambda_{elspot}|\,\lambda)]*e_S(t)*\lambda_{elbas} \tag{5}$$

Therefore, the total revenue that the battery owner achieves from selling the energy to Nord Pool day-ahead and intraday markets is the sum of the revenues earned from trading at Elspot and Elbas markets:

$$\sum_{t=1}^{T=24}e_S(t)*\mathbb{I}\,(\lambda_{elspot}|\,\lambda)*\lambda_{elspot}+\sum_{t=1}^{T=24}[1-\mathbb{I}\ (\lambda_{elspot}|\,\lambda)]*e_S(t)*\lambda_{elbas} \tag{6}$$

6.1.2 Cost aroused for purchasing energy for the battery system

In order to charge the battery, the battery owner should buy energy from the market to keep the charge level of the battery at the desired range. It is critical to plan an optimized schedule that determine the best time slots that the energy should be purchased from the market. To buy energy, the battery owner should submit a demand bid to Elspot market. The bid contains the energy volume that the battery owner plans to buy for specified hours of the following day and the price that wishes to pay.

Using the indicator function $\mathbb{I}(.)$ defined before, the total energy that is bought from the day-ahead market (Elspot) is:

$$\sum_{t=1}^{T}[1-\mathbb{I}\ (\lambda_{elspot}|\,\lambda)]*e_d(t) \tag{7}$$

The total cost spent to buy energy from the Elspot day-ahead market is calculated as:

$$\sum_{t=1}^{T=24}[1-\mathbb{I}\ (\lambda_{elspot}|\,\lambda)]*e_d(t)*\lambda_{elspot} \tag{8}$$

The amount of energy which could not be bought from the Elspot day-ahead market is the difference between the total amount of demand energy and the total energy that is purchased from the day-ahead market:

$$\sum_{t=1}^{T=24}e_d(t)\text{ - }\sum_{t=1}^{T=24}[1-\ (\lambda_{elspot}|\,\lambda)]*e_d(t) \tag{9}$$

Similar to the supply bid case which was analyzed above, it is assumed that the amount of energy which could not be purchased from the Elspot day-ahead market will be bought from Elbas intraday market.

The total cost aroused from purchasing the rest of the required energy in the Elbas intraday market is calculated as:

$$\sum_{t=1}^{T=24} e_d(t) * \lambda_{elbas} - \sum_{t=1}^{T=24}[1 - (\lambda_{elspot}| \lambda)] * e_d(t) * \lambda_{elbas} \qquad (10)$$

Therefore, the total cost that the battery owner pays to buy energy from Nord Pool day-ahead and intraday markets is the sum of the spent costs to Elspot and Elbas markets:

$$\sum_{t=1}^{T=24}[1 - \mathbb{I}\ (\lambda_{elspot}| \lambda)] * e_d(t) * \lambda_{elspot} + \sum_{t=1}^{T=24} e_d(t) * \mathbb{I}\ (\lambda_{elspot}| \lambda) * \lambda_{elbas} \quad (11)$$

6.1.3 Objective function of the optimization problem

From the above calculated revenues and costs, the objective function can be formulated based on maximizing the expected value of the profit. The expected profit value is gained from the difference between the expected value of revenue achieved from selling the battery energy to market, and expected value of costs paid for buying the energy from the market across all time slots.

$$\underset{e_s, e_d, \lambda}{\text{Max}}\ E\{\sum_{t=1}^{T} e_s(t) * \mathbb{I}\ (\lambda_{elspot}| \lambda) * \lambda_{elspot} + [1 - \mathbb{I}\ (\lambda_{elspot}| \lambda)] * e_s(t) * \lambda_{elbas}\} -$$
$$E\{\sum_{t=1}^{T}[1 - \mathbb{I}\ (\lambda_{elspot}| \lambda)] * e_d(t) * \lambda_{elspot} + e_d(t) * \mathbb{I}\ (\lambda_{elspot}| \lambda) * \lambda_{elbas}\} \qquad (12)$$

So, by solving the above-mentioned optimization problem, the optimal energy to be sold or purchased through supply and demand bids, will be determined for each hour of the following day.

6.2 Optimization problem solving method

The objective function that was formulated above, is a stochastic non-linear optimization problem. It is stochastic since it includes prices of Elspot and Elbas markets, which are random variables and are known only after the clearance of markets. Also, it is non-linear because of the existence of indicator function $\mathbb{I}$ (.).

The formulated optimization problem includes three (3) variables $e_s(t)$, $e_d(t)$ and $\lambda(t)$ that it is intended to find their optimal values. Also, the value of the indicator function $\mathbb{I}$ (.) depend on the price variable $\lambda(t)$. This makes the solving of the problem complicated, because the indicator function introduces discontinuity and non- differentiability into the equation. So, first some simplifications should be made that leads to solve the optimization problem.

If the optimal price is drawn out of the equation and is calculated separately, the value of the indicator function $\mathbb{I}$ (.) would be known in each hour beforehand, and also the equation will be independent from value of $\lambda(t)$ variable. So, a non-linear optimization problem with three variables for each hour (i.e. 72 variables for T=24 hours) will be mitigated to a linear equation with two (2) variables for each hour (i.e. 48 variables for T=24 hours).

6.2.1 Optimal bidding solution

In the first phase, the optimal price should be identified. Depending on the historical data of market prices, an optimal price can be determined for each time frame by calculating the mean of the available data of market prices for each time slot cleared during one year period.

In this thesis, historical prices of Elspot and Elbas markets in 2016 are used [4]. The mean value of Elspot and Elbas prices for each hour of the day in 2016 is calculated and are presented in below figures:

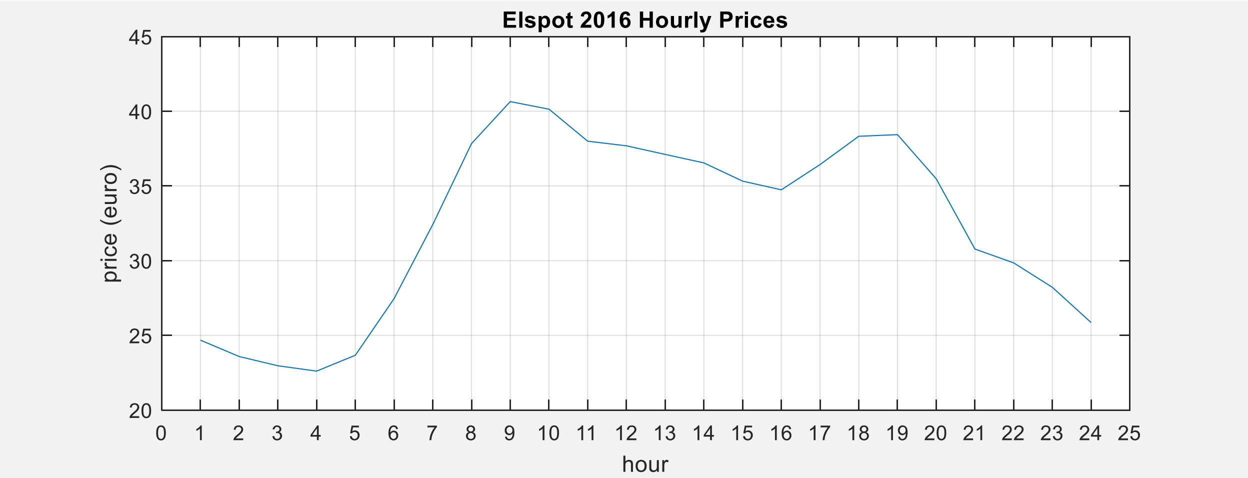


Figure 5 Elspot hourly prices - Average 2016

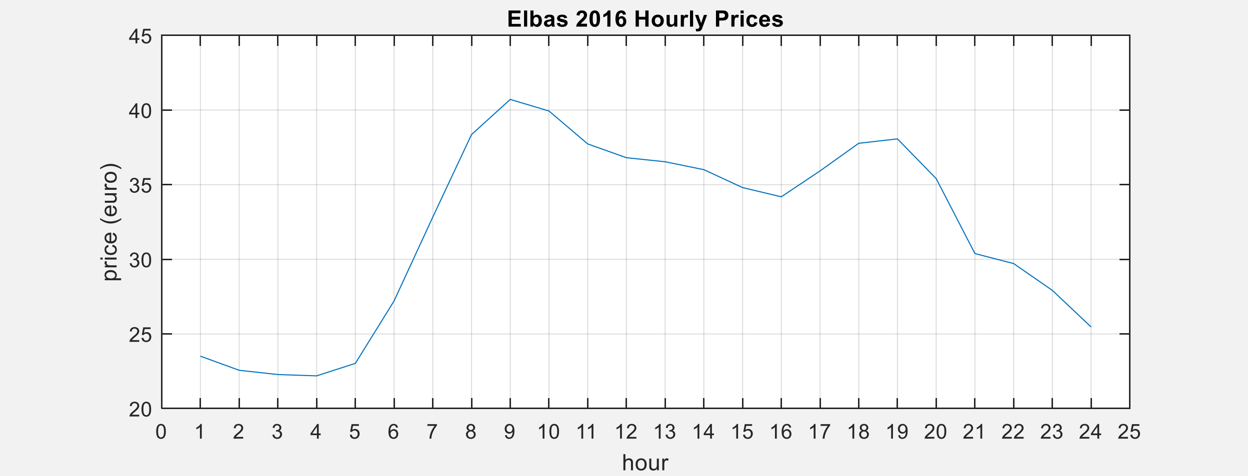


Figure 6 Elbas hourly prices - Average 2016

The historical prices of Nord Pool markets present diverse price values for the same hours of the day in different months. For instance, in January 2016 the electricity was traded with a much higher value in some hours of the day when compared with the traded prices for the similar hours of the day in the other months. Hourly prices of January 2016 is depicted in figure 7.

A comparison between hourly prices in January 2016 and average hourly prices of the whole year 2016 is illustrated in figure 8.

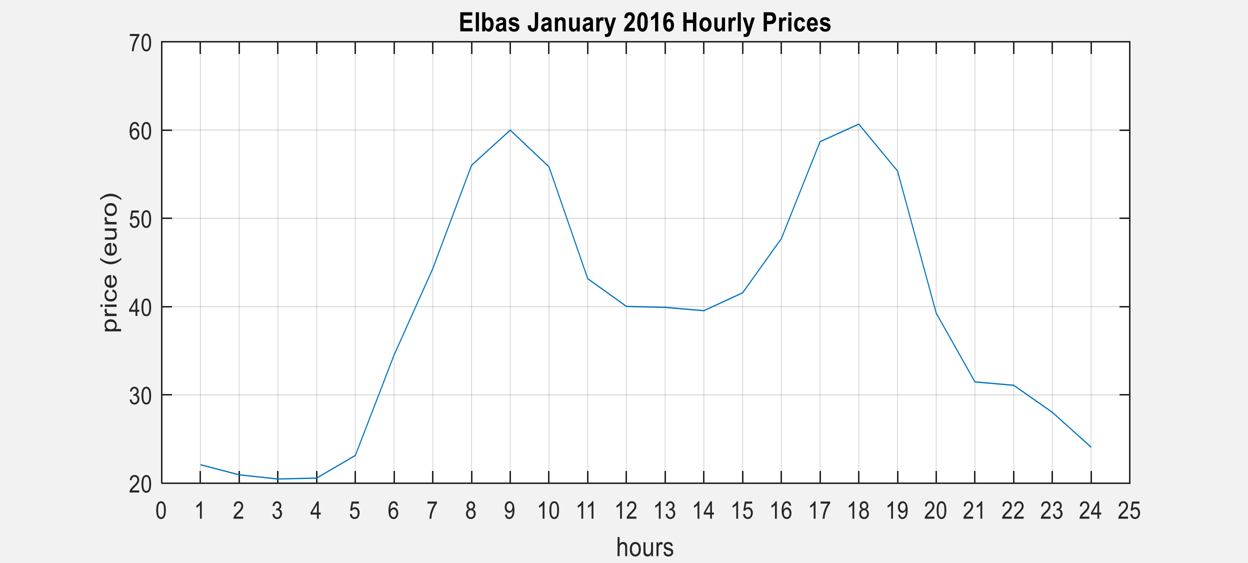


Figure 7 Elbas hourly prices - January 2016

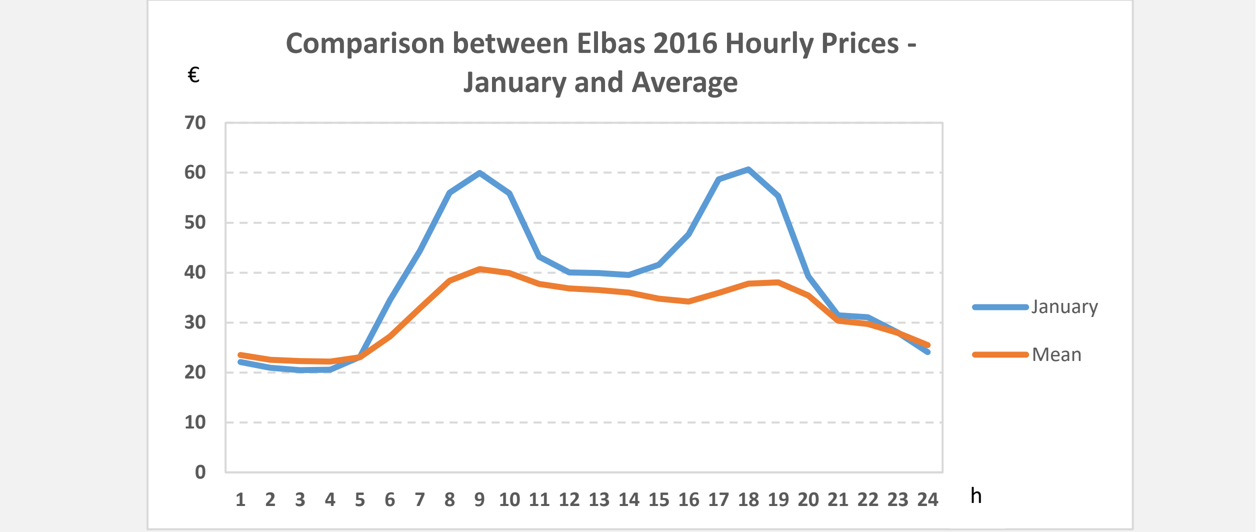


Figure 8 Comparison between Elbas January and average prices

Therefore, in order to participate in Nord Pool markets the optimal price should be calculated separately for each month of the year. Furthermore, the historical price data of Elspot day-ahead and Elbas intraday markets show that the Elbas prices are usually higher in each hour when is compared with Elspot prices. So, to be in the safe side, in this thesis the optimal price for each time slot is calculated separately for each month of the year based on Elbas historical price data.
In the second phase the optimization problem is solved independent from $\lambda(t)$ in order to find the optimal values for $e_s(t)$ and $e_d(t)$ for $T = 24$ hours. In other words, the optimal supply and demand energies for each hour will be determined by solving the optimization problem to obtain the maximum profit from trading battery energy in the Nord Pool electricity markets.

6.2.2 Impacts of electricity markets uncertainties on optimal solution

Generally, one of the challenges which affect the optimization scheduling of the battery system is the uncertainty nature of the markets. Uncertainty in price and consumption endangers the taken scheduling strategies. Definitely, the optimal price should be determined based on consumption that may be different from what is estimated by the battery owner. Any error in the forecasting or any unforeseen event can affect the optimization, and consequently brings some risks for the provider.

In this thesis, the optimal price is not based on forecasting methods, but on historical price data. In this way the price and consumption uncertainties are treated automatically in the optimization problem. Using historical price data is a common approach in optimization problems as it prohibits the complex uncertainty modelling of the markets. In this master optimal hourly prices are calculated for each month of the year separately, instead of specifying the same hourly price for each date of the year. The calculations are based on 2016 historical prices. This approach shows satisfactory results, however, the optimal price offered by the battery owner always involves associated risks.

6.3 Constraints

Any optimization problem seeks to minimize or maximize an objective function. Commonly, objective function subjects to various constraints respect to the variables that need to be optimized. The constraints have an important role in solving an optimization problem and should be characterized and taken into account accurately. Different kinds of constraints can be applied to an objective function. This involves liner or non-linear equality or non-equality constraints. Bound constraints can also be defined for an optimization problem.

Before the constraints definitions, the battery specifications should be characterized:

Battery Specifications

C_{batt}	battery capacity (600 kWh)
$\mathrm{SOC}_{\mathrm{max}}$	maximum battery state of charge (90%)
SOC_{min}	minimum battery state of charge (10%)
C_{max}	maximum battery capacity level (540 kWh)
C_{min}	minimum battery capacity level (60 kWh)
C_{crt}	initial battery capacity level (500 kWh)
eff	battery efficiency (1)
$e_{s_{max}}$	maximum supply energy (480 kWh)
$e_{d_{max}}$	maximum demand energy (480 kWh)
P_{max}	maximum power (1080 kW)

The constraints which are applied to the optimization problem of this thesis are defined as follows:

1) $0 \leq e_s(t) \leq e_{s_{max}}$

This constraint defines a set of lower and upper bounds on the variable $e_s(t)$ which ensures that the supply energy remains between 0 and maximum discharge level of the battery in any given hour. In this thesis the maximum discharge level of the battery is defined as the difference between the maximum and the minimum capacity levels of the battery. The minimum and maximum capacity levels of the battery have been defined in battery specifications and are dependent on the minimum and maximum state of charge and the total capacity level of the battery.

2) $0 \leq e_d(t) \leq e_{d_{max}}$

This constraint defines a set of lower and upper bounds on the variable $e_d(t)$ which ensures that the demand energy remains between 0 and maximum charge level of the battery in any given hour. In this thesis the maximum charge level of the battery is defined as the difference between the maximum and minimum capacity levels of the battery. The maximum and minimum capacity levels of the battery have been defined in battery specifications and are dependent on the maximum and minimum state of charge and the total capacity level of the battery.

3) $C_{crt} + \sum_t^T e_d(t) - \sum_t^T e_s(t) \geq C_{min}$

This constraint ensures that the stored energy at the battery in different time slots is not less than the minimum capacity level of the battery. The stored energy in the battery is defined by adding the initial charge level of the battery to the difference between the total amount of energy that is purchased from the market and the energy which is sold to the market. The minimum and initial capacity levels of the battery have been defined in battery specifications and are dependent on the minimum state of charge and the total capacity level of the battery.

4) $C_{crt} + \sum_t^T e_d(t)$ - $\sum_t^T e_S(t) \leq C_{max}$

This constraint ensures that the stored energy at the battery in different time slots is not greater than the maximum capacity level of the battery. The stored energy in the battery is defined by adding the initial charge level of the battery to the difference between the total amount of energy that is purchased from the market and the energy which is sold to the market. The maximum and initial capacity levels of the battery have been defined in battery specifications and are dependent on the maximum state of charge and the total capacity level of the battery.

The constraints 3) and 4) ensure that the total stored energy at the battery at each time frame is always within the permitted range ($C_{min} \leq C_{crt} + \sum_t^T e_d(t)$ - $\sum_t^T e_S(t) \leq C_{max}$)

5) $\sum_t^T e_S(t) \leq 12 * (C_{max} - C_{min})$

This constraint ensures that summation of the submitted supply energies in different hours is not greater than a specific value. This value is defined by twelve (12) times of the maximum available capacity level of the battery. The maximum capacity level of the battery that can be offered as supply energy is the difference between the maximum and minimum capacity levels of the battery system. Choice of this range is justified by the fact that the battery cannot offer its maximum available capacity more frequently than every other hour during the day.

6) $\sum_t^T e_d(t) \leq 12 * (C_{max} - C_{min})$

This constraint is similar to constraint 5), but for demand energies. This constraint ensures that summation of the submitted demand energies in different time slots is not greater than a specific value. This value is defined as twelve (12) times of the maximum free capacity level of the battery. The maximum free capacity level of the battery is the difference between the maximum and minimum capacity levels of the battery system. Choice of this range is justified by the fact that the battery cannot be charged to its maximum free capacity level more frequently than every other hour during the day.

7) $e_S(t) * e_d(t) = 0$

This non-linear equality constraint ensures that the battery system cannot be in charging mode and discharging mode simultaneously.

8) $e_S(t) + e_S(t+1) \leq C_{max} - C_{min}$

This constraint ensures that the sum of two sequential supply energy is not greater than the difference between the maximum and minimum capacity levels of the battery.

9) $e_d(t) + e_d(t+1) \leq C_{max} - C_{min}$

This constraint ensures that the sum of two sequential demand energy is not greater than the difference between the maximum and minimum capacity levels of the battery.

6.4 Algorithms utilized for solving the optimization problem

As explained in chapter 6.1.3 the objective function of the optimization problem introduced in this thesis is:

$$\underset{e_s, e_d, \lambda}{\text{Max}} E\{\textstyle\sum_{t=1}^{T} e_S(t) * \mathbb{I}\ (\lambda_{elspot} | \lambda) * \lambda_{elspot} + [1 - \mathbb{I}\ (\lambda_{elspot} | \lambda)] * e_S(t) * \lambda_{elbas}\} - E\{\textstyle\sum_{t=1}^{T}[1 - \mathbb{I}\ (\lambda_{elspot} | \lambda)] * e_d(t) * \lambda_{elspot} + e_d(t) * \mathbb{I}\ (\lambda_{elspot} | \lambda) * \lambda_{elbas}\}$$

In the chapter 6.1 the steps of the mathematically formulating the optimization problem were explained. The aim of the optimization in this thesis is to maximize the objective function. Most of the optimization problem solvers work based on minimizing a loss function. In order to solve the optimization problem which aims to maximize an objective function, the proper solution is to minimize the negative of the objective function.

In this thesis the above-mentioned optimization problem with respect to constraints explained before, is solved by Matlab®. Two Matlab® optimization functions are investigated to solve the problem: ‘fmincon’ and ‘ga’. Fmincon is a gradient-based method that is designed to work on problems where the objective and constraint functions are both continuous and have continuous first derivatives. An algorithm which is utilized by fmincon function to solve the optimization problem is ‘Interior Point Algorithm’. Matlab® ga optimization function finds the minimum of a fitness function using ‘Genetic Algorithm’.

Both of these algorithms deal well with the stochastic behavior of the markets.

The algorithms and working principles of mentioned optimization functions, fmincon and ga, which are applied in this thesis, will be described more in the next section.

Because of the existence of a non-linear constraint in the optimization problem, $e_s(t) * e_d(t) = 0$, which ensures that the battery cannot be in charging and discharging mode at the same time, Matlab® optimization functions like ‘linprog’ are not applicable to the optimization problem of this thesis, because non-linear constraints are not supported by them.

Solving the optimization problem provides 48 outputs which are the optimal capacity values that should be sold to the market or purchased from the market for each hour of the following day to obtain the maximum profit. Also, the value of the objective function, which is ‘profit’ here, is calculated based on the optimal capacity values.

The optimization results show that using the Matlab® fmincon function is a better solver and returns higher value of the objective function i.e. more profit, in comparison with applying ga function.

6.4.1 Interior-point algorithm

Matlab® fmincon function finds minimum of constrained nonlinear multivariable function. Fmincon is applicable to continues type of objective functions and continues type of constraints which also have continues first derivatives.

Different optimization algorithms can be chosen for fmincon function. It includes interior-point, trust-region-reflective, sqp, sqp-legacy and active-set. Interior-point algorithm is the default algorithm that fmincon uses.

Interior-point handles large, sparse problems, as well as small dense problems. The algorithm satisfies bounds at all iterations. It is a large-scale algorithm [5, 6].

The interior-point (also known as barrier method) approach to constrained minimization is to solve a sequence of approximate minimization problems. Best solution is achieved by traversing the interior of the feasible region [5, 6].

The original problem is:

$$\min_{x} f(x) \text{ subject to } h(x) = 0 \text{ and } g(x) \leq 0.$$

First, the algorithm converts the original problem which subjects to equality and non-equality constraints to an approximate problem that is a sequence of equality constrained problems. These problems are easier to solve than the original inequality-constrained problem.

For each $\mu > 0$, the approximate problem is:

$$\min_{x,s} f(x,s) = \min_{x,s} f(x) - \mu \sum_i \ln(s_i) \text{ , subject to } h(x) = 0 \text{ and } g(x) + s = 0$$

To solve the approximate problem, the algorithm uses one of two main types of steps at each iteration:

- A *direct* step in (x, s). This step attempts to solve the Karush–Kuhn–Tucker (KKT) equations for the approximate problem via a linear approximation. This is also called a Newton step.

  KKT conditions are necessary first-order conditions for a solution in a non-linear optimization problem.

  The KKT conditions use the auxiliary Lagrangian function:

  $$L(x,\lambda) = f(x) + \Sigma\lambda_{g,i}\, g_i(x) + \Sigma\lambda_{h,i} h_i(x).$$

  The KKT conditions are:

  $$\nabla_x L(x,\lambda) = 0,\ \lambda_{g,i}\, g_i(x) = 0\ \forall i$$

  The vector λ is the Lagrange multiplier vector. Its length is the total number of constraints.

- A *CG* (conjugate gradient) step, using a trust region. In this case, the algorithm adjusts both x and s, keeping the slacks s positive. The approach is to minimize a quadratic approximation to the approximate problem in a trust region, subject to linearized constraints.

By default, the algorithm first attempts to take a direct step. If it cannot, it attempts a CG step.

At each iteration the algorithm decreases a merit function:

$$f(x, s) + \nu \,\|(h(x), g(x) + s)\|$$

The parameter ν may increase with iteration number in order to force the solution towards feasibility.

If an attempted step does not decrease the merit function, the algorithm rejects the attempted step, and attempts a new step [5, 6].

6.4.1.1 Optimization results using Interior-point algorithm

As mentioned before in chapter 6.2.1, the hourly electricity prices of Nord Pool markets are various in different months of the year. Consequently, optimal hourly price is calculated exclusively for each month. Due to this reason different results are obtained by solving the optimization problem for each month.

As a sample, the optimization result for January is displayed in following table.

The fmincon solution process shows 59 iterations occur to find the optimal solution.

The below results are obtained as optimal hourly supply energy $e_S(t)$:

Table 1 Optimal hourly supply energies by using interior-point algorithm

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Supply energy (kWh)	272,54	0	12,01	0	0	0	0	9,03	414,71	0	2,79	0	0	0	5,17	0	0	0	288,45	0	10,36	0	28,75	0

The below results are obtained as optimal hourly demand energy $e_d(t)$:

Table 2 Optimal hourly demand energies by using interior-point algorithm

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Demand energy (kWh)	0	122,89	0	183,55	0	0	9,06	0	0	36,58	0	24,15	0	18,46	0	0	0	205,11	0	0	0	10,18	0	0

The profit obtained from solving the optimization problem is different for each month. The highest profit is achieved for January and the lowest for July.

The value of objective function for January is achieved: 25.26 €/day which shows the daily amount of earned profit (euro) from optimal bidding.

Below chart shows the optimal values for supply energies that should be sold to market and demand energies that should be purchased from the market at each hour of the day in January:

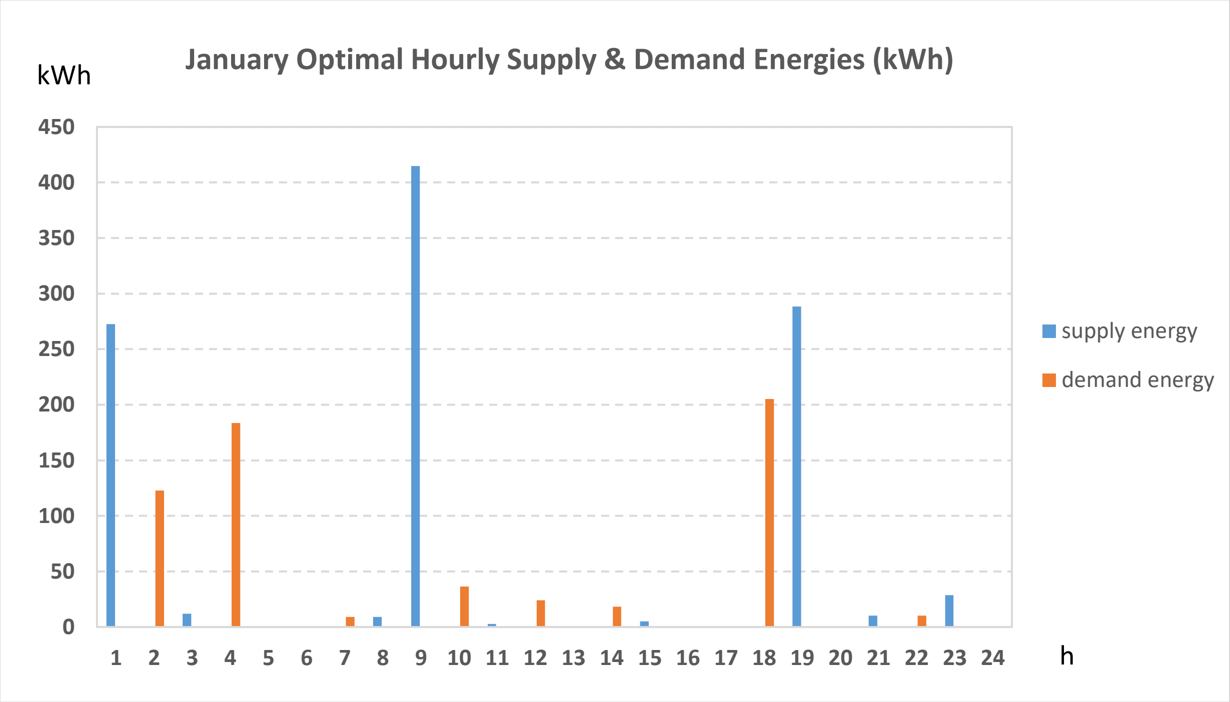


Figure 9 Optimal hourly supply and demand energies using interior-point algorithm

Below plot shows the objective function value. This means the daily profit that the battery owner gains from energy trading in market is almost 25.26 euro.

The reason behind the negative sign of the function value that is shown in the plot refers to the fact that optimization problem is to ‘maximize’ the objective function in this thesis. As explained before, ‘maximizing’ optimization is solved by minimizing the negative of the objective function. The maximum of the optimized objective function is the negative of the reported function value shown on the plot.

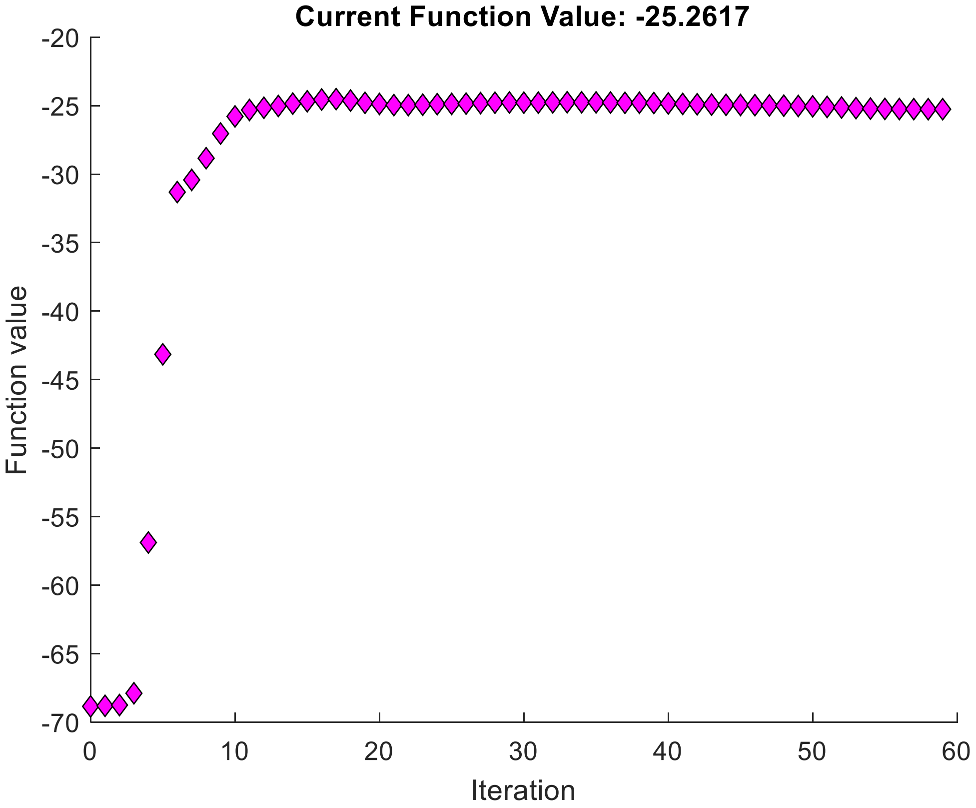


Figure 10 Objective function value

Also, the solution process of fmincon for each iteration is available in Appendix A, which shows the specifications of 59 iterations that are performed to find the optimal solution:

The profit gained in each month of 2016 and in the whole year using interior point algorithm by Matlab® fmincon function is summarized in below table:

Table 3 Profit value using Matlab fmincon function

	Profit €/day fmincon
Mean 2016	**17,6351**
January	25,2617
February	14,5698
March	14,4498
April	14,0890
May	16,3688
June	18,9268
July	16,1370
August	15,7290
September	18,4712
October	18,4894
November	17,9917
December	16,0416
Year 2016	**6303,69 €/year**

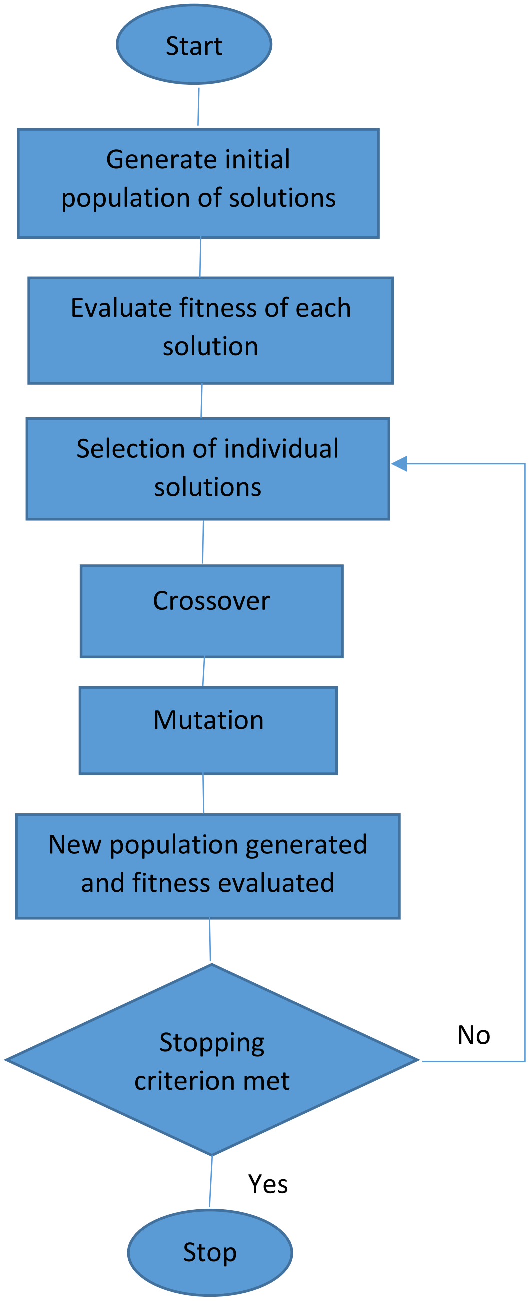
6.4.2 Genetic algorithm

Matlab® GA function has been also studied for solving the formulated stochastic optimization problem of this thesis. GA finds minimum of function using genetic algorithm. Genetic Algorithm (GA) is used to search approximate solutions of optimization problems. The genetic algorithm solver can be used for mixed-integer or continuous-variable optimization, constrained or unconstrained [7, 8].

Genetic algorithms are commonly used to generate high-quality solutions to optimization problems by relying on bio-inspired operators such as mutation, crossover and selection. Genetic algorithm is one of the well-known member of evolutionary algorithms [7, 8].

The working mechanism of genetic algorithm starts with creating random initial population. GA conducts a stochastic search from the initial population to find the possible solution. Afterwards, the algorithm creates a sequence of new populations by using the current population. The algorithm usually selects new populations that have better fitness values. The fitness is the value of the objective function in the optimization problem being solved. Fitness value shows how good a solution is. Each member of the current population is evaluated based on their fitness value. Some members are chosen as parents and some as elites, and are transferred to the next population. Childs are produced from parents by mutation or crossover methods and replace the current population. Each successive produced population is called a new generation. The new generation is used in the next iteration of the algorithm. This is an iterative process, till one of the stopping condition is met. Stopping conditions include producing maximum number of generations, reaching to a decent fitness level or exceeding time limit [7, 8]

The flowchart of genetic algorithm working principle is depicted as follows:



Below figures from the MathWorks® show how the genetic algorithm works:

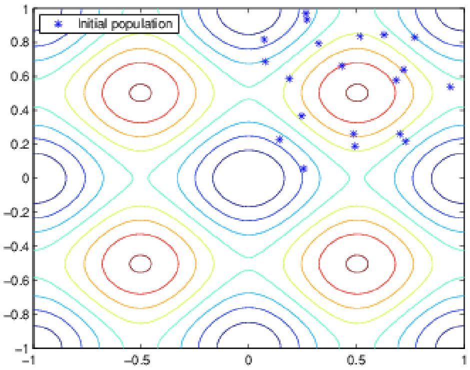


Figure 11 Creating a random initial population *(Mathworks, 2017)*

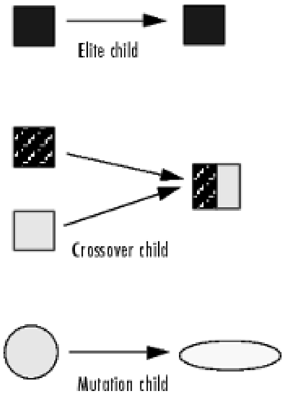


Figure 12 Three types of children *(Mathworks, 2017)*

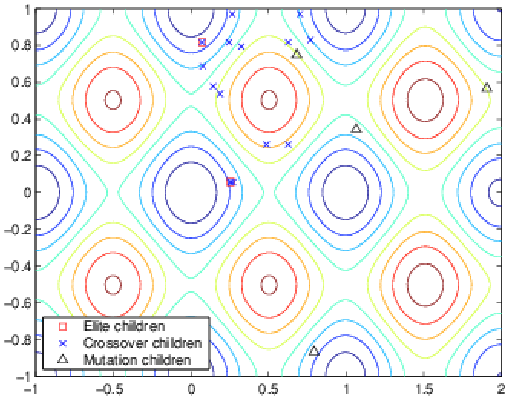


Figure 13 Population at the second generation which are elite, crossover, or mutation children *(Mathworks, 2017)*

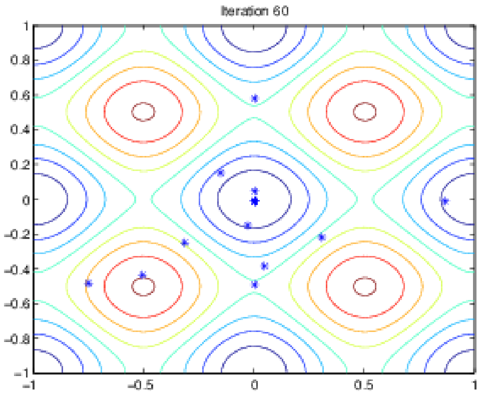


Figure 14 Populations at iterations 60 *(Mathworks, 2017)*

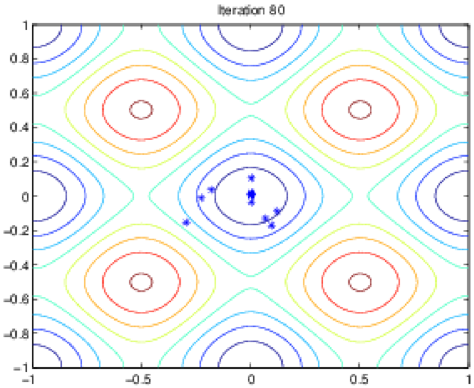


Figure 15 Populations at iterations 80 *(Mathworks, 2017)*

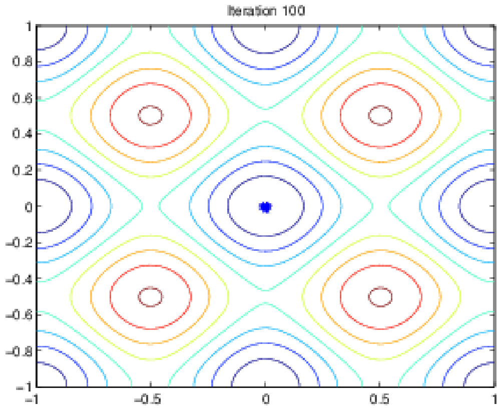


Figure 16 Populations at iterations 100 *(Mathworks, 2017)*

Genetic algorithm is usually designed for unconstrained optimizations. So, when utilizing for constrained problems, some adaptations should be performed. In genetic algorithm one of the approaches for solving constrained optimization problems is penalty method. In this method the constrained problem is replaced with an unconstrained problem which is formed by adding a penalty function to the main objective function. Penalty function penalize infeasible solutions by decreasing their fitness values. The solution of the new formed unconstrained problem converges to the global optimal solution of the main constrained problem [7, 8].

The genetic algorithm in integer programming with ga tries to minimize a penalty function instead of fitness (objective) function.

When there are integer variables or constraints in an optimization problem, Matlab® ga function has some limitations. For instance, in this case ga does not accept any equality constraints.

In the optimization problem of this thesis there is an equality non-linear constraint which was explained in chapter 6.3, $e_S(t) * e_d(t) = 0$, which ensures the battery system cannot be in a charging and discharging mode at the same time. In order to be able to solve the problem with Matlab® genetic algorithm, a tolerance value (e.g. 0.01) is defined and included in the non-linear equality constraint to change the equality constraint to a non-equality constraint.

As explained before, the optimal hourly price is calculated separately for each month of the year. For this reason different results are obtained by solving the optimization problem for each month. As a sample, the optimization result for January is presented in the next section.

6.4.2.1 Optimization results using genetic algorithm

The below results are obtained for optimal hourly supply energy $e_S(t)$ by ga:

Table 4 Optimal hourly supply energies by using genetic algorithm

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Supply energy (kWh)	31	0	0	0	210	0	5	0	11	0	0	0

Hour	13	14	15	16	17	18	19	20	21	22	23	24
Supply energy (kWh)	0	0	0	17	0	0	423	0	475	0	451	0

The below results are obtained for optimal hourly demand energy $e_d(t)$:

Table 5 Optimal hourly demand energies by using genetic algorithm

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Demand energy (kWh)	0	25	0	0	0	70	0	20	0	97	0	0

Hour	13	14	15	16	17	18	19	20	21	22	23	24
Demand energy (kWh)	0	2	14	0	0	42	0	463	0	454	0	0

Also the value of objective function is achieved: 14.70 which shows the amount of earned daily profit (euro) from optimal bidding in January. The value of profit from using genetic algorithm is less than the profit gained (25.26 €/day) when applying Matlab® fmincon function with interior point algorithm.

It should be noted that ga is stochastic, so its results change with every time that the program runs. Below chart shows the optimal supply and demand energies for each hour:

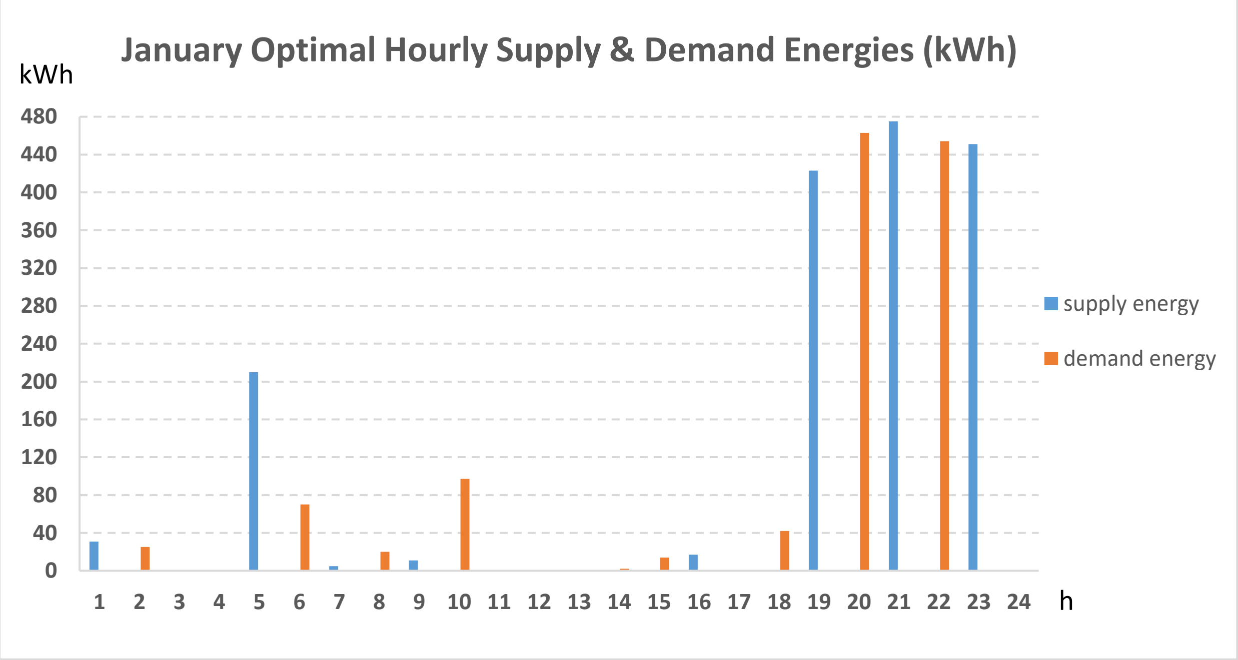


Figure 17 Optimal hourly supply and demand energies using genetic algorithm

The below plot shows the best and mean value of penalty function:

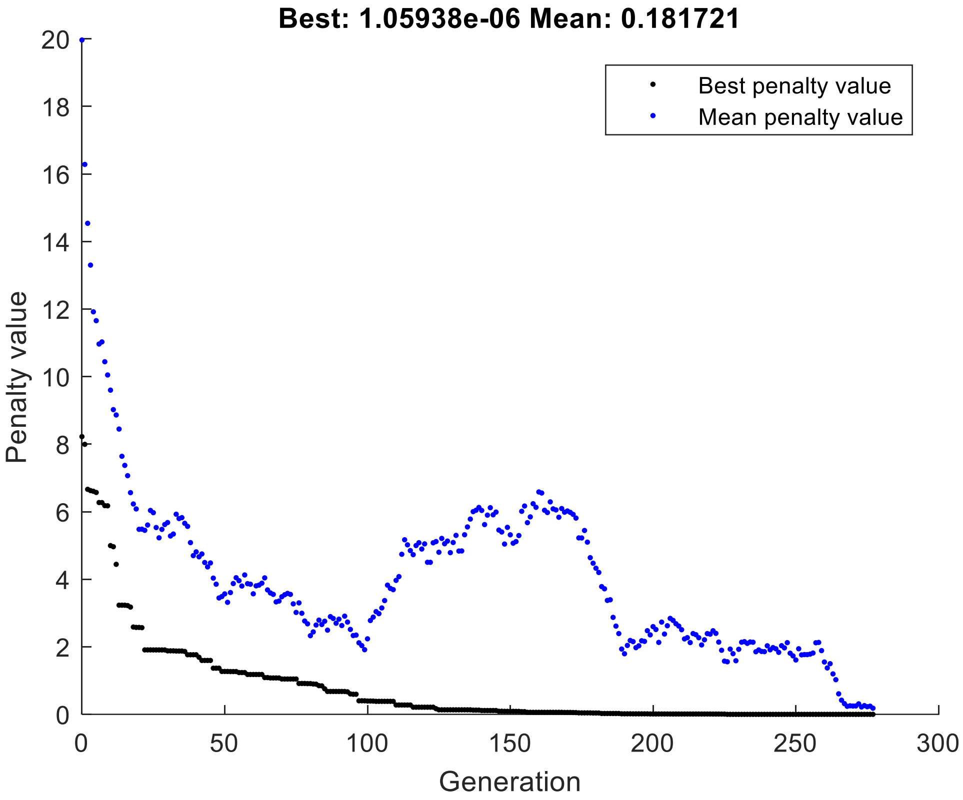


Figure 18 Penalty function value

As explained in previous section, ga tries to minimize a penalty function. A smaller value of penalty function means more convergence to the global optimal solution. The best value of penalty function is calculated 1.0594e-6 here which is entirely acceptable and presented as below plot:

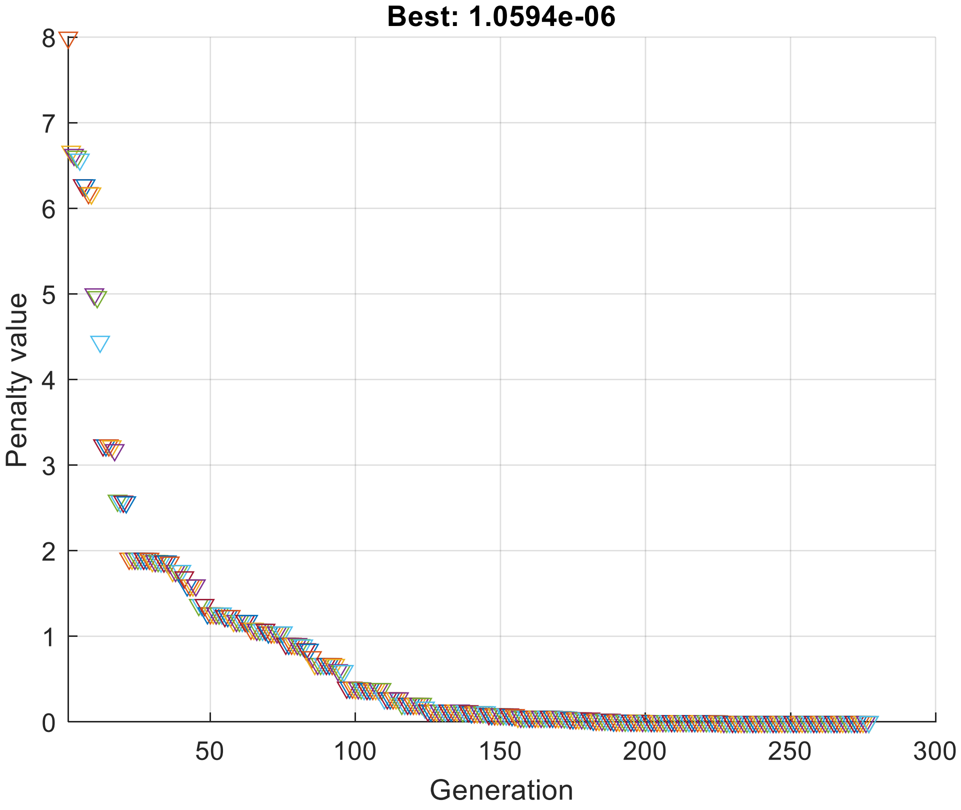


Figure 19 Best penalty function value

Below options are set in the code:

MaxStallGenerations = 50; allows the solver to try for a while

FunctionTolerance = 1e-7; specifies a stricter stopping criterion than usual

MaxGenerations = 300; allows more generations than default

Following plot presents stopping criteria which determines the cause of the termination of algorithm. Here the algorithm stops because the average change in the penalty fitness value less than options.FunctionTolerance.

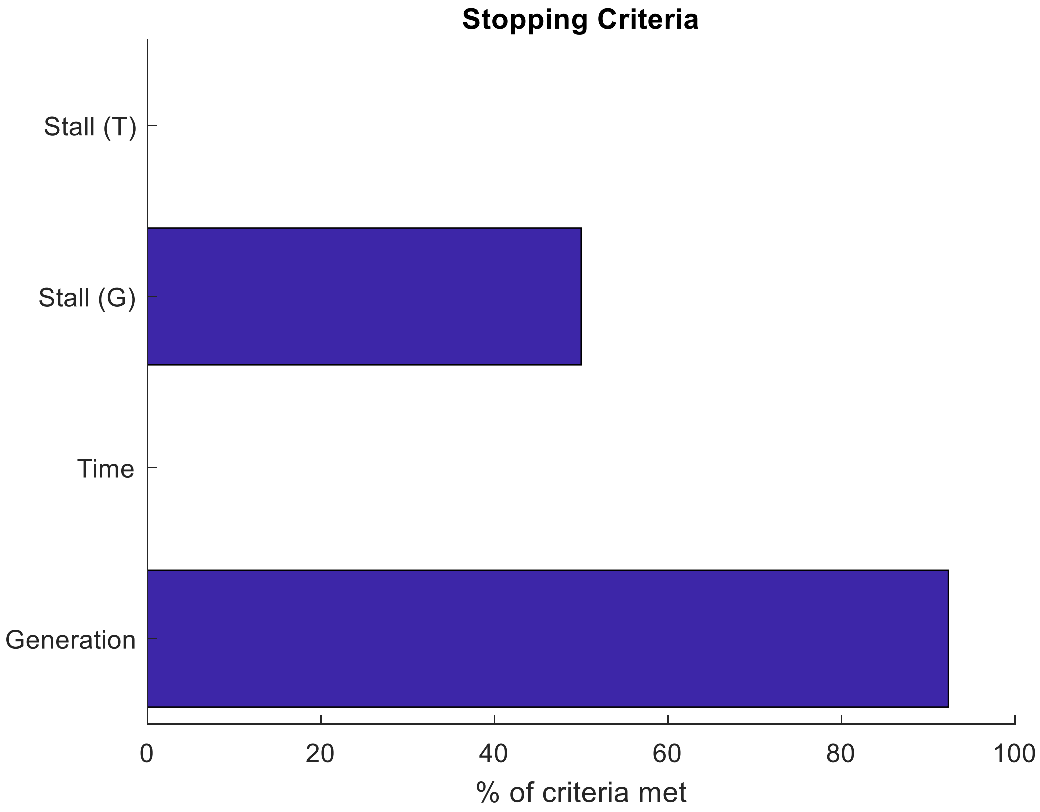


Figure 20 Stopping criteria

The profit gained in each month of 2016 and in the whole year using genetic algorithm by Matlab® ga function are summarized in below table.

Table 6 Profit value using Matlab ga function

	GA **Profit €/day**
Mean 2016	11,7950
January	14,7069
February	9,9417
March	5,7688
April	6,2793
May	6,4222
June	7,8870
July	9,1316
August	4,4244
September	8,8183
October	6,7953
November	7,7173
December	8,0896
Year 2016	**2924,87 €/year**

6.5 Battery system costs

In addition to the cost that the battery owner should pay to purchase energy for charging the battery, the cost of the battery itself should also be considered in calculations. The battery cost depend on the cycle life of the battery and is different for each battery type.

Cycle life of a battery is the maximum number of charge-discharge cycles of the battery prior battery's breakdown and is a function of depth of discharge (DOD). Frequent charging and discharging of the battery and deep cycles expedite the cycle life of the battery system.

In this thesis 5000 cycle life for battery and 750 €/kWh cost is considered. So, the cost of the battery use C_b (€/kWh) without taking battery losses into account is calculated as:

$$C_b = \frac{Price\ of\ battery}{cycle-life} = 0.15\ €/kWh \tag{13}$$

The charging and discharging energies of the battery determine the costs of the battery during each time frame. The sum of calculated supply and demand energies in January 2016 by using interior-point algorithm is 1654 kWh per day and by using genetic algorithm is 2810 kWh per day. Based on the charging/discharging energies, the battery cost is calculated 124 €/day and 210.7 €/day respectively. The daily profit obtained by solving the optimization problem for January was calculated 25.26 € by interior-point algorithm and 14.7 € by genetic algorithm. If the battery cost is reduced from the calculated profit, the final value would be negative. In other words, counting the cost of the battery besides the cost that should be paid for charging the battery, exceed the value of revenue earned by selling the energy of the battery to market. Similarly, the profitability of the battery system in the other months is negative due to the expensive battery costs.

In conclusion, optimization results shows that trading the battery system in Nord Pool market is not beneficial for battery owner when all costs are addressed.

7 OPTIMIZING THE EXPLOITATION OF BATTERY CAPACITY FOR FINGRID FREQUENCY MARKETS

7.1 Fingrid frequency price analysis

In this thesis, besides Nord Pool markets, battery system is also investigated to be employed in Fingrid hourly market of frequency controlled reserves i.e. Frequency Controlled Normal Operation Reserve (FCR-N) and Frequency Controlled Disturbance Reserve (FCR-D).

Frequency is controlled constantly by the Fingrid reserves products. Frequency of the power grid determines the balance between consumption and production. If the grid frequency drops below the 50 Hz, it means the power fed to the grid is not sufficient to meet the amount of consumption. In order to increase the grid frequency, the generation should be risen or the consumption should be reduced. Correspondingly, if frequency goes beyond 50 Hz, it means the generation exceeds demands. So, the generation should be decreased or the consumption should be increased to lower the grid frequency.

If frequency changes 0.10 Hz, the normal operation reserve regulation unit shall be activated in three minutes. The normal frequency range is defined between 49.90 and 50.10 Hz and the dead-band in frequency regulation is set between 49.95 and 50.05 Hz. This means, whenever frequency drops to lower than 49.95 Hz or rise above 50.05 Hz, the FCR-N is activated [37].

The frequency controlled disturbance reserve is activated in serious defects. The activation time is depending on the involved resource [37].

For frequency controlled normal operation reserve and frequency controlled disturbance reserve there are two different hourly markets via which Fingrid purchases required power when needed.

Fingrid has defined the minimum bidding capacity as 0.1 MW for the frequency controlled normal operation reserve and 1 MW for the frequency controlled disturbance reserve [37]. Provider should specify the capacity in MW and price on availability (€/MW,h) in each bid. The provider can submit several independent bids, which will be processed separately by Fingrid [43].

Fingrid hourly transactions show that FCR-N market has higher average hourly prices than FCR-D market [34, 35]. 2016 average price of frequency in FCR-N market is 16.81 €/MW, while average price of frequency is 5.15 €/MW in FCR-D market in the same year.

Below figures show hourly prices of FCR-N and FCR-D markets in 2016 [34, 35]. Also, hourly average prices of both Fingrid frequency markets in 2016 are calculated and a comparison between the prices of two markets has plotted accordingly:

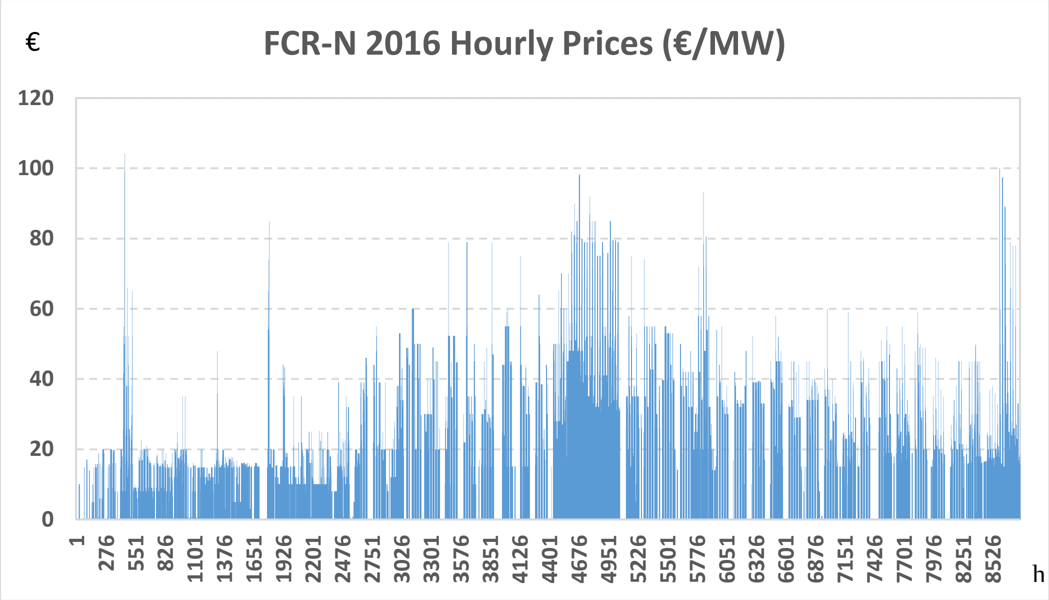


Figure 21 FCR-N hourly prices – Year 2016

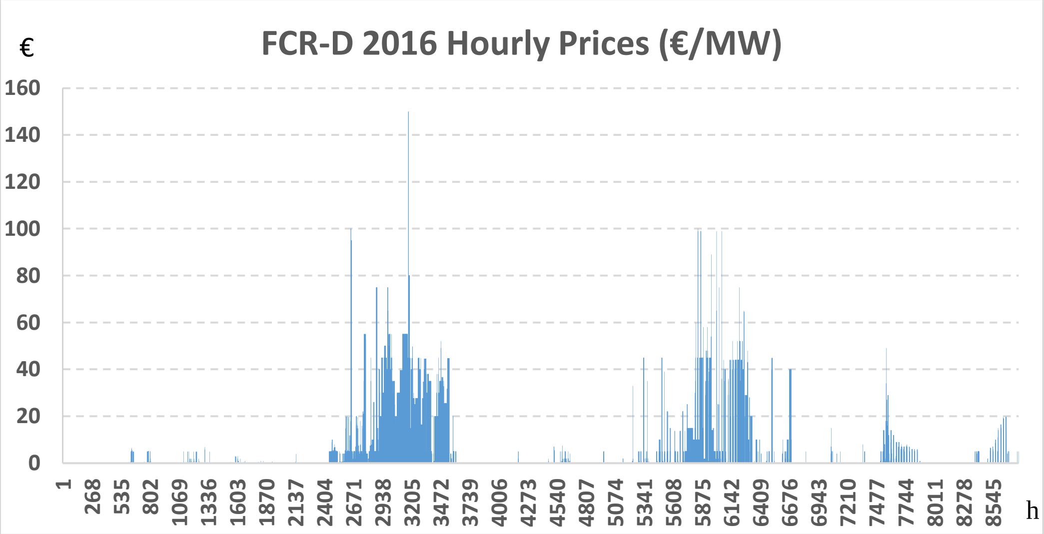


Figure 22 FCR-D hourly prices – Year 2016

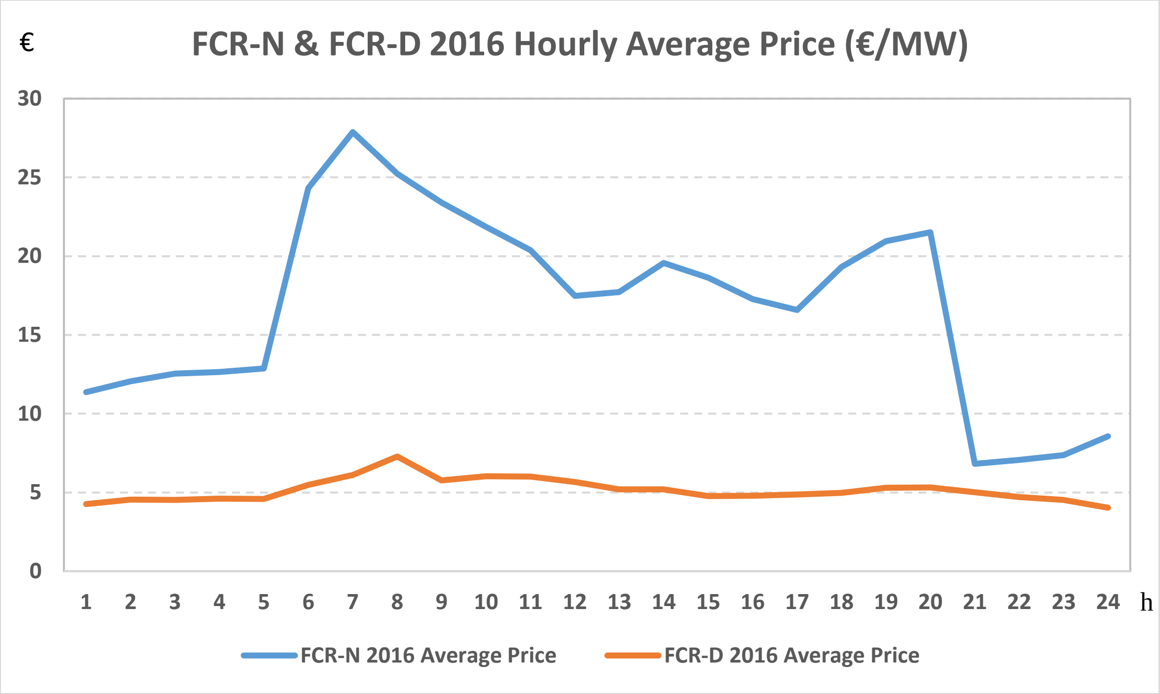


Figure 23 FCR-N & FCR-D hourly prices – Average year 2016

It should be noted that although studies on year 2016 on Fingrid frequency markets show that the hourly average price of FCR-D market is significantly less than FCR-N market, but in some particular months the FCR-D prices are higher. For example, FCR-D prices are remarkably higher in May 2016 in comparison with FCR-N prices in the same month [34, 35].

Below figures show a comparison between hourly prices of FCR-N and FCR-D markets in May 2016.

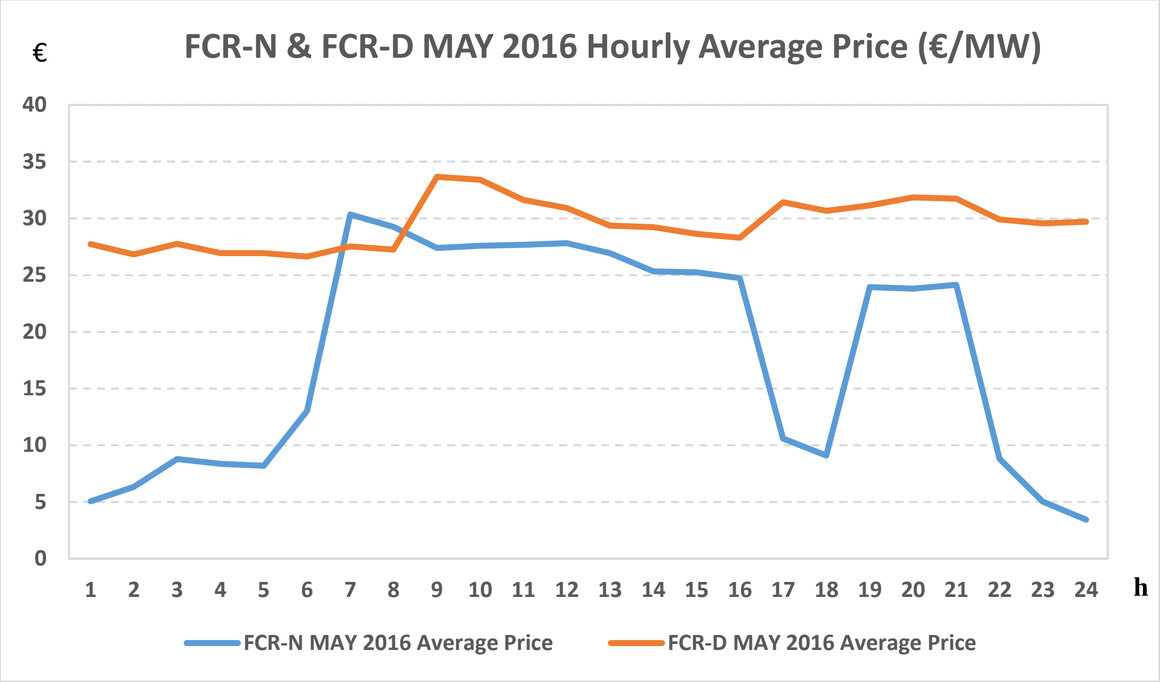


Figure 24 FCR-N & FCR-D hourly prices – Average May 2016

Due to the diverse market values in different months of the year, it is recommended to determine the optimal price for each month of the year independent from the other months. In this thesis, frequency analysis is conducted based on historical frequency data of May 2016.

There are some hours in both FCR-N and FCR-D markets that Fingrid does not carry out any transactions. FCR-N market had 35% zero value hours in 2016 while FCR-D market had 75% zero value hours in the same year. This means Fingrid does not buy electricity from frequency regulating hourly markets in those hours [34, 35].

In opposite to the average zero-value hours in the whole year 2016, May 2016 had few zero-value hours in FCR-D market. In the stated month, FCR-D market had only 11.1% zero-value hours totally. However, FCR-N market had 43% zero-value hours in the same month, which is higher than the percentage of zero-value hours of the 2016 whole year [34, 35].

The zero/non-zero value hours of year 2016 and May 2016 are presented in below charts.

The zero value hours are only determined after the market clearance. This makes simultaneous participation in other markets impossible for those hours.

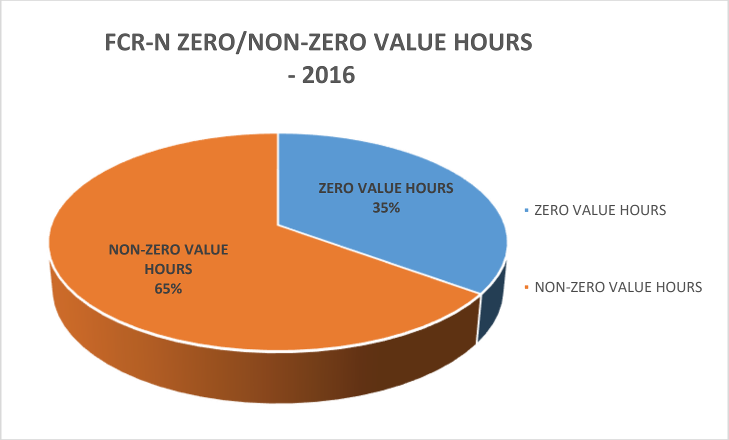


Figure 25 FCR-N zero/non-zero value hours – Year 2016

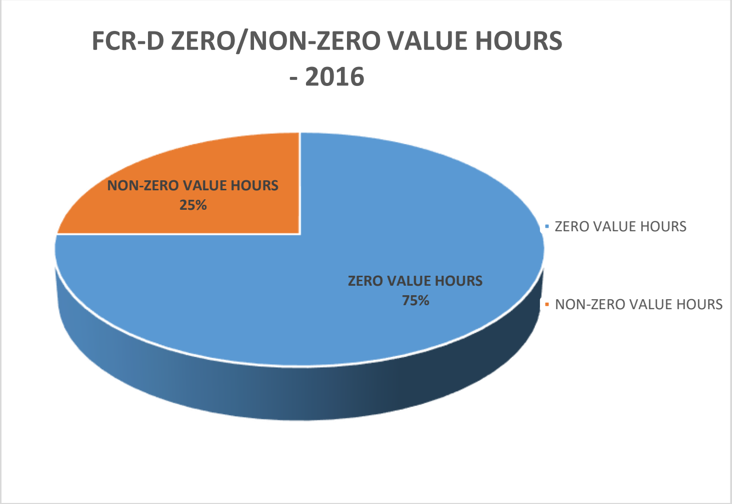


Figure 26 FCR-D zero/non-zero value hours – Year 2016

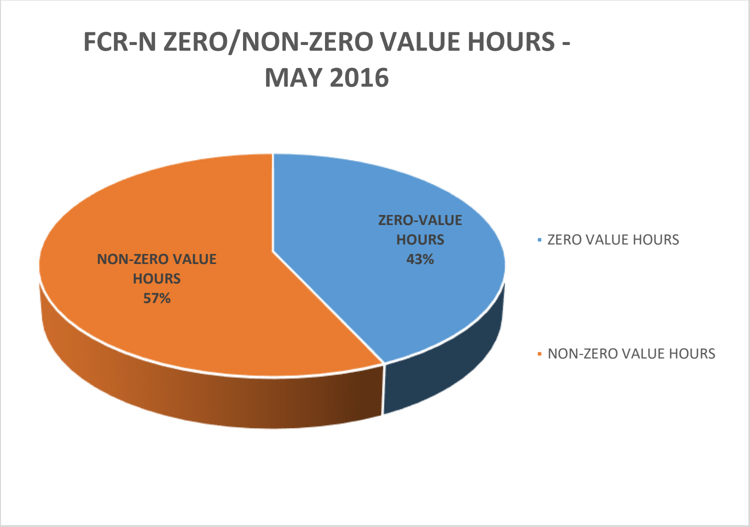


Figure 27 FCR-N zero/non-zero value hours – May 2016

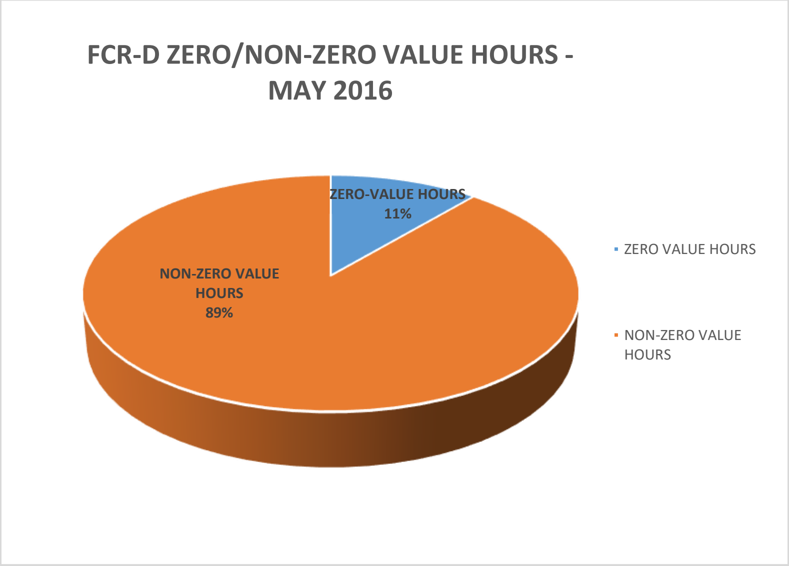


Figure 28 FCR-D zero/non-zero value hours – May 2016

In this thesis, Fingrid FCR markets (FCR-N & FCR-D) have been evaluated in order to find out the best scenario for battery capacity allocation. It should be noted that the battery cannot provide the same capacity simultaneously in Fingrid frequency regulation markets and Nord Pool markets. Furthermore, the same battery capacity cannot be allocated to FCR-N and FCR-D markets at the same hour.

7.2 Data analysis of frequency deviations of May 2016 on average hourly basis

The frequency control demand varies depending on the requirements of power grid and cannot be predicted beforehand. However, studying the quality of frequency of the previous years and the regulation demands assists to determine the potential scheduling for battery capacity allocation to Fingrid frequency control markets [40, 41].

For this purpose, Fingrid frequency data of both FCR-N & FCR-D markets in May 2016 is investigated [40].

7.2.1 Data analysis of frequency deviations of FCR-N market

Frequency containment reserve market for normal operation (FCR-N) is activated when the frequency deviates from the pre-defined dead-band (between 49.95 and 50.05). Over frequency deviation refers to frequencies greater or equal to 50.05 Hz (including frequencies greater than 50.1 Hz), while under frequency deviation in FCR-N market refers to frequencies under or equal to 49.95 Hz [37].

In order to conduct the frequency analysis of May 2016 on average hourly basis, the frequency deviations of each hour of each day of the month have been extracted from the Fingrid database [40] at the primary step, and the average hourly deviations were calculated accordingly afterwards. The calculated average time duration that the frequency was out of the FCR-N dead-band for each hour of the day in May 2016 show that hours 0 and 23 had the highest over-frequency deviations (1535.7 seconds & 1053.2 seconds), while hours 7 and 8 had the highest under-frequency deviations (815 seconds & 738.6 seconds).

The total time duration of frequency deviation, whether under or over the FCR-N dead-band, on hourly basis reveals that hour 0 and 23 had the highest frequency deviations in the mentioned month. Frequency was not in the dead-band for 1660.3 seconds in hour 0 and for 1565.14 seconds in hour 23.

The time duration of frequency fluctuations out of the FCR-N dead-band in May 2016 based on average hourly durations, is calculated 398.13 minutes per day. In other words, in average the frequency was outside of the standard FCR-N dead-band range for 27.6% of time of the day in May 2016.

In May 2016, the longest under frequency deviation (frequencies under or equal to 49.95 Hz, but not less than 49.90 Hz) happened in 25th day of the month at hour 11. The frequency was between 49.90 and 49.95 Hz for 2123.70 seconds of the mentioned hour. However, the longest over frequency deviation happened in 18th of the month at hour 9 for 3433.2 seconds.

The average time duration of FCR-N frequency deviations in May 2016 on hourly basis are plotted below. Also, the comparison between the longest and the average frequency deviation times are plotted in the following charts.

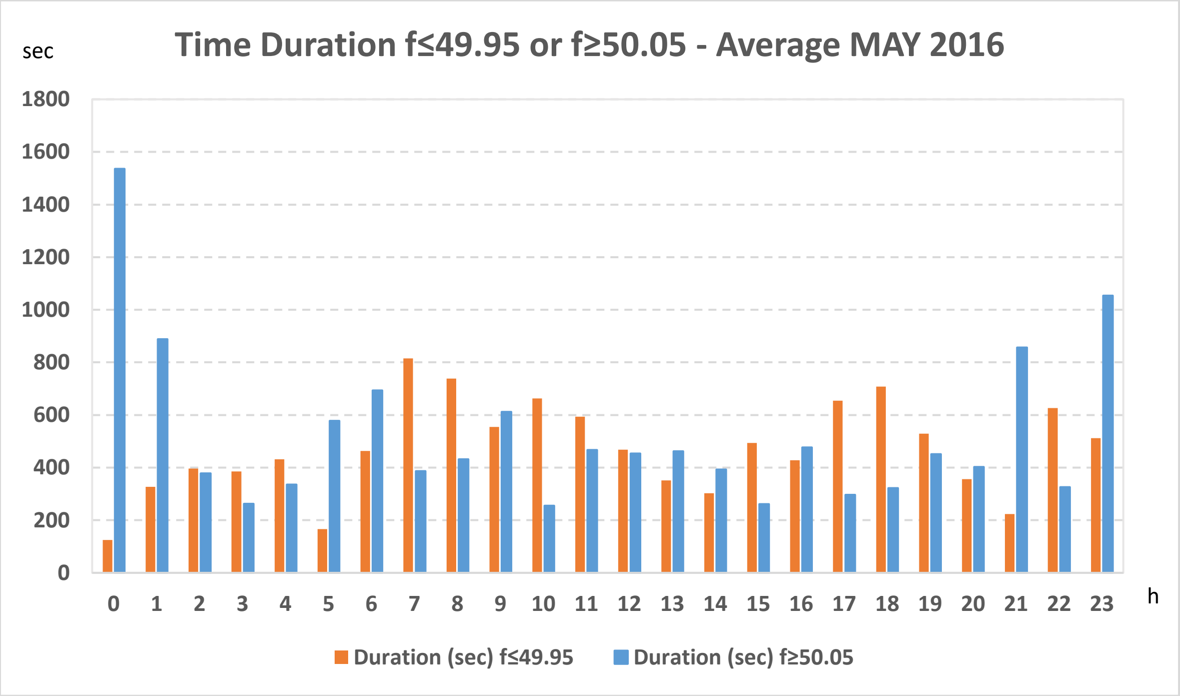


Figure 29 Time duration frequency ≤ 49.95 or ≥ 50.05 Hz – Average May 2016

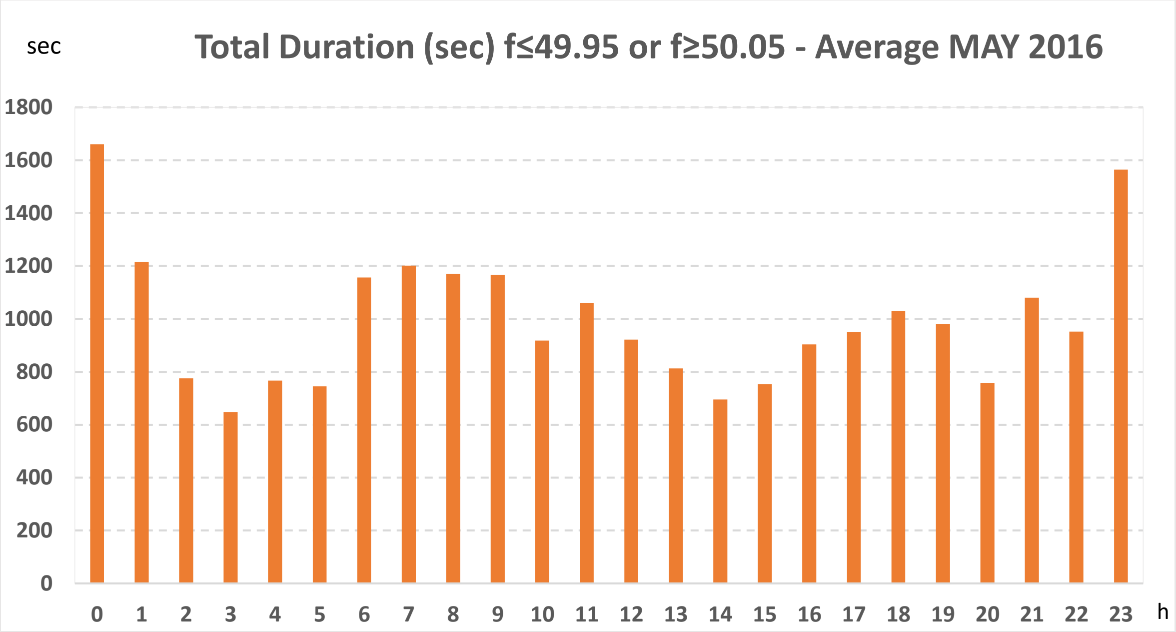


Figure 30 Total time duration frequency ≤ 49.95 or ≥ 50.05 Hz – Average May 2016

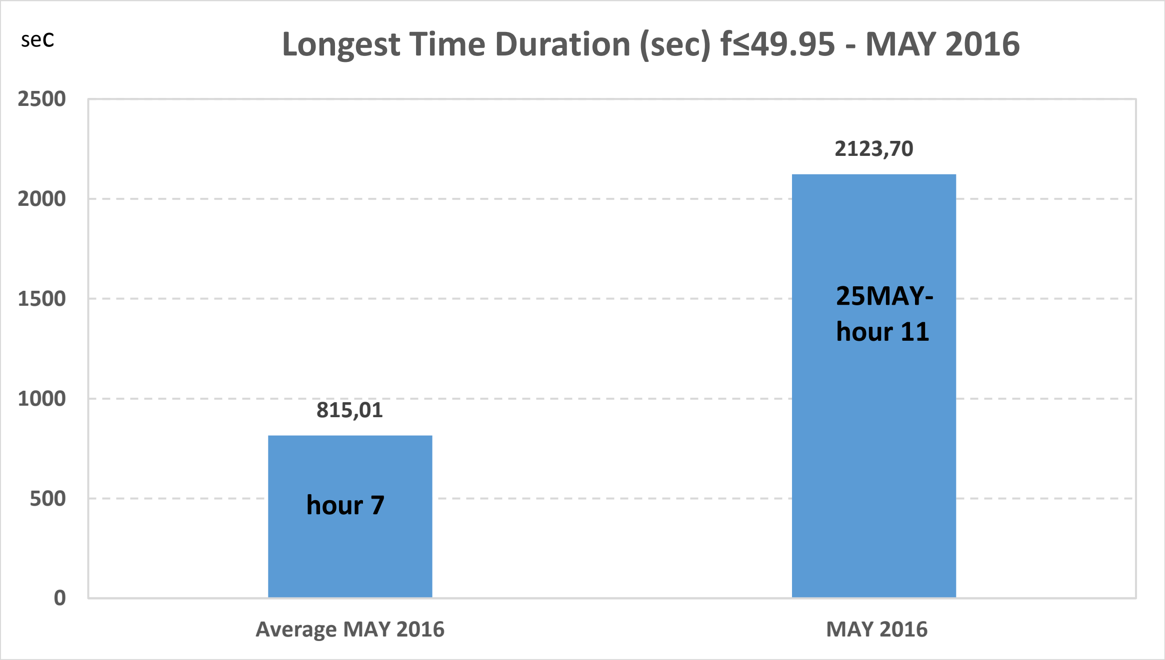


Figure 31 Longest time duration frequency ≤ 49.95 Hz – May 2016

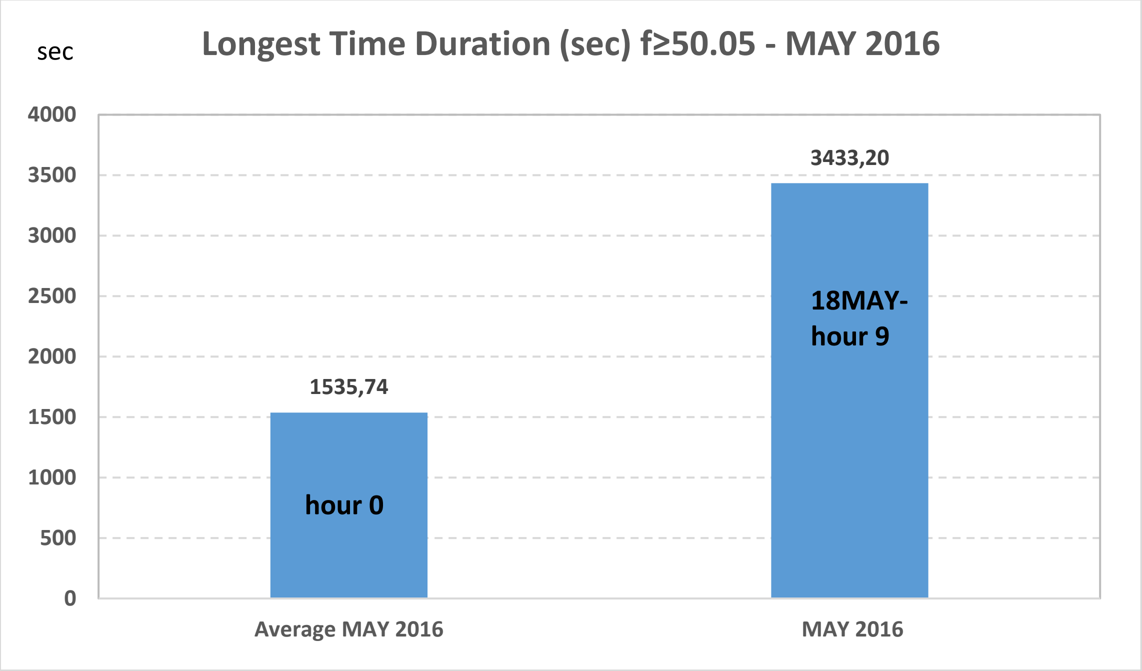


Figure 32 Longest time duration frequency ≥ 50.05 Hz – May 2016

7.2.2 Data analysis of frequency deviations of FCR-D market

Frequency containment reserve market for disturbances (FCR-D) is only activated if the frequency drops below 49.90 Hz [37]. FCR-D market is one direction market.

Similar to FCR-N market, the frequency analysis has been performed for FCR-D market likewise [40].

The calculated average time duration that the frequency was below 49.90 Hz for each hour of the day in May 2016 show that hours 7 and 8 had the highest deviations (269.1 seconds & 137.2 seconds). These hours are the same hours that the FCR-N market was activated in May 2016, i.e. frequency was between 49.90 and 49.95 Hz.

The time duration of frequency felled below 49.90 in May 2016 based on average hourly durations, is calculated 27.2 minutes per day. In other words, in average, the frequency was less than 49.90 Hz for 1.9% of time of the day in May 2016.

In May 2016, the longest FCR-D frequency deviation happened in 18th day of the month at hour 11. The frequency was less than 49.90 Hz for 1008.7 seconds of the mentioned hour.

The average time duration of FCR-D frequency deviations in May 2016 on hourly basis are plotted below. Also, the comparison between the longest and the average frequency deviation times are plotted in the following charts.

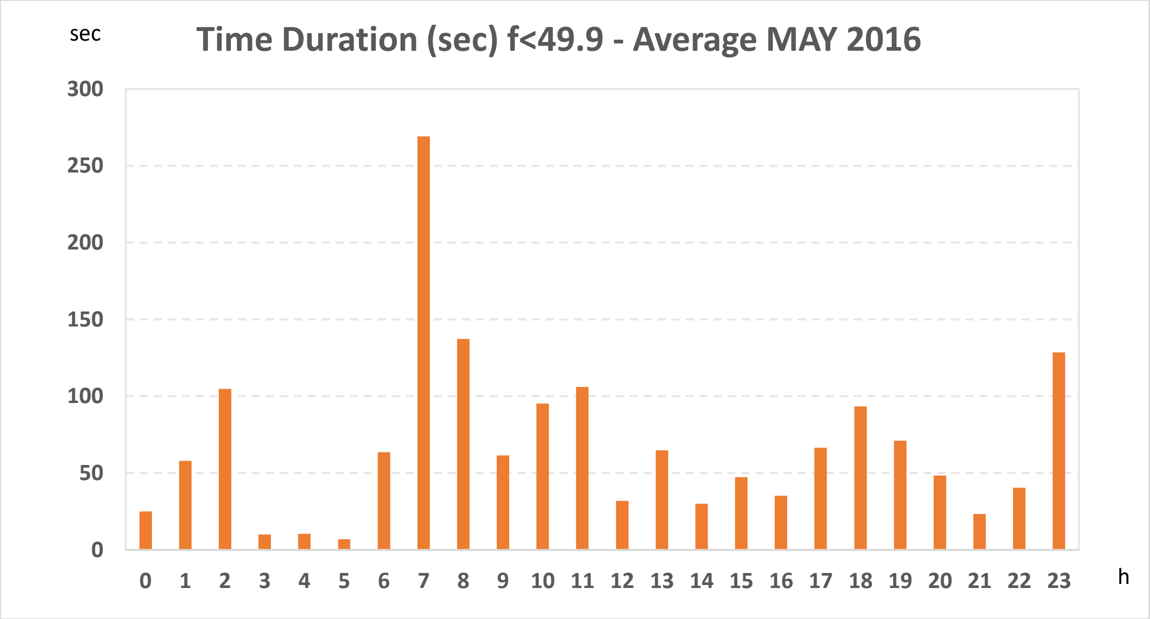


Figure 33 Time duration frequency < 49.90 Hz – Average May 2016

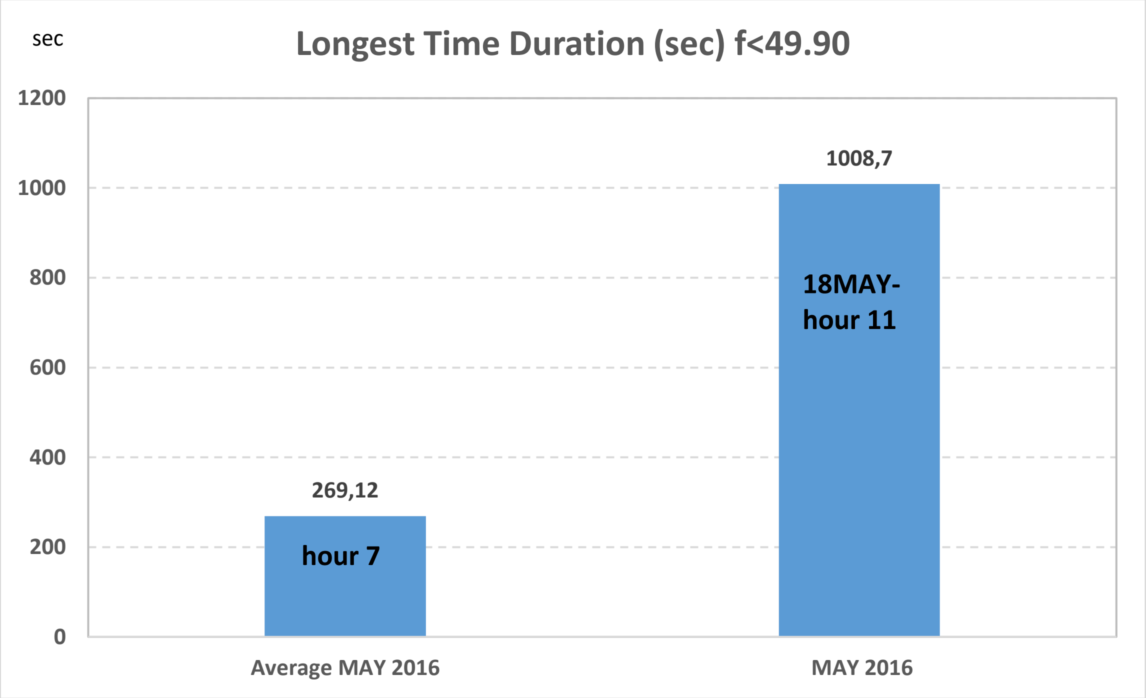


Figure 34 Longest time duration frequency < 49.90 Hz – May 2016

The above-mentioned frequency quality analysis of May 2016 are used for scheduling of battery system in Fingrid FCR-N and FCR-D markets.

7.3 Data analysis of frequency deviations of first week of May 2016

The average hourly frequency deviations of May 2016 is not sufficient solely to determine how the battery capacity can be allocated to market in future. Although the average data of frequency deviations in one month give a relative recognition about the situation of frequency markets, but the frequency deviations of each day may be totally different with the average deviations of the month. For instance, as mentioned before, in May 2016 in average, the longest over frequency time was 1535.7 seconds in hour 0 and the longest under frequency time (with FCR-N dead band requirement) was approximately 815 seconds in hour 7. It can be interpreted that the maximum over frequency time duration was 42.7 % of the hour (belongs to hour 0) and maximum under frequency time duration was 22.6% of the hour (belongs to hour 7). Also, considering the frequency deadband requirement of FCR-D market, reveals that the maximum time duration that the frequency was less than 49.90 Hz was 7.5% of the hour (belongs to hour 7).

However, the daily frequency data analysis of the first week of May 2016, includes higher maximum time duration that the frequency was outside the range with FCR-N and FCR-D dead-band requirements [40]. For instance, on 6th of May 2016, the under-frequency duration in hour 22 was 57.2% of the hour which is more than 2.5 times of the maximum under-frequency duration of the May in average. Also, on the same date the over-frequency duration in hour 0 was 81.9% of the hour which is near 2 times of the maximum over-frequency duration of the May in average. Considering FCR-D dead-band, on 2nd of May 2016, the under-frequency duration in hour 7 was 27.1% of the hour, which is more than 3 times of the maximum under-frequency duration of May in average.

Because of the significant difference between the daily analysis results and the average monthly analysis results, in this thesis the battery capacity allocation to frequency markets is studied both for the May 2016 in average and also day by day for the first week of the month.

The purpose of conducting the daily analysis is to find out with knowing the real frequency deviations in each day, how the power of the battery system can be allocated to FCR-N and FCR-D markets in that particular day.

The longest duration that the frequency was out of standard range in each day of the first week of May 2016 is summarized in below tables based on the dead-band requirements of FCR-N and FCR-D markets separately. Also, the longest time duration of under/over frequency deviations of May 2016 in average is indicated at the last row of each table.

Table 7 Longest duration 49.90 ≤frequency ≤ 49.95 Hz

49.90 Hz ≤ FREQUENCY ≤ 49.95 Hz		
DATE	**DURATION (seconds)**	**HOUR**
1 MAY 2016	1848.5	22
2 MAY 2016	1510.7	4
3 MAY 2016	1853	9
4 MAY 2016	1980	2
5 MAY 2016	1444.6	8
6 MAY 2016	2058	22
7 MAY 2016	1657.8	9
AVERAGE MAY 2016	815.01	7

Table 8 Longest duration frequency ≥ 50.05 Hz

FREQUENCY ≥ 50.05 Hz		
DATE	**DURATION (seconds)**	**HOUR**
1 MAY 2016	2403.1	21
2 MAY 2016	2204.9	6
3 MAY 2016	2588.7	0
4 MAY 2016	2361.6	13
5 MAY 2016	2521.2	1
6 MAY 2016	2947.9	0
7 MAY 2016	2252.7	12
AVERAGE MAY 2016	1535.7	0

Table 9 Longest duration frequency < 49.90 Hz

FREQUENCY < 49.90 Hz		
DATE	**DURATION (seconds)**	**HOUR**
1 MAY 2016	637.3	23
2 MAY 2016	975.7	7
3 MAY 2016	290.4	18
4 MAY 2016	743.7	2
5 MAY 2016	564.7	8
6 MAY 2016	597.7	7
7 MAY 2016	369.8	9
AVERAGE MAY 2016	269.1	7

Also, the time duration of frequency deviations for each day of the mentioned week are plotted in Appendix B.

7.4 Capacity allocation of BESS to Fingrid frequency markets

Fingrid markets are power markets unlike Nord Pool markets which are energy market. Thus, the submitted bids to Fingrid frequency markets should be based on availability of the battery's power (MW) and not energy (MWh) [43].

The time duration that the battery is required to be employed in the FCR-N or FCR-D market is proportional to the time duration that the frequency is outside of the standard frequency range of the related market. This time duration also determines the battery consumed energy and the remaining battery charge in each time frame. The battery state of charge (SOC) that is evaluated at the end of each hour, beside the time that the battery will be utilized in the subsequent hour, specifies the feasible amount of battery power that can be offered by the battery owner to Fingrid market for each hour of the day. Hence, the hourly optimal battery capacity that should be proposed to Fingrid frequency markets is determined.

The exact time duration that the battery will be employed in the market cannot be specified beforehand, due to the unpredictable nature of frequency. However, the historical frequency quality data helps to make an estimation based on the situation of the similar hours/days of the previous years. In this thesis, the historical frequency data of May 2016 has been used for performing the mentioned analysis.

In the chapter 7.2 the average time that the frequency was outside the standard frequency range in each hour of the day was characterized for May 2016. Also, the time durations of frequency deviations of the same month was specified daily for the first week of month in chapter 7.3. Studying the figures 30 and 33 clarifies that in each hour of the day the frequency is out of the standard range in a partial time duration of each hour.

With attention to the fact that the frequency fluctuations does not take place in a large fraction of hour (focusing on May 2016 in average), it can be concluded that the battery is needed to be occupied in short portion of time in each hour of the day. For instance, considering May 2016 in average, if battery was employed in the Fingrid frequency containment reserve market for normal operation (FCR-N), it had to be in charging mode for maximum 42.7% of the hour (belongs to hour 0) and it had to be in discharging mode for maximum 22.6% of the hour (belongs to hour 7). Apparently, in the FCR-D market the battery should be discharged for much less percent of hour in comparison with FCR-N market. For instance in the same month, battery had to be in discharging mode for maximum 7.5% of hour (belongs to hour 7).

The probability distribution of battery occupation in FCR-N market in May 2016 in average is plotted by Matlab® as below:

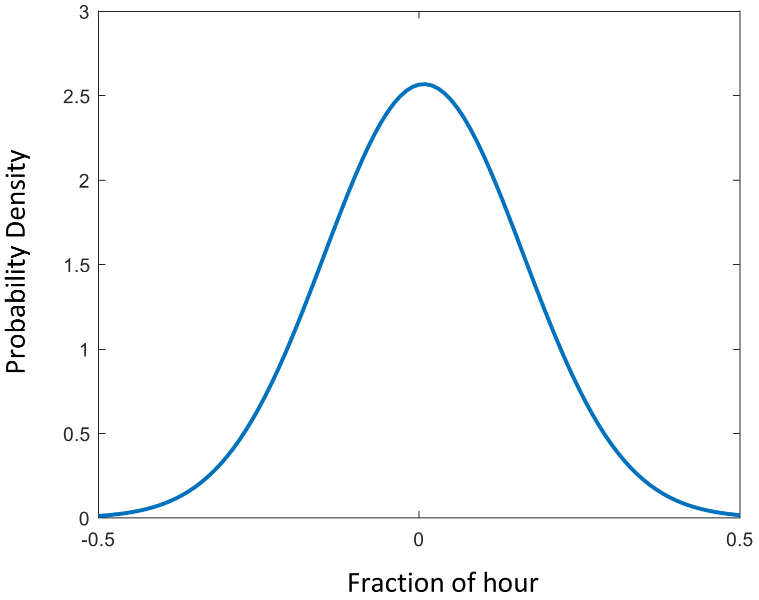


Figure 35 Probability distribution of battery occupation in FCR-N market

When the availability of the battery capacity is offered to Fingrid market, the battery should have the capability to inject the power declared in the bid to the grid in the times that the frequency falls below 49.95 or 49.90 Hz, and absorbs power from the grid in the times that the frequency moves beyond 50.05 Hz. Battery provider should be always committed to the availability of the battery power which is accepted by Fingrid for that specific hour. According to Fingrid bidding rules and regulations, if the reserve capacity verified by means of measurements is below trading carried out in the hourly market, reserve holder shall pay Fingrid 100 per cent of the price in the hour in question in compensation for capacity not supplied [43].

Based on the frequency deviations in May 2016, the charging/discharging time of the battery, when employed in Fingrid FCR-N and FCR-D markets, in each hour of the day in average of the month is summarized accordingly. The charging/discharging time of the battery in the first week of May 2016 are available in Appendix C.

Table 10 Duration of battery charging/discharging (%) in FCR-N market – Average May 2016

AVERAGE MAY 2016 FCR-N		
hour	**Battery Discharging Time (% hour)**	**Battery Charging Time (% hour)**
0	3,46 %	42,66 %
1	9,07 %	24,69 %
2	11,02 %	10,51 %
3	10,71 %	7,29 %
4	11,98 %	9,32 %
5	4,63 %	16,06 %
6	12,88 %	19,26 %
7	22,64 %	10,72 %
8	20,52 %	11,99 %
9	15,40 %	16,98 %
10	18,42 %	7,09 %
11	16,48 %	12,97 %
12	13,00 %	12,61 %
13	9,77 %	12,82 %
14	8,42 %	10,90 %
15	13,70 %	7,25 %
16	11,88 %	13,23 %
17	18,17 %	8,24 %
18	19,66 %	8,96 %
19	14,68 %	12,53 %
20	9,89 %	11,18 %
21	6,22 %	23,79 %
22	17,40 %	9,04 %
23	14,22 %	29,26 %

Table 11 Duration of battery charging/discharging (%) in FCR-D market – Average May 2016

AVERAGE MAY 2016 FCR-D	
hour	**Battery Discharging Time (% hour)**
0	0,70 %
1	1,61 %
2	2,91 %
3	0,28 %
4	0,29 %
5	0,19 %
6	1,77 %
7	7,48 %
8	3,81 %
9	1,71 %
10	2,65 %
11	2,95 %
12	0,89 %
13	1,80 %
14	0,84 %
15	1,31 %
16	0,98 %
17	1,85 %
18	2,60 %
19	1,98 %
20	1,34 %
21	0,65 %
22	1,12 %
23	3,57 %

For those hours that the battery should be in use for a short time frame, just a few amount of the battery energy will be shifted during that particular hour. Therefore, the battery state of charge will not be changed dramatically at the end of those hours, but still should be calculated as precise as possible by using the available historical information.

Based on the charging/discharging time of the battery and the initial power of the battery in each specified hour, the energy stored in the battery and the consumed energy of the battery are calculated and the battery final state of charge (SOC) at the end of each time frame is specified.

The calculated battery charge level at the end of each particular hour, characterizes the optimal power for the subsequent hour. The battery charge level should always be in the permitted range. The minimum and maximum charge levels of the battery have been defined in battery specifications in chapter 6.3 and are dependent on the defined minimum and maximum state of charge and the total capacity level of the battery.

The frequency variation outside the standard frequency range can occur at any spot inside an hour e.g. beginning, middle or end of hour. The order of over and under frequency times should also be considered in battery capacity scheduling, as the order of over and under frequency times determine the charging and discharging sequence of the battery. The battery charging and discharging should be always performed in such a way that the charge level of the battery does not fall below the minimum accepted level or rise above the maximum accepted level, at any time spot. In other words, optimal battery capacity scheduling should ensure that in addition to the charge level of the battery at the end of each hour, the charge level of the battery at any time spot inside the hour is also within the permitted range. Thus, the optimal scheduling should not be influenced by the time of frequency variations inside an hour. Ignoring this fact can change the battery scheduling and may even increase the revenue obtained from attending in frequency regulating market, however it involves risks of battery over/under charge in some time spots.

In order to determine the hourly battery schedule for attending in Fingrid frequency markets, i.e FCR-N and FCR-D, two methods are investigated in this thesis. In the first method, an optimization problem is defined, formulated and solved by Matlab to specify the hourly optimal power that can be offered to Fingrid. The aim of the optimization is to obtain the maximum profit with attention to the applied technical constraints. The optimization problem is solved for both FCR-N and FCR-D markets by considering the requirements of each market, and by applying the calculated frequency deviations of May 2016 in average besides the calculated frequency deviations of each day of the first week of May 2016 separately.

In the second method, a constant battery power is assumed to be offered for all hours of the day to Fingrid, and based on the time duration of frequency deviations, the state of charge of battery is evaluated at the end of each hour. The required energy that should be purchased from intra-day market, Elbas, is calculated and the revenue obtained from selling battery power to Fingrid and the cost that should be paid to buy energy for the battery are calculated. Because of the unpredictable frequency changes and the involved uncertainties in frequency markets, this method is studied to evaluate how the battery state of charge changes by offering a fixed amount of power for all hours of the day.

7.4.1 Capacity optimization of BESS for FCR-N and FCR-D markets

Mathematical optimization is the best way to find the optimal values of an objective function subjects to different constrains. However, for performing the optimization of the battery capacity allocation to Fingrid frequency markets, time duration of frequency deviations should be known.

This is a viable option when the optimization is conducted based on the historical data of frequency deviations and not on real-time frequency deviations, which are unpredictable and cannot be known beforehand.

Here, based on the historical frequency data of May 2016, the optimization problem is solved for both FCR-N and FCR-D markets. Although, the optimization result cannot be developed to real-time, it still gives a valuable vision about the behavior of battery system if employed in the Fingrid frequency markets.

7.4.1.1 Mathematical modeling of BESS optimization problem

The purpose of this section is to mathematically formulate the optimization problem of the battery capacity for Fingrid FCR-N and FCR-D markets.

Fingrid frequency markets are power markets, so the hourly optimal power of the battery system to be offered in the competitive bidding of FCR-N market should be determined by solving the optimization problem.

When the battery owner submit a bid to FCR-N or FCR-D market, the declared power should be available irrespective of exploitation by Fingrid or not. Otherwise the battery owner should pay penalty compensation for the power which was not provided.

When providing a specific amount of battery power in each hour, the state of charge (SOC) of the battery changes depending on the time that the battery was in use in that particular hour. The battery should always have the at least minimum amount of charge level after each power transaction. Also, the charge level of the battery should not exceed the maximum permitted level. As mentioned in chapter 6.3, the minimum and maximum SOC of the battery system is defined 10% and 90% of the battery rated capacity.

The frequency containment reserve markets can be divided into $T = 24$ hourly time frames. For each hour the power (MW) and the price on availability (€/MW, h) should be specified in the bid. After the deadline for submitting the bids, Fingrid processes the bids. The compensation to be paid to reserve holder is determined separately for each hour on the basis of the most expensive bid ordered. Fingrid pays reserve holder compensation on the basis of the volumes verified by means of measurements; however, at the most for trading agreed within the hourly market.

7.4.1.2 Objective function of the optimization problem

The aim of conducting optimization is to find hourly optimal amount of battery power and price for participation in frequency containment reserve markets by maximizing the profit. The profit value is the difference between the revenue gained from selling availability of battery power to Fingrid, and the battery costs.

The revenue is calculated by multiplying the power component P by the price λ. The battery cost depends on the average of total charging e_{chrg} and discharging energy $e_{dischrg}$ of the battery. C_b is the battery cost per kWh. So, generally the optimization problem is formulated as:

$$\underset{P,\lambda,e_{chrg},e_{dischrg}}{\text{Max}} \left\{ \sum_{t=1}^{T} P(t) * \lambda(t) - \sum_{t=1}^{T} \frac{e_{chrg}(t) + e_{dischrg}(t)}{2} * C_b \right\} \tag{14}$$

By solving the above-mentioned optimization problem, the optimal power to be sold to Fingrid frequency markets will be determined for each hour of the following day.

It should be noted that as FCR-D market is one-direction market and is activated only for major under-frequency deviations (less than 49.90 Hz). In other words, the battery will not be charged at any point by attending in this market. Hence, the battery charging energy e_{chrg} of the above objective function is zero for this market and the battery cost can be defined as $\sum_{t=1}^{T} e_{dischrg} * C_b$ for FCR-D market. Consequently, the objective function for FCR-D market is:

$$\underset{P,\lambda,e_{dischrg}}{\mathrm{Max}} \{\sum_{t=1}^{T} P(t) * \lambda(t) - \sum_{t=1}^{T} e_{dischrg}(t) * C_b\} \tag{15}$$

7.4.1.3 Optimal bidding solution

It should be noted that in this thesis the optimization problem explained in the previous chapter is solved for May 2016 in average and also for first week of the same month day by day.

Depending on the historical data of the frequency market prices [34, 35], an optimal price can be determined for each time frame by calculating the mean of the market prices of each hour cleared during one year period. The price analysis is done in chapter 7.1 for both FCR-N and FCR-D markets for the year 2016 in general and also for the May 2016 in addition. The mentioned calculated average hourly prices of May 2016 are used for solving the optimization problem. Furthermore, the real hourly price of the first week of May 2016 are utilized to solve the optimization problem for each day of the stated week.

As explained before, there are some zero-value hours in both FCR-N and FCR-D markets that Fingrid does not carry out any transactions. In these hours the battery power, which is offered to market, is not used and the charge level of the battery remains like the previous hour. For instance on 7th of May 2016, in FCR.N market there was only one non-zero-value hour in the day (belongs to hour 0). So, on that day if battery was employed in the FCR-N market the initial charge level of the battery remained the same after the first power transaction.

It is remarkably important to address these hours in solving process of optimization problem.

After clarifying the hourly price, the optimal power is determined by solving the optimization problem.

7.4.1.4 Constraints

The constraints which are applied to the above-mentioned optimization problem are defined as follows:

1) $0 \leq P(t) \leq P_{max}$

This constraint defines a set of lower and upper bounds on the variable $P(t)$ to ensures that the optimum power remains between 0 and maximum battery power in any given hour. In this thesis the maximum power of the battery is defined as 90% of the battery rated power.

2) $SOC_{min} \leq SOC(t) \leq SOC_{max}$

This constraint ensures that the battery state of charge (SOC) in each time frame remains between the minimum and maximum allowed charge level of the battery. In this thesis the minimum and maximum charge level of the battery is defined as 90% and 10% of battery capacity in kWh. Fulfilling this constraint is vital to ensure the battery will not be under/over charged at any hour of the day. The battery state of charge at the end of each hour is the sum of the initial charge level of the battery at the beginning of that hour and the amount of battery charging and discharging energy during that particular hour. The amount of charging/discharging energy of the battery depends on the time duration of frequency deviation in each hour.

3) $SOC_{min} \leq SOC(t-1) + e_{chrg}(t) \leq SOC_{max}$

The over frequency deviation may occur at any spot inside an hour e.g. beginning, middle or end of hour. The time duration of over-frequency deviation can be in sequence. So, the battery optimizations should performed in such a way that the battery charge level does not exceed the maximum defined level at any point, if all of the over-frequency deviations happens in sequence during that particular hour. This constraint ensure that battery will not be over-charged at any time spot inside the hour, even if it is required that the battery be charged continuously during that hour.

It should be noted that this constraint is not applicable to FCR-D market, as the battery will not be charged at all by attending in this market. So, the charging energy e_{chrg} is zero and this constraints is converted to constraint no. 2.

4) $SOCmin \leq SOC(t-1) - e_{dischrg}(t) \leq SOCmax$

The under frequency deviation may occur at any spot inside an hour e.g. beginning, middle or end of hour. The time duration of under-frequency deviation can be in sequence. So, the battery optimizations should performed in such a way that the battery charge level does not fall below the maximum defined level at any point, if all of the under-frequency deviations happens in sequence during that particular hour. This constraint ensure that battery will not be under-charged at any time spot inside the hour, even if it is required that the battery be discharged continuously during that hour.

It should be noted that this constraint is not applicable to FCR-D market, as FCR-D market is a one direction market and the battery will only be discharged by attending in this market. Therefore, this constraints is covered by the constraint no. 2.

In this thesis the battery power optimization problem for Fingrid with respect to constraints explained above, is solved by Matlab® function ‘fmincon’. Fmincon is a gradient-based method that is designed to work on problems where the objective and constraint functions are both continuous and have continuous first derivatives. An algorithm which is utilized by fmincon function to solve the optimization problem is ‘Interior Point Algorithm’. The working principle and the solving mechanism of this algorithm was explained before in chapter 6.4.1.

The optimization problem is solved for both FCR-N and FCR-D markets for May 2016 in average and separately for the first week of May 2016 day by day.

7.4.1.5 Optimization results for FCR-N market

Below table show the hourly optimal power that should be offered to FCR-N market for May 2016 in average. Scheduling of the battery system with the optimal hourly power calculated by the optimization program yields the maximum profit. The hourly optimal powers and the objective function values are plotted under the tables for each case. The function value plot shows the daily profit that the battery owner gains from attending in FCR-N market. The reason behind the negative sign of the function value that is shown in the relevant plots refers to the fact that here the optimization problem is to 'maximize' the objective function. The program performs this by minimizing the negative of objective function. Also, the plot of SOC of the battery is presented which shows how the battery's state of charge changes during 24 hours. The results for the first week of May 2016 is available in Appendix D.

Table 12 Optimal hourly power for FCR-N market – Average May 2016

AVERAGE MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	25,4	0,42	0,66	29,8	0,30	929,3	1079,6	160,1	178,1	989,2	373,1	771,5

AVERAGE MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1045,5	1079,6	1079,7	984,8	0,6	0,3	96,0	518,2	1079,8	0,2	0,2	0,1

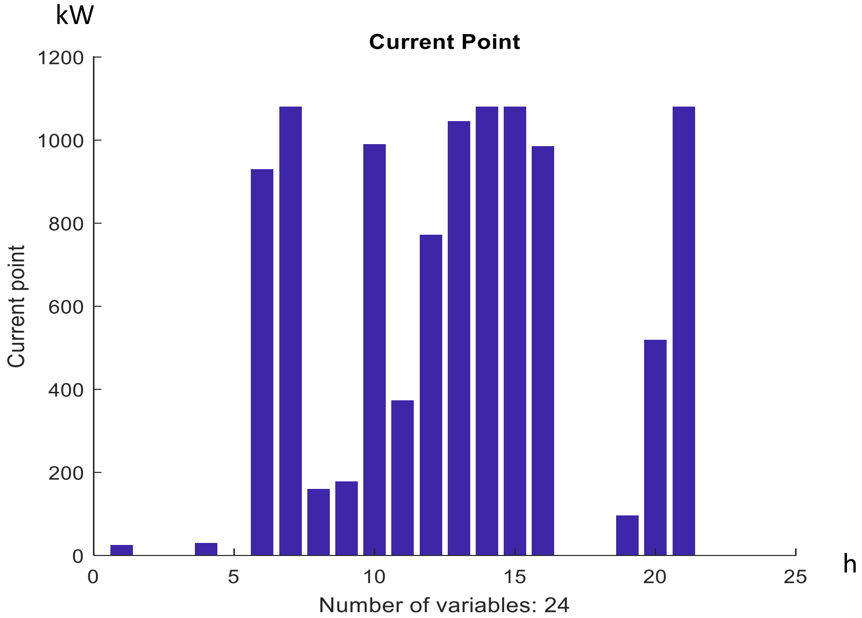


Figure 36 Optimal hourly power for FCR-N market - Average May 2016

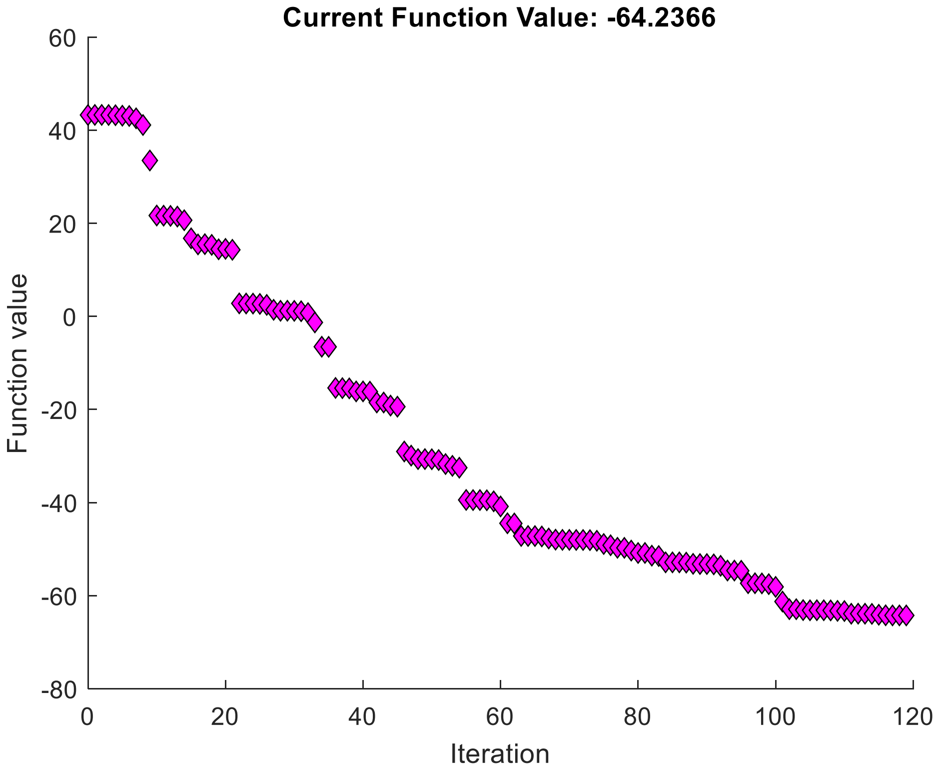


Figure 37 Objective function value

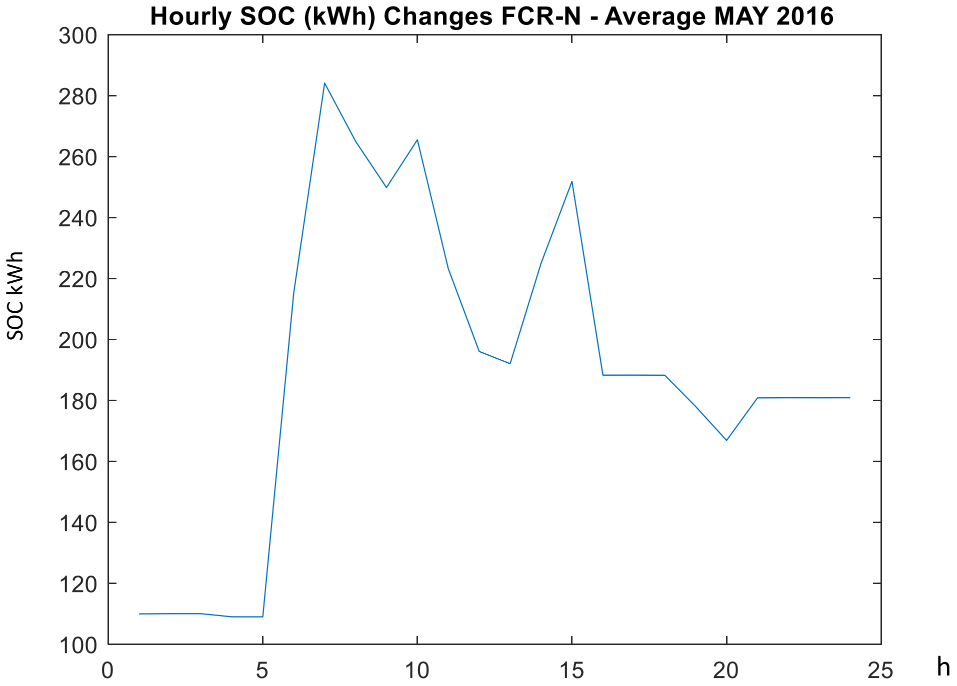


Figure 38 Hourly SOC changes of battery system in FCR-N market - Average May 2016

Below figure shows continues SOC changes of the battery during the first week of May 2016 with optimum power values.

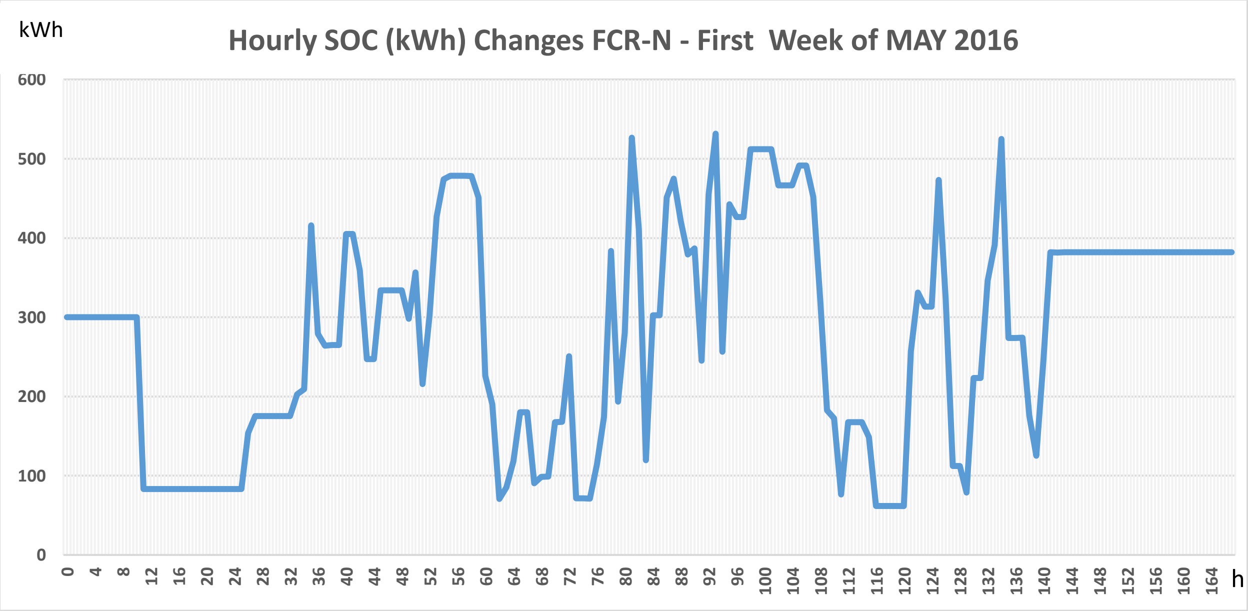


Figure 39 Hourly SOC changes of battery system in FCR-N market - first week of May 2016

The initial charge level of the battery on 1st of May 2016 is supposed to be 300 kWh. The optimization has been done on each day based on the remained charge level in the battery from the previous day. Thus, it is not required to purchase energy for the battery at the end of the day. At the end of the stated week, the charge level of the battery is calculated as 382 kWh.

The optimization results based on frequency deviations of May 2016 show that FCR-N market can be a profitable market for battery owner if the battery scheduling is performed by applying an optimization program. However, in order to implement an optimization program, frequency deviation data is needed. This requirement threatens the effectiveness of the optimization method in real-time applications.

Below chart shows the daily profit gained from optimizing the battery power for attending in FCR-N market in May 2016.

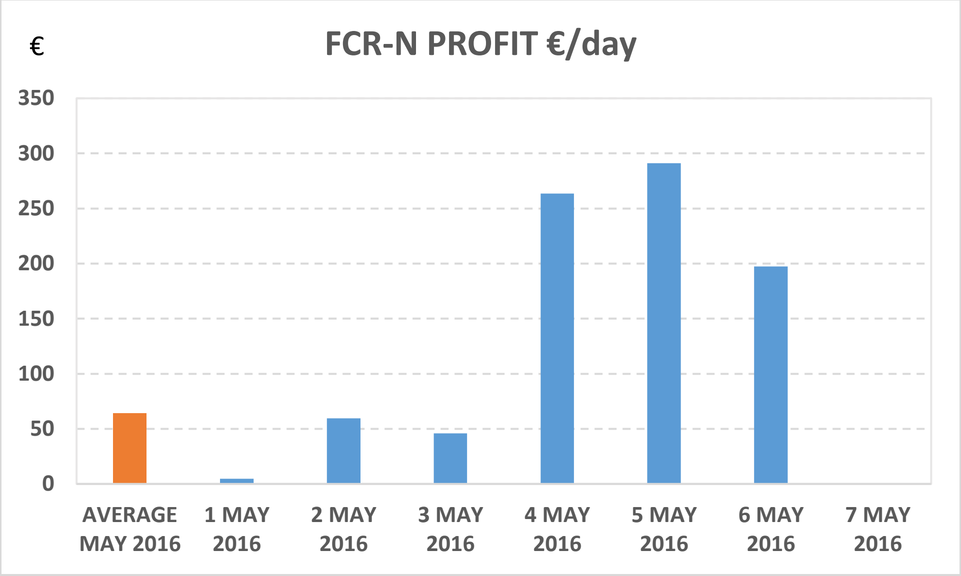


Figure 40 Profit in FCR-N market by using optimization method – May 2016

7.4.1.6 Optimization results for FCR-D market

Below tables show the hourly optimal power that should be offered to FCR-D market for May 2016 in average. Scheduling of the battery system with the optimal hourly power calculated by the optimization program yields the maximum profit. The hourly optimal powers and the objective function values are plotted under the tables for each case. The function value plot shows the daily profit that the battery owner gains from attending in FCR-D market. Also, the plot of SOC of the battery is presented which shows changes of the battery's state of charge during 24 hours.
Results for first week of May 2016 day by day is available in Appendix E.

Table 13 Optimal hourly power for FCR-D market - Average May 2016

AVERAGE MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	1080	1080	1080	1080	1080	1080	1080	962,2	1080	1080	1080	1080

AVERAGE MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080

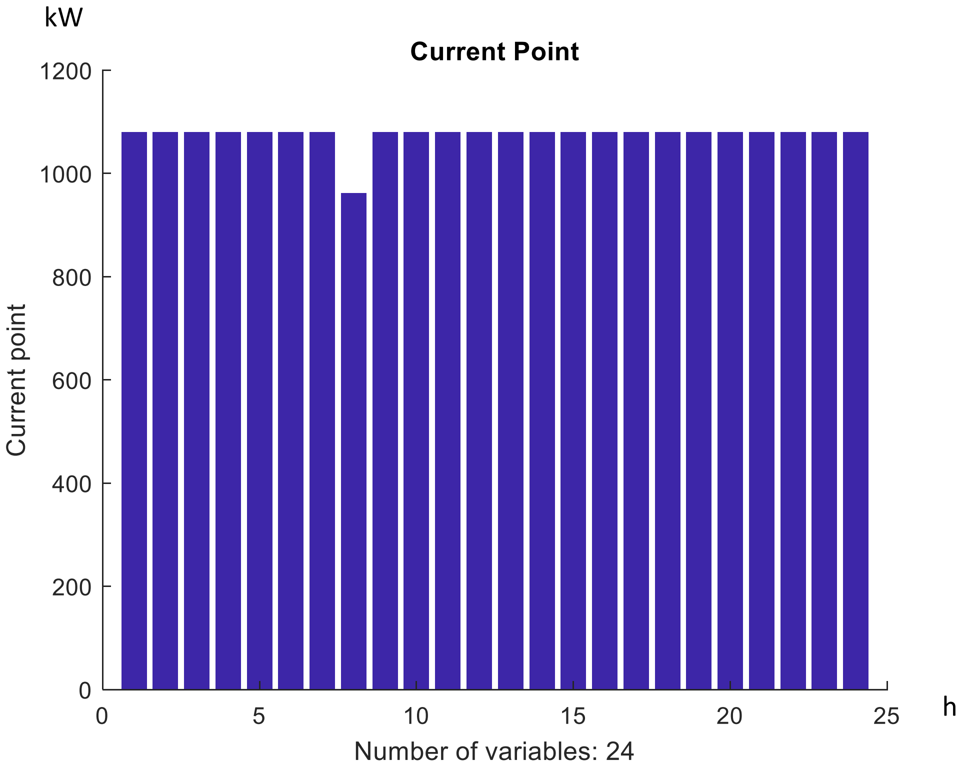


Figure 41 Optimal hourly power in FCR-D market - Average May 2016

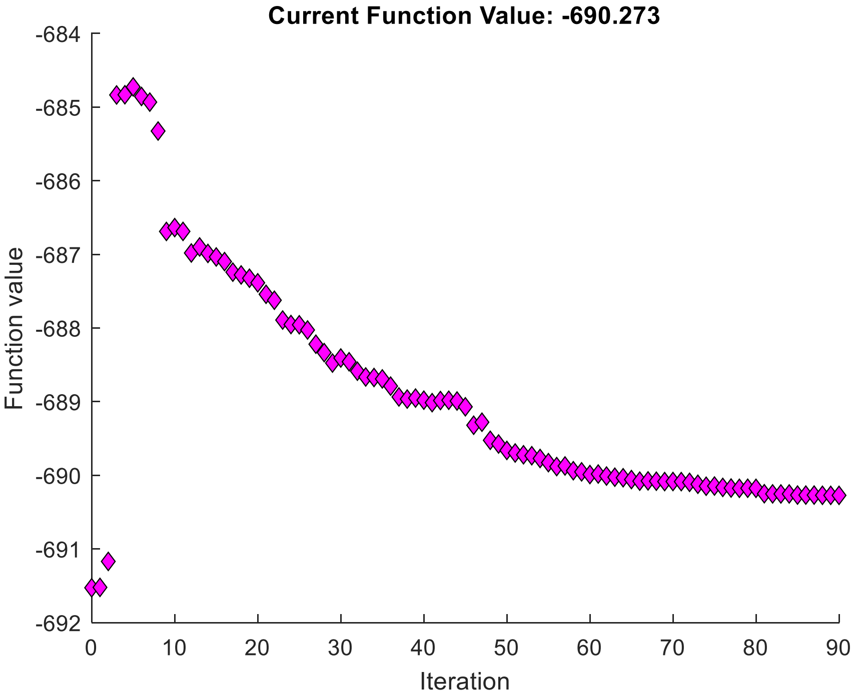


Figure 42 Objective function value

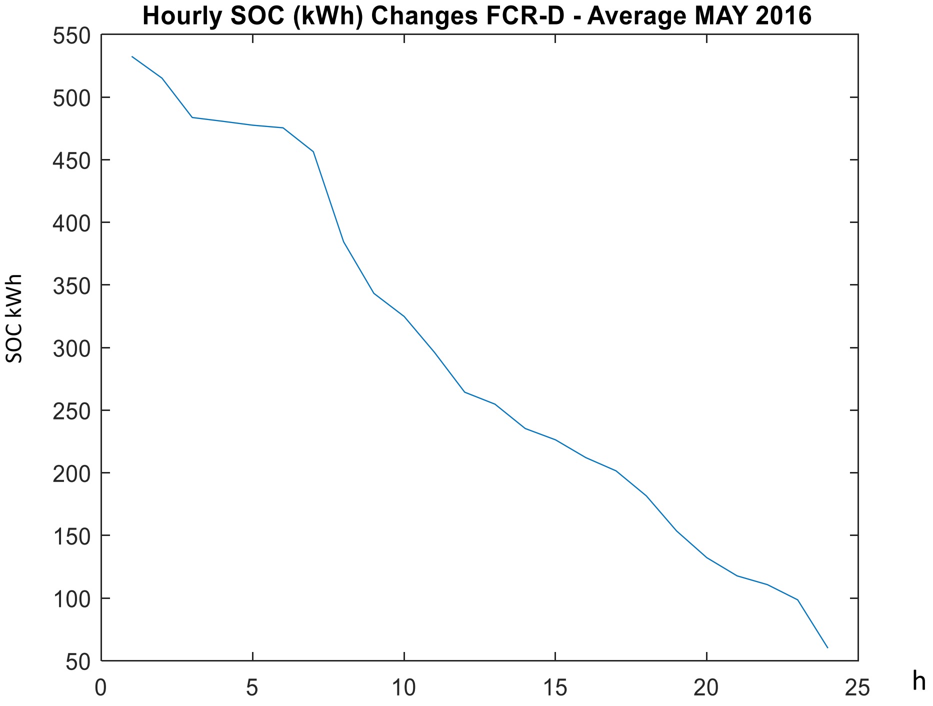


Figure 43 Hourly SOC changes of battery system in FCR-D market - Average May 2016

The results of battery power optimization for FCR-D markets show that the maximum power of the battery can be offered for most of the hours, due to short time duration of major under-frequency deviations (<49.90 Hz) and consequent low level of battery discharging.

As the battery will be only discharged by attending in FCR-D market, the initial charge level of the battery should be set to be on its maximum level at the beginning of each day. Therefore, the amount of discharged energy of the battery should be purchased from Nord Pool market at the end of each day. In this thesis it is assumed that the energy is purchased from Elbas intra-day market. Hence, the costs of purchasing energy to charge the battery should be reduced from the amount of profit which was calculated by the optimization program. The summary of the amount of required energy, the related cost and the final profit is presented in below table:

Table 14 Final profit of utilizing battery system in FCR-D market by using optimization method – May 2016

Date	**Energy to be purchased (kWh)**	**Cost of purchasing energy from Elbas (€)**	**Final profit (€/day)**
1 MAY 2016	231,90	5,23	586,38
2 MAY 2016	271,11	6,09	817,24
3 MAY 2016	212,34	4,62	1183,92
4 MAY 2016	479,94	10,88	1190,22
5 MAY 2016	480,00	9,85	1027,04
6 MAY 2016	479,78	8,74	775,48
7 MAY 2016	260,05	2,53	434,17
AVERAGE MAY 2016	480,00	10,98	679,28

Below chart shows the daily profit gained from optimizing the battery power for attending in FCR-D market.

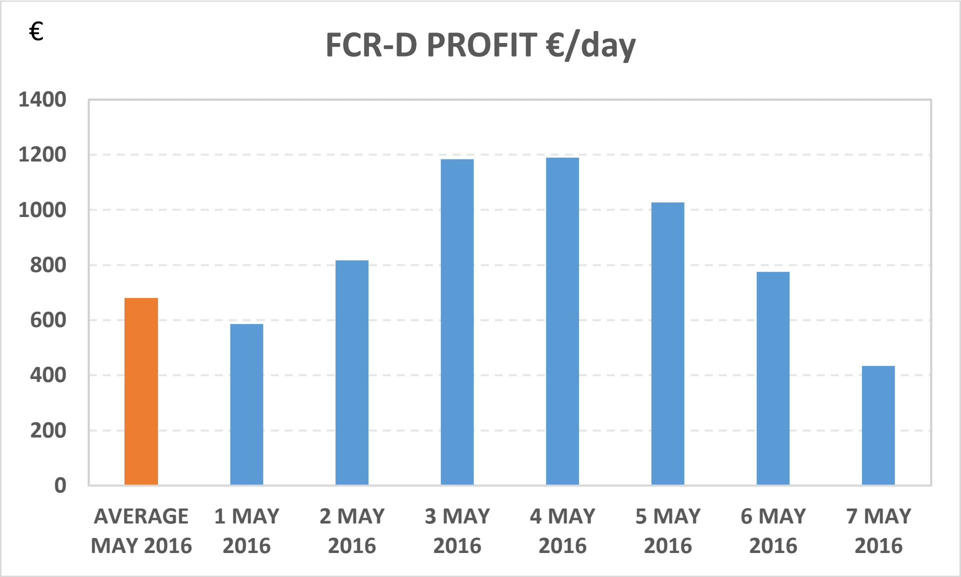


Figure 44 Profit in FCR-D market by using optimization method – May 2016

Comparison between the final profit of optimization of the battery capacity for FCR-N and FCR-D markets shows a higher profit is gained from participating in FCR-D market in May 2016 in average, and also for each day of the first week of the month. The reason can be addressed to the greater hourly power that can be offered to FCR-D market and also remarkably high price of the FCR-D market in May 2016. The highest gained profit in FCR-N market is 291.1 € on 5th of May 2016 while it is 1190.2 € on 4th of May 2016 in FCR-D market.

As it was mentioned in the previous section, in order to implement an optimization program, frequency deviation data is needed. In FCR-D market, the frequency deviations are shorter than the frequency deviations of FCR-N market. So, the optimization method involves less risks when utilized in FCR-D market, although the effectiveness cannot be guaranteed in real-time applications.

7.4.2 Constant capacity allocation of BESS to FCR-N and FCR-D markets

Besides the above-mention performed optimization method, another method of battery capacity allocation to Fingrid frequency markets is studied in this thesis. In this method, it is assumed a constant battery power is offered for all hours of the day to FCR-N and FCR-D markets, and the charge level of the battery is evaluated at the end of each hour. If, battery is under-charged at any hour, the energy that is needed to charge the battery should be purchased from one of the Nord Pool markets, here Elbas intra-day market. In contrast, if the battery is over-charged, a compensation penalty should be paid to Fingrid for the amount of power that could not be provided. Applying this method, the revenue obtained from selling battery power to Fingrid and the cost that should be paid to buy energy for charging the battery are calculated and the profitability of participation in Fingrid frequency markets are evaluated.

Because of the unpredictable frequency changes and the involved uncertainties in frequency markets, performing an accurate real-time optimization is unrealizable. So, another methods is also studied in this thesis to evaluate the profitability of attending in frequency markets without conducting any optimization beforehand, and by just offering a fixed amount of power in all hours of the day.

7.4.2.1 Results of constant capacity allocation of BESS to FCR-N market

The results of allocating a constant power of the battery system to FCR-N market are presented in this section. The hourly SOC of the battery, the required energy to be purchased from Elbas intra-day market to charge the battery, revenue, costs and profit at the end of the day are calculated and summarized in the following tables for May 2016 in average. The results for the first week of May 2016 is available in Appendix F.

It should be noted that the fixed power for FCR-N market is assumed to be 600 kW.

The calculated profit of dedicating a fixed power amount of battery to FCR-N market with considering the battery costs and the cost of buying energy from Elbas intra-day market to charge the battery, show profitability only for 4th, 5th and 6th of May 2016. The May 2016 in average, and the other days of the first week of the month are not profitable. Furthermore, in the mentioned profitable days the battery runs over-charged or under-charged in some hours. In other word, the declared power cannot be provided to the market on some hours of the mentioned profitable days.

So, the battery owner should pay penalty to Fingrid for those hours that the power could not be provided. Reducing the penalty cost from the profit, will cause negative income for the mentioned days as well.

Therefore, with attention to involved risk of under-over charging of the battery and with attention to expensive battery costs values, it can be concluded that participating in FCR-N market with a fixed battery power for all hours of the day is not profitable.

Below table shows the calculated daily revenue, costs and profit of May 2016 in average:

Table 15 Results of utilizing battery system in FCR-N market by using fixed power allocation method - Average May 2016

AVERAGE MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	600,00	60,00	295,20	0,00	3,04	0,00	20,75	-17,71
2	600,00	295,20	388,88	0,00	3,80	0,00	15,19	-11,39
3	600,00	388,88	385,87	0,00	5,26	0,00	9,69	-4,43
4	600,00	385,87	365,37	0,00	5,01	0,00	8,10	-3,09
5	600,00	365,37	349,39	0,00	4,91	0,00	9,58	-4,67
6	600,00	349,39	417,96	0,00	7,81	0,00	9,31	-1,50
7	600,00	417,96	456,23	0,00	18,21	0,00	14,46	3,74
8	600,00	456,23	384,74	0,00	17,55	0,00	15,01	2,53
9	600,00	384,74	333,57	0,00	16,43	0,00	14,63	1,80
10	600,00	333,57	343,07	0,00	16,55	0,00	14,57	1,98
11	600,00	343,07	275,05	0,00	16,61	0,00	11,48	5,13
12	600,00	275,05	253,95	0,00	16,69	0,00	13,25	3,44
13	600,00	253,95	251,65	0,00	16,16	0,00	11,53	4,64
14	600,00	251,65	269,95	0,00	15,20	0,00	10,17	5,04
15	600,00	269,95	284,88	0,00	15,15	0,00	8,69	6,46
16	600,00	284,88	246,17	0,00	14,85	0,00	9,43	5,42
17	600,00	246,17	254,29	0,00	6,35	0,00	11,30	-4,95
18	600,00	254,29	194,66	0,00	5,46	0,00	11,88	-6,42
19	600,00	194,66	130,43	0,00	14,37	0,00	12,88	1,49
20	600,00	130,43	117,57	0,00	14,29	0,00	12,25	2,04
21	600,00	117,57	125,32	0,00	14,48	0,00	9,48	5,00
22	600,00	125,32	230,73	0,00	5,28	0,00	13,50	-8,22
23	600,00	230,73	180,56	0,00	3,01	0,00	11,90	-8,89
24	600,00	180,56	270,78	0,00	2,06	0,00	19,56	-17,50
TOTAL					**258,54**	**0,00**	**298,60**	**-40,05**

7.4.2.2 Results of constant capacity allocation of BESS to FCR-D market

Similar to the previous section, dedicating a constant amount of battery power for all of the hours of the first week of May 2016 and May 2016 in average is studied for FCR-D market and the results are presented in this section.

Due to the usual short time duration of frequency deviations less than 49.90 Hz, a greater power, 700 kW, is examined for FCR-D market in comparison with the examined fixed power 600 kW for FCR-N market.

It should be noted that at the end of the day the battery should be fully charged to be able to attend in the FCR-D market on the next day.

The calculated profit of dedicating a fixed power amount of battery to FCR-D market with considering the battery costs and the cost of buying energy from Elbas intra-day market to charge the battery, shows profitability for the May 2016 in average, and also for each day of the first week of the month. The battery does not run under-charged in any hour during the mentioned days, except on 4th of May that the charge level of the battery decreases under the minimum level 3 times during the day. In these hours the required energy for charging the battery should be purchased from the Elbas intra-day market. Applying penalty costs that should be paid to Fingrid for 4th of May, still confirms the profitability of participating in FCR-D market in May 2016.

However, as it was mentioned previously, May 2016 was an exceptional month that FCR-D prices was extremely high. Considering the average prices of the market in year 2016, the profitability results will be definitely lower.

Obviously, comparing the results of the fixed power method with the results of optimization method presents higher profit values when optimization method is applied. However, due to the unknown frequency deviations in real-time applications, optimization method involves higher risk levels in comparison with the fixed power method.

The calculated profit results are shown in below chart:

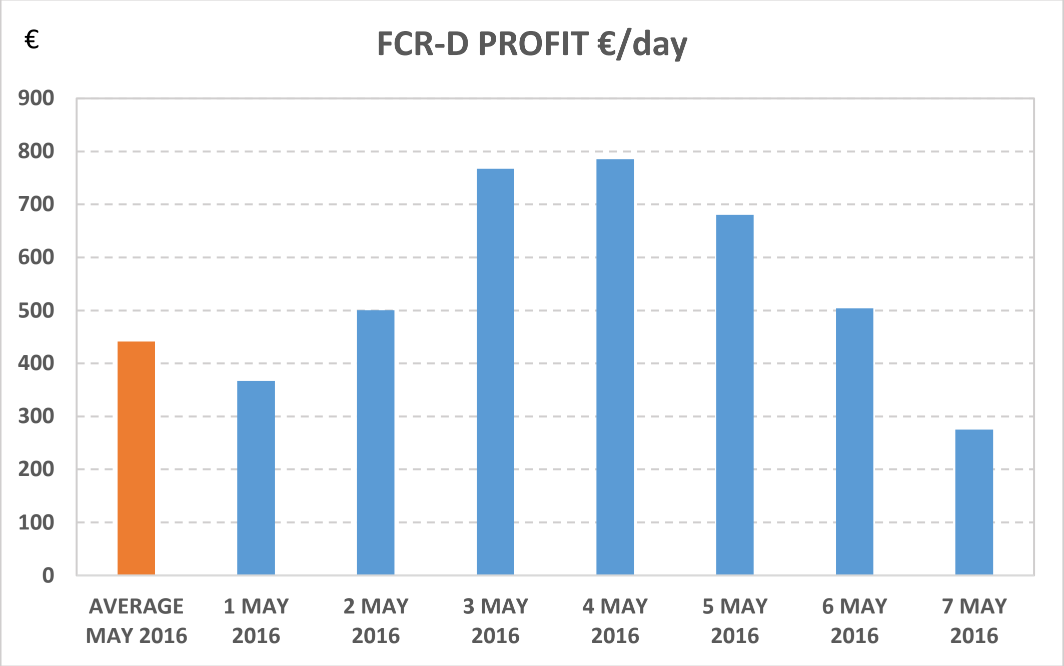


Figure 45 Profit in FCR-D market by using fixed power allocation method – May 2016

The hourly SOC of the battery, the required energy to be purchased from Elbas intra-day market to charge the battery, revenue, costs and profit at the end of the day are calculated and summarized in the following tables for May 2016 in average. Results of the first week of May 2016 day by day is available in Appendix G.

Table 16 Results of utilizing battery system in FCR-D market by using fixed power allocation method – Average May 2016

AVERAGE MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	700,00	540,00	535,13	0,00	19,40	0,00	0,73	18,67
2	700,00	535,13	523,87	0,00	18,78	0,00	1,69	17,09
3	700,00	523,87	503,49	0,00	19,44	0,00	3,06	16,38
4	700,00	503,49	501,54	0,00	18,87	0,00	0,29	18,57
5	700,00	501,54	499,50	0,00	18,87	0,00	0,31	18,56
6	700,00	499,50	498,15	0,00	18,64	0,00	0,20	18,44
7	700,00	498,15	485,80	0,00	19,27	0,00	1,85	17,42
8	700,00	485,80	433,47	0,00	19,08	0,00	7,85	11,23
9	700,00	433,47	406,78	0,00	23,57	0,00	4,00	19,56
10	700,00	406,78	394,83	0,00	23,39	0,00	1,79	21,60
11	700,00	394,83	376,29	0,00	22,13	0,00	2,78	19,35
12	700,00	376,29	355,65	0,00	21,63	0,00	3,10	18,54
13	700,00	355,65	349,45	0,00	20,55	0,00	0,93	19,62
14	700,00	349,45	336,84	0,00	20,47	0,00	1,89	18,58
15	700,00	336,84	330,99	0,00	20,04	0,00	0,88	19,17
16	700,00	330,99	321,79	0,00	19,80	0,00	1,38	18,42
17	700,00	321,79	314,94	0,00	22,01	0,00	1,03	20,98
18	700,00	314,94	302,01	0,00	21,46	0,00	1,94	19,52
19	700,00	302,01	283,83	0,00	21,80	0,00	2,73	19,08
20	700,00	283,83	269,99	0,00	22,30	0,00	2,08	20,23
21	700,00	269,99	260,59	0,00	22,22	0,00	1,41	20,81
22	700,00	260,59	256,06	0,00	20,93	0,00	0,68	20,25
23	700,00	256,06	248,19	0,00	20,69	0,00	1,18	19,51
24	700,00	248,19	223,18	316,82	20,79	7,25	3,75	9,79
TOTAL					**496,14**	**7,25**	**47,52**	**441,37**

8 KEY RESULTS AND DISCUSSION

The purpose of this thesis was to provide a methodology to determine an optimal allocation of the battery system capacity to electricity markets with considering the technological and economic tradeoffs associated with the requirements of markets and specifications of battery system. The optimal allocation strategy was studied by developing an optimization model for the battery system allocation to Nord Pool energy markets and Fingrid frequency markets. Furthermore, another battery capacity allocation method was studied for Fingrid frequency markets. The battery system that was studied in this thesis has a small rate of energy/power 600 kWh/1.2 MW.

Firstly, utilizing of battery system in Nord Pool Elspot day-ahead and Elbas intra-day markets were investigated. For this purpose, an optimization model was developed for these markets by mathematically formulating the problem which subjects to different constraint. In order to solve the optimization problem two algorithms were studied: interior-point algorithm and genetic algorithm. The results reveal that interior-point algorithm is a better solution than the genetic algorithm for the defined optimization problem. The price data of Elspot and Elbas markets of 2016 was used to characterize the optimal solution. The optimization problem was solved for the year 2016 in average and for each month of the year separately. The optimization results indicate that although utilizing the battery system in Elspot and Elbas markets can produce a few amount of revenue, but including the high amount of battery costs leads to unprofitability in all of studied months.

The exploitation of the battery system capacity for dedicating to Fingrid frequency containment reserve markets for normal operation (FCR-N) and disturbances (FCR-D) was studied.

For this purpose two methods were investigated. In the first method, the optimization problem is modeled and solved to determine the optimal battery capacity allocation to each FCR-N and FCR-D markets. The purpose of optimization was defined to maximize the profit with observing the market prices, battery costs, technical constraints of battery system and requirements of each market. A deep analysis was performed on the frequency deviations that were extracted from the Fingrid database and the values of required variables were calculated for May 2016 in average and for the first week of May 2016 day by day. The optimization problem was solved by Matlab® interior-point algorithm. The final results disclose that by applying an optimization method employing the battery system in FCR-N and FCR-D markets is economically beneficial for battery owner. The results present higher profit value from attending in FCR-D market in May 2016 than

FCR-N market in the same month, due to the exceptional high FCR-D market prices and less frequency deviations (<49.90 Hz) in the stated month.

The challenging issue of applying the optimization method for Fingrid frequency markets is that at least an estimation of time durations of hourly frequency deviations should be available to be able to specify the optimal solution. This requirement endangers the suitability of applying the optimization method in real-time applications. Hence, another method was also studied to evaluate the scheduling of battery capacity allocation to Fingrid frequency markets.

In the second method, the profitability of battery system was evaluated with assumption of offering a fixed battery power for all hours of the day to each FCR-N and FCR-D markets. The feasibility of the method was studied by examining the state of charge of battery at the end of each hour and by calculating the required energy that should be purchased from an energy market to charge the battery and the compensation penalty that should be paid to Fingrid for the hours that the declared power could not be provided. The battery costs were also addressed in calculating the profit. The results of applying this method demonstrate that utilizing the battery system in FCR-N market is not profitable for battery owner, because of the high amount of battery costs and because of the frequent under/over-charging of the battery system that occurs during each day due to the unadjusted scheduling of battery capacity and the consequent penalty payments to Fingrid. However, the results of applying the fixed-power method show the profitability of participation in FCR-D market in May 2016. The reasons are referred to the required short discharging time of the battery system and exceptional high market prices of the mentioned month. Obviously, comparing the gained profit from applying the fixed power method and optimization method for attending in FCR-D market, identifies higher profit values when optimization method is used.

Below chart presents a comparison between the profitability of utilizing the battery system in each market for May 2016 in average and for each day of the first week of the month.

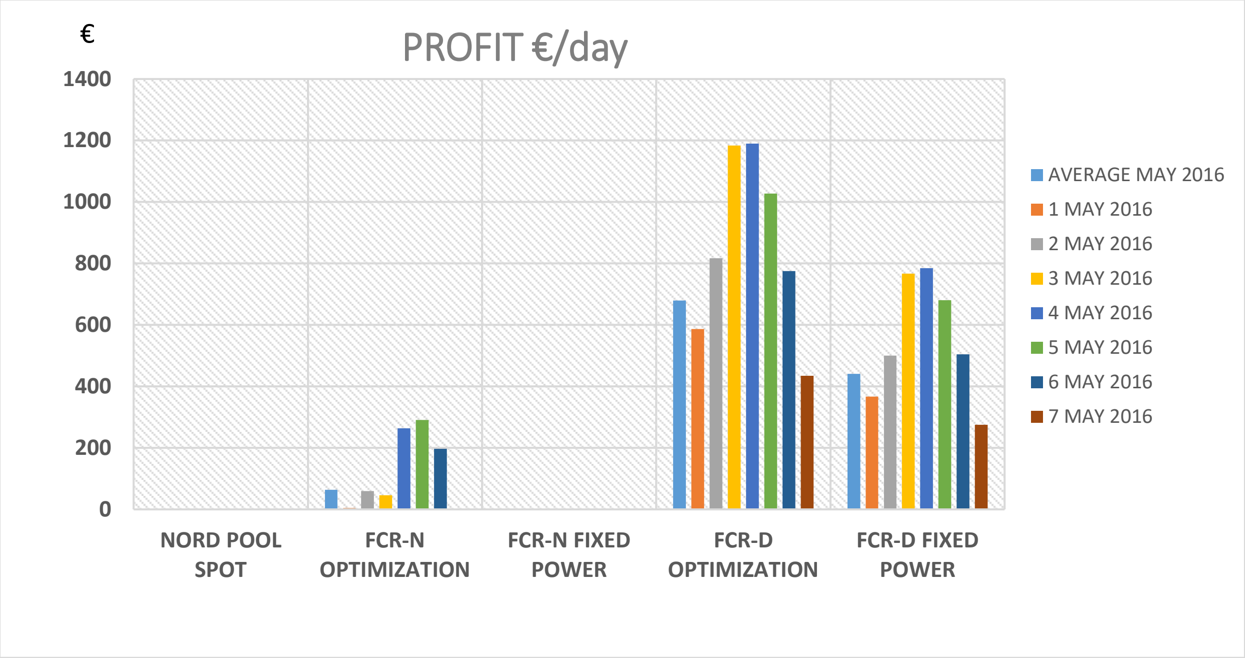


Figure 46 Comparison between the profitability of utilizing the battery system in different markets - May 2016

9 CONCLUSION

The developed optimization model for battery system for participating in Nord Pool day-ahead and intra-day markets, Elspot and Elbas shows that employing the battery system in these markets is not profitable for battery owner. The amount of revenue that is gained from selling the battery energy to market is close to the amount of costs that the battery owner should pay to purchase energy for charging the battery. Although the optimal scheduling of the battery system can produce a low amount of profit in the daily energy transactions of the battery, the final profit will be negative when the high amount of battery costs are taking into account. If the required energy for charging the battery is provided from another source like solar power, the battery system may be profitable for battery owner when attends in Nord Pool spot market.

In order to investigate the profitability of the battery system in Fingrid frequency containment reserve markets for normal operation (FCR-N) and for disturbances (FCR-D), two methods were studied. In the first method an optimization model for battery system was developed based on the real historical data of frequency deviations in May 2016. The optimization results show that the battery system is profitable in both FCR-N and FCR-D markets. The battery costs have been also taken into account. The optimization results show higher profit values by participating in FCR-D market than FCR-N based on May 2016 data. The deficiency of applying the optimization method for scheduling the battery system for FCR-N and FCR-D markets, is the dependency of this method to the durations of frequency deviations.

In the second method a constant amount of battery power was supposed to be dedicated to Fingrid frequency markets for all hours of the day. The results of applying this method show that utilizing the battery system in FCR-N market is not profitable due to the high amount of battery costs and the penalty that should be paid to Fingrid for the hours that the declared power could not be provided to market. On the other hand, the results of applying this method show that utilizing the battery system in FCR-D market is profitable with considering the battery costs and penalty payments (if any). The profitability of battery system in FCR-D market is based on the data of May 2016 and cannot be expanded to other months.

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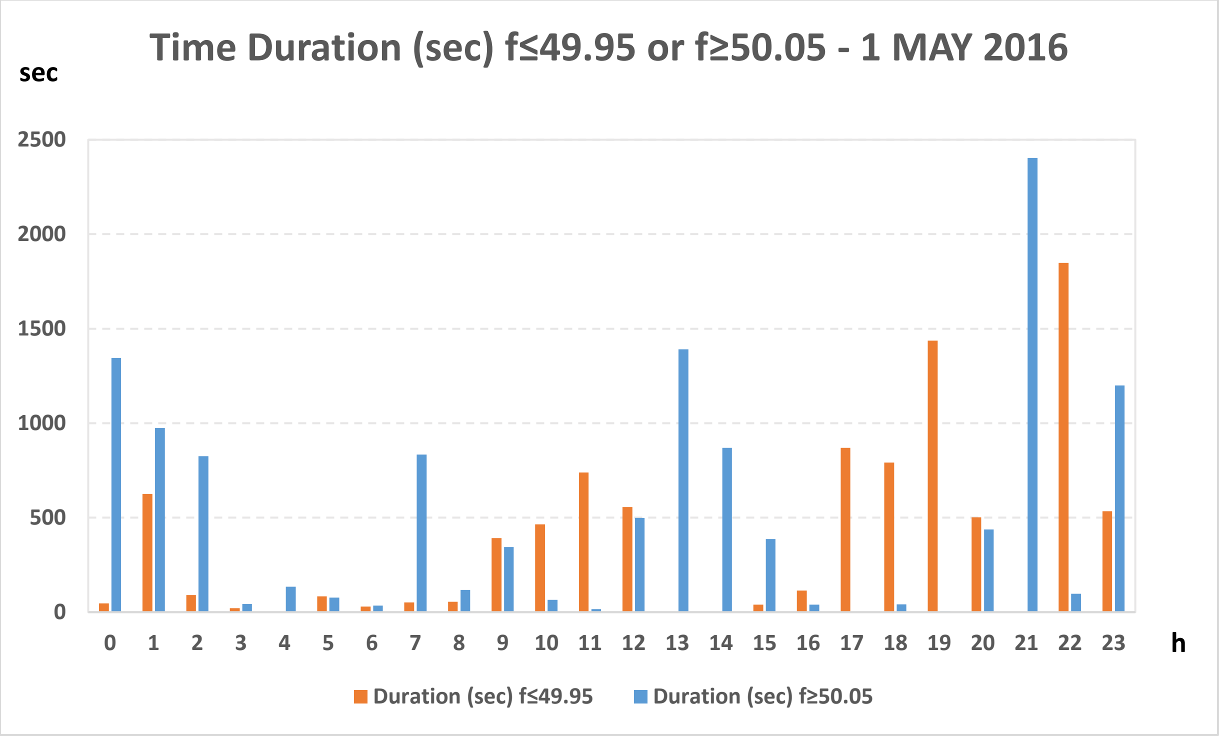
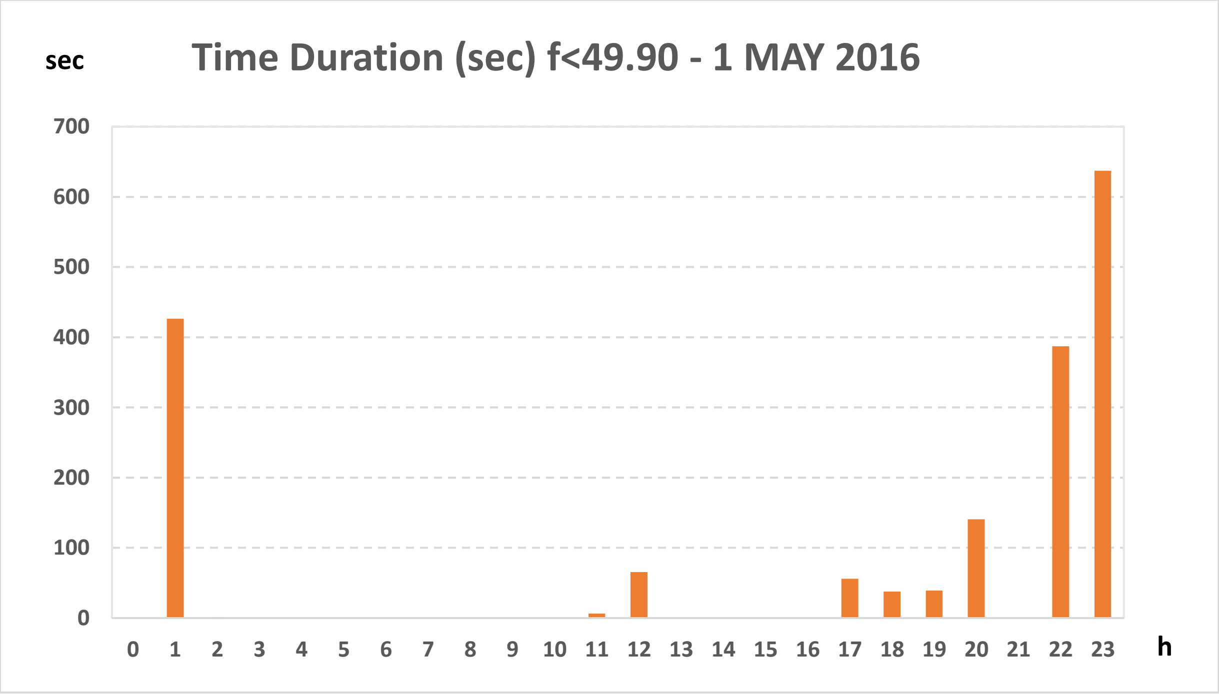
Appendix A: Fmincon solution process

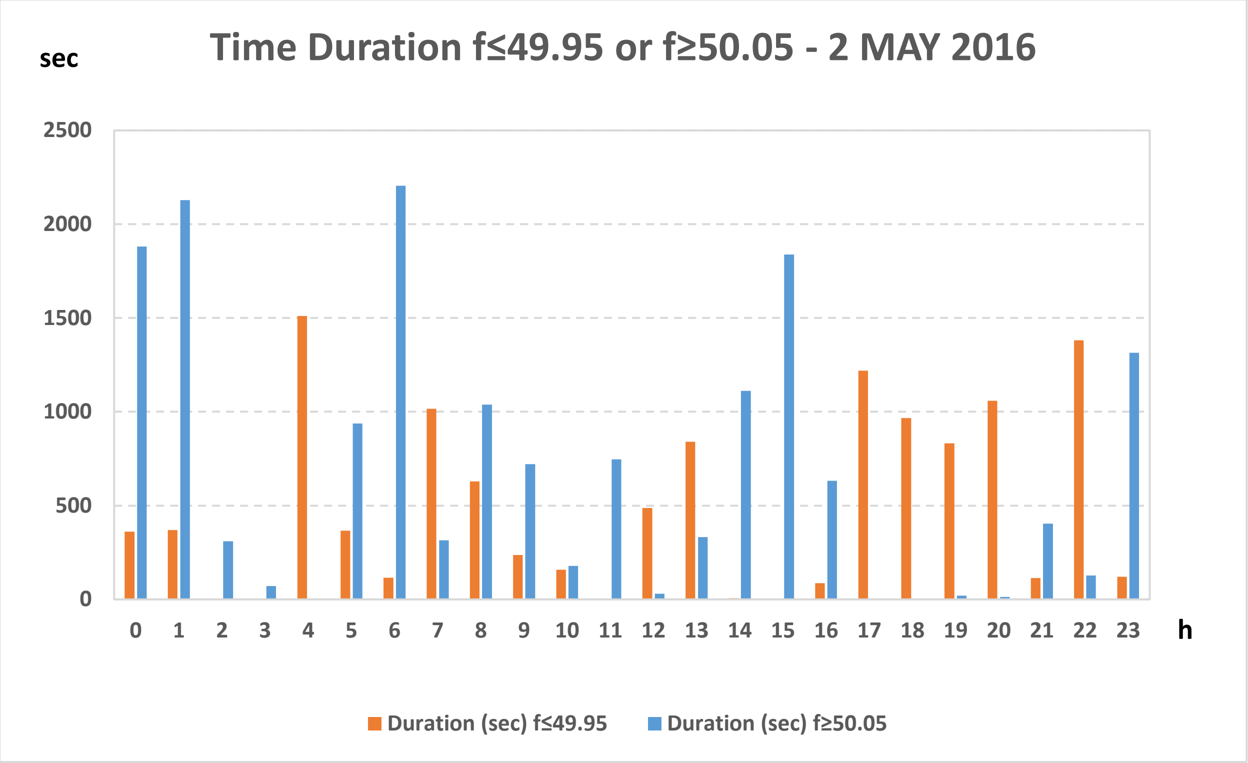
```
                                        First-order    Norm of
 Iter F-count          f(x)  Feasibility  optimality       step
    0      49  -6.885290e+01   2.000e+04   3.045e-02
    1      98  -6.881088e+01   1.998e+04   3.045e-02  3.695e-01
    2     147  -6.875616e+01   1.995e+04   3.045e-02  5.804e-01
    3     196  -6.789494e+01   1.955e+04   3.045e-02  9.594e+00
    4     245  -5.689239e+01   1.429e+04   3.117e-02  1.233e+02
    5     294  -4.315391e+01   7.704e+03   3.240e-02  1.528e+02
    6     343  -3.131200e+01   2.302e+03   3.283e-02  1.295e+02
    7     392  -3.042328e+01   1.946e+03   3.294e-02  6.019e+00
    8     441  -2.883940e+01   1.311e+03   3.323e-02  1.054e+01
    9     490  -2.703998e+01   5.944e+02   3.370e-02  1.186e+01
   10     539  -2.578903e+01   1.273e+02   3.418e-02  8.292e+00
   11     588  -2.531759e+01   9.228e+00   3.448e-02  3.194e+00
   12     637  -2.515666e+01   2.837e-01   3.467e-02  1.194e+00
   13     687  -2.502625e+01   1.517e-01   3.489e-02  1.080e+00
   14     737  -2.485483e+01   8.248e-02   3.521e-02  1.501e+00
   15     787  -2.468368e+01   4.507e-02   3.559e-02  1.646e+00
   16     837  -2.455714e+01   2.475e-02   3.602e-02  1.606e+00
   17     887  -2.452564e+01   1.384e-02   3.655e-02  1.831e+00
   18     937  -2.463311e+01   8.064e-03   3.733e-02  2.938e+00
   19     987  -2.479501e+01   4.821e-03   3.833e-02  3.963e+00
   20    1037  -2.487857e+01   3.273e-03   3.901e-02  2.602e+00
   21    1086  -2.496299e+01   1.246e-03   4.004e-02  3.589e+00
   22    1135  -2.496352e+01   4.601e-04   4.080e-02  2.267e+00
   23    1185  -2.493395e+01   2.810e-04   4.140e-02  1.799e+00
   24    1235  -2.489506e+01   1.774e-04   4.217e-02  2.462e+00
   25    1285  -2.487471e+01   1.217e-04   4.326e-02  3.718e+00
   26    1335  -2.485185e+01   8.406e-05   4.442e-02  3.947e+00
   27    1385  -2.481864e+01   5.522e-05   4.525e-02  2.778e+00
   28    1435  -2.478679e+01   3.518e-05   4.572e-02  1.534e+00
   29    1484  -2.477116e+01   1.002e-05   4.633e-02  1.913e+00
   30    1534  -2.478499e+01   6.410e-06   4.646e-02  3.991e-01
   31    1584  -2.478382e+01   4.115e-06   4.674e-02  7.891e-01
   32    1633  -2.476242e+01   1.304e-06   4.765e-02  2.683e+00
   33    1683  -2.475317e+01   8.532e-07   4.831e-02  1.999e+00
   34    1733  -2.475506e+01   5.551e-07   4.907e-02  2.364e+00
   35    1783  -2.476482e+01   3.523e-07   4.986e-02  2.482e+00
   36    1833  -2.477689e+01   2.216e-07   5.047e-02  1.936e+00
   37    1882  -2.479484e+01   6.650e-08   5.121e-02  2.323e+00
   38    1932  -2.479039e+01   4.309e-08   5.134e-02  3.679e-01
   39    1982  -2.480972e+01   2.583e-08   5.149e-02  5.276e-01
   40    2032  -2.484201e+01   1.468e-08   5.171e-02  8.315e-01
```

```
41   2082   -2.487568e+01   8.191e-09   5.206e-02   1.220e+00
42   2132   -2.490380e+01   4.624e-09   5.251e-02   1.511e+00
43   2182   -2.492503e+01   2.586e-09   5.296e-02   1.531e+00
44   2232   -2.494048e+01   1.412e-09   5.333e-02   1.290e+00
45   2282   -2.495337e+01   7.848e-10   5.356e-02   9.332e-01
46   2332   -2.496742e+01   4.413e-10   5.372e-02   6.909e-01
47   2382   -2.498382e+01   2.456e-10   5.383e-02   5.786e-01
48   2432   -2.500326e+01   1.321e-10   5.392e-02   5.786e-01
49   2482   -2.502686e+01   6.948e-11   5.402e-02   6.825e-01
50   2532   -2.505600e+01   3.746e-11   5.416e-02   8.897e-01
51   2582   -2.509328e+01   2.057e-11   5.435e-02   1.232e+00
52   2632   -2.513782e+01   1.136e-11   5.461e-02   1.590e+00
53   2682   -2.518277e+01   6.298e-12   5.489e-02   1.738e+00
54   2732   -2.521921e+01   3.444e-12   5.514e-02   1.560e+00
55   2782   -2.523937e+01   2.010e-12   5.530e-02   1.007e+00
56   2832   -2.524972e+01   1.239e-12   5.539e-02   6.161e-01
57   2882   -2.525641e+01   7.851e-13   5.545e-02   4.206e-01
58   2932   -2.526187e+01   5.061e-13   5.548e-02   3.180e-01
59   2989   -2.526171e+01   4.989e-13   5.548e-02   5.166e-03
```

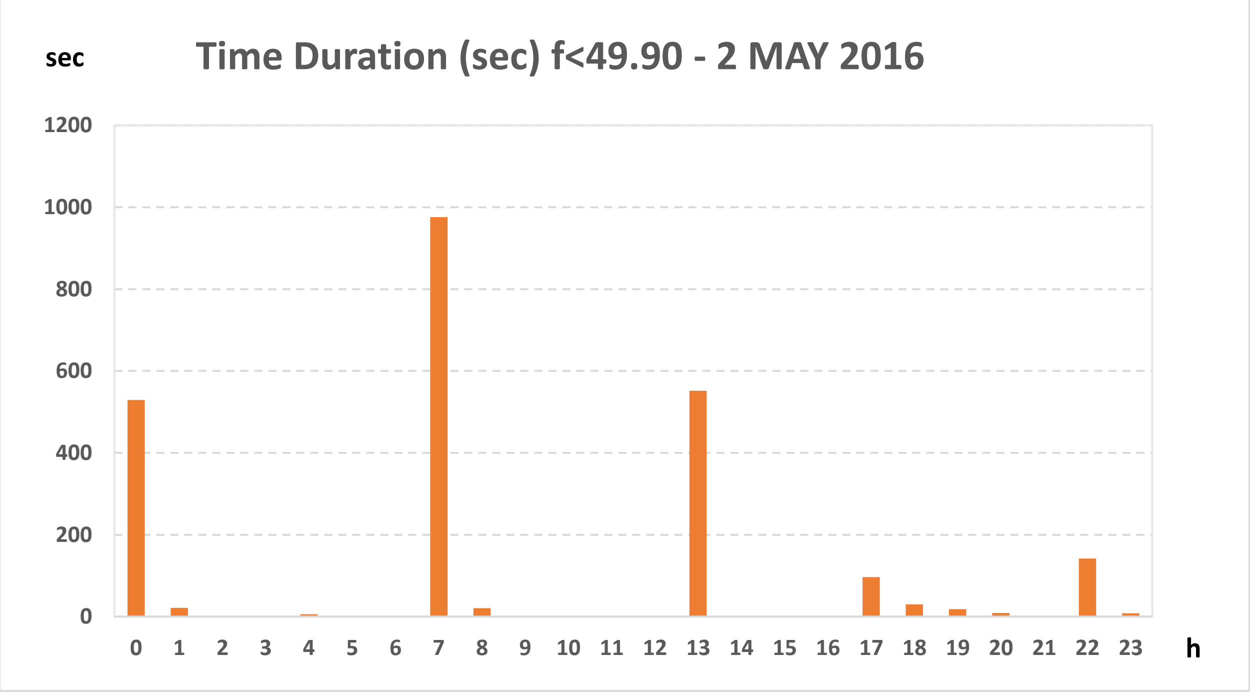
Appendix B: Time duration of frequency deviations – first week of May 2016







sec
Time Duration f≤49.95 or f≥50.05 - 2 MAY 2016
2500
2000
1500
1000
500
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
h
Duration (sec) f≤49.95
Duration (sec) f≥50.05



sec
Time Duration (sec) f<49.90 - 2 MAY 2016
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1000
800
600
400
200
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
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19
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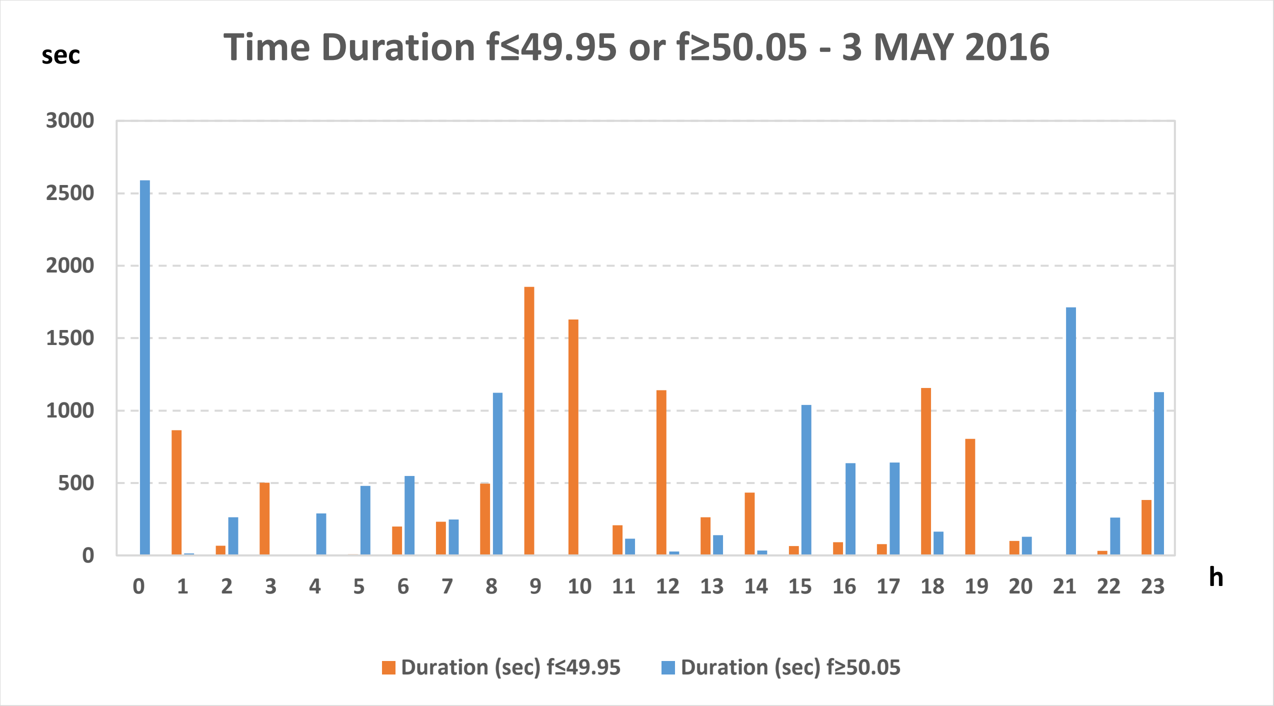
21
22
23
h


Time Duration f≤49.95 or f≥50.05 - 3 MAY 2016
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1000
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0
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1
2
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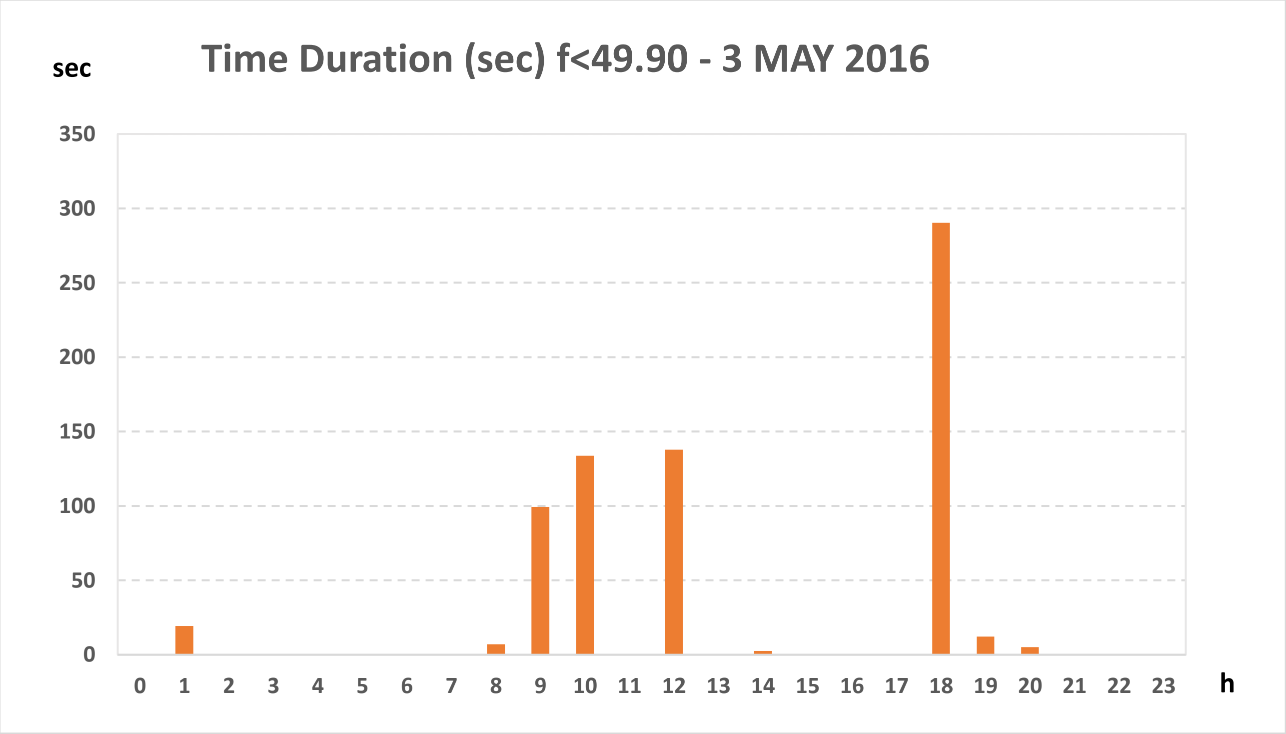
h
Duration (sec) f≤49.95
Duration (sec) f≥50.05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250
200
150
100
50
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1
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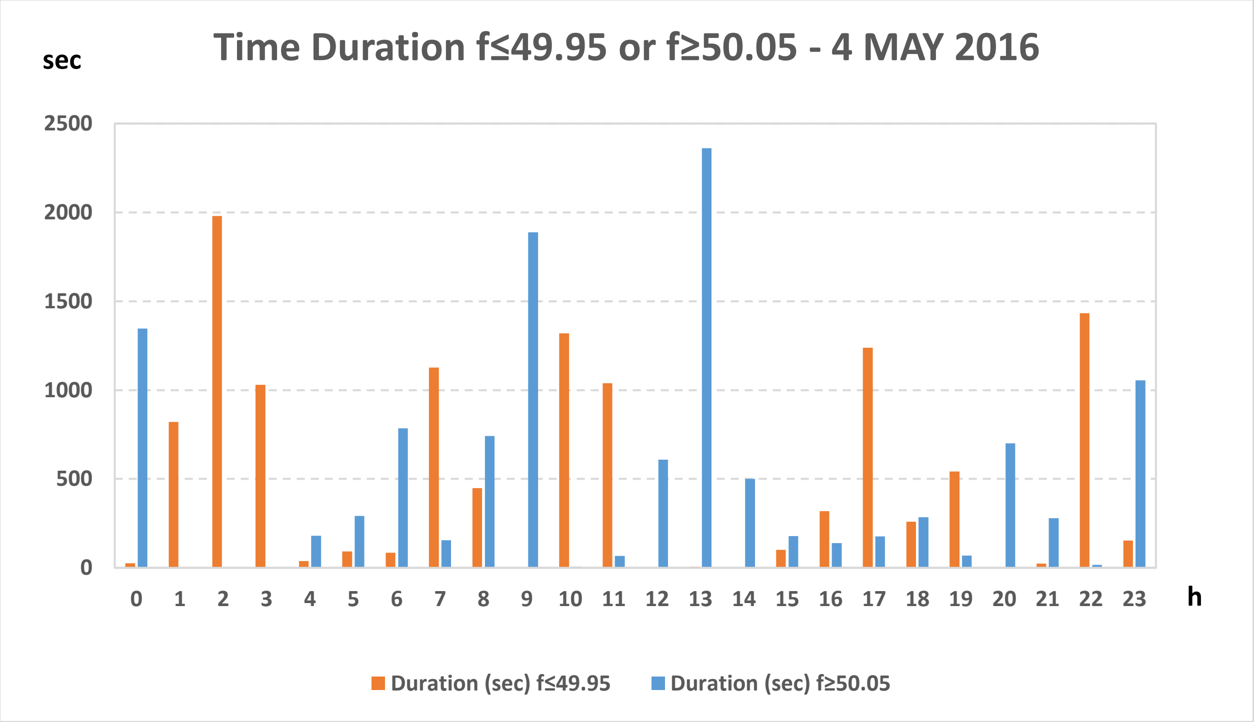
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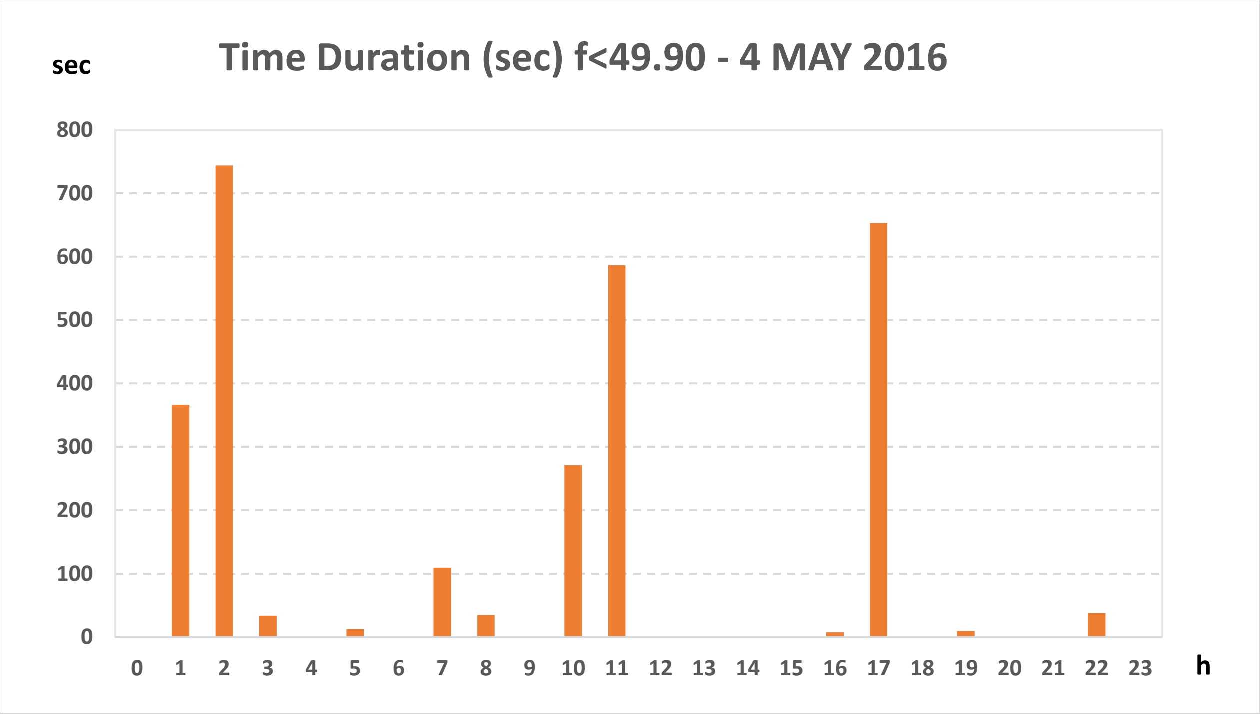
Duration (sec) f≥50.05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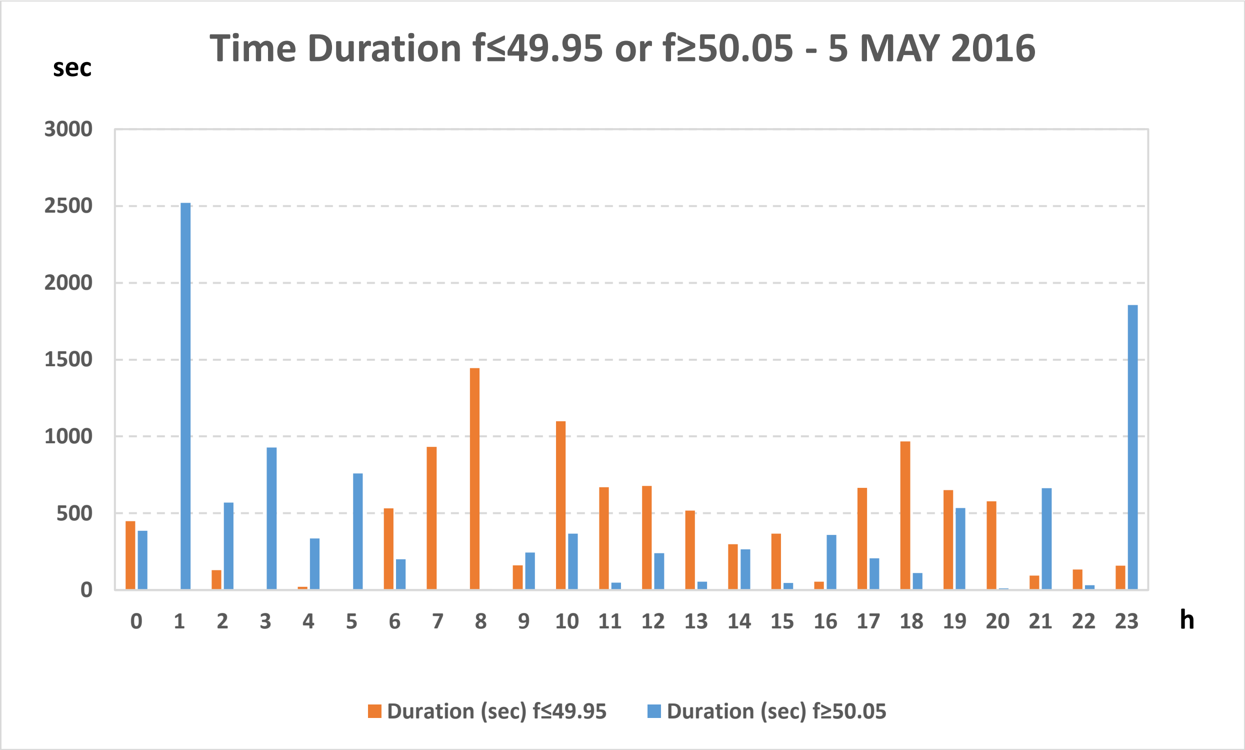
h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2500
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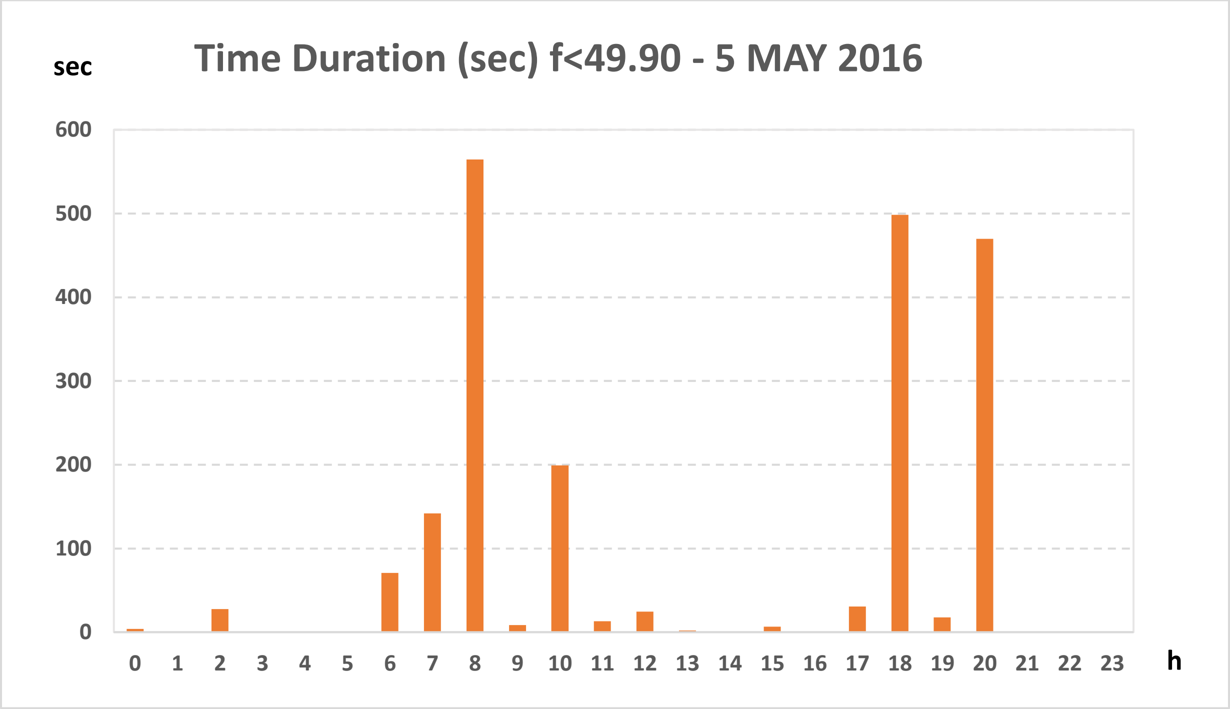
Duration (sec) f≥50.05


Time Duration (sec) f<49.90 - 5 MAY 2016
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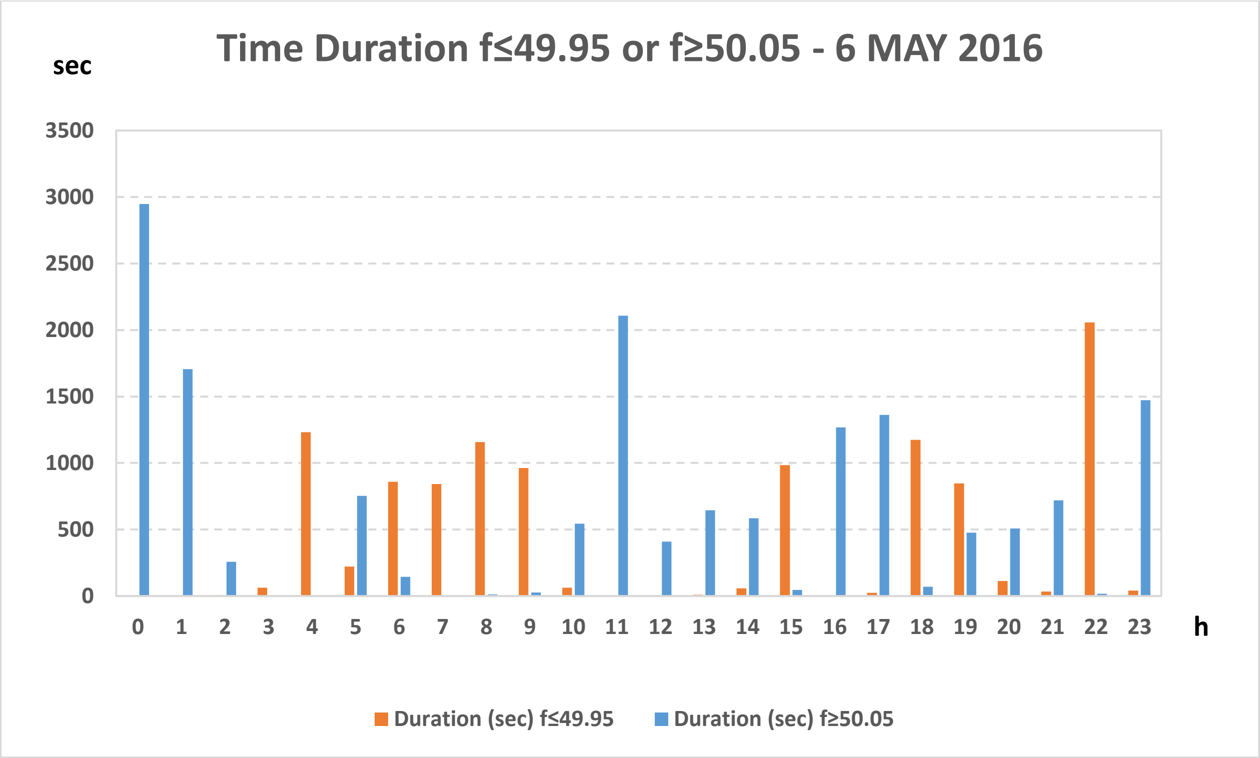
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
h


Time Duration f≤49.95 or f≥50.05 - 6 MAY 2016
sec
3500
3000
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2000
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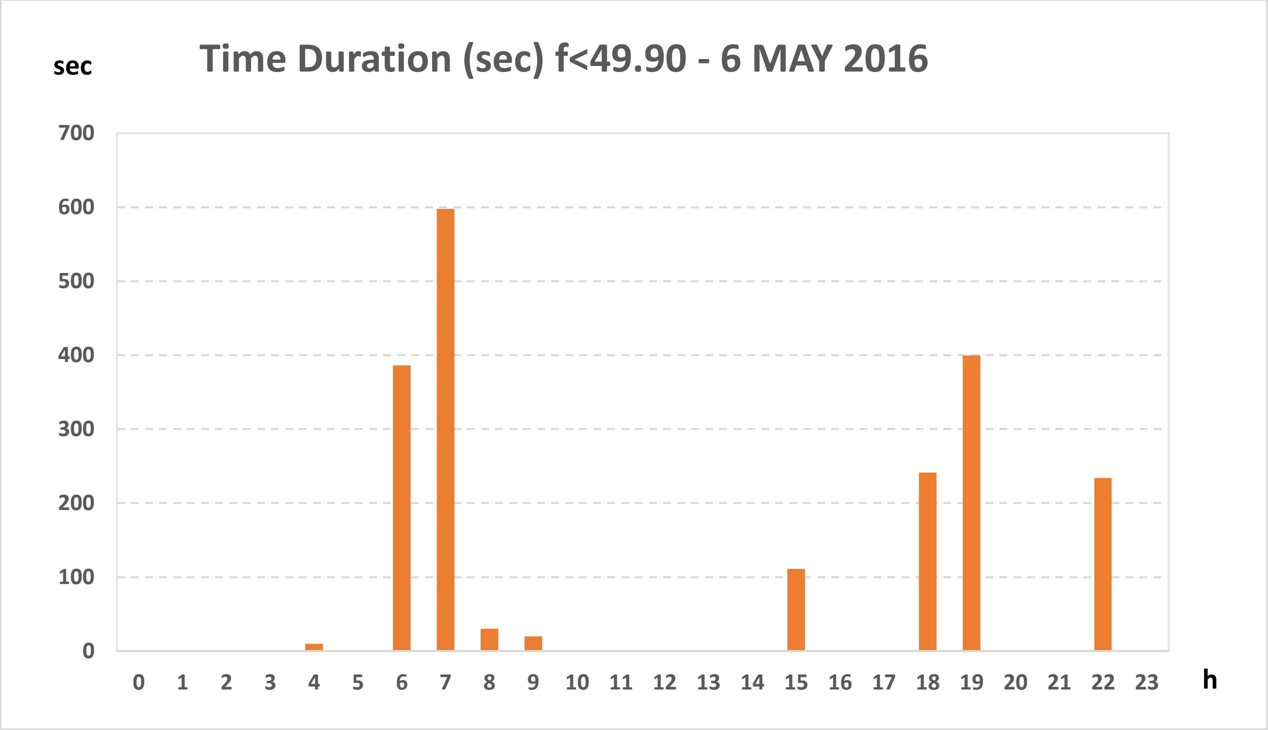
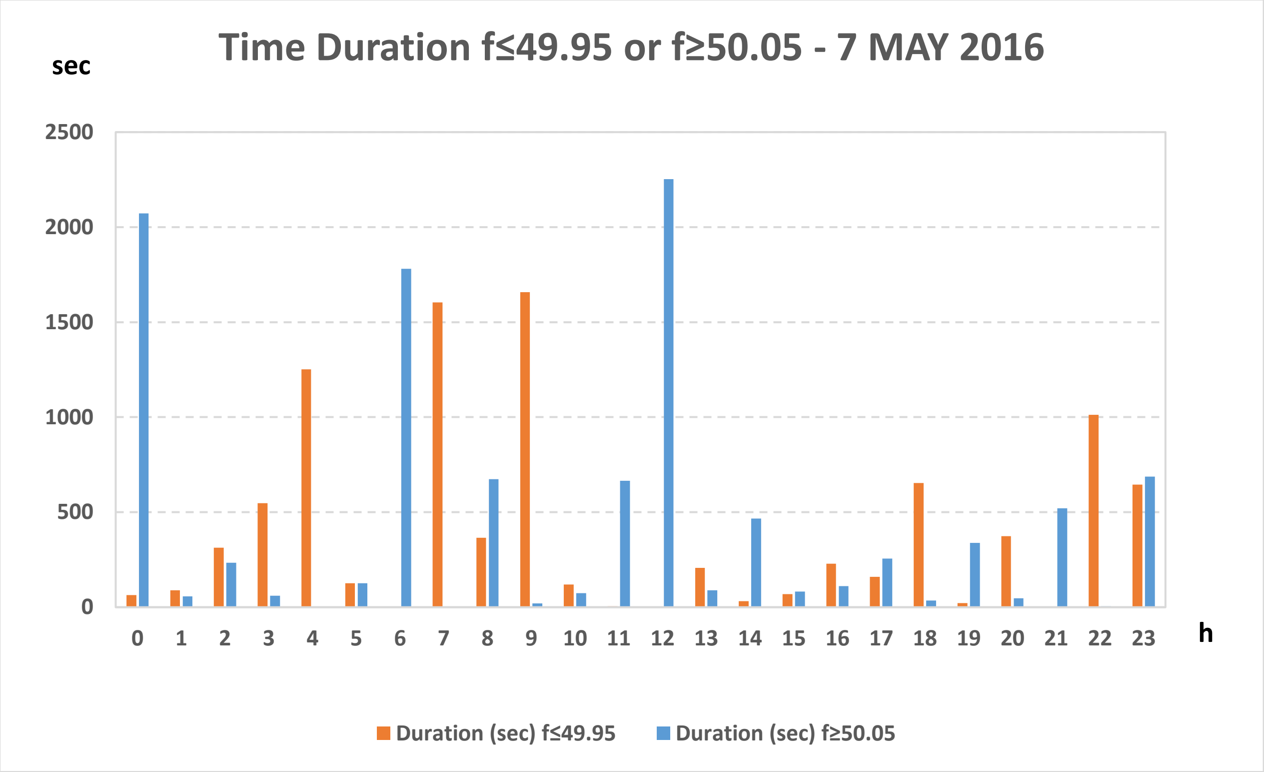
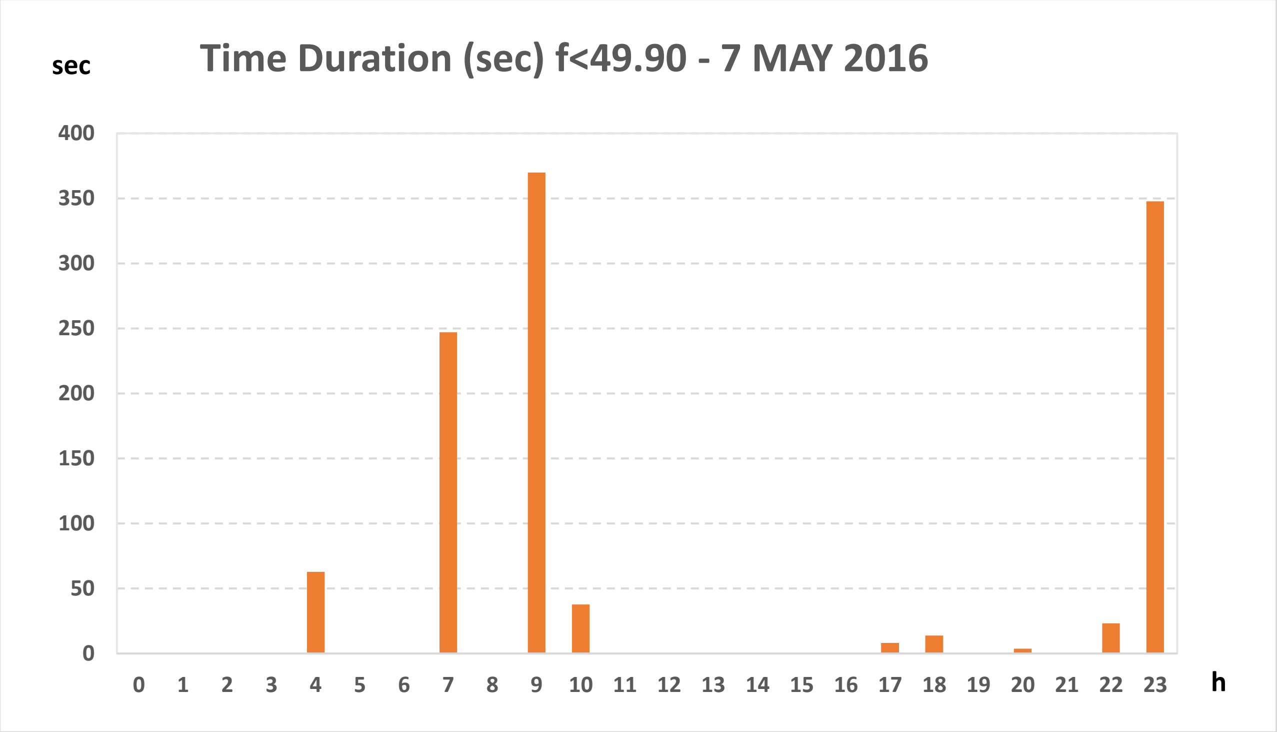
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
h
Duration (sec) f≤49.95
Duration (sec) f≥50.05


Time Duration (sec) f<49.90 - 6 MAY 2016
sec
700
600
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
h


Time Duration f≤49.95 or f≥50.05 - 7 MAY 2016
sec
2500
2000
1500
1000
500
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
h
Duration (sec) f≤49.95
Duration (sec) f≥50.05


Time Duration (sec) f<49.90 - 7 MAY 2016
sec
400
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
h

Appendix C: Battery charging/discharging time (% hour) – first week of May 2016

1 MAY 2016 FCR-N		
hour	**Battery Discharging Time (% hour)**	**Battery Charging Time (% hour)**
0	1,30 %	37,37 %
1	17,40 %	27,06 %
2	2,50 %	22,94 %
3	0,57 %	1,22 %
4	0,00 %	3,76 %
5	2,35 %	2,16 %
6	0,84 %	0,96 %
7	1,41 %	23,16 %
8	1,52 %	3,27 %
9	10,91 %	9,57 %
10	12,92 %	1,81 %
11	20,54 %	0,46 %
12	15,47 %	13,83 %
13	0,00 %	38,66 %
14	0,00 %	24,18 %
15	1,08 %	10,73 %
16	3,16 %	1,10 %
17	24,17 %	0,00 %
18	21,98 %	1,15 %
19	39,93 %	0,10 %
20	13,96 %	12,16 %
21	0,00 %	66,75 %
22	51,35 %	2,71 %
23	14,82 %	33,33 %

1 MAY 2016 FCR-D	
hour	**Battery Discharging Time (% hour)**
0	0,00 %
1	11,84 %
2	-0,03 %
3	0,00 %
4	0,00 %
5	0,00 %
6	0,00 %
7	0,00 %
8	0,00 %
9	0,00 %
10	0,00 %
11	0,18 %
12	1,82 %
13	0,00 %
14	0,00 %
15	0,00 %
16	0,00 %
17	1,55 %
18	1,05 %
19	1,09 %
20	3,91 %
21	0,00 %
22	10,75 %
23	17,70 %

2 MAY 2016 FCR-N		
hour	**Battery Discharging Time (% hour)**	**Battery Charging Time (% hour)**
0	10,01 %	52,24 %
1	10,28 %	59,13 %
2	0,00 %	8,59 %
3	0,00 %	1,98 %
4	41,96 %	0,00 %
5	10,18 %	26,04 %
6	3,22 %	61,25 %
7	28,21 %	8,76 %
8	17,48 %	28,85 %
9	6,57 %	20,03 %
10	4,38 %	4,98 %
11	0,00 %	20,74 %
12	13,55 %	0,84 %
13	23,34 %	9,23 %
14	0,19 %	30,86 %
15	0,00 %	51,07 %
16	2,39 %	17,56 %
17	33,88 %	0,00 %
18	26,83 %	0,00 %
19	23,13 %	0,53 %
20	29,41 %	0,34 %
21	3,17 %	11,22 %
22	38,35 %	3,52 %
23	3,35 %	36,53 %

2 MAY 2016 FCR-D	
hour	**Battery Discharging Time (% hour)**
0	14,70 %
1	0,60 %
2	0,00 %
3	0,00 %
4	0,16 %
5	0,00 %
6	0,00 %
7	27,10 %
8	0,56 %
9	0,00 %
10	0,00 %
11	0,00 %
12	0,00 %
13	15,33 %
14	0,00 %
15	0,00 %
16	0,00 %
17	2,68 %
18	0,84 %
19	0,51 %
20	0,25 %
21	0,00 %
22	3,95 %
23	0,23 %

3 MAY 2016 FCR-N		
hour	**Battery Discharging Time (% hour)**	**Battery Charging Time (% hour)**
0	0,02 %	71,91 %
1	24,01 %	0,36 %
2	1,88 %	7,29 %
3	13,92 %	0,05 %
4	0,00 %	8,06 %
5	0,23 %	13,32 %
6	5,57 %	15,26 %
7	6,45 %	6,89 %
8	13,74 %	31,18 %
9	51,47 %	0,00 %
10	45,23 %	0,00 %
11	5,76 %	3,23 %
12	31,69 %	0,78 %
13	7,31 %	3,87 %
14	12,03 %	0,96 %
15	1,79 %	28,86 %
16	2,54 %	17,68 %
17	2,15 %	17,79 %
18	32,14 %	4,58 %
19	22,38 %	0,00 %
20	2,79 %	3,56 %
21	0,00 %	47,59 %
22	0,85 %	7,24 %
23	10,65 %	31,29 %

3 MAY 2016 FCR-D	
hour	**Battery Discharging Time (% hour)**
0	0,00 %
1	0,54 %
2	0,00 %
3	0,00 %
4	0,00 %
5	0,00 %
6	0,00 %
7	0,00 %
8	0,20 %
9	2,76 %
10	3,72 %
11	0,00 %
12	3,83 %
13	0,00 %
14	0,07 %
15	0,00 %
16	0,00 %
17	0,00 %
18	8,07 %
19	0,34 %
20	0,14 %
21	0,00 %
22	0,00 %
23	0,00 %

4 MAY 2016 FCR-N		
hour	**Battery Discharging Time (% hour)**	**Battery Charging Time (% hour)**
0	0,70 %	37,38 %
1	22,81 %	0,03 %
2	55,00 %	0,00 %
3	28,59 %	0,00 %
4	1,04 %	5,02 %
5	2,57 %	8,11 %
6	2,37 %	21,80 %
7	31,29 %	4,33 %
8	12,45 %	20,58 %
9	0,00 %	52,43 %
10	36,65 %	0,15 %
11	28,85 %	1,86 %
12	0,00 %	16,91 %
13	0,15 %	65,60 %
14	0,12 %	13,91 %
15	2,79 %	4,98 %
16	8,84 %	3,88 %
17	34,41 %	4,91 %
18	7,23 %	7,93 %
19	15,04 %	1,92 %
20	0,00 %	19,44 %
21	0,65 %	7,75 %
22	39,81 %	0,48 %
23	4,27 %	29,30 %

4 MAY 2016 FCR-D	
hour	**Battery Discharging Time (% hour)**
0	0,00 %
1	10,17 %
2	20,66 %
3	0,94 %
4	0,00 %
5	0,34 %
6	0,00 %
7	3,04 %
8	0,96 %
9	0,00 %
10	7,53 %
11	16,29 %
12	0,00 %
13	0,00 %
14	0,00 %
15	0,00 %
16	0,20 %
17	18,14 %
18	0,00 %
19	0,26 %
20	0,00 %
21	0,00 %
22	1,04 %
23	0,00 %

5 MAY 2016 FCR-N		
hour	**Battery Discharging Time (% hour)**	**Battery Charging Time (% hour)**
0	12,48 %	10,71 %
1	0,00 %	70,03 %
2	3,63 %	15,82 %
3	0,00 %	25,79 %
4	0,58 %	9,33 %
5	0,00 %	21,11 %
6	14,77 %	5,58 %
7	25,87 %	0,00 %
8	40,13 %	0,10 %
9	4,48 %	6,80 %
10	30,55 %	10,21 %
11	18,57 %	1,35 %
12	18,83 %	6,69 %
13	14,34 %	1,53 %
14	8,30 %	7,37 %
15	10,22 %	1,30 %
16	1,50 %	9,98 %
17	18,49 %	5,75 %
18	26,85 %	3,11 %
19	18,09 %	14,86 %
20	16,03 %	0,30 %
21	2,60 %	18,40 %
22	3,72 %	0,89 %
23	4,38 %	51,53 %

5 MAY 2016 FCR-D	
hour	**Battery Discharging Time (% hour)**
0	0,11 %
1	0,00 %
2	0,77 %
3	0,00 %
4	0,00 %
5	0,00 %
6	1,97 %
7	3,94 %
8	15,69 %
9	0,24 %
10	5,53 %
11	0,36 %
12	0,68 %
13	0,05 %
14	0,00 %
15	0,19 %
16	0,00 %
17	0,85 %
18	13,85 %
19	0,49 %
20	13,04 %
21	0,00 %
22	0,00 %
23	0,00 %

6 MAY 2016 FCR-N		
hour	Battery Discharging Time (% hour)	Battery Charging Time (% hour)
0	0,08 %	81,89 %
1	0,00 %	47,40 %
2	0,23 %	7,14 %
3	1,74 %	0,09 %
4	34,21 %	0,00 %
5	6,13 %	20,94 %
6	23,86 %	4,03 %
7	23,37 %	0,00 %
8	32,15 %	0,32 %
9	26,73 %	0,77 %
10	1,75 %	15,14 %
11	0,10 %	58,53 %
12	0,00 %	11,38 %
13	0,30 %	17,89 %
14	1,65 %	16,24 %
15	27,32 %	1,30 %
16	0,00 %	35,21 %
17	0,68 %	37,86 %
18	32,64 %	1,95 %
19	23,52 %	13,24 %
20	3,13 %	14,11 %
21	0,94 %	20,01 %
22	57,17 %	0,51 %
23	1,12 %	40,90 %

6 MAY 2016 FCR-D	
hour	Battery Discharging Time (% hour)
0	0,00 %
1	0,00 %
2	0,00 %
3	0,00 %
4	0,28 %
5	0,00 %
6	10,73 %
7	16,60 %
8	0,84 %
9	0,55 %
10	0,00 %
11	0,00 %
12	0,00 %
13	0,00 %
14	0,00 %
15	3,09 %
16	0,00 %
17	0,00 %
18	6,71 %
19	11,10 %
20	0,00 %
21	0,00 %
22	6,50 %
23	0,00 %

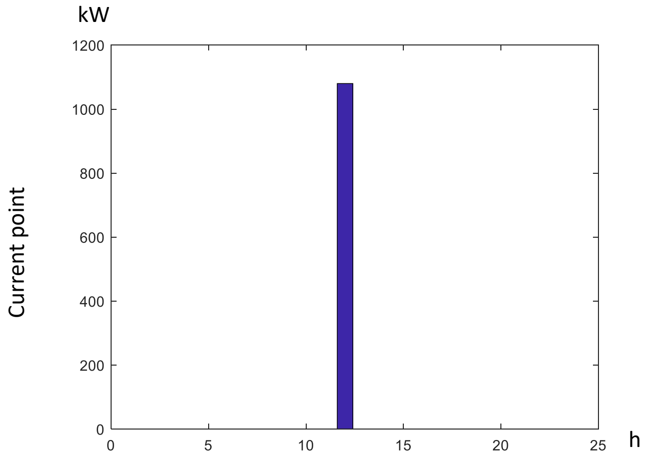
7 MAY 2016 FCR-N		
hour	**Battery Discharging Time (% hour)**	**Battery Charging Time (% hour)**
0	1,78 %	57,58 %
1	2,49 %	1,60 %
2	8,72 %	6,50 %
3	15,23 %	1,66 %
4	34,75 %	0,00 %
5	3,50 %	3,50 %
6	0,00 %	49,46 %
7	44,57 %	0,00 %
8	10,15 %	18,74 %
9	46,05 %	0,56 %
10	3,31 %	2,08 %
11	0,15 %	18,50 %
12	0,00 %	62,58 %
13	5,74 %	2,47 %
14	0,88 %	12,95 %
15	1,93 %	2,28 %
16	6,38 %	3,09 %
17	4,46 %	7,09 %
18	18,15 %	0,97 %
19	0,61 %	9,41 %
20	10,40 %	1,31 %
21	0,02 %	14,46 %
22	28,14 %	0,14 %
23	17,94 %	19,08 %

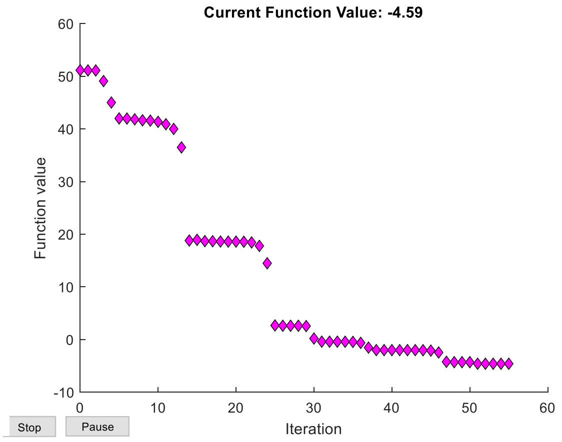
7 MAY 2016 FCR-D	
hour	**Battery Discharging Time (% hour)**
0	0,00 %
1	0,00 %
2	0,00 %
3	0,00 %
4	1,75 %
5	0,00 %
6	0,00 %
7	6,86 %
8	0,00 %
9	10,27 %
10	1,05 %
11	0,00 %
12	0,00 %
13	0,00 %
14	0,00 %
15	0,00 %
16	0,00 %
17	0,23 %
18	0,38 %
19	0,00 %
20	0,10 %
21	0,00 %
22	0,64 %
23	9,66 %

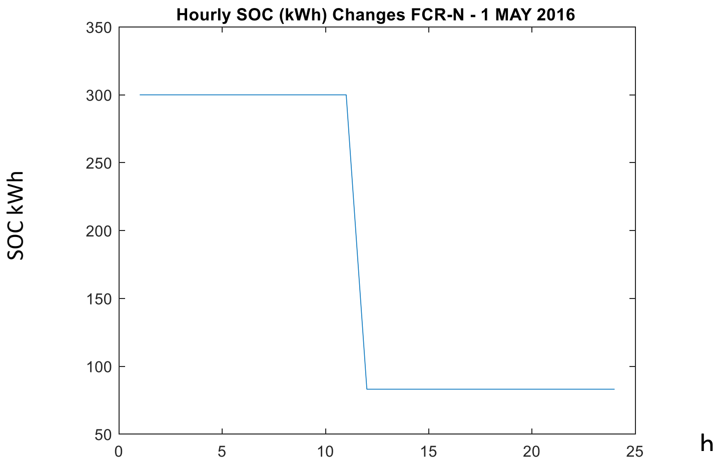
Appendix D: Optimal hourly power for FCR-N market by using optimization method - first week of May 2016

1 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1080,00

1 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

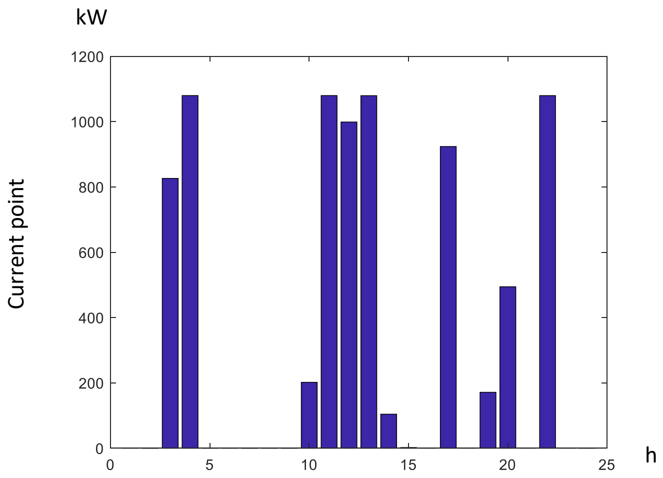


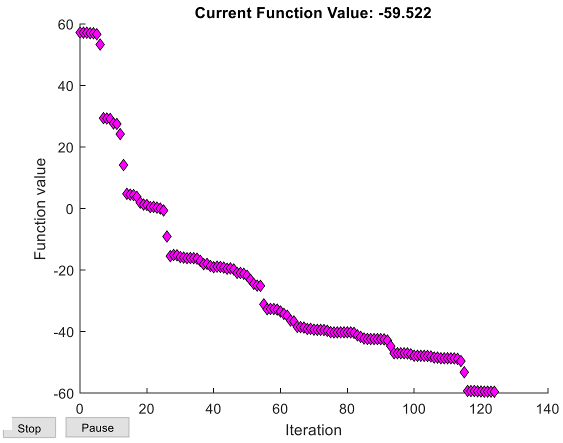


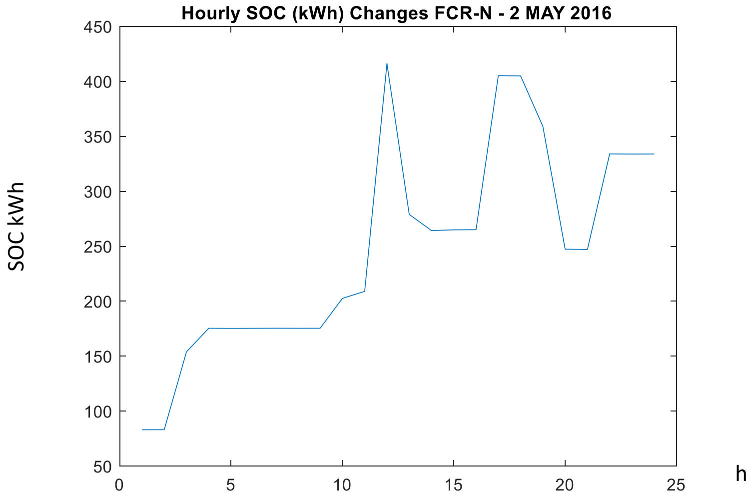


2 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	0,00	0,10	826,1	1079,7	0,19	0,26	0,11	0,19	0,13	201,8	1079,7	998,7

2 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1079,4	104,2	2,11	0,30	923,7	0,65	171,2	494,3	0,86	1079,6	0,37	0,17

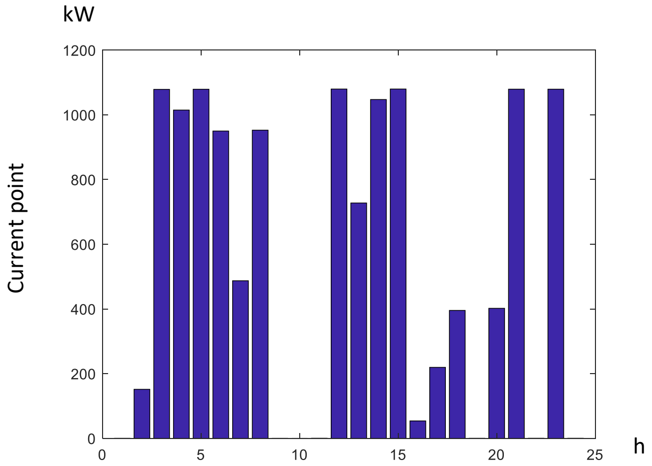


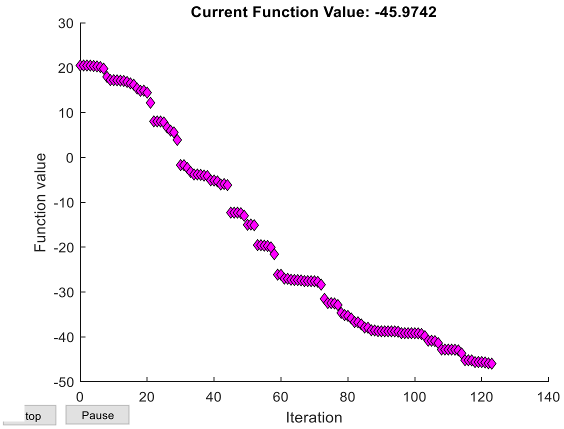


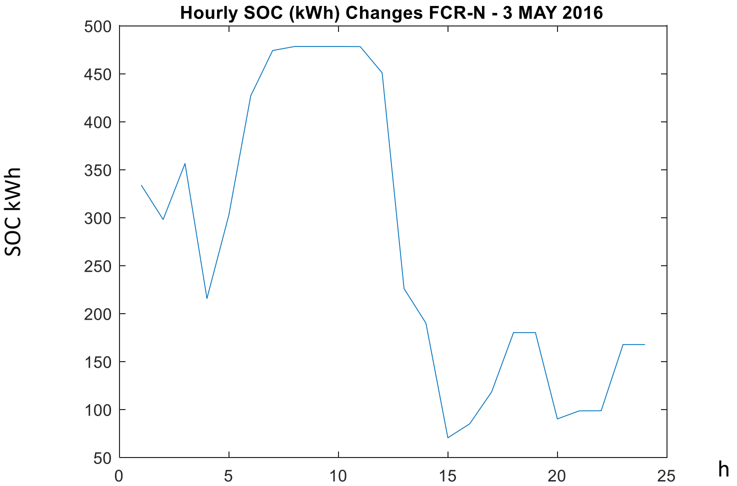


3 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	0,07	151,6	1078,7	1014,7	1079,1	949,9	487,1	952,6	0	0	0,2	1079,7

3 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	727,5	1047,3	1079,7	54	219,5	395,5	0,1	402	1079,3	0,2	1079	0,2

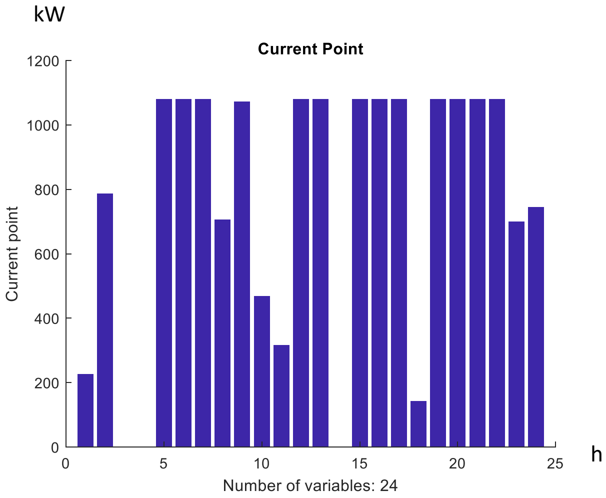


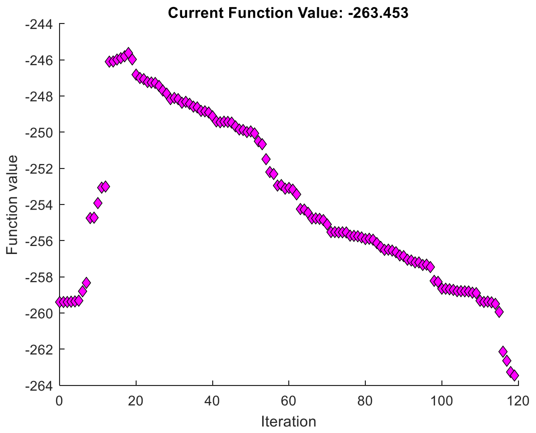


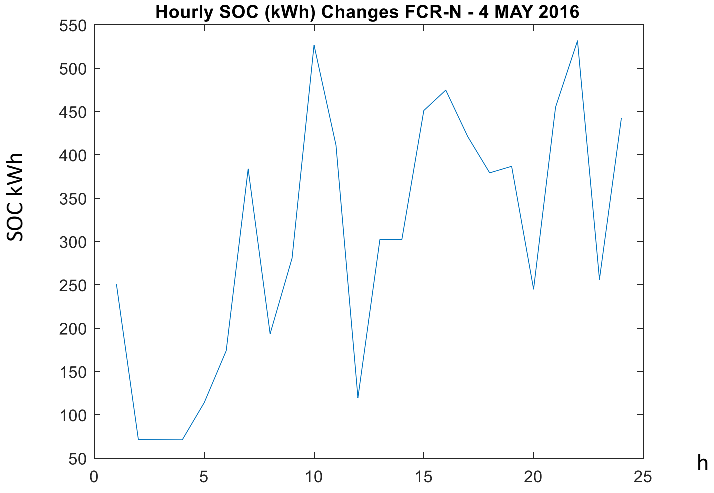


4 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	226	787	0,1	0,3	1079,8	1079,7	1079,8	705,7	1072	469	316,6	1079,9

4 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1080	0,02	1080	1080	1079,7	142	1080	1080	1079,8	1079,8	700	744,5

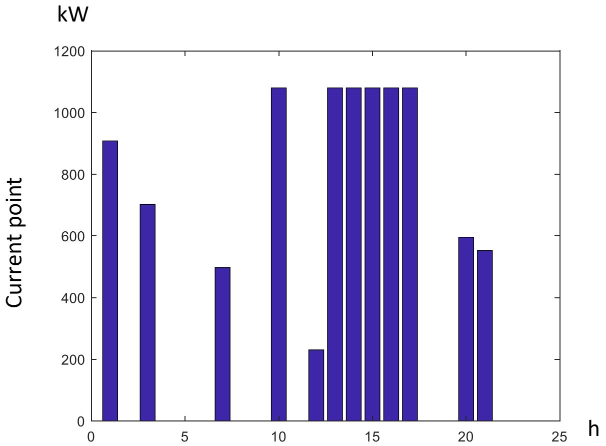


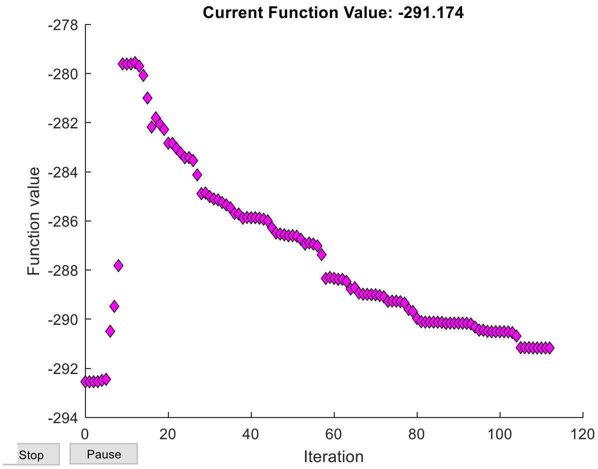


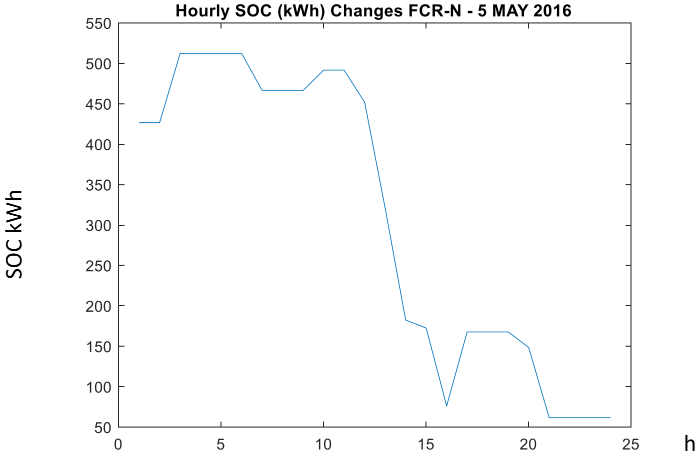


5 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	908,1	0	702,1	0	0	0	497,4	0	0	1080	0	230,6

5 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1080	1080	1080,	1080	1080	0,00	0,00	595,8	552,4	0,00	0,00	0,00

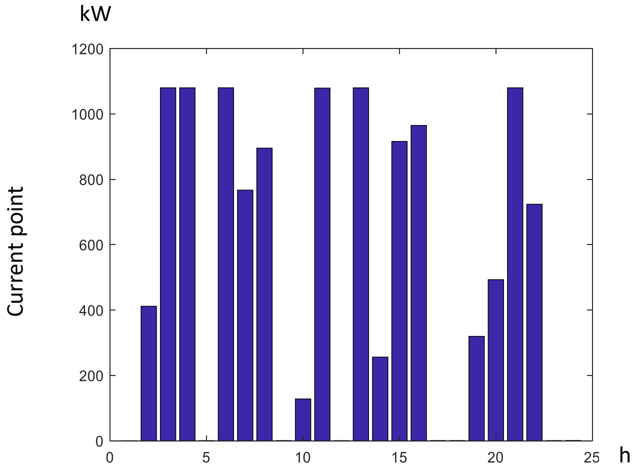


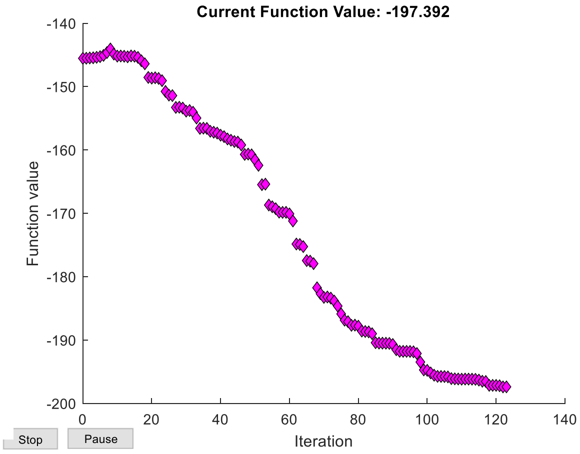


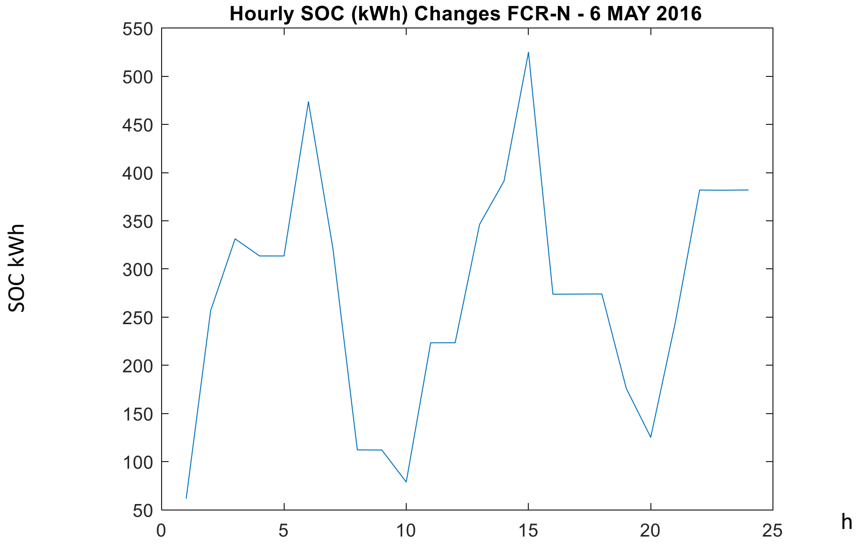


6 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	0	411,6	1079,8	1079,8	0,1	1080	766,8	895,2	0,2	128	1078,8	0,06

6 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1079,7	255,9	915,7	964,7	0,4	0,3	319,5	493	1079,8	723,6	0,2	0,6

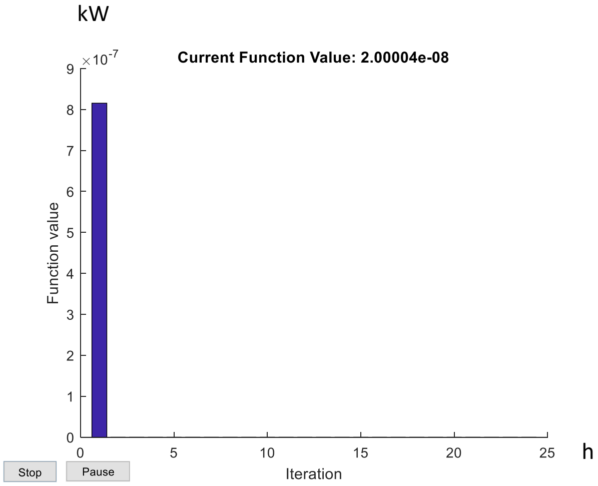


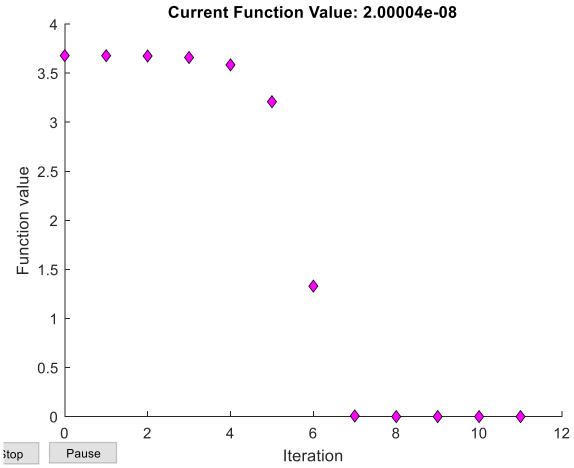


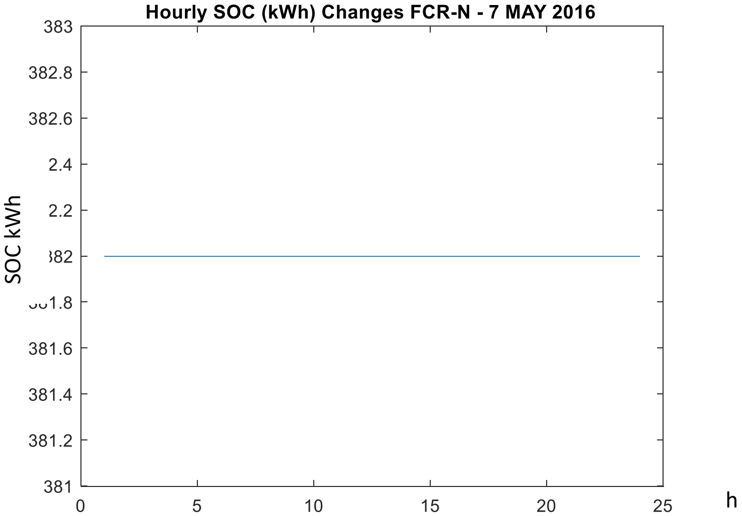


7 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	0	0	0	0	0	0	0	0	0	0	0	0

7 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	0	0	0	0	0	0	0	0	0	0	0	0



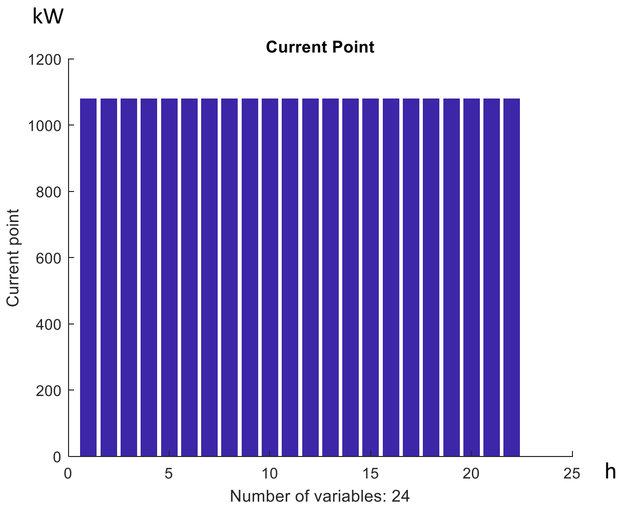


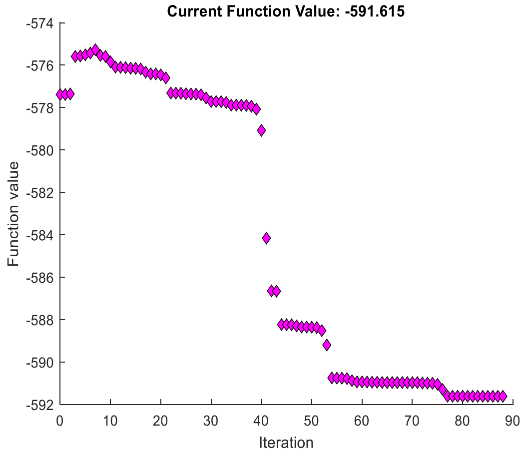


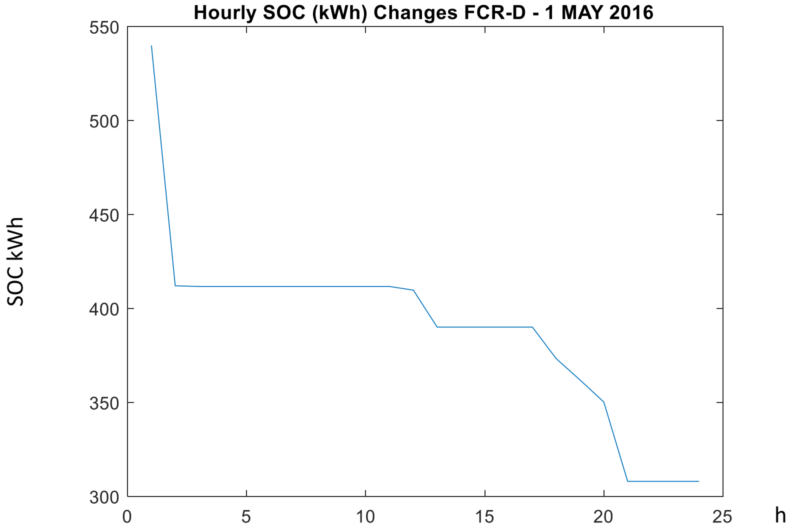
Appendix E: Optimal hourly power for FCR-D market by using optimization method - first week of May 2016

1 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080

1 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	0	0

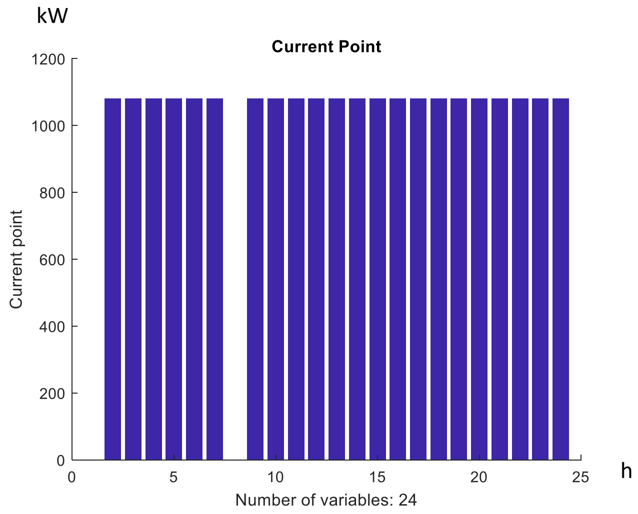


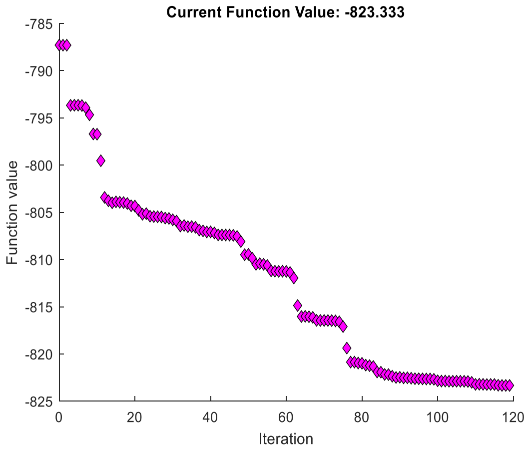


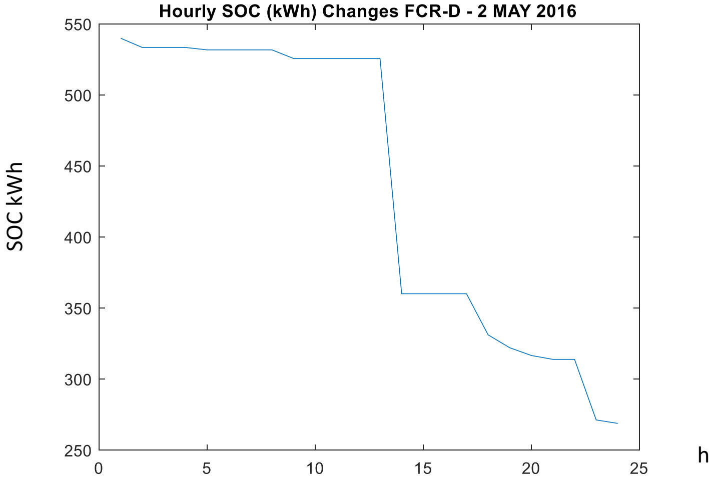


2 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	0	1080	1080	1080	1080	1080	1080	0	1080	1080	1080	1080

2 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080

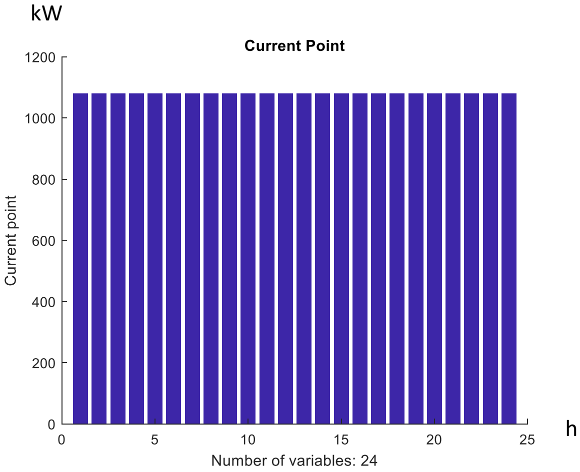


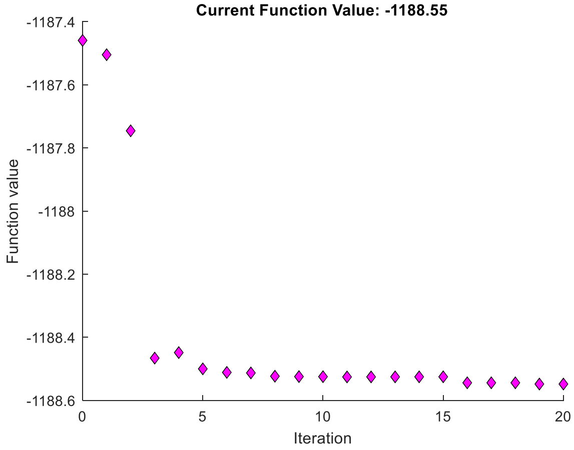


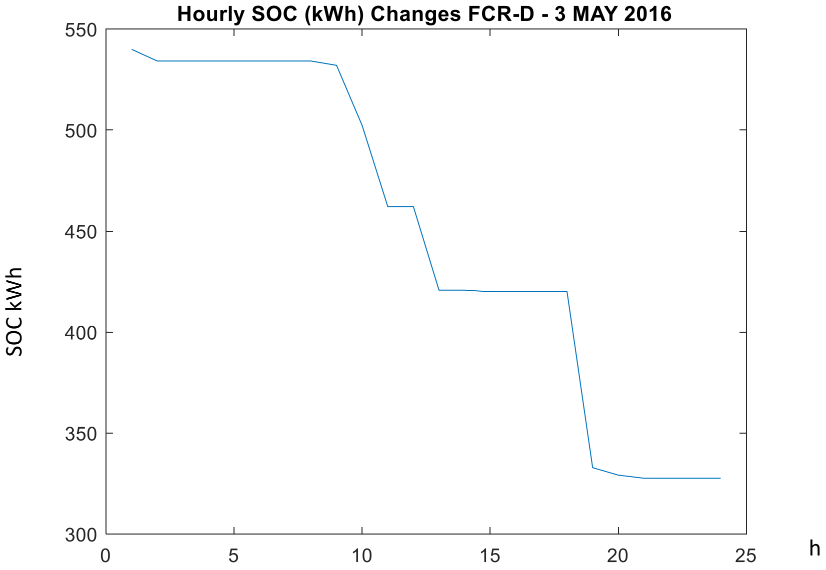


3 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080

3 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080

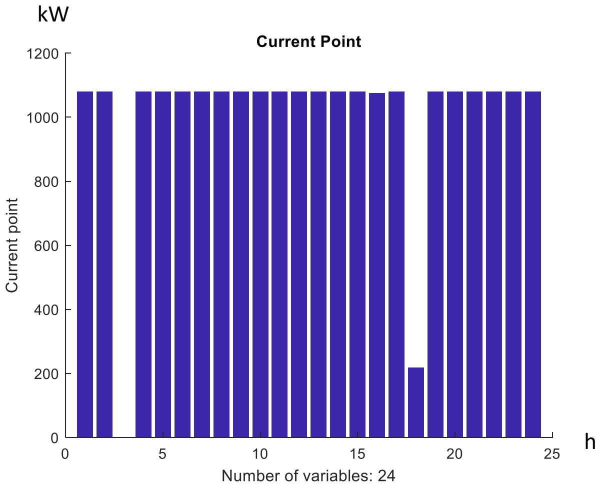


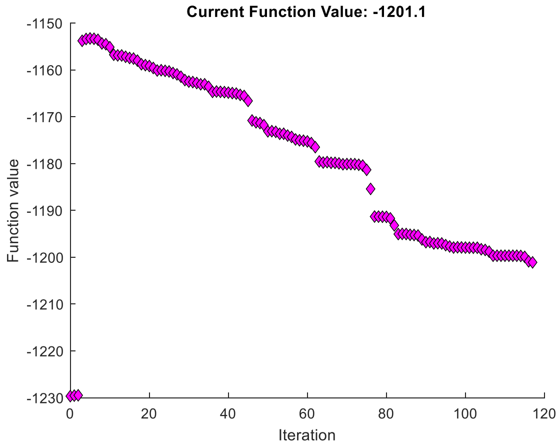


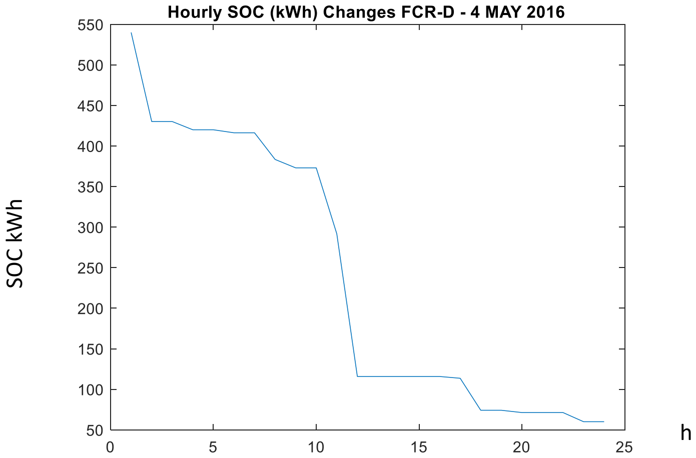


4 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	1079,9	1079,9	0,2	1079,9	1079,9	1079,9	1079,9	1079,9	1079,9	1079,9	1079,9	1079,9

4 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1079,9	1079,9	1079,9	1075	1079,9	217,5	1079,9	1079,9	1079,9	1079,9	1079,9	1079,9

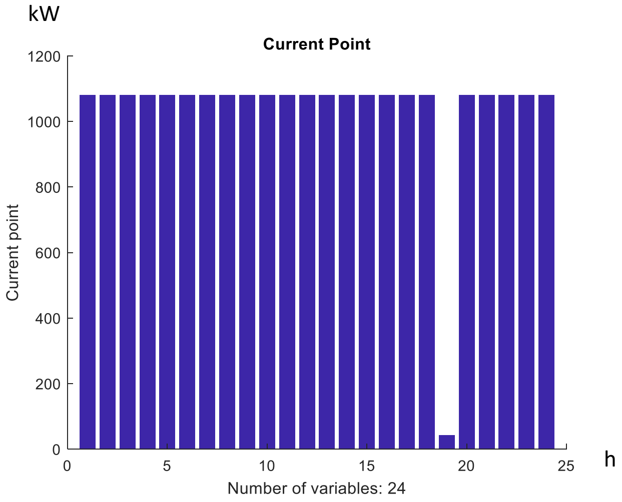


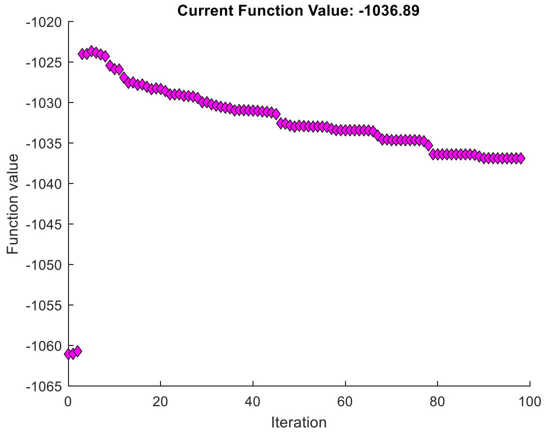


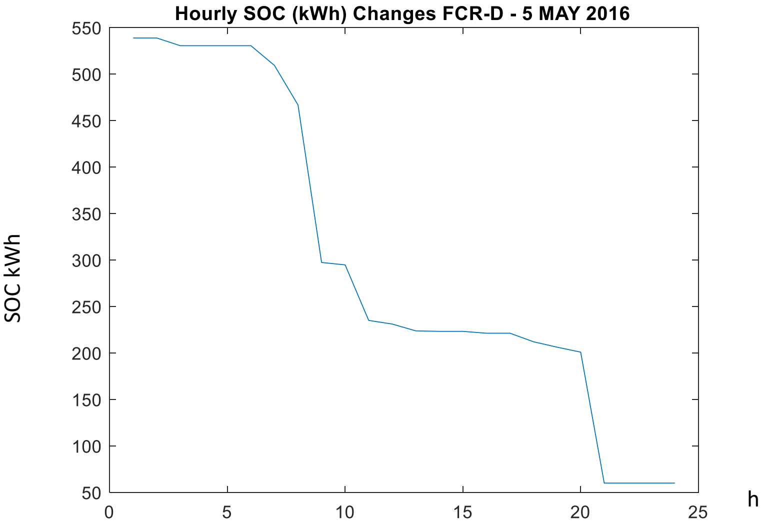


5 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080

5 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1080	1080	1080	1080	1080	1080	42	1080	1080	1080	1080	1080

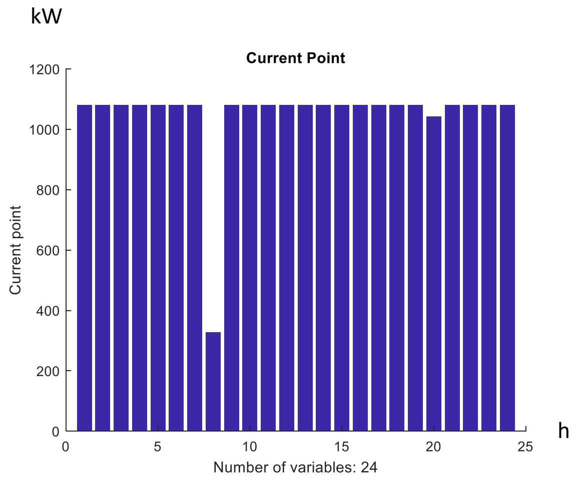


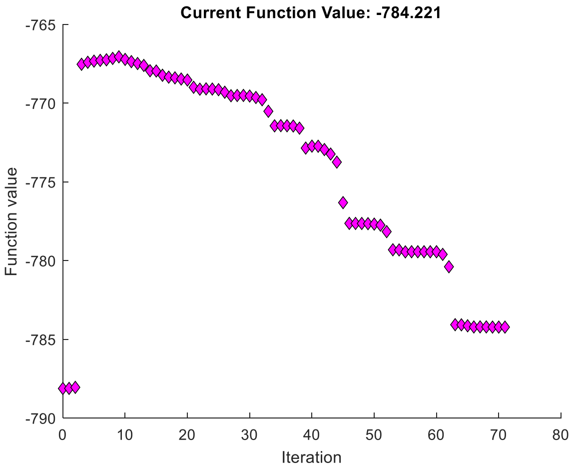


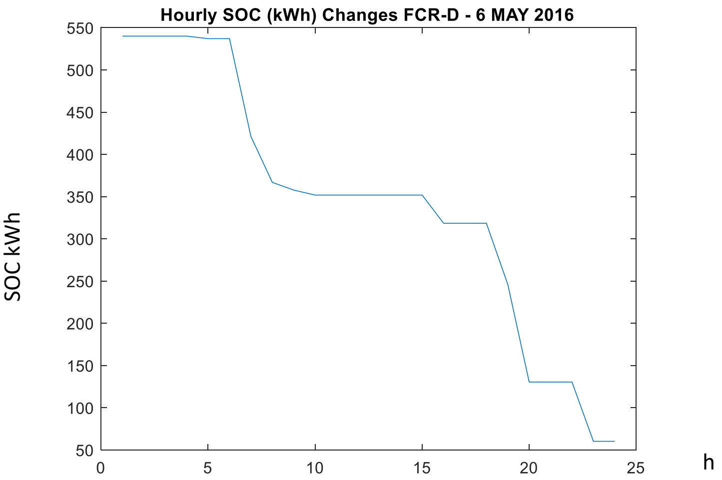


6 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	1079,9	1079,9	0,2	1079,9	1079,9	1079,8	1079,9	327,3	1079,9	1079,9	1079,9	1079,9

6 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1079,9	1079,9	1079,9	1079,8	1079,9	217,5	1079,8	1041,8	1079,9	1079,8	1079,8	1079,9

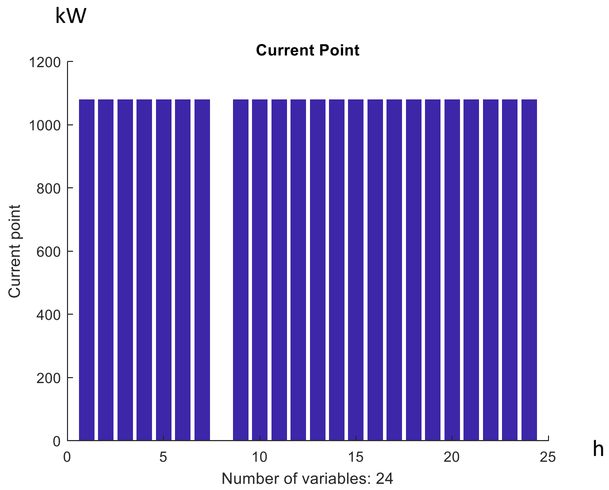


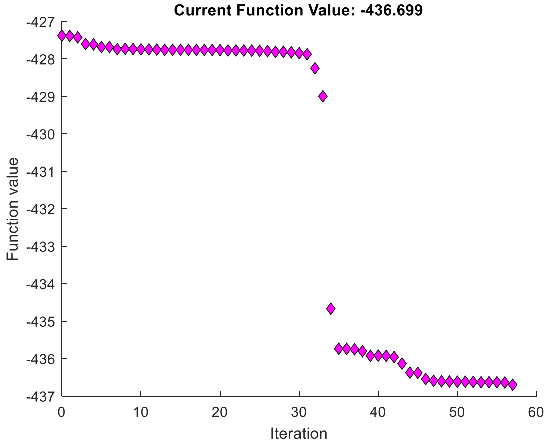


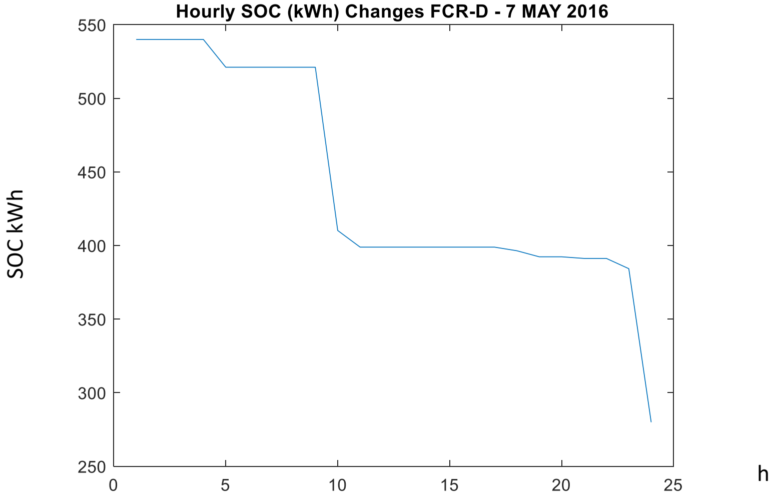


7 MAY 2016												
Hour	1	2	3	4	5	6	7	8	9	10	11	12
Power (kW)	1079,9	1079,9	1079,9	1079,9	1079,9	1079,9	1079,9	0,1	1079,9	1079,7	1079,9	1079,9

7 MAY 2016												
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Power (kW)	1079,9	1079,9	1079,9	1079,9	1079,9	1079,9	1079,9	1080	1079,9	1079,9	1079,7	1079,8







Appendix F: Results of utilizing battery system in FCR-N market by using fixed power allocation method - first week of May 2016

1 MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	600,00	60,00	276,43	0,00	4,80	0,00	17,40	-12,60
2	600,00	276,43	276,43	0,00	0,00	0,00	0,00	0,00
3	600,00	276,43	276,43	0,00	0,00	0,00	0,00	0,00
4	600,00	276,43	276,43	0,00	0,00	0,00	0,00	0,00
5	600,00	276,43	276,43	0,00	0,00	0,00	0,00	0,00
6	600,00	276,43	276,43	0,00	0,00	0,00	0,00	0,00
7	600,00	276,43	276,43	0,00	0,00	0,00	0,00	0,00
8	600,00	276,43	276,43	0,00	0,00	0,00	0,00	0,00
9	600,00	276,43	276,43	0,00	0,00	0,00	0,00	0,00
10	600,00	276,43	276,43	0,00	0,00	0,00	0,00	0,00
11	600,00	276,43	209,77	0,00	0,30	0,00	6,63	-6,33
12	600,00	209,77	89,27	0,00	12,00	0,00	9,45	2,55
13	600,00	89,27	79,43	0,00	12,00	0,00	13,19	-1,19
14	600,00	79,43	311,38	0,00	0,30	0,00	17,40	-17,10
15	600,00	311,38	311,38	0,00	0,00	0,00	0,00	0,00
16	600,00	311,38	311,38	0,00	0,00	0,00	0,00	0,00
17	600,00	311,38	311,38	0,00	0,00	0,00	0,00	0,00
18	600,00	311,38	311,38	0,00	0,00	0,00	0,00	0,00
19	600,00	311,38	311,38	0,00	0,00	0,00	0,00	0,00
20	600,00	311,38	311,38	0,00	0,00	0,00	0,00	0,00
21	600,00	311,38	311,38	0,00	0,00	0,00	0,00	0,00
22	600,00	311,38	711,90	0,00	0,30	0,00	30,04	-29,74
23	600,00	711,90	711,90	0,00	0,00	0,00	0,00	0,00
24	600,00	711,90	711,90	0,00	0,00	0,00	0,00	0,00
TOTAL					**29,70**	**0,00**	**94,10**	**-64,40**

2 MAY 2016

Hour	CONSTANT Power kW	Energy kWh	SOC (kWh)	Required Energy kWh	Revenue €	Cost of buying energy ELBAS €	Battery Cost €	Profit €
1	600,00	60,00	60,00	0,00	0,00	0,00	0,00	0,00
2	600,00	60,00	353,07	0,00	7,20	0,00	31,24	-24,04
3	600,00	353,07	404,57	0,00	7,20	0,00	3,87	3,34
4	600,00	404,57	416,43	0,00	7,20	0,00	0,89	6,31
5	600,00	416,43	164,65	0,00	7,20	0,00	18,88	-11,68
6	600,00	164,65	259,85	0,00	7,20	0,00	16,30	-9,10
7	600,00	259,85	608,00	0,00	7,20	0,00	29,01	-21,81
8	600,00	540,00	423,32	0,00	4,80	0,00	16,64	-11,84
9	600,00	423,32	491,55	0,00	3,60	0,00	20,85	-17,25
10	600,00	491,55	572,32	0,00	12,00	0,00	11,97	0,03
11	600,00	540,00	543,57	0,00	12,00	0,00	4,21	7,79
12	600,00	540,00	664,43	0,00	12,00	0,00	9,33	2,67
13	600,00	540,00	463,77	0,00	12,00	0,00	6,48	5,52
14	600,00	463,77	379,08	0,00	12,00	0,00	14,65	-2,65
15	600,00	379,08	563,10	0,00	12,00	0,00	13,98	-1,98
16	600,00	540,00	846,43	0,00	12,00	0,00	22,98	-10,98
17	600,00	540,00	631,02	0,00	12,00	0,00	8,98	3,02
18	600,00	540,00	336,73	0,00	12,00	0,00	15,25	-3,25
19	600,00	336,73	175,77	0,00	12,00	0,00	12,07	-0,07
20	600,00	175,77	40,20	19,80	12,00	0,46	10,65	0,89
21	600,00	60,00	-114,42	60,00	12,00	1,41	13,39	-2,80
22	600,00	60,00	108,30	0,00	12,00	0,00	6,47	5,53
23	600,00	108,30	-100,67	60,00	13,80	1,35	18,84	-6,39
24	600,00	60,00	259,05	0,00	4,80	0,00	17,95	-13,15
TOTAL					**226,20**	**3,21**	**324,88**	**-101,89**

3 MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	600,00	60,00	491,35	0,00	4,80	0,00	32,37	-27,57
2	600,00	491,35	349,43	0,00	7,20	0,00	10,97	-3,77
3	600,00	349,43	381,90	0,00	7,20	0,00	4,13	3,07
4	600,00	381,90	298,70	0,00	7,20	0,00	6,29	0,92
5	600,00	298,70	347,03	0,00	7,20	0,00	3,63	3,58
6	600,00	347,03	425,57	0,00	7,20	0,00	6,10	1,10
7	600,00	425,57	483,72	0,00	7,20	0,00	9,37	-2,17
8	600,00	483,72	486,35	0,00	7,20	0,00	6,01	1,20
9	600,00	486,35	590,95	0,00	12,00	0,00	20,22	-8,22
10	600,00	540,00	540,00	0,00	0,00	0,00	0,00	0,00
11	600,00	540,00	268,62	0,00	16,80	0,00	20,35	-3,55
12	600,00	268,62	253,42	0,00	12,00	0,00	4,04	7,96
13	600,00	253,42	67,97	0,00	15,60	0,00	14,61	0,99
14	600,00	67,97	47,33	12,67	7,20	0,27	5,03	1,90
15	600,00	60,00	-6,40	60,00	7,20	1,29	5,85	0,07
16	600,00	60,00	222,43	0,00	7,20	0,00	13,79	-6,59
17	600,00	222,43	313,27	0,00	7,20	0,00	9,10	-1,90
18	600,00	313,27	407,08	0,00	7,20	0,00	8,97	-1,77
19	600,00	407,08	241,75	0,00	7,20	0,00	16,52	-9,32
20	600,00	241,75	107,47	0,00	7,20	0,00	10,07	-2,87
21	600,00	107,47	112,13	0,00	7,20	0,00	2,86	4,34
22	600,00	112,13	397,65	0,00	7,20	0,00	21,41	-14,21
23	600,00	397,65	436,02	0,00	7,20	0,00	3,64	3,56
24	600,00	436,02	559,83	0,00	7,20	0,00	18,87	-11,67
TOTAL					**190,80**	**1,56**	**254,20**	**-64,96**

4 MAY 2016

Hour	CONSTANT Power kW	Energy kWh	SOC (kWh)	Required Energy kWh	Revenue €	Cost of buying energy ELBAS €	Battery Cost €	Profit €
1	600,00	60,00	280,08	0,00	7,20	0,00	17,14	-9,94
2	600,00	280,08	143,37	0,00	12,00	0,00	10,28	1,72
3	600,00	143,37	-186,63	60,00	12,00	1,26	24,75	-14,01
4	600,00	60,00	-111,52	60,00	12,00	1,24	12,86	-2,11
5	600,00	60,00	83,87	0,00	12,00	0,00	2,73	9,27
6	600,00	83,87	117,13	0,00	12,00	0,00	4,81	7,19
7	600,00	117,13	233,70	0,00	22,80	0,00	10,88	11,93
8	600,00	233,70	71,95	0,00	18,00	0,00	16,03	1,97
9	600,00	71,95	120,77	0,00	18,00	0,00	14,86	3,14
10	600,00	120,77	435,35	0,00	18,00	0,00	23,59	-5,59
11	600,00	435,35	216,38	0,00	19,20	0,00	16,56	2,64
12	600,00	216,38	54,42	5,58	19,20	0,23	13,82	5,15
13	600,00	60,00	161,47	0,00	19,20	0,00	7,61	11,59
14	600,00	161,47	554,18	0,00	19,20	0,00	29,59	-10,39
15	600,00	540,00	622,73	0,00	18,00	0,00	6,32	11,69
16	600,00	540,00	553,12	0,00	22,80	0,00	3,50	19,30
17	600,00	540,00	510,20	0,00	13,80	0,00	5,72	8,08
18	600,00	510,20	333,17	0,00	15,60	0,00	17,70	-2,10
19	600,00	333,17	337,37	0,00	22,80	0,00	6,82	15,98
20	600,00	337,37	258,62	0,00	22,80	0,00	7,63	15,17
21	600,00	258,62	375,27	0,00	22,80	0,00	8,75	14,05
22	600,00	375,27	417,87	0,00	20,40	0,00	3,78	16,62
23	600,00	417,87	181,85	0,00	20,40	0,00	18,13	2,27
24	600,00	181,85	332,03	0,00	10,80	0,00	15,10	-4,30
TOTAL					**411,00**	**2,74**	**298,95**	**109,32**

5 MAY 2016

Hour	CONSTANT Power kW	Energy kWh	SOC (kWh)	Required Energy kWh	Revenue €	Cost of buying energy ELBAS €	Battery Cost €	Profit €
1	600,00	60,00	49,35	10,65	12,00	0,21	10,43	1,36
2	600,00	60,00	60,00	0,00	0,00	0,00	0,00	0,00
3	600,00	60,00	133,13	0,00	13,80	0,00	8,75	5,05
4	600,00	133,13	133,13	0,00	0,00	0,00	0,00	0,00
5	600,00	133,13	133,13	0,00	0,00	0,00	0,00	0,00
6	600,00	133,13	133,13	0,00	0,00	0,00	0,00	0,00
7	600,00	133,13	78,00	0,00	28,80	0,00	9,16	19,64
8	600,00	78,00	-77,22	60,00	31,80	1,09	11,64	19,07
9	600,00	60,00	-180,15	60,00	31,80	1,33	18,10	12,37
10	600,00	60,00	73,92	0,00	31,80	0,00	5,08	26,72
11	600,00	73,92	-48,13	60,00	31,80	1,44	18,34	12,02
12	600,00	60,00	-43,35	60,00	31,80	1,52	8,96	21,32
13	600,00	60,00	-12,78	60,00	31,80	1,50	11,48	18,82
14	600,00	60,00	-16,85	60,00	31,80	1,48	7,14	23,18
15	600,00	60,00	54,43	5,57	31,80	0,15	7,05	24,60
16	600,00	60,00	6,48	53,52	31,80	1,00	5,19	25,62
17	600,00	60,00	110,90	0,00	15,60	0,00	5,17	10,44
18	600,00	110,90	34,48	25,52	15,60	0,63	10,91	4,06
19	600,00	60,00	-82,43	60,00	22,80	1,51	13,48	7,81
20	600,00	60,00	40,62	19,38	20,40	0,45	14,83	5,12
21	600,00	60,00	-34,37	60,00	20,40	1,27	7,35	11,78
22	600,00	60,00	60,00	0,00	0,00	0,00	0,00	0,00
23	600,00	60,00	60,00	0,00	0,00	0,00	0,00	0,00
24	600,00	60,00	60,00	0,00	0,00	0,00	0,00	0,00
TOTAL					**435,60**	**13,56**	**173,06**	**248,98**

6 MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	600,00	60,00	60,00	0,00	0,00	0,00	0,00	0,00
2	600,00	60,00	344,40	0,00	13,80	0,00	21,33	-7,53
3	600,00	344,40	385,83	0,00	15,60	0,00	3,32	12,29
4	600,00	385,83	375,95	0,00	15,60	0,00	0,83	14,77
5	600,00	375,95	170,70	0,00	15,60	0,00	15,39	0,21
6	600,00	170,70	259,60	0,00	15,60	0,00	12,18	3,42
7	600,00	259,60	140,62	0,00	22,80	0,00	12,55	10,25
8	600,00	140,62	0,40	59,60	25,80	2,21	10,52	13,07
9	600,00	60,00	-131,02	60,00	20,40	2,69	14,61	3,10
10	600,00	60,00	-95,78	60,00	19,20	2,14	12,38	4,68
11	600,00	60,00	140,35	0,00	20,40	0,00	7,60	12,80
12	600,00	140,35	490,97	0,00	25,80	0,00	26,38	-0,58
13	600,00	490,97	559,22	0,00	19,20	0,00	5,12	14,08
14	600,00	540,00	645,57	0,00	19,20	0,00	8,19	11,01
15	600,00	540,00	627,53	0,00	19,20	0,00	8,05	11,15
16	600,00	540,00	383,85	0,00	19,20	0,00	12,88	6,32
17	600,00	383,85	595,08	0,00	0,30	0,00	15,84	-15,54
18	600,00	540,00	763,07	0,00	0,30	0,00	17,34	-17,04
19	600,00	540,00	355,85	0,00	20,40	0,00	15,56	4,84
20	600,00	355,85	294,17	0,00	20,40	0,00	16,54	3,86
21	600,00	294,17	360,05	0,00	20,40	0,00	7,76	12,64
22	600,00	360,05	474,45	0,00	10,80	0,00	9,43	1,37
23	600,00	474,45	134,52	0,00	10,80	0,00	25,96	-15,16
24	600,00	134,52	373,20	0,00	10,80	0,00	18,91	-8,11
TOTAL					**381,60**	**7,04**	**298,66**	**75,90**

7 MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	600,00	60,00	394,80	0,00	12,00	0,00	26,72	-14,72
2	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
3	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
4	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
5	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
6	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
7	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
8	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
9	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
10	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
11	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
12	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
13	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
14	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
15	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
16	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
17	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
18	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
19	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
20	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
21	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
22	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
23	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
24	600,00	394,80	394,80	0,00	0,00	0,00	0,00	0,00
TOTAL					**12,00**	**0,00**	**26,72**	**-14,72**

Appendix G: Results of utilizing battery system in FCR-D market by using fixed power allocation method - first week of May 2016

1 MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	700,00	540,00	540,00	0,00	10,50	0,00	0,00	10,50
2	700,00	540,00	457,13	0,00	28,00	0,00	12,43	15,57
3	700,00	457,13	456,89	0,00	28,00	0,00	0,04	27,97
4	700,00	456,89	456,89	0,00	28,00	0,00	0,00	28,00
5	700,00	456,89	456,89	0,00	28,00	0,00	0,00	28,00
6	700,00	456,89	456,89	0,00	28,00	0,00	0,00	28,00
7	700,00	456,89	456,89	0,00	28,00	0,00	0,00	28,00
8	700,00	456,89	456,89	0,00	28,00	0,00	0,00	28,00
9	700,00	456,89	456,89	0,00	21,00	0,00	0,00	21,00
10	700,00	456,89	456,89	0,00	14,00	0,00	0,00	14,00
11	700,00	456,89	456,89	0,00	14,00	0,00	0,00	14,00
12	700,00	456,89	455,63	0,00	14,00	0,00	0,19	13,81
13	700,00	455,63	442,88	0,00	14,00	0,00	1,91	12,09
14	700,00	442,88	442,88	0,00	14,00	0,00	0,00	14,00
15	700,00	442,88	442,88	0,00	14,00	0,00	0,00	14,00
16	700,00	442,88	442,88	0,00	14,00	0,00	0,00	14,00
17	700,00	442,88	442,88	0,00	14,00	0,00	0,00	14,00
18	700,00	442,88	432,01	0,00	14,00	0,00	1,63	12,37
19	700,00	432,01	424,66	0,00	14,00	0,00	1,10	12,90
20	700,00	424,66	417,03	0,00	14,00	0,00	1,14	12,86
21	700,00	417,03	389,69	0,00	10,50	0,00	4,10	6,40
22	700,00	389,69	389,69	0,00	14,00	0,00	0,00	14,00
23	700,00	389,69	314,43	0,00	10,50	0,00	11,29	-0,79
24	700,00	314,43	190,51	349,49	10,50	7,89	18,59	-15,98
TOTAL					**427,00**	**7,89**	**52,42**	**366,69**

2 MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	700,00	540,00	437,08	0,00	10,50	0,00	15,44	-4,94
2	700,00	437,08	432,86	0,00	31,50	0,00	0,63	30,87
3	700,00	432,86	432,86	0,00	31,50	0,00	0,00	31,50
4	700,00	432,86	432,86	0,00	31,50	0,00	0,00	31,50
5	700,00	432,86	431,77	0,00	31,50	0,00	0,16	31,34
6	700,00	431,77	431,77	0,00	31,50	0,00	0,00	31,50
7	700,00	431,77	431,77	0,00	31,50	0,00	0,00	31,50
8	700,00	431,77	242,05	0,00	10,50	0,00	28,46	-17,96
9	700,00	242,05	238,13	0,00	31,50	0,00	0,59	30,91
10	700,00	238,13	238,13	0,00	31,50	0,00	0,00	31,50
11	700,00	238,13	238,13	0,00	31,50	0,00	0,00	31,50
12	700,00	238,13	238,13	0,00	31,50	0,00	0,00	31,50
13	700,00	238,13	238,13	0,00	14,00	0,00	0,00	14,00
14	700,00	238,13	130,79	0,00	21,00	0,00	16,10	4,90
15	700,00	130,79	130,79	0,00	21,00	0,00	0,00	21,00
16	700,00	130,79	130,79	0,00	21,00	0,00	0,00	21,00
17	700,00	130,79	130,79	0,00	21,00	0,00	0,00	21,00
18	700,00	130,79	112,05	0,00	21,00	0,00	2,81	18,19
19	700,00	112,05	106,16	0,00	21,00	0,00	0,88	20,12
20	700,00	106,16	102,62	0,00	21,00	0,00	0,53	20,47
21	700,00	102,62	100,85	0,00	21,00	0,00	0,27	20,73
22	700,00	100,85	100,85	0,00	21,00	0,00	0,00	21,00
23	700,00	100,85	73,22	0,00	21,00	0,00	4,14	16,86
24	700,00	73,22	71,64	468,36	21,00	10,52	0,24	10,24
TOTAL					**581,00**	**10,52**	**70,25**	**500,23**

3 MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	700,00	540,00	540,00	0,00	21,00	0,00	0,00	21,00
2	700,00	540,00	536,25	0,00	31,50	0,00	0,56	30,94
3	700,00	536,25	536,25	0,00	31,50	0,00	0,00	31,50
4	700,00	536,25	536,25	0,00	35,00	0,00	0,00	35,00
5	700,00	536,25	536,25	0,00	35,00	0,00	0,00	35,00
6	700,00	536,25	536,25	0,00	35,00	0,00	0,00	35,00
7	700,00	536,25	536,25	0,00	35,00	0,00	0,00	35,00
8	700,00	536,25	536,25	0,00	35,00	0,00	0,00	35,00
9	700,00	536,25	534,87	0,00	35,00	0,00	0,21	34,79
10	700,00	534,87	515,56	0,00	35,00	0,00	2,90	32,10
11	700,00	515,56	489,54	0,00	35,00	0,00	3,90	31,10
12	700,00	489,54	489,54	0,00	35,00	0,00	0,00	35,00
13	700,00	489,54	462,73	0,00	35,00	0,00	4,02	30,98
14	700,00	462,73	462,73	0,00	35,00	0,00	0,00	35,00
15	700,00	462,73	462,22	0,00	35,00	0,00	0,08	34,92
16	700,00	462,22	462,22	0,00	35,00	0,00	0,00	35,00
17	700,00	462,22	462,22	0,00	31,50	0,00	0,00	31,50
18	700,00	462,22	462,22	0,00	31,50	0,00	0,00	31,50
19	700,00	462,22	405,76	0,00	31,50	0,00	8,47	23,03
20	700,00	405,76	403,36	0,00	31,50	0,00	0,36	31,14
21	700,00	403,36	402,37	0,00	31,50	0,00	0,15	31,35
22	700,00	402,37	402,37	0,00	31,50	0,00	0,00	31,50
23	700,00	402,37	402,37	0,00	31,50	0,00	0,00	31,50
24	700,00	402,37	402,37	137,63	31,50	3,00	0,00	28,50
TOTAL					**791,00**	**3,00**	**20,64**	**767,36**

4 MAY 2016

Hour	CONSTANT Power kW	Energy kWh	SOC (kWh)	Required Energy kWh	Revenue €	Cost of buying energy ELBAS €	Battery Cost €	Profit €
1	700,00	540,00	540,00	0,00	31,50	0,00	0,00	31,50
2	700,00	540,00	468,79	0,00	28,00	0,00	10,68	17,32
3	700,00	468,79	324,19	0,00	28,00	0,00	21,69	6,31
4	700,00	324,19	317,61	0,00	28,00	0,00	0,99	27,01
5	700,00	317,61	317,61	0,00	28,00	0,00	0,00	28,00
6	700,00	317,61	315,20	0,00	28,00	0,00	0,36	27,64
7	700,00	315,20	315,20	0,00	28,00	0,00	0,00	28,00
8	700,00	315,20	293,91	0,00	28,00	0,00	3,19	24,81
9	700,00	293,91	287,18	0,00	52,50	0,00	1,01	51,49
10	700,00	287,18	287,18	0,00	52,50	0,00	0,00	52,50
11	700,00	287,18	234,49	0,00	52,50	0,00	7,90	44,60
12	700,00	234,49	120,45	0,00	52,50	0,00	17,11	35,39
13	700,00	120,45	120,45	0,00	45,50	0,00	0,00	45,50
14	700,00	120,45	120,45	0,00	45,50	0,00	0,00	45,50
15	700,00	120,45	120,45	0,00	31,15	0,00	0,00	31,15
16	700,00	120,45	120,45	0,00	31,15	0,00	0,00	31,15
17	700,00	120,45	119,03	0,00	35,00	0,00	0,21	34,79
18	700,00	119,03	-7,96	60,00	35,00	1,60	19,05	14,35
19	700,00	60,00	60,00	0,00	38,50	0,00	0,00	38,50
20	700,00	60,00	58,17	1,83	38,50	0,05	0,27	38,17
21	700,00	60,00	60,00	0,00	38,50	0,00	0,00	38,50
22	700,00	60,00	60,00	0,00	35,00	0,00	0,00	35,00
23	700,00	60,00	52,69	7,31	35,00	0,17	1,10	33,73
24	700,00	60,00	60,00	480,00	35,00	10,88	0,00	24,12
TOTAL					**881,30**	**12,70**	**83,57**	**785,03**

5 MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	700,00	540,00	539,22	0,00	31,50	0,00	0,12	31,38
2	700,00	539,22	539,22	0,00	38,50	0,00	0,00	38,50
3	700,00	539,22	533,84	0,00	38,50	0,00	0,81	37,69
4	700,00	533,84	533,84	0,00	38,50	0,00	0,00	38,50
5	700,00	533,84	533,84	0,00	38,50	0,00	0,00	38,50
6	700,00	533,84	533,84	0,00	38,50	0,00	0,00	38,50
7	700,00	533,84	520,07	0,00	38,50	0,00	2,07	36,44
8	700,00	520,07	492,50	0,00	38,50	0,00	4,14	34,36
9	700,00	492,50	382,69	0,00	38,50	0,00	16,47	22,03
10	700,00	382,69	381,04	0,00	21,00	0,00	0,25	20,75
11	700,00	381,04	342,31	0,00	21,00	0,00	5,81	15,19
12	700,00	342,31	339,78	0,00	28,00	0,00	0,38	27,62
13	700,00	339,78	335,04	0,00	28,00	0,00	0,71	27,29
14	700,00	335,04	334,69	0,00	21,00	0,00	0,05	20,95
15	700,00	334,69	334,69	0,00	21,00	0,00	0,00	21,00
16	700,00	334,69	333,38	0,00	21,00	0,00	0,20	20,80
17	700,00	333,38	333,38	0,00	31,50	0,00	0,00	31,50
18	700,00	333,38	327,41	0,00	31,50	0,00	0,90	30,60
19	700,00	327,41	230,46	0,00	31,50	0,00	14,54	16,96
20	700,00	230,46	227,02	0,00	31,50	0,00	0,52	30,98
21	700,00	227,02	135,71	0,00	31,50	0,00	13,70	17,80
22	700,00	135,71	135,71	0,00	21,00	0,00	0,00	21,00
23	700,00	135,71	135,71	0,00	38,50	0,00	0,00	38,50
24	700,00	135,71	135,71	404,29	31,50	8,30	0,00	23,20
TOTAL					**749,00**	**8,30**	**60,64**	**680,06**

6 MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	700,00	540,00	540,00	0,00	31,50	0,00	0,00	31,50
2	700,00	540,00	540,00	0,00	24,50	0,00	0,00	24,50
3	700,00	540,00	540,00	0,00	24,50	0,00	0,00	24,50
4	700,00	540,00	540,00	0,00	24,50	0,00	0,00	24,50
5	700,00	540,00	538,06	0,00	24,50	0,00	0,29	24,21
6	700,00	538,06	538,06	0,00	24,50	0,00	0,00	24,50
7	700,00	538,06	462,98	0,00	24,50	0,00	11,26	13,24
8	700,00	462,98	346,76	0,00	21,00	0,00	17,43	3,57
9	700,00	346,76	340,85	0,00	21,00	0,00	0,89	20,11
10	700,00	340,85	337,00	0,00	21,00	0,00	0,58	20,42
11	700,00	337,00	337,00	0,00	21,00	0,00	0,00	21,00
12	700,00	337,00	337,00	0,00	21,00	0,00	0,00	21,00
13	700,00	337,00	337,00	0,00	21,00	0,00	0,00	21,00
14	700,00	337,00	337,00	0,00	24,50	0,00	0,00	24,50
15	700,00	337,00	337,00	0,00	24,50	0,00	0,00	24,50
16	700,00	337,00	315,38	0,00	21,00	0,00	3,24	17,76
17	700,00	315,38	315,38	0,00	24,50	0,00	0,00	24,50
18	700,00	315,38	315,38	0,00	24,50	0,00	0,00	24,50
19	700,00	315,38	268,44	0,00	24,50	0,00	7,04	17,46
20	700,00	268,44	190,76	0,00	24,50	0,00	11,65	12,85
21	700,00	190,76	190,76	0,00	24,50	0,00	0,00	24,50
22	700,00	190,76	190,76	0,00	24,50	0,00	0,00	24,50
23	700,00	190,76	145,26	0,00	24,50	0,00	6,83	17,68
24	700,00	145,26	145,26	394,74	24,50	7,19	0,00	17,31
TOTAL					**570,50**	**7,19**	**59,21**	**504,10**

7 MAY 2016								
Hour	**CONSTANT Power kW**	**Energy kWh**	**SOC (kWh)**	**Required Energy kWh**	**Revenue €**	**Cost of buying energy ELBAS €**	**Battery Cost €**	**Profit €**
1	700,00	540,00	540,00	0,00	24,50	0,00	0,00	24,50
2	700,00	540,00	540,00	0,00	17,50	0,00	0,00	17,50
3	700,00	540,00	540,00	0,00	17,50	0,00	0,00	17,50
4	700,00	540,00	540,00	0,00	14,00	0,00	0,00	14,00
5	700,00	540,00	527,77	0,00	14,00	0,00	1,83	12,17
6	700,00	527,77	527,77	0,00	12,46	0,00	0,00	12,46
7	700,00	527,77	527,77	0,00	12,46	0,00	0,00	12,46
8	700,00	527,77	479,74	0,00	1,40	0,00	7,20	-5,80
9	700,00	479,74	479,74	0,00	12,46	0,00	0,00	12,46
10	700,00	479,74	407,84	0,00	12,46	0,00	10,79	1,67
11	700,00	407,84	400,51	0,00	10,43	0,00	1,10	9,33
12	700,00	400,51	400,51	0,00	14,00	0,00	0,00	14,00
13	700,00	400,51	400,51	0,00	14,00	0,00	0,00	14,00
14	700,00	400,51	400,51	0,00	14,00	0,00	0,00	14,00
15	700,00	400,51	400,51	0,00	14,00	0,00	0,00	14,00
16	700,00	400,51	400,51	0,00	10,43	0,00	0,00	10,43
17	700,00	400,51	400,51	0,00	10,43	0,00	0,00	10,43
18	700,00	400,51	398,91	0,00	10,43	0,00	0,24	10,19
19	700,00	398,91	396,25	0,00	10,43	0,00	0,40	10,03
20	700,00	396,25	396,25	0,00	14,00	0,00	0,00	14,00
21	700,00	396,25	395,53	0,00	14,00	0,00	0,11	13,89
22	700,00	395,53	395,53	0,00	10,43	0,00	0,00	10,43
23	700,00	395,53	391,02	0,00	10,43	0,00	0,68	9,75
24	700,00	391,02	323,39	216,61	14,00	2,11	10,14	1,75
TOTAL					**309,75**	**2,11**	**32,49**	**275,15**