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FINAL REPORT: MULTI-OBJECTIVE ROLE OF BATTERY ENERGY STORAGES IN AN ENERGY SYSTEM

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Final report: Multi-objective role of battery energy storages in an energy system

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Preface

This report presents the key results based on the data, pilots and publications of the project ”Multi-objective role of battery energy storages in an energy system” carried out at Lappeenranta University of Technology (LUT) between November 2016 and December 2017. The members of the research group were professor Jarmo Partanen, Dr. Samuli Honkapuro, Dr. Juha Haakana, Dr. Jukka Lassila, Dr. Andrey Lana, Ville Tikka, M.Sc., Nadezda Belonogova, M.Sc., Jouni Haapaniemi, M.Sc., Arun Narayanan, M.Sc. and Dr. Aleksei Romanenko. The research was funded by the Finnish Electricity Research Pool (ST-Pooli), the Promotion Centre for Electrical Safety (STEK), Helen Ltd, Helen Electricity Network Ltd, Fingrid Oyj and Landis+Gyr Oy. The steering group held five meetings, in addition to which the study was complemented by e-mail discussions.

The conclusions, results and suggestions for future actions presented in this report are the authors' views only and do not tie the funding organizations in any way.

Lappeenranta January 2018

Authors

Alkusanat

Tässä raportissa esitetään energiavarastohankkeen tulosaineistoista, piloteista ja julkaisuista koostettuja tuloksia. Tutkimushankkeen on toteuttanut aikavälillä 11/2016–12/2017 Lappeenrannan teknillisen yliopiston (LUT) Sähkömarkkinalaboratorion tutkimusryhmä, johon kuuluivat professori Jarmo Partanen, TkT Samuli Honkapuro, TkT Juha Haakana, TkT Jukka Lassila, TkT Andrey Lana, DI Ville Tikka, DI Nadezda Belonogova, DI Jouni Haapaniemi, DI Arun Narayanan ja TkT Aleksei Romanenko. Tutkimushankkeen rahoittivat yhteisrahoituksella ST-pooli, STEK, Helen Oy, Helen Sähköverkko Oy, Fingrid Oyj ja Landis+Gyr Oy. Ohjausryhmä kokoontui selvitystyön aikana viisi kertaa, minkä lisäksi selvitystyöhön saatiin kommentteja sähköpostitse. Hankkeen raportissa esitetyt johtopäätökset, tulokset ja mahdolliset toimenpide-ehdotukset ovat tutkijoiden näkemyksiä, eivätkä sido selvitystyön tilaajia millään tavoin.

Lappeenrannassa tammikuussa 2018

Tekijät

Abstract

This research project aimed at establishing an interconnection between multiple battery storage units as well as defining and testing operation strategies for battery energy systems in different use cases. The project took full benefit of the existing battery storage infrastructure located in Helsinki (Suvilahti), Suomenniemi (storage in an LVDC microgrid) and Lappeenranta (LUT Green Campus stationary and mobile storages). Each of these storages was in active operation already before the project started. However, the storages are operated independently of each other, and their operation is not yet fully optimized for the needs of electricity markets and the power system.

In the research project, a storage system has a stakeholder-specific multi-objective role, which means that the storage system has to respond to several service requests simultaneously. This may mean, for instance, operating at the same time in the frequency control in the electricity markets, trading electricity in the day-ahead, intraday, and ancillary markets, simultaneously offering various services to local network operations and several other stakeholders. This kind of multi-objective operation requires full understanding of interactions of different markets and stakeholders and risks related to the conflicting objectives of the stakeholders.

One of the key outcomes of the project work was the establishment of a connection to the Suvilahti BESS unit through an IEC 104 protocol. Another outcome was constructing a simulation tool in Matlab that enables testing of numerous scenarios of a single BESS unit operation with different operating parameters and various operating strategies. The major part of the analyses was done based on the results of the simulation tool. There are two further main outcomes of the project. The first one is that it is technically possible to remotely control multiple BESS units against multiple tasks according to a pre-defined logic. The second outcome of the project is that a BESS can and should be operated against multiple tasks simultaneously. During such an operation, there may or may not emerge a conflict of objectives between the involved stakeholders. The nature of the conflicts has been investigated and the methods to mitigate the conflict have been analysed. The aggregation of BESS resources is one way to mitigate the conflict of objectives.

Tiivistelmä

Tässä suomenkielisessä tiivistelmässä esitetään Akkujen monitavoitteinen rooli energiajärjestelmässä -projektin keskeisimmät havainnot ja tulokset, jotka on käsitelty laajemmin englanninkielisessä kokotekstissä.

Energiajärjestelmässä on tapahtumassa merkittäviä muutoksia tuotanto- ja kulutusrakenteen muutoksien johdosta. Uusiutuvan tuotannon osuus järjestelmässä kasvaa jatkuvasti ja vähentää helposti säädettävän voiman ja inertian määrää verkossa. Energiajärjestelmän ja toimialan on pystyttävä vastaamaan muutoksiin uudenlaisilla teknisillä ratkaisuilla ja liiketoimintamalleilla. Akkuenergiavarastojen roolin energiajärjestelmässä voidaan sanoa olevan väistämätön, sillä akkuenergiavarastot vastaavat erinomaisen hyvin nopean säätövoiman tarpeeseen ja samalla toimivat lyhyen aikavälin energiavarastoina. Nykyisin käytössä olevien markkinamallien ja regulaation ei voida kuitenkaan nähdä tukevan akkuenergiavastojen täysimittaista hyödyntämistä. Tässä tutkimusprojektissa tarkastellaan akkuenergiavastojen roolia energiajärjestelmässä eri toimijoiden näkökulmasta. Tarkastelussa keskitytään yksittäisten akkuvarastojen toiminnan lisäksi akkuvarastokokonaisuuden hallintaan. Projektissa ei oteta kantaa akkuteknologiaan, mutta toteutetaan demonstraatiojärjestelmä jo käyttöönotettuja akkuenergiavarastoja hyödyntäen. Projektin keskeinen tavoite on toteuttaa demonstraatiojärjestelmä todellisessa toimintaympäristössä, eikä ainoastaan laboratorioympäristössä.

Energiajärjestelmätoimijoiden roolit

Energiajärjestelmän parissa on useita toimijoita, joilla on selkeä intressi hyödyntää akkuenergiavarastojen dynaamisia ominaisuuksia. Kantaverkkoyhtiöllä on vastuu kantaverkkojen tehotasapainosta, mikä ilmenee esimerkiksi taajuudenhallintareserveinä, joita kantaverkkoyhtiö Fingrid ostaa reservipalveluiden tuottajilta. Akkuenergiavarasto on teknisiltä ominaisuuksiltaan sen kaltainen resurssi, että se vastaa erinomaisen hyvin taajuudenhallinnan tarpeisiin nopealla tehovasteella. Tyypillisesti taajuudenhallinnassa käytettävien reservituotteiden energiasisältö on pieni, mikä tukee myös akkuenergiavastojen kaltaisia reservejä. Toisaalta myös jakeluyhtiöillä on useita käyttökohteita akkuenergiavarastoille. Akkuenergiavarastoja voidaan käyttää verkon tukemiseen leikkaamalla tehopiikkejä tuotannosta tai kulutuksesta. Lisäksi akkuvarastot tarjoavat erinomaisen työkalun jännitteenlaadun hallintaan esimerkiksi loistehoa säätämällä. On kuitenkin huomioitava, että nykyinen regulaatioympäristö ei mahdollista jakeluverkkoyhtiölle akkuvarastojen täysimittaista hyödyntämistä. Sähkönmyyjillä on mahdollisuus käyttää akkuvarastoja energiataseen hallintaan, mutta kustannustaso ei välttämättä ole nykyisellään toimintaa suosiva. Akkuenergiavastojen käyttömahdollisuudet eivät rajoitu edellä mainittuihin toimijoihin, vaan hyötyjä voi olla myös asiakastasolla. Akkuvaraston olleessa asennettuna kiinteistöön tai kiinteistön kaltaiseen kohteeseen voidaan akkuvarastolla parantaa paikallista jännitteenlaatua tai

toimitusvarmuutta.

Resurssien tehokas hyödyntäminen

Projektin yksi päätavoitteista oli muodostaa selkeä kuva akkuvarastojen ohjaamiseen vaadittavan ongelmakokonaisuuden hallinnasta. Ohjaukseen liittyvää problematiikkaa lähestytään määrittelemällä ohjauksen tavoitefunktio matemaattisessa muodossa. Tämä antaa hyvät edellytykset rakentaa kokonaiskuva akkuvarastojen monitavoitteiseen käyttöön liittyvistä haasteista. Useiden sovellusten päällekkäinen käyttäminen akkuvarastojen kanssa on useissa tapauksissa hyvin mahdollista. Esimerkiksi yhden loisteho- ja pätötehosovelluksen samanaikainen käyttö onnistuu hyvin pienillä rajoituksilla. Usean pätötehosovelluksen samanaikainen käyttö ei ole mahdollista kuin joissain erikoistapauksissa. Tyypilliset rajoitteet muodostuvat markkinapaikkojen sopimusehdoista mutta toisaalta myös akkuvarastojen fyysisistä rajoitteista. Esimerkkinä kahdesta päällekkäisestä pätötehosovelluksesta voidaan mainita akkuenergiavaraston toiminta paikallisena varavoimana ja samaan aikaan taajuudenhallintareservinä. Käytännössä akku pystyy osallistumaan taajuudenhallintaan rajoitetulla kapasiteetilla lähes jatkuvasti pois lukien tilanteet, joissa varavoimatoiminnallisuutta tarvitaan.

Akkuvaraston kapasiteettia voidaan myös jakaa sovellusten kesken, mutta tämän seurauksena markkinoille voidaan tarjota vain rajallinen osuus kapasiteetista. Usean varaston aggregointi tarjoaa enemmän mahdollisuuksia jakaa resurssia useammille markkinoille. Tämä tarjoaa myös mahdollisuuden hallita riskejä, jotka voisivat realisoitua todennäköisemmin yksittäisten varastojen tapauksessa. Esimerkiksi taajuusohjatun käyttöreservin yhteydessä yksittäisen akkuenergiavaraston kapasiteetin ennustaminen voi olla hyvin haastavaa, mutta joukko akkuja antaa mahdollisuuden jakaa resurssin tuotantovastuuta ja näin ollen mahdollistaa kapasiteettiriskin hallinnan.

Laskentamalli ja herkkyysanalyysit

Matemaattisen ongelman taustoittamisen pohjalta muodostettiin simulaatiomalleja, joilla voidaan laskea akkuenergiavarastojen hyötyjä eri markkinapaikoilla. Laskentamalli antaa myös hyvät valmiudet analysoida eri toimijoiden rooleja ja taloudellisia hyötyjä tai menetyksiä. Tämä luo pohjan toimijoiden mahdollisten ristiriitojen todentamiseen ja taloudellisten vaikutusten analysointiin.

Projektissa tehtiin herkkyysanalyysejä taajuusohjattujen käyttöreservien parametreja varioimalla. Analyysien perusteella voidaan sanoa, että taajuusohjatun käyttöreservin parametrien valinta vaikuttaa merkittävästi akkuenergiavarastojen takaisinmaksuaikaan. Merkittävimmät parametrit olivat taajuusvastekäyrä ja tehon muutosnopeus. Reagointiajan muuttamisen ei havaittu juurikaan vaikuttavan akkuenergiavaraston takaisinmaksuaikaan. Havaittiin myös, että normaalin taajuusohjatun käyttöreservin tuntimarkkinoille osallistuminen on kannattavampaa matalalla hintarajalla, kunhan korvaus on riittävä kattamaan käyttökustannukset. Esimerkiksi säätösähkömarkkinalle osallistuminen yhdessä taajuusohjattujen käyttöreservien kanssa ei puolestaan näyttänyt tuovan merkittävää etua.

Tekninen toteutus ja testaus

Projektin puitteissa toteutettiin ohjausjärjestelmä, joka mahdollisti akkuresurssien reaaliaikaisen ohjauksen ja paikallisten ohjausten aktivoinnin. Ohjausjärjestelmä perustuu teollisuudessa yleisesti käytettyihin standardiratkaisuihin. Tietoliikenneyhteydet rakennettiin todelliseen toimintaympäristöön tai sitä vastaaviin olosuhteisiin. Valtaosa tietoliikenneyhteyksistä hyödyntää julkista tietoliikenneverkkoa VPN-yhteyksillä suojattuna. Projektissa päädyttiin käyttämään IEC-standardoitua IEC 60870-5-104 -kommunikaatioprotokollaa. Kyseinen protokollan toiminta perustuu TCP/IP-protokollaan ja toimii Ethernet-yhteyden päällä. IEC 104 -protokolla on hyvin yleisesti käytössä energiajärjestelmissä, joten teollisuudella on hyvä valmius hyödyntää protokollaa.

IEC 104 -protokollaan tehtiin muuttujamäärittelyt, jotka vastasivat akkuvarastojen ohjauksen tarpeita. Protokollan tekninen toteutus tehtiin jokaiselle ohjattavalle akkuresurssille ja ohjaavalle päätelaitteelle. Ohjaavana päätelaitteena käytettiin virtuaalipalvelinta, johon oli asennettu Linux-käyttöjärjestelmä. Ohjaavan palvelimen toteutus hyödyntää avoimen lähdekoodin kirjastoja ja osin projektissa kehitettyjä muokattuja ohjelmistoja.

Ohjaavan päätelaitteen ohjauslogiikka perustuu sovellusten prioriteettijärjestyksen määrittämiseen. Jokaisen akkuvaraston paikallisella ohjauksella on useita sovelluksia, joita voidaan aktivoida priorisoituna tietyssä järjestyksessä. Paikallisen ohjauksen tehtävä on huolehtia, että sovellusten päällekkäinen toiminta ei aiheuta toiminnallisuuden tai turvallisuuden kannalta ongelmia. Paikallinen sovellus voi olla esimerkiksi loistehonkompensointi, jännitteensäätö tai taajuusohjattukäyttöreservi kantaverkon tarpeisiin. Toisaalta myös hyvin alueen verkon tai asiakkaan toimitusvarmuuteen liittyvät sovellukset kuten varavoima ovat mahdollisia.

Ohjausjärjestelmää testattiin marraskuun puolivälistä joulukuun 2017 loppuun asti. Testijakson aikana käytettiin kaikkia ohjattavia resursseja. Akkuresurssien pääasiallinen tarkoitus oli osallistua taajuusohjatunkäyttöreservin tuottamiseen, sillä se on yksi kannattavimmista sovelluksista. Akut osallistuivat myös loistehonkompensointiin, jännitteensäätöön. Suomenniemen LVDC akkuvarasto toimi lisäksi varavoimakapasiteettina, joka osaltaan rajoitti muiden sovellusten toimintaa.

Testausjakson aikana havaittiin useita ongelmatilanteita resurssien teknisiin ominaisuuksiin ja kommunikaatioyhteyksiin liittyen. LUT:n akkuresurssien osallistumista jouduttiin rajoittamaan akkukennojen balansointiin liittyvien ongelmien vuoksi. Helenin Suvilahden akkuvaraston kommunikaatioyhteydessä havaittiin muutamia poikkeavaisuuksia, mutta tämä ei juurikaan vaikuttanut varaston ohjaukseen. Akkuvarastojen testijakso sujui pääpiirteittäin suunnitelmien mukaan. Päätuloksena voidaan todeta, että akkuvarastoja voidaan ohjata IEC 104 -protokollaa hyödyntämällä. Testijakson aikana kerätty mittausaineisto vahvistaa analyysien johtopäätökset, mutta lyhyen verifiointijakson takia tuloksen tilastollinen varmuus ei ole kovin suuri. Ohjauksen toteutuksen yhteydessä tehtiin paljon havaintoja järjestelmän asennukseen liittyen. Keskeisin huomio oli, että useiden yhteyksien rinnakkainen hallinta ei kuitenkaan ole kovin joustavaa staattisten VPN-yhteyksien vuoksi. Jos vastaavia resursseja halutaan käyttää laajamittaisesti, on järjestelmän helppo skaalattavuus ensiarvoisen tärkeää. Vaikka käytetyt ratkaisut ovat teollisuudelle ja toimialalle hyvin tuttuja, olisi perustelua selvittää muiden kommunikaatioprotokollien käyttöä.

Johtopäätökset ja avoimet kysymykset

Projektin konkreettisin tulos on demonstraatiokokonaisuus, jossa mahdollistettiin usean erityyppisen akkuenergiavaraston etäohjaus keskitettyä ohjauslogiikkaa käyttäen. Toteutuksen selkeästi haastavin vaihe oli integroida kaupallisessa toimintaympäristössä oleva Helen Oy:n Suvilahden sähkövarasto (akkuenergiavarasto) osaksi tutkimusprojekteissa rakennettuja akkuenergiavarastoja ja niiden ohjausta. Ohjaus toteutettiin käyttäen standardoituja protokollia ja teollisuudenalalle tuttuja tietoliikenneratkaisuja.

Merkittävä tulos on myös simulaatiomalli, joka antaa valmiudet tarkastella eri toimijoiden rooleja ja eri markkinapaikkojen hyötyjä akkuenergiavarasoille. Analyysien perustella on hyvin selkää, että tällä hetkellä taajuussäätyvät käyttöreservit ovat kannattavimpia sovelluskohteita akkuenergiavarastojen kannalta. Suurin osa muista markkinapaikoista on liian energiaintensiivisiä akkuenergiavarastojen kannattavuuden näkökulmasta. Toisaalta useille markkinapaikoille osallistumiseen on olemassa selkeä kannuste, sillä vapaana olevaa akkuenergiavarastoresurssia voidaan hyödyntää muilla markkinapaikoilla ja näin ollen saada lisähyötyä. On kuitenkin huomioitava, että markkinapaikan on tarjottava kompensaatio, joka kattaa akkuenergiavaraston käyttökulut.

Contents

List of abbreviations

AC	alternating current
BESS	battery energy storage system
BPM	balancing power market
CEI	customer-end inverter
DC	direct current
DER	distributed energy resource
DG	distributed generation
DR	demand response
DSP	digital signal processing
DSO	distribution system operator
EV	electric vehicle
HEV	hybrid electric vehicle
FRC	frequency containment reserve
GC	Green Campus
G2V	grid to vehicle
HV	high voltage
ICT	information and communication technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IO	input-output
IP	Internet protocol
IT	information technology
MV	medium voltage
MVDC	medium voltage direct current
NPV	net present value
LAN	local area network
LTO	lithium-titanate battery
LV	low voltage
LVAC	low-voltage alternating current
LVDC	low-voltage direct current
LUT	Lappeenranta University of Technology
PB	power band
PCC	point of common coupling
PV	photovoltaic
PQ	active-reactive power
V2G	vehicle to grid

VPN	virtual private network
VR	voltage regulation
RPC	reactive power compensation
SOC	state of charge
TLS	transport layer security
TCP	transmission control protocol
TOU	time-of-use
TSO	transmission system operator
UPS	uninterrupted power of supply

1 Introduction

The energy sector has been undergoing significant changes in the past decade. The proportion of renewable resources has increased in recent years, and traditional arrangements of the power system have started to change over to more flexible and dynamic structures. There are four evolutionary changes that cause an increased need for flexibility in the electricity system. Firstly, the proportion of intermittent renewable energy is growing. Secondly, renewable electricity generation is increasingly injected in a decentralized manner into the system. Thirdly, an increase in the electrical load is expected, resulting from a shift from fossil-fuelled systems toward energy efficient electrical equipment for transport and heating [1]. Fourthly, the number of traditional controllable power plants is stagnating or even decreasing [2]. As a result of the combination of these four evolutionary changes, maintaining the electricity power balance while respecting electricity grid constraints is becoming increasingly challenging [3].

The emergence of a large amount of small-scale flexible energy resources leads to the fact that also new players are entering the market, such as operators of the aggregated small-scale resources (aggregators), IT service providers, energy service companies, prosumers and microgrid operators. At the same time, there are energy stakeholders in the electricity power system and the markets such as generators, the transmission system operator (TSO), electricity retailers, distribution system operators (DSOs) and end-users with their interests and goals. All these stakeholders, in particular the TSO, DSOs and retailers, will have a need for the same flexible energy and power resources in particular moments of time for the sake of their business. However, the present regulatory framework and market design do not always allow the cost-effective use of distributed controllable energy resources so that every involved stakeholder would benefit from it. This is due to the arising conflict of interests between the multiple stakeholders when operating the resources.

1.1 Objectives of the stakeholders

The main objectives of the stakeholders are listed in Table 1. A battery energy storage system (BESS) can be seen as a good opportunity not only for the TSO and retailers but also for the DSOs. The most significant benefits can be achieved in peak shaving, which affects the distribution network dimensioning and interruption management applications. In addition, a BESS can be used for reactive power compensation and voltage control.

1.1.1 Reactive power compensation/voltage control

Batteries can be used to consume or supply reactive power in the distribution network. Reactive power can be used either to adjust voltage or control the reactive power balance at the system level.

Table 1: Objectives of the stakeholders.

Stakeholder	*Retailer*	*TSO*	*DSO*	*Customer*
Objectives	Short-term risk management Minimization of imbalance Portfolio optimization	Frequency regulation	Reactive power compensation Smoothing varying loads Peak shaving, voltage control/ backup, UPS	Solar PV self-consumption Price arbitrage at the TOU tariff Participation in DR programs

The reactive power balance of the electricity network is typically measured at the system level, where the Finnish national transmission system operator Fingrid controls the operation of the system. Fingrid sets the rules/prices for the reactive power usage, which the local DSOs have to follow within the connection points to the TSO's grid. If the DSO takes/supplies reactive power from/to the TSO's grid, the DSO has to pay for it according to the PQ window requirements. In this case, the BESS operated by the DSO could be used to control the reactive power within the connection point. The control could be arranged by a centralized BESS (e.g. at the primary substation level) or several distributed BESS units located downstream on the network down to the LV network level.

However, even though the benefits of the BESS on the distribution system operation are clear, the present electricity regulatory model and legislation do not support the use of storages in the distribution network operation. For instance, the winter package [4] published in the late 2016 provides that the DSOs are not able to own storages in any case if service providers offer capacity for such a purpose. However, the topic is still under discussion.

1.2 Role of BESS in the future flexible energy systems

Energy storages have numerous technical advantages over the controllable load or generation resources, such as:

- capability of working in both the generation and load modes
- very fast and precise response to the control signal
- no payback effect as with thermostatically controlled loads
- being equipped with a power electronics unit makes it possible to also provide reactive power services (both supply and consumption)
- relatively high efficiency

These advantages make BESS suitable for multiple applications from active-power-intensive ones such as frequency regulation to energy-intensive uses such as peak shaving, energy arbitrage, backup power, and further on to reactive-power-intensive ones, such as reactive power compensation and voltage control. The disadvantage of BESS is still their high cost of technology. However, with the growing market, the price has steadily decreased over the past few years at a rate of approx. 19% [5].

These factors underline the message that BESS is a potential candidate to meet the needs of the future flexible energy system. Whether this potential will be realized and on which scale depends on numerous factors. One of them is the regulatory framework and market design, the primary objective of which is to attract energy resources into the markets and the power system in the most cost-effective and cost-reflective way for the social welfare.

1.3 Structure of the report

Chapter 2 lists the objectives of the report and the corresponding tasks that need to be executed in order to reach the objectives.

Chapter 3 describes the demonstration platforms of the four BESS units.

Chapter 4 presents the developed simulation tool to operate a single BESS unit in multiple applications, including the decision-making logic at the second, hour and day resolution levels. The tool further enables to carry out a sensitivity analysis with the target of formulating the recommendations for the optimal operating parameters of a single BESS unit.

Chapter 5 provides the results of the profitability analyses and a method to determine the break-even market price level at which the BESS investments are paid back within a certain number of years.

Chapter 6 demonstrates the nature of the conflict of interests between various applications and aims at defining possible operating strategies when the BESS capacity can be simultaneously allocated to multiple tasks.

Chapter 7 addresses the technical implementation of the connection between multiple BESS units.

Chapter 8 focuses on the challenges related to the aggregation and control of multiple BESS units for multiple tasks and discusses the value that such aggregation adds.

Chapter 9 presents the main results obtained from the test period of the BESS control through the established connection.

Chapter 10 introduces the mathematical formulation of the problem and suggests possible ways to solve it.

Finally, **Chapter 11** formulates the contribution of the present research and outlines the further research questions.

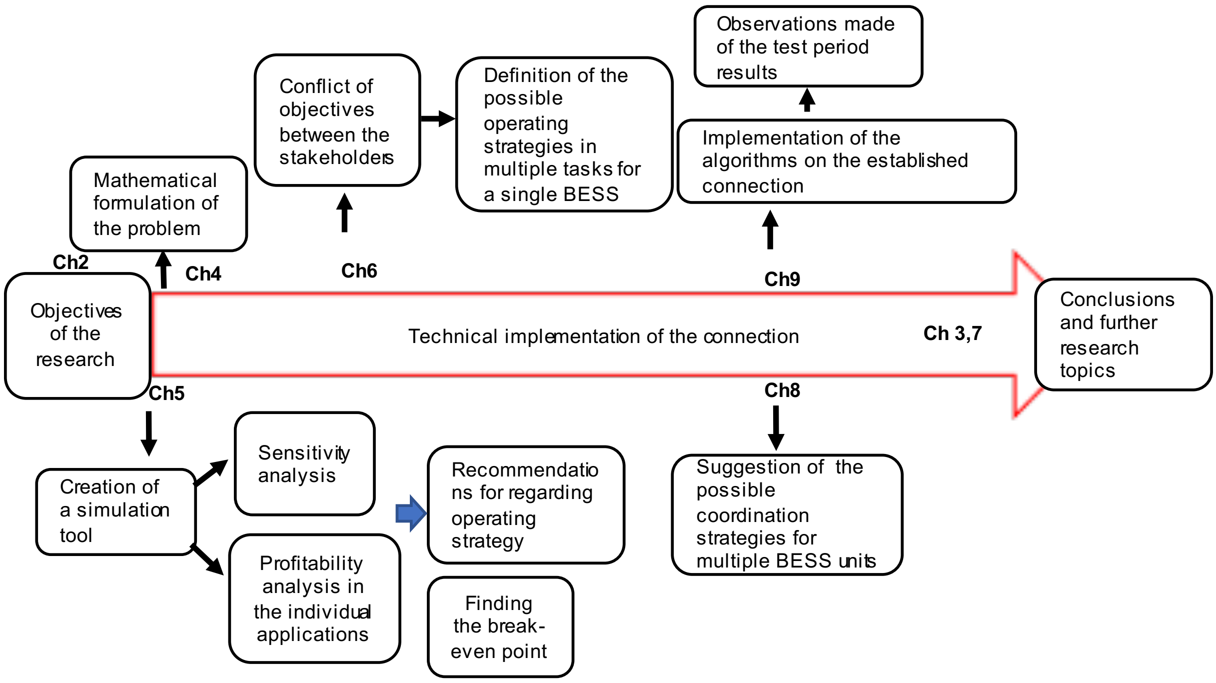

Figure 1: Structure of the report.

2 Objectives of the research

The main objectives of the research are:

1. Definition of the operating environment, formulation of the objectives of the energy system stakeholders and the role of battery energy storages (BESS) in the future energy system.
2. Identification of the major conflicts of interests between the multiple stakeholders blocking the cost-effective deployment of BESS units in multiple applications.
3. Development of an operating strategy by establishing a decision-making framework to operate a single BESS unit and multiple BESS units in multiple tasks.
4. Selection of the promising applications for a single BESS unit and analysis of the conflict between them, which occurs as a result of the simultaneous operation of the BESS in multiple applications. The applications under consideration are:
   - Reserve for power balance (hourly FCR-N and FCR-D markets)
   - Energy cost optimization (e.g. in the balancing power market)
   - Reactive power compensation
   - Definition of how the input parameters such as electricity market prices and rules, the transmission (frequency quality) and distribution grid (reactive power) parameters and the BESS parameters affect the outcome. Mathematical formulation of the decision-making problem in an uncertain environment.
5. Formulation of the future research topics and questions for mitigating the hindrance of the BESS entrance to multiple applications.

In order to achieve the specified objectives, the following tasks and subtasks have to be carried out:

1. Technical implementation of the coordination and control of multiple units of BESS. In this project, the BESS units are located in Suvilahti (Helsinki) and Suomenniemi (south-eastern Finland), in addition to which there are LUT stationary and mobile battery units. This task consists of the following subtasks:
   - Selection of suitable communication architectures
   - Mapping of measurement and control variables to the selected protocol approach
   - Implementation of the communication interfaces on the controllable resources
   - Implementation of the master unit to control the resources
   - Implementation of the point-to-point connection between the resources and the master unit
2. Testing of the control algorithms on the constructed ICT connection between the BESS units.
3. Sensitivity analysis on the parameters related to the bidding strategy and the hour- and second-level operation logic of a single BESS unit. Furthermore, the data of several years

are considered in the simulations.

The main contributions of the research are:

1. Construction of the control system between multiple BESS units
2. Development of a tool in MATLAB that simulates the operation of BESS in various applications. The simulation tool allows to carry out various analyses, such as profitability assessment, sensitivity analysis and investigation of the conflict of interests, with various input parameters.
3. Definition of the nature of conflict between various applications and possible ways to mitigate it
4. Mathematical formulation of the problem and suggestions for possible solving tools and methods
5. Description of further research questions

3 Demonstration platforms

In this chapter, demonstration platforms are introduced in brief. The project focuses on integration of several resources under one control system, not on developing active grid resources, and thus, several existing resources are used in the present project. The resources share quite a few common characteristics besides all being battery energy storages of some form.

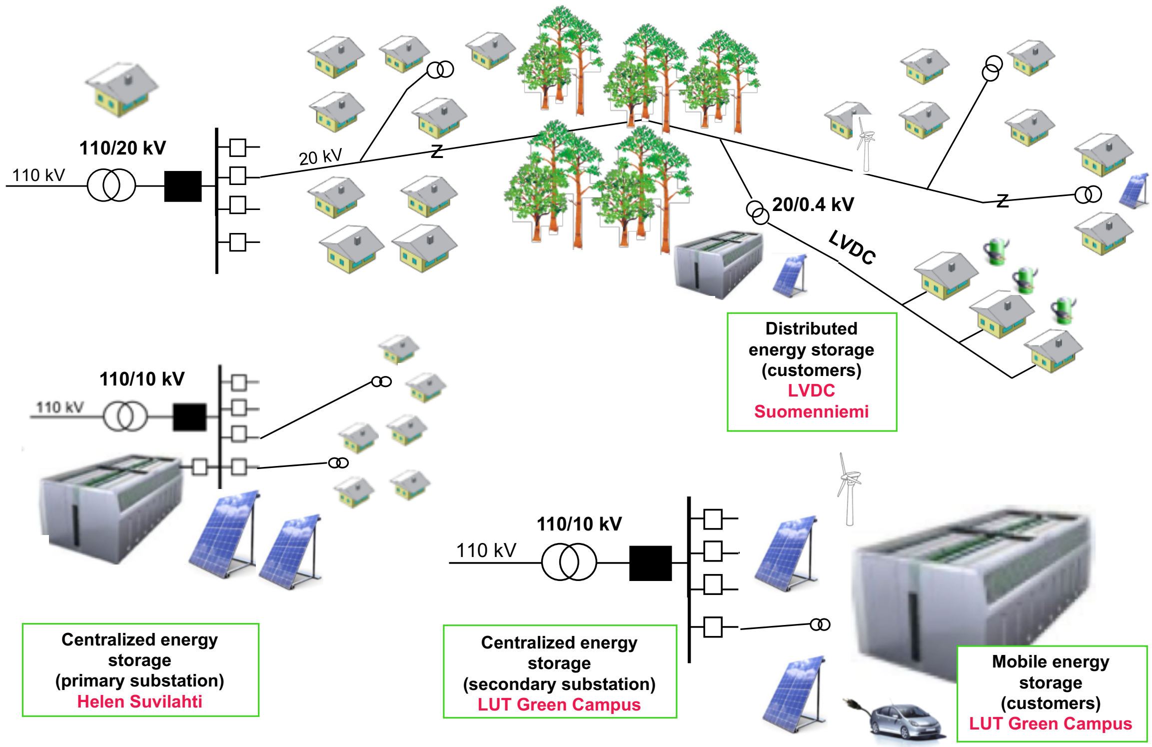

Figure 2: Illustration of the demonstration platforms used in the project.

Demonstration platforms used in the study are all connected to different levels of the distribution grid. Figure 2 presents resource locations at different levels of the distribution grid. The battery of Helen located in Suvilahti Helsinki is connected to the urban medium-voltage grid, while the LVDC network in Suomenniemi is connected to the rural medium-voltage grid. The LVDC site can be considered a microgrid with a full capability to operate in the island mode with the assistance of battery resources within the microgrid. The Green Campus battery is connected to the building complex low-voltage grid with multiple other active resources such as smart electric vehicle (EV) charging poles.

3.1 Helen Suvilahti

In August 2016, Helen Ltd commissioned the largest battery energy storage system (BESS), ”Suvilahden sähkövarasto”, in the Nordic countries. The BESS, rated 1.2 MW/600 kWh, was built by Toshiba Transmission and Distribution Europe S.p.A. using state-of-the-art SCIB battery modules by Toshiba and supplied to Helen by Landis + Gyr Ltd. The BESS is located in Suvilahti, an urban district in the downtown of Helsinki, the capital of Finland. The BESS is installed next to a primary substation of the local DSO, Helen Electricity Network, where Helen commissioned the first large-scale (340 kWp) solar power plant in Finland 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. The battery has the following properties:

- 600 kWh, 1.2 MW nominal ratings, 50% overload capability
- 15 000 Toshiba SCIB lithium-titanate battery (LTO) cells
- Integrated system inside a 12.192 m (40 ft) 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

3.2 Green Campus battery energy storage

The LUT Green Campus stationary battery energy storage system is a part of the Green Campus network, and it is developed to serve different kinds of test runs in the laboratory environment. The BESS can also be used together with the Green Campus solar power plants. The structure is based on the Suomenniemi BESS, but it has a higher capacity and power output. The BESS was commissioned in January 2016. The main difference is that the BESS in the laboratory is unipolar, because the BESS is connected to the unipolar laboratory LVDC network. The length of the LVDC network is 200 m, and it currently supplies one customer-end inverter (CEI). Additionally, the BESS enables external connection to both the DC and AC sides of the system, enabling versatile use of the BESS for various research purposes. The control and monitoring systems are further developed from the Suomenniemi system, enabling more accurate control over the BESS.

- 132 kWh, 188 kW
- 230 pcs LiFePO4 batteries
- Self-manufactured by LUT
- Full voltage 790 V, empty 690 V (unipolar connection)
- Direct connection to the laboratory DC network
- Commercial grid-tie rectifying converter with bidirectional power transmission
- Commercial battery energy management system
- DSP-based card for BESS control and measurements
- Full control and monitoring through a web-based interface
- Indoor installation (LUT Green Campus)
- Commissioned in January 2016

- The BESS enables:
  - BESS current/power control
  - Rectifier current/power control
  - LVDC network congestion management
  - LVDC network island operation
  - Frequency-controlled reserve for the LUT grid
  - Reactive power control at the rectifier (rectifier feature)

3.3 LVDC research site battery

The Suomenniemi BESS is a part of an LVDC distribution system research site located in an actual distribution network, owned by the energy company Suur-Savon Sähkö and operated by the DSO Järvi-Suomen Energia Oy. The research site, designed and implemented by LUT, was commissioned in June 2012, and the BESS has been in operation since October 2014. The LVDC research site is supplied from the medium-voltage network, and it consists of grid-tie rectifying converters with bidirectional power flow, 1.7 km undergrounded bipolar ±750 V DC network and three galvanically isolated CEIs supplying four actual end-customers. Detail description of research-site structure is given in [6]. The BESS has a converterless direct connection to the DC network, and the rectifier units are used to control the power flow of the BESS and the LVDC system [7]. Because the DC network is bipolar, the BESS consists of series-connected BESS A and BESS B, both with control devices and measurements of their own. The BESS is designed to be an integrated part of the LVDC network, and it supports the diversified use of the LVDC smart grid. The control and monitoring system [8] enables the implementation of different control functions from the low-level power control algorithms to the high-level market-based BESS control strategies.

- 2x30 kWh, 2x30 kW
- 2x235 pcs LiFePO4 batteries
- Self-manufactured by LUT
- Direct connection to the DC network, no converters
- Full voltage ±790 V, empty voltage ±710 V (bipolar connection)
- Charging and discharging control using the rectifier
- Commercial battery energy management system
- DSP-based card for the BESS control and measurements
- Full control and monitoring through a web-based interface
- Installed in two cable distribution cabinets, outdoor installation
- Commissioned in October 2014
- LVDC system and BESS enable
  - BESS current/power control

- Rectifier current/power control
- LVDC network congestion management
- LVDC network island operation
- Frequency-controlled reserve for the MV grid
- Reactive power control at the rectifier

3.4 Green Campus plug-in hybrid and smart charging pole

The LUT Green Campus hybrid electric vehicle (HEV) with G2V and V2G properties has been developed to operate as a mobile research testbed for different energy market and grid applications. The present methodology has been tested and verified recently in the Green Campus environment. In this project, a commercial EV is used to demonstrate the smart charging functionality as a part of a larger control system. Properties of the modified plug-in-hybrid vehicle:

- 1.3 kWh, 27 kW (NiMH) and 4.3 kWh, 3 kW (LiFePO4)
- Management system enables flexible customization of storage and charging applications
- Implemented applications: frequency containment reserve (FCR), charging cost minimization and peak cutting application
- Management can be stand-alone or functions can be aggregated by the Green Campus energy management system
- In operation since 2014

The smart charging pole applied in the demonstration system is an Ensto Chago EVC100 [9] mode 3 compatible charging pole. The charging pole has a compact Linux computer as an interface device allowing charging pole integration to the control system at LUT Green Campus. The local control functions have been implemented on the interface device as follows:

- Frequency containment application
- Allows the charging power to be decreased when the frequency reaches the set point limit
- The charging current limit can be set within the interval from 6 to 32 amps
- Market application
- Allows the charging to be power limited based on market signals
- Control signal is based on the LUT Green Campus control system (centralized control)
- Peak shaving
- Charging power limitation can be triggered by any monitored power measurement signal in the campus area
- Charging power limit trigger can be a fixed limit or dynamically set based on a certain monitored resource

The power limit response is highly dependent on the vehicle to be charged. Each manufacturer

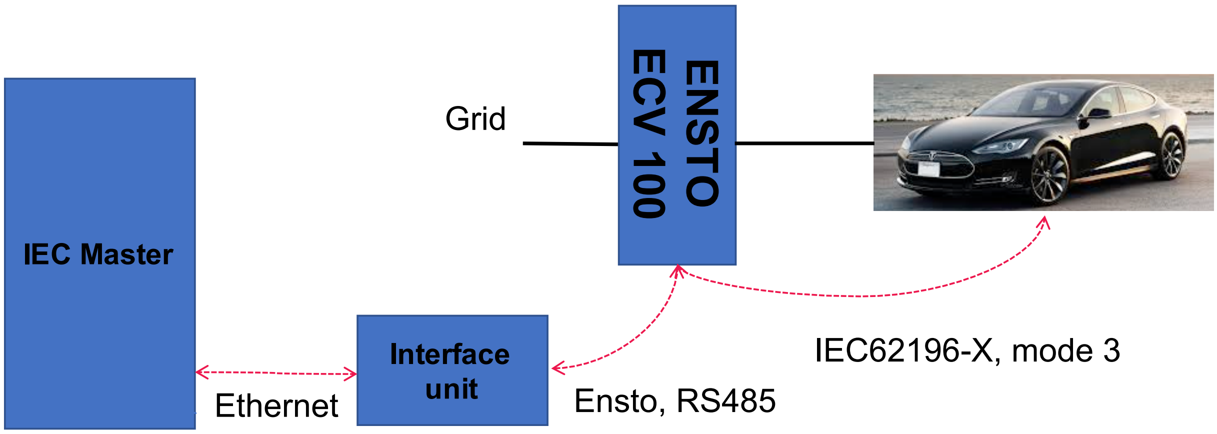

Figure 3: Smart charging pole and communication system.

has a control system of its own to adjust the charging power according to the value required by the charging pole, and thus, the exact response speed of such a system is difficult to define. Further, the maximum charging power is dependent on the onboard charger of the car, and consequently, also the absolute power decrease of the system varies by the make of car, model and current state of charge (SOC).

Nevertheless, it is worth mentioning that the above issues may become more or less irrelevant as the number of similar types of smart charging applications increases. The power decrease resource available will be easier to estimate by statistical tools. Further, the average response of such a system can be estimated as the number of charging spots increases. This, however, is not in the scope of the present research.

4 Mathematical formulation of the problem

The mathematical formulation of the multi-objective problem is described here. The problem will not be solved mathematically within the scope of the project, but the mathematical presentation of the problem helps understand the challenges related to the problem. The problem can be formulated as a decision-making problem in an uncertain environment. The uncertain factors are:

- frequency deviation
- electricity market prices
- distribution grid state (load level, need for reactive power)

The structure of the mathematical formulation is presented in Figure 4. The problem formulation proceeds in a bottom-up direction from part A to part D.

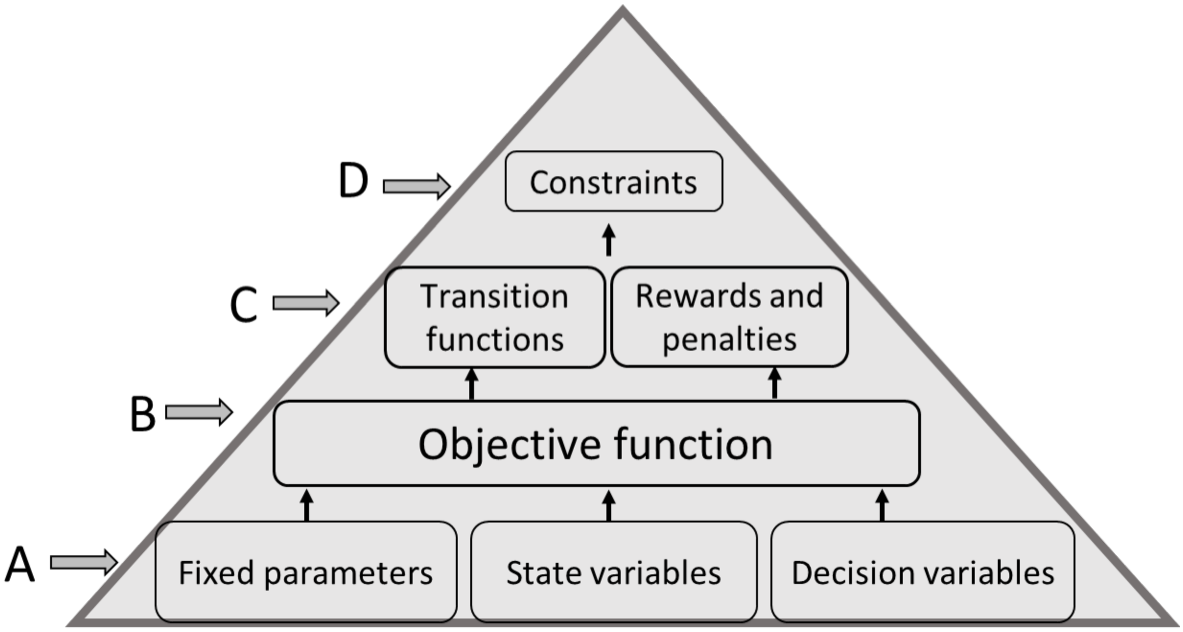

Figure 4: Problem formulation structure.

First, the environment is described with the help of fixed parameters and state and decision variables. Next, the objective function is formulated. After that, the approach to reach the defined objective is expressed through the transition probability matrix together with rewards and penalties. Finally, the constraints are defined. In the following sections, the parts of problems A, B, C and D will be described in detail.

4.1 Part A: definition of variables

Firstly, fixed parameters are the ones that do not change in a decision-making process. The following parameters are given for the *i*th BESS unit:

P_{maxi} maximum charging and discharging power capacity unit [kW]
SOC_{MINi} maximum SOC level, [kWh]
SOC_{MAXi} minimum SOC level, [kWh]
η_{RTi} round-trip efficiency of the battery [p.u.]
E_{MAXi} usable energy capacity of the BESS unit [kWh]
$N_{cyclesi}$ number of cycles
C_{BESSi} unit cost [€/kWh]

Secondly, state variables are defined. A state variable is a time-varying characteristic of the model that represents the storage of mass/volume of the time-varying quantity of interest within the system/model. A number of different state variables taken together can be used to define the state of the system/model. The following state variables are defined at hour t:

$SOC(t,i)$ battery SOC level, or the amount of energy in the ith BESS unit [kWh]
$P(t,i)$ active load in a distribution network where the ith BESS unit is located [kW]
$Q(t,i)$ grid reactive load [kVar]
$PV(t,i)$ solar PV output in a distribution network i [kWh]

As a result, the state of the model consisting of n BESS units can be defined using a state vector:

$$\begin{aligned} S_t = [&SOC(t)1, SOC(t)2, ...SOC(t)N; \\ &P(t)1, P(t)2, ...P(t)N; \\ &Q(t)1, Q(t)2, ...Q(t)N; \\ &PV(t)1, PV(t)2, ...PV(t)N] \end{aligned} \tag{1}$$

Thirdly, decision (control) variables are defined. A control or decision variable is the one that can be changed by the user/decision-maker with the aim of modifying/controlling the behaviour and/or response of the system. The following decision variables are defined at hour t:

$E_{\mathrm{DA}}(t)$ active energy bid to the day-ahead market [kWh]
$E_{\mathrm{BPM}}(t)$ total flexible energy used for the balancing power market [kWh]
$P_{\mathrm{FCR}}(t)$ total power bid to the frequency reserve market (normal or disturbance operation) [kW]
$P_{\mathrm{peak},i}(t)$ peak power to be cut by the ith BESS unit in the ith distribution grid [kW]
$Q_{\mathrm{RPC},i}(t)$ reactive power to be compensated by the ith BESS unit in the

*i*th distribution grid [kVar]

Each decision variable can be represented as a sum of services offered by multiple BESS units:

$$E_{\mathrm{DA}}(t) = \sum_{i=1}^{N} \beta_{\mathrm{DA}}^{i}(t) E_{\mathrm{DA}}^{i}(t) \tag{2}$$

$$E_{\mathrm{BPM}}(t) = \sum_{i=1}^{N} \beta_{\mathrm{BPM}}^{i}(t) E_{\mathrm{BPM}}^{i}(t) \tag{3}$$

$$P_{\mathrm{FCR}}(t) = \sum_{i=1}^{N} \beta_{\mathrm{FCR}}^{i}(t) P_{\mathrm{FCR}}^{i}(t) \tag{4}$$

where $\beta_{\mathrm{DA}}^{i}(t)$, $\beta_{\mathrm{BPM}}^{i}(t)$, $\beta_{\mathrm{FCR}}^{i}(t)$ are binary variables that take the value of 1 if the *i*th BESS unit is used for the day-ahead, balancing power or FCR markets or 0 if the BESS unit is not used in the applications.

As a result, a matrix of binary variables can be formed for each hour of the day for a 24-hour period for a system of four BESS units:

$$\begin{bmatrix} \square & \beta^{1}(t) & \beta^{2}(t) & \beta^{3}(t) & \beta^{4}(t) \\ \mathrm{DA} & \square & \square & \square & \square \\ \mathrm{BPM} & \square & \square & \square & \square \\ \mathrm{FCR} & \square & \square & \square & \square \\ \mathrm{PB} & \square & \square & \square & \square \\ \mathrm{RPC} & \square & \square & \square & \square \end{bmatrix} \tag{5}$$

Multiple possible combination matrices can be obtained for each hour. Each of the combinations leads to a different model propagation in the following 24-hour period. Thus, the number of combinations grows exponentially, and the problem becomes computationally very exhaustive.

However, the number of possible states in each hour is limited by economic and technical constraints, which are expressed by transition functions and constraints, respectively. Below, the transition functions and constraints are specified. Before that, the objective function is derived.

4.2 Part B: Objective function

The main long-term (years) objective of a BESS operator is to maximize the profit over a specific period of time. Considering the applications in which the BESS is operated, the profit can be expressed as:

$$Profit = \max \sum_{t=1}^{T} P_{\mathrm{FCR}}(t) + P_{\mathrm{BPM}}(t) + P_{\mathrm{RPC}}(t) + P_{\mathrm{peak}}(t), \tag{6}$$

where

T	long-term period of time (for example, one year)
$P_{\mathrm{FCR}}(t)$	profit from the FCR hourly market in hour t [€]
$P_{\mathrm{BPM}}(t)$	profit from the balancing power market in hour t [€]
$P_{\mathrm{RPC}}(t)$	profit from the reactive power compensation in hour t [€]
$P_{\mathrm{peak}}(t)$	profit from the peak load cut in hour t [€]

The challenge here is that the profits from grid-related applications cannot be scaled down to a 1-hour period owing to a lack of regulatory framework for those services. For example, the tariffs for the RPC tasks in a distribution network are given on a monthly basis [ref], whereas tariffs for a peak load cut service in the grid are presently absent. Regardless of the type of the grid-related service, the value it delivers to the BESS operator depends on:

- Economic regulations for this service (present fees and sanctions if not staying within the predefined limits)
- Cost of devices installed in the grid providing that service: compensators, reactors, on-tap load changers, power electronic devices (distributed generation (DG) units, others), demand response (DR)
- Frequency of occurrence (how often the service should be provided) and cost of failure/damage that the lack of service causes to the grid

The research question of how to scale the value to a 1-hour resolution is outside the scope of this project. However, a 1-hour resolution value of a service will have an impact on the definition of the priority of applications for the BESS. Next, the profit components of each application can be broken down into revenue and cost components:

$$Profit_{\mathrm{application}} = \int_{t=1}^{T} Revenue_{\mathrm{application}}(t) - Cost_{\mathrm{application}}(t)dt \tag{7}$$

As a result, the objective is to maximize the profit over a specific period of time. This means that the revenues are to be maximized and the costs to be minimized.

4.3 Part C: Transition function, penalties and rewards

The formulated objective function in the previous section determines what has to be done (i.e., maximize the profits). This section will show us how to achieve the target. For this reason, transition functions are introduced.

The objective of introducing a transition function is to set up the rules of the BESS unit operation in a certain application. In other words, how can we define for which application a particular BESS unit should be used during the following hour(s) in order to fulfill the objective function?

The transition functions represent the rules of prioritization of applications in every time step so that the profit is maximized over a longer time period. In this research project, the transition function takes a greedy approach. It is the easiest and most straightforward approach to implement.

In practice, however, maximizing the short-term profits does not always lead to the maximum long-term profits. The short-term objective reaches the local optimum, which is not always the global optimum in the long run. The greedy approach suggests that in each time step, such an application is prioritized in the first order that delivers the highest benefit to the BESS operator. For each application, the total benefit is expressed by the function:

$$Fi(t) = P_{\mathrm{DR,i}}(t) + P_{\mathrm{DR,X}}(t) + P_{\mathrm{DR,Y}}(t) + P_{\mathrm{DR,Z}}(t), \tag{8}$$

where

$Fi(t)$	function of the benefit expected from the application i [€]
$P_{\mathrm{DR,i}}(t)$	profit expected from the first-priority application i [€]
$P_{\mathrm{DR,X,Y,Z}}(t)$	profit expected from the second-priority applications X, Y, Z [€]

$$\textit{Priority}\ 1\text{-}2\text{-}3\text{:}\quad Reward_{123} = Reward_{DR1} + LimReward_{DR2} + LimReward_{DR3}$$

$$\textit{Priority}\ 3\text{-}1\text{-}2\text{:}\quad Reward_{312} = Reward_{DR3} + LimReward_{DR1} + LimReward_{DR2}$$

$$\textit{Priority}\ 2\text{-}1\text{-}3\text{:}\quad Reward_{213} = Reward_{DR2} + LimReward_{DR1} + LimReward_{DR3}$$

$$Selected\ priority = \max(Reward_{123}, Reward_{312}, Reward_{213})$$

Figure 5: Selecting the priority of multiple applications.

The limited reward from an application can be due to two main reasons. The first type of penalty is when a BESS unit was scheduled for the application but the BESS could not provide resources due to technical limitations (for example, a saturated SOC level caused by other applications).

The second type of penalty is a lost opportunity, when a BESS unit was not scheduled for the application.

The rewards and penalties are explained in Table 2.

Table 2: Rewards and penalties from market- and grid-related applications.

DR marketplace	Reward	Penalty
Day-ahead market	Decreased cost of electricity through energy arbitrage	Increased cost of electricity because of consumption at high price hour
Balancing power market	Profit obtained through energy arbitrage	Missing profit from not participating in BP
FCR-N (D) hourly market	Reward for availability of power capacity	Cost of power purchase from another bidder
Peak shaving	Penalty avoided for exceeding power limit	One-time penalty defined according to the cost of capacity
Reactive power	Reduction/elimination of monthly reactive power payments to Fingrid	Excessive reactive power/monthly payments, need to install additional reactors

4.4 Part D: Constraints

The constraints are classified into three groups. First, the BESS-related ones, reflecting the technical constraints of charging and discharging energy and power:

Charging and discharging power of the *i*th BESS unit in each time moment is limited by the maximum value:

$$P^i(t) \leq P^i_{\max}. \tag{9}$$

SOC level in each time moment has to be between the minimum and maximum levels:

$$SOC^i_{\mathrm{MIN}} \leq SOC^i(t) \leq SOC^i_{\mathrm{MAX}}. \tag{10}$$

Reactive power is limited by the maximum value:

$$Q^i(t) \leq Q^i_{\max}. \tag{11}$$

Second, application-related constraints, reflecting the rules of BESS operation in an application. For instance, in the FCR-N hourly market, the BESS operation is defined by the dead band width, droop slope, activation time, response time and energy capacity required in the BESS. In the balancing power market instead, the BESS operation is defined by the bid energy capacity and the regulation of the hour (up-regulation or down-regulation).

Third, constraints that one application sets on another when simultaneous multiple tasks are scheduled. These constraints will define whether a conflict of interests emerges or not when multiple tasks are executed simultaneously. This type of constraints will define a priority order that delivers the highest benefit to a BESS operator. In the literature [10] [11], special attention has been devoted to possible methods to solve a decision-making problem in an uncertain environment. The major challenge of such a problem is that decisions have to be made before the uncertainty is revealed. The final goal of solving the problem is to find such an operating strategy (termed as an optimal policy), which delivers the highest reward over a specific time period. An essential part of finding such an optimal policy includes learning. In such problems, there is always one or multiple decision-maker(s) and an environment in which the decisions are made (see Figure 6). Applied to the BESS control problem, the multiple marketplaces represent an environment where a BESS operator acts as an agent aiming at collecting maximum reward in the environment over a longer period of time.

Figure 6: Agent making actions in an environment and getting reward from them.

The problem has been simplified, for instance, by fixing various assumptions or looking at the problem from a particular perspective. The solving methods include Markov Decision Processes and stochastic programming [12], dynamic programming [13], stochastic mixed integer linear program [14] and data-driven machine learning methods [15]. Recently, reinforcement learning, a field in machine learning, has gained a lot of attention in the research field [16]. Its advantage is that it allows to solve a problem in an uncertain environment without knowing the full model of the environment. This overview of the problem nature and methods used in the literature illustrates the complexity of the problem and its solving methods. There are numerous ways to solve the problem owing to advances in the areas of machine learning, control theory, applied mathematics and availability of more powerful computational facilities. Because of the complexity of the problem and time and resource limitations, the optimization of the problem is not within the scope of the project. Instead, it is put aside to the list of further research questions found in the last chapter.

5 Simulation tool of BESS operation

A simulation tool was created in the MATLAB environment in order to carry out various analyses needed to address the set objectives. First, the basic terms will be explained. After that, the structure of the simulation tool is presented. Finally, various scenarios are tested with the help of the tool, and the results are given in this and the following chapters.

5.1 Explanation of the terms used in the report

The main requirement for the profitable operation of an energy storage unit is that the total annual savings obtained from different applications are higher or equal to the annual cost of the battery use.

$$S_{\text{total}} \geq Cost_{\text{annual}} \tag{12}$$

$$S_{\text{total}} = S_{\text{peakcut}} + S_{\text{RPC}} + S_{\text{FCR}} + S_{\text{BPM}} \tag{13}$$

S_{total} are the total annual savings obtained from such applications as peak cut, reactive power compensation, price arbitrage in different electricity markets (balancing power market) and provision of frequency regulation reserve in the FCR hourly markets. In order to calculate the annual cost of the battery use, let us introduce the term for the minimum annual stored energy in the battery:

$$E_{\text{stored\_min}} = \frac{\text{Total stored energy over the lifetime (cycles)}}{\text{Lifetime (years)}} \tag{14}$$

$$\text{Total stored energy} = N_{\text{cycles}} Capacity(DoD_{100\%})\eta_{\text{RT}} \tag{15}$$

If the annual energy stored in the battery is less than $E_{\text{stored\_min}}$, the lifetime of the battery will be limited by years, otherwise by the number of cycles. The annual stored energy will vary from year to year depending on the electricity market price volatility, frequency deviation and the need for grid services such as peak load cut and reactive power compensation. The annual cost of the battery use can be calculated as follows:

$$Cost_{\text{annual}} = \begin{cases} C1, E_{\text{stored}} < E_{\text{stored\_min}} \\ C2, E_{\text{stored}} \geq E_{\text{stored\_min}} \end{cases} \tag{16}$$

$$C1 = \frac{\text{Total Investments}}{\text{Lifetime (years)}} \tag{17}$$

$$C2 = price_{\mathrm{kWh}} E_{\mathrm{stored}} \tag{18}$$

$$price_{\mathrm{kWh}} = \frac{Cost_{\mathrm{kWh}} Capacity(DoD_{100\%})}{N_{\mathrm{cycles}} Capacity(DoD_{100\%}) \eta_{\mathrm{RT}}}, \tag{19}$$

where

$C1$	Calendar-aging-based annual cost of use [€]
$C2$	Cycle-aging-based annual cost of use [€]
Lifetime	the number of years equal to the payback period, in this case, equal to the guaranteed lifetime [years]
$Cost_{\mathrm{kWh}}$	unit cost of the battery capacity [€/kWh]
N_{cycles}	number of cycles with a full depth of discharge (DoD), given by the battery manufacturer
η_{RT}	round-trip efficiency of the battery (charging/discharging) [p.u.]
$price_{\mathrm{kWh}}$	price of energy stored in the battery [€/kWh]
$Capacity(DoD_{100\%})$	total usable capacity of the battery [kWh]

The profitability requirement of a BESS unit on an electricity market is guaranteed when the market price difference between charging and discharging events is at least as high as the price of stored energy:

$$Price(ty)_{\mathrm{discharge}} - Price(tx)_{\mathrm{charge}} \geq price_{\mathrm{kWh}} \tag{20}$$

5.2 Implementation of BESS control

The implementation of BESS operation (charging and discharging) against multiple control signals can be realized through two platforms: upper-level decision-making and lower-level implementation. Figure 7 illustrates the structure of such control implementation. The upper-level contains the control algorithms and logics and serves as software while the lower-level platform serves as hardware that enables the implementation of the algorithms from the upper level. The database in the upper level obtains up-to-date information about the power system and electricity market data, weather forecasts and BESS state. This information allows to make decisions at the upper level upon which tasks, in which priority, how much power and energy the specific BESS unit should consume or supply in which hours of the day. The obtained decisions are sent down to the lower-level implementation platform through the telecommunication channel, where they are realized on the BESS premises. The updated BESS parameters after the realized commands are sent back to the upper-level decision-making platform, where they are taken into account when making decisions for the following hours.

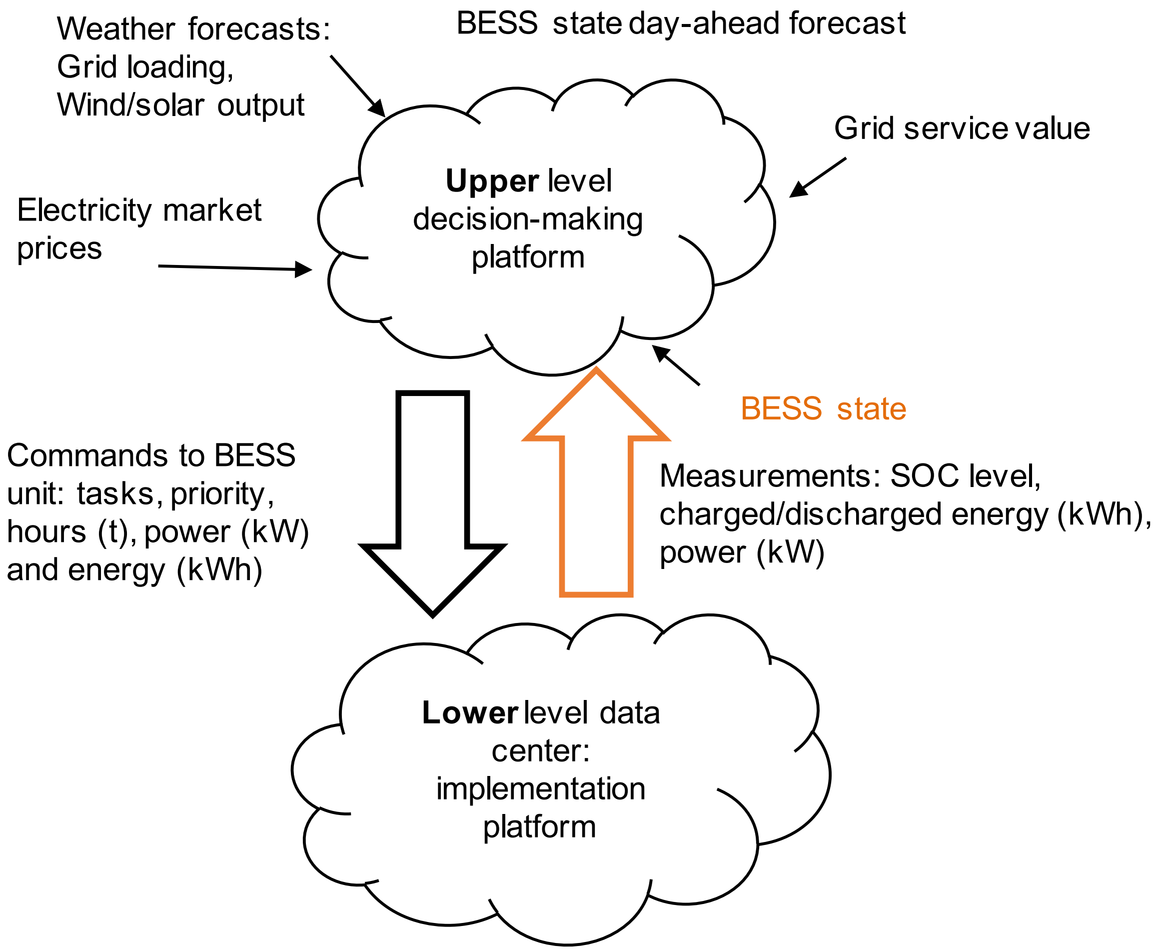

Figure 7: Upper and lower levels of the platform.

The research project concentrates on the upper-level decision-making logic and the technical implementation of the interconnection between the two platforms.

5.3 Capacity allocation to multiple tasks: electricity market bidding sequence

The capacity allocation procedure is divided into a planning phase and an operational phase. The planning is outlined the day before the physical delivery (see Figure 8). The considered system-level applications are the Nordpool day-ahead market, the Frequency Containment Reserve hourly market in normal (FCR-N) and disturbance (FCR-D) operation and the balancing power market in the Nordic countries. The grid-level tasks comprise reactive power compensation, active peak power shaving and voltage control.

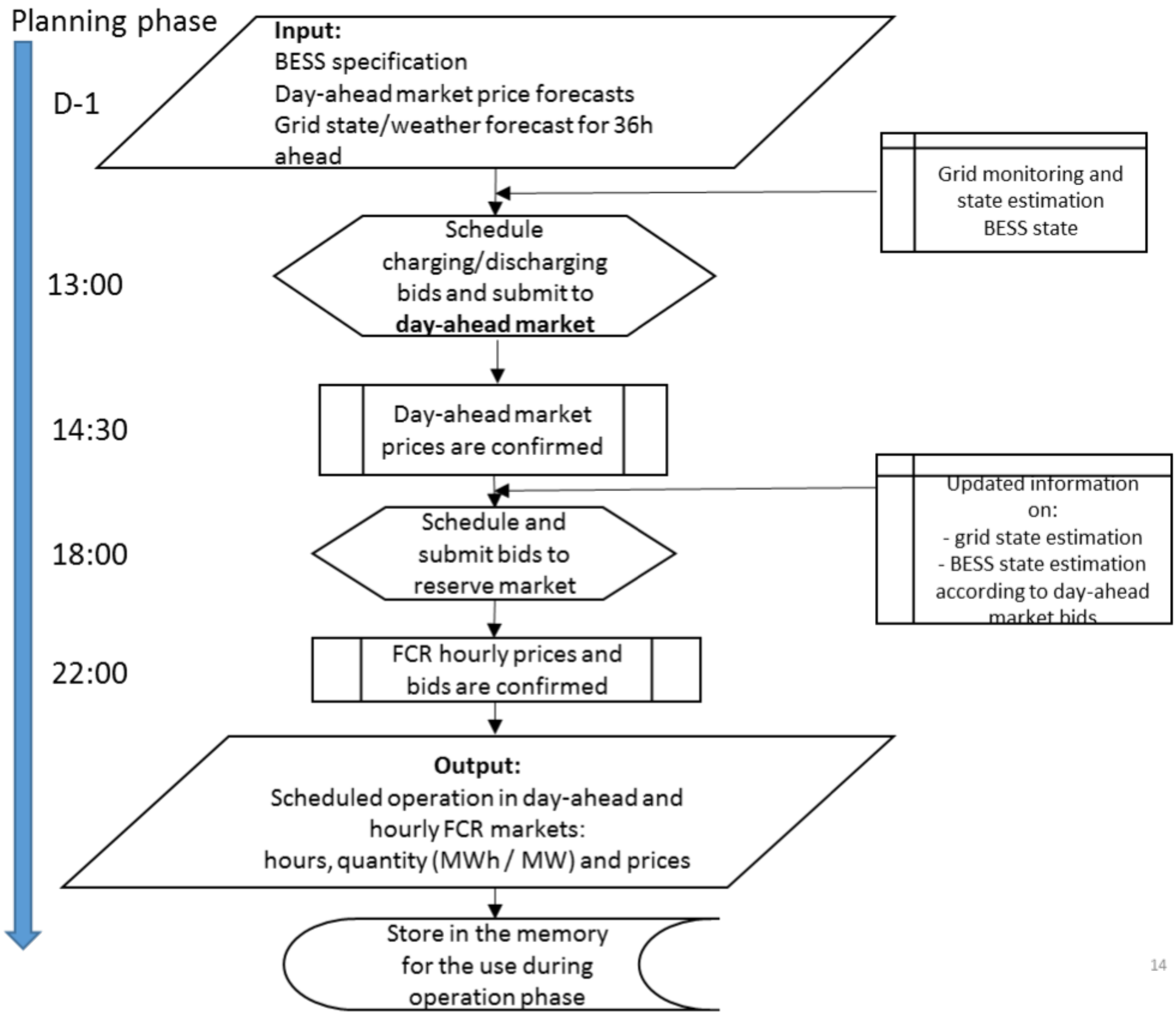

Figure 8: Planning phase.

The output of the planning phase is known at the end of the day at 10:00 pm when the results from the TSO are obtained regarding which bids have been accepted for the next day. The output includes the information on how much power/energy is offered to which market, at which hour and at which price during the next day. After this phase, the scheduled applications are known for each hour, and the approximate SOC level can be estimated (see Figure 9).

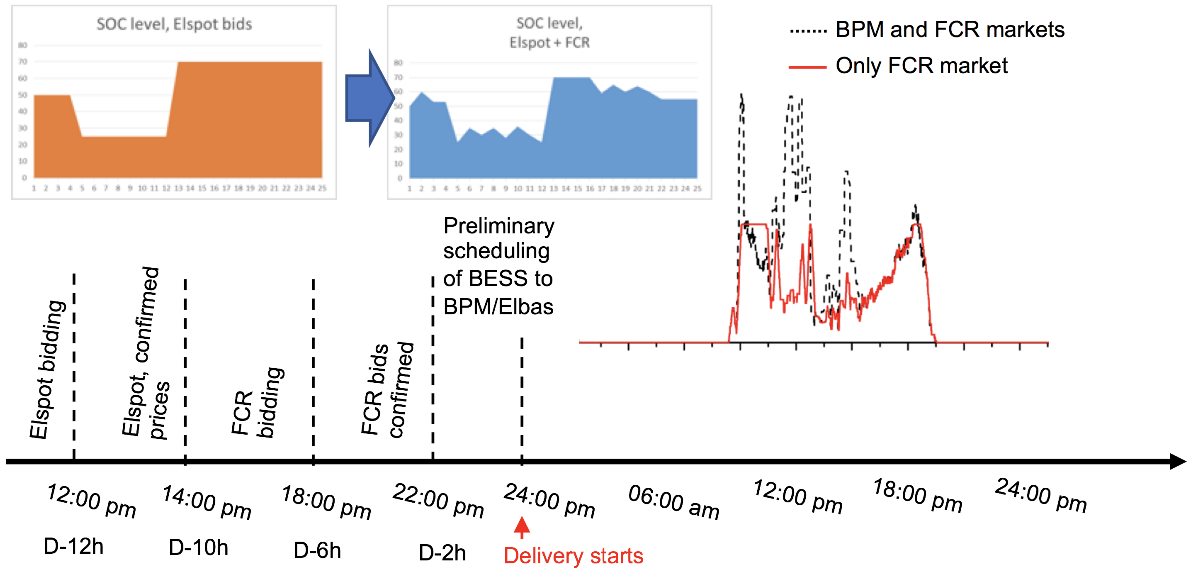

Figure 9: Electricity market bidding sequence and approximate SOC level.

The next phase is an operational phase (see Figure 10), where the decisions are reconsidered in each hour for the hour ahead. This time, the decisions are made regarding to which applications the BESS capacity will be allocated. In this phase, the planning-phase decisions are reconsidered according to the updated information about the local grid state and price forecasts in the intra-day markets (e.g., the Elbas intra-day market and the balancing power market). First, the scheduled and alternative applications are listed and classified into grid- and market-related ones. Next, the procedures presented in the green box in Figure 10 are executed:

1. Define whether the two or more scheduled and alternative applications conflict with each other or not during the hour in question. The conflict means that BESS capacity allocation to one task limits its availability and revenue from the other task(s). It can also mean that the need for task A is more important than the need for task B in hour t; however, the reward mechanism does not reflect it. The conflicting nature depends on many things, for instance, BESS technical operational constraints, regulatory framework, time of the day and BESS location, and it will be analysed later in the report.
2. After the conflict of interests is analysed, rewards and penalties are calculated for the participation in each application.

Finally, conclusions are made regarding the priority of the tasks, and the BESS is scheduled to operate accordingly, after which the BESS state is updated for the decision-making process for the next hour.

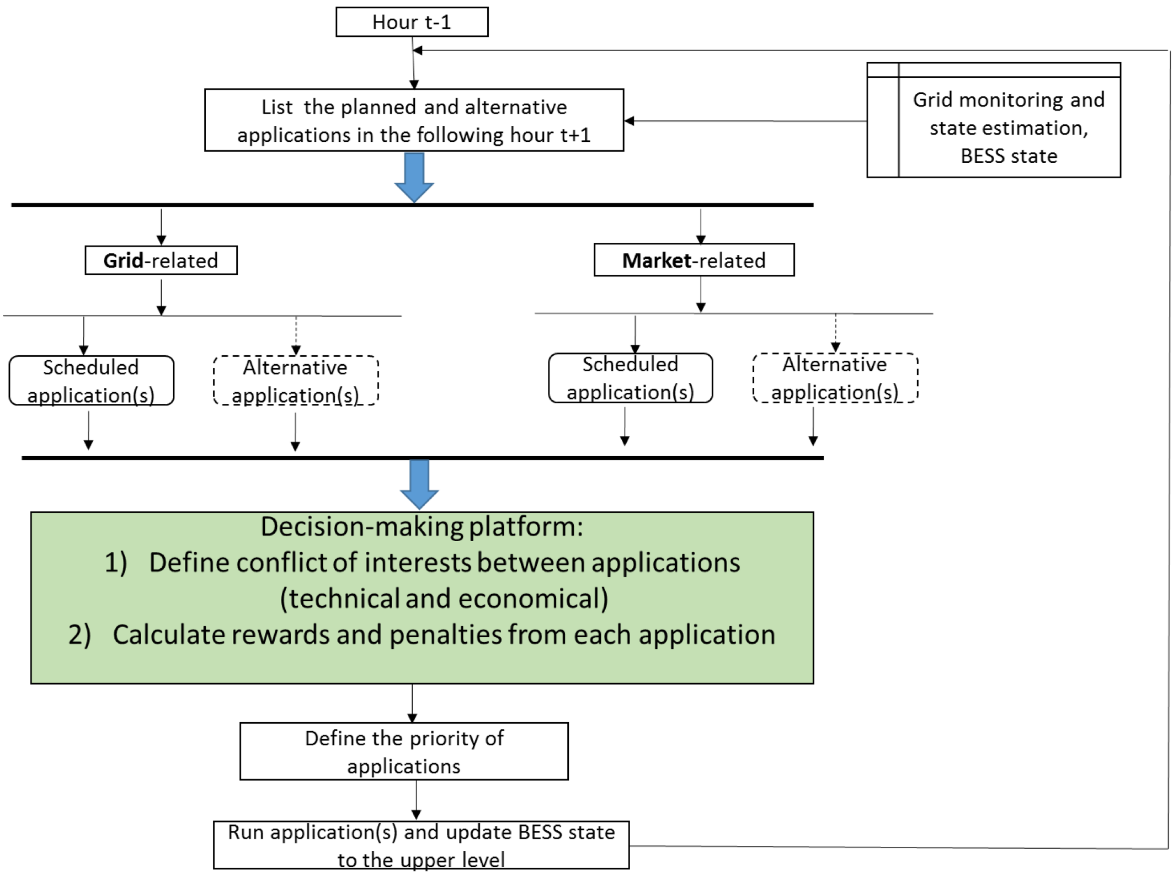

Figure 10: Operational phase.

5.4 Simulation tool logic

During the building stage of the simulation tool in MATLAB, the primary goal was to make it as flexible as possible to the input parameters and not fix it to any specific operating environment. The structure of the tool is presented in Figure 11. It can be seen that the tool is divided into smaller parts, called toolboxes, according to the time resolution: day, hour, second and year. In the day-resolution logic, the planning phase logic is modelled (as presented in Figure 8). In the hour-resolution logic, the operational-phase logic is modelled (see Figure 12). In the second-resolution logic, the definition of charging/discharging power is obtained according to the control signal (for instance, frequency deviation) and set operating parameters (droop slope, activation time, response time). In the last toolbox, the techno-economic parameters are calculated using the outcome from the set-up operation logic in the day-, hour- and second-resolution toolboxes. The principles of the techno-economic analysis are presented in Section 1.20. An output from each toolbox serves as an input to the following toolbox. Besides that, each toolbox has its own input called Logic D, Logic H and Logic S, where the input parameters can be varied.

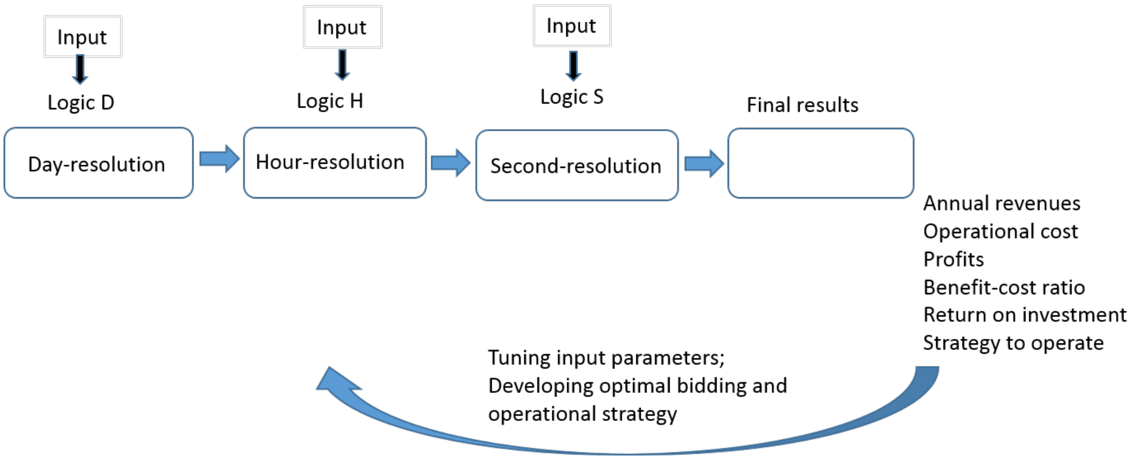

Figure 11: Impact of day-, hour- and second-resolution logic to the output parameters.

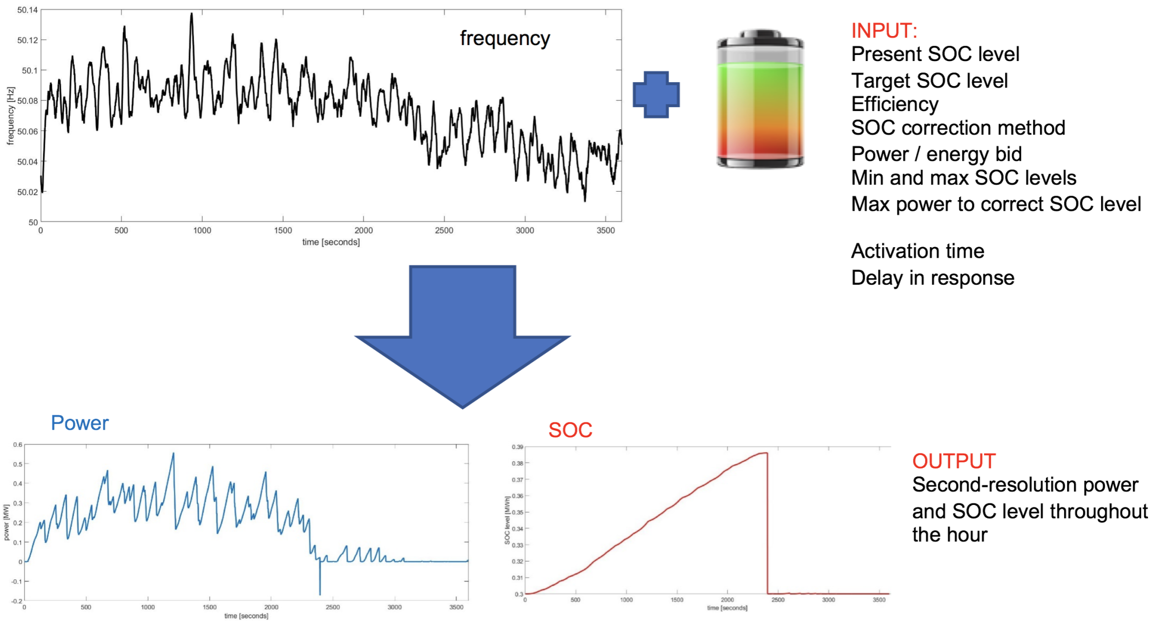

Figure 12: Hour-resolution toolbox.

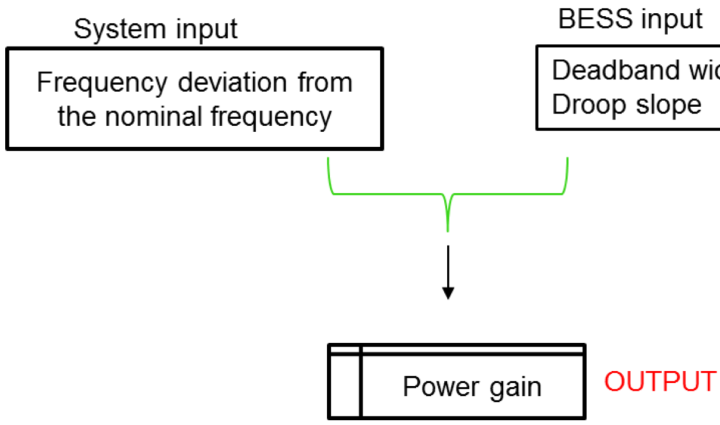

Figure 13: Hour-resolution toolbox.

The secondary goal of the simulation tool is to test numerous scenarios with various input parameters in each of the three toolboxes, in other words, carry out sensitivity analyses. The final goal of the simulation tool is to find a combination of the input parameters to each of the toolboxes that provides the optimum or close-to-optimum techno-economic results, and thus, a recommended operational strategy can be obtained. However, this goal is out of the scope of the project, but it is included in the further research questions in the last chapter of this report.

5.5 Sensitivity analyses

The number of possible variable parameters can be so large that it is computationally challenging to carry out sensitivity analyses. Therefore, it is important to state the goals of the sensitivity analysis and then derive the parameters and combination of parameters that we are interested in. The specific questions within the sensitivity analyses in the context of this research are the following:

1. How much does the size of price bid to the FCR hourly markets affect the revenues?
2. How do the droop slope, activation time and response time affect the energy stored in a BESS and thereby the profit?
3. How sensitive is the annual profit to the frequency quality and the frequency hourly market prices?

This knowledge makes it possible to fine-tune the control parameters at different resolution levels with the final goal of optimizing the outcome parameters (see Figure 14).

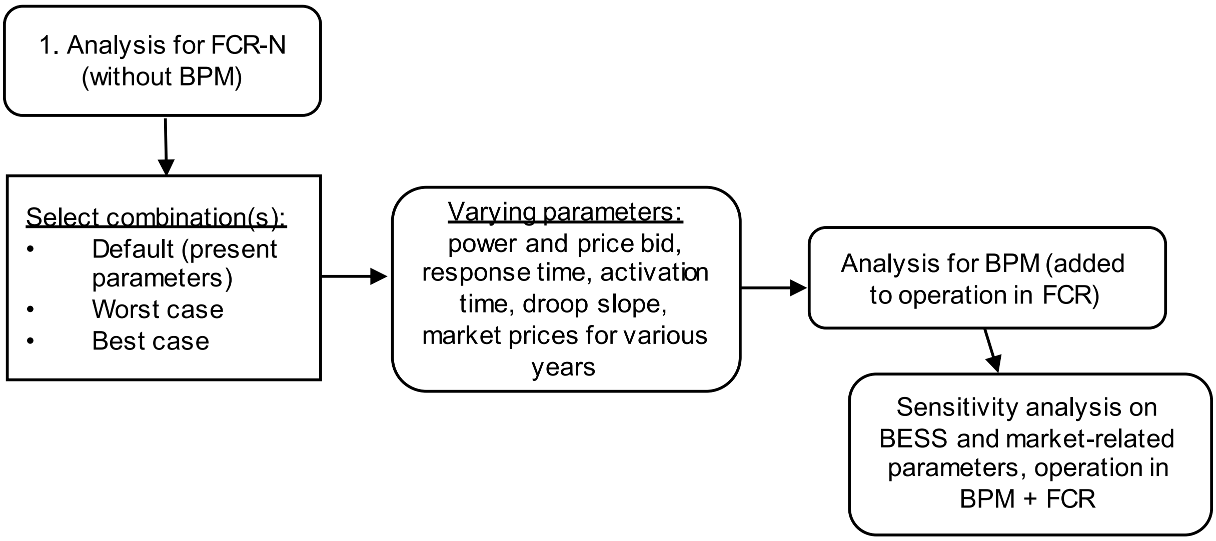

Figure 14: Flow of the sensitivity analyses.

In the further subsections, some of the parts are presented in more detail.

5.6 Frequency regulation with varying parameters (activation time, response time, droop slope)

The parameters of BESS operation for the frequency regulation are illustrated in Figure 15.

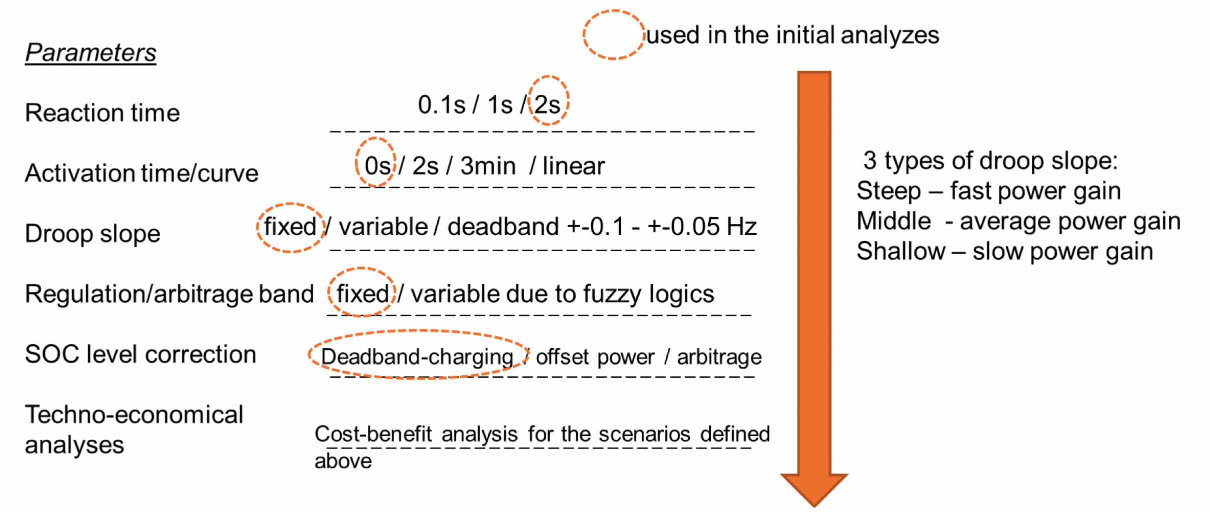

Figure 15: Varying parameters for a sensitivity analysis.

The selected varying parameters are droop slope, activation time and response time. The droop slope was varied from steep (fast power gain) to shallow (slow power gain) (see Figure 16) by the droop parameter:

$$\sigma = -\frac{\frac{\Delta f}{50}}{\frac{\Delta P}{P_n}}100 \tag{21}$$

$$\Delta f = [0.01; 0.05; 0.1] Hz \tag{22}$$

$$\sigma = [0.02; 0.1; 0.2] \tag{23}$$

where $\Delta = 0.01$Hz represents a steep slope and $\Delta f = 0.1$Hz represents a shallow slope.

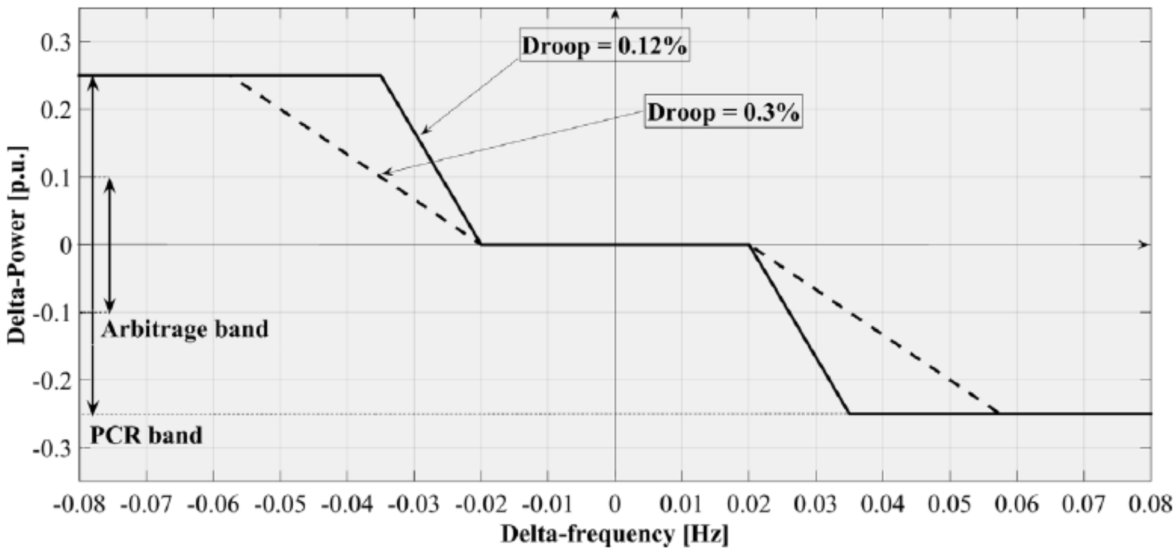

Figure 16: Varying droop slope from steep to shallow [17].

The activation time was selected to be 0.01 s, 2 s and 180 s, and the response time was selected to be 0 s, 1 s and 2 s. In the FCR-N hourly market, the activation time requirement is 180 s, which means that the power has to reach the promised power bid within 3 min from the frequency deviation moment. The power increase has to be more or less linear, which is also modelled in the simulation tool. The assumption for the power bid was 0.48 MW and the price bid was 10 €/MW.

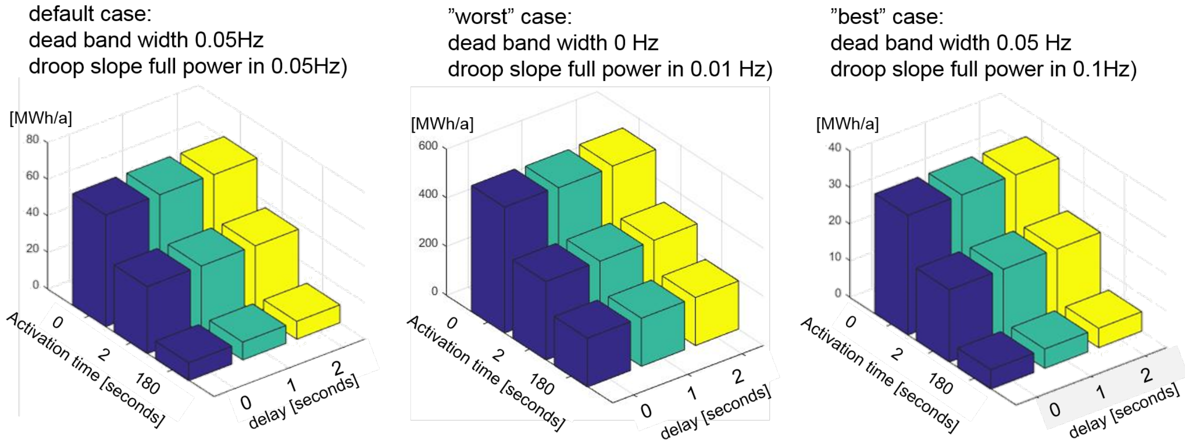

Figure 17: Impact of activation and delay time on the annual energy stored in the BESS.

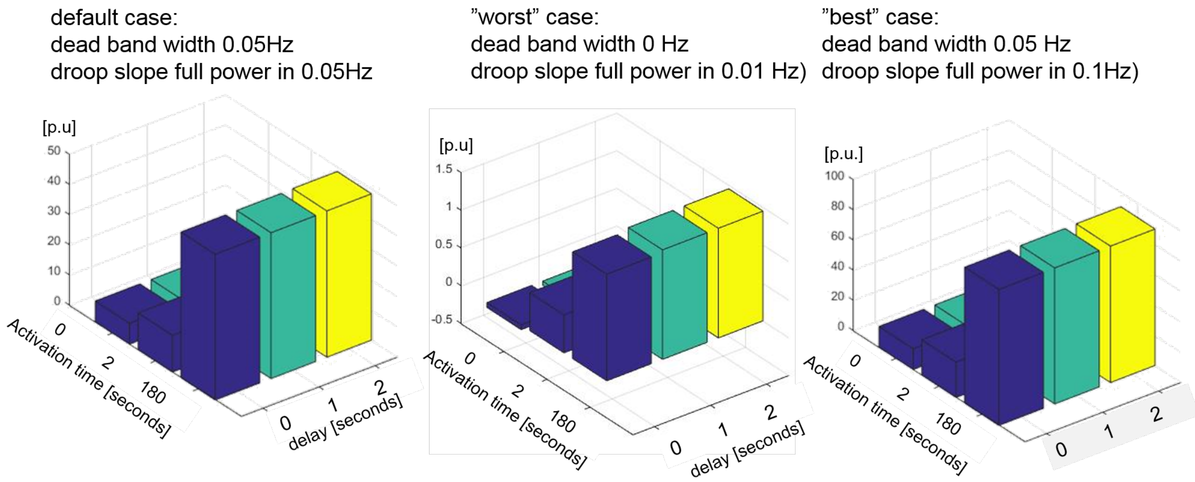

Figure 18: Impact of activation and delay time on the benefit-cost ratio of BESS operation.

The results show that the activation time has a major impact on the annual energy and thereby on the operational annual costs.

- The "worst" case is the worst one for the BESS operator because of the high operational costs. However, such a case may be preferable for the TSO most of the time. If the TSO wants the BESS to provide a fast reserve response, the remuneration mechanism should be reconsidered so that it compensates for the high operational energy-related costs and it is thus economically attractive for BESS operators to provide a fast response to frequency deviation.
- The cycle lifetime above 10–20 years is not feasible for the BESS operation (limited by power electronics and calendar lifetime). For a profitable operation, battery cycles should be used out by the time the battery reaches the calendar lifetime. Therefore, energy-dense

applications should be found that increase the usage of the BESS and thereby the number of revenue streams to the BESS operator.

5.7 Market price analysis: FCR-N, FCR-D hourly market and balancing power market

Figure 19 presents the number of hours when the price was higher than the size of a price bid.

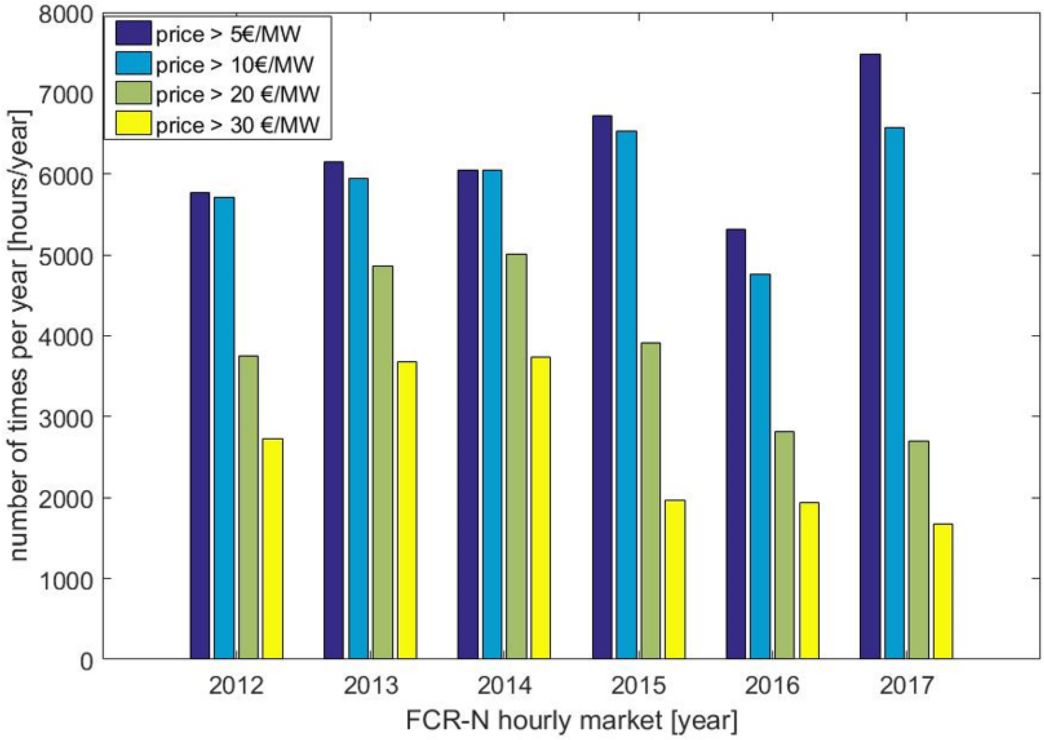

Figure 19: Number of hours when the market price was higher than the price bid.

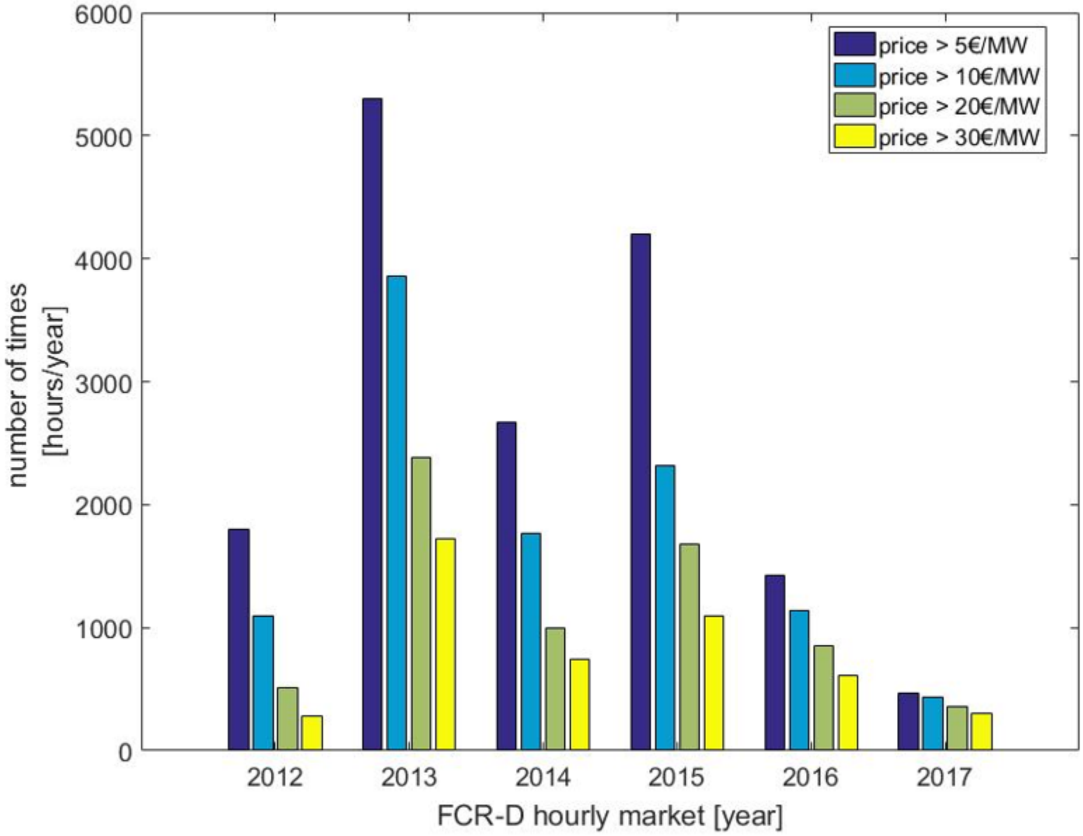

Figure 20: Number of hours when the market price was higher than the price threshold.

At the same time, the frequency quality has decreased over the past few years. It means that the duration of frequency being continuously outside the dead band width has increased. This, in turn, means that the operational cost of the battery due to the energy stored is also increasing.

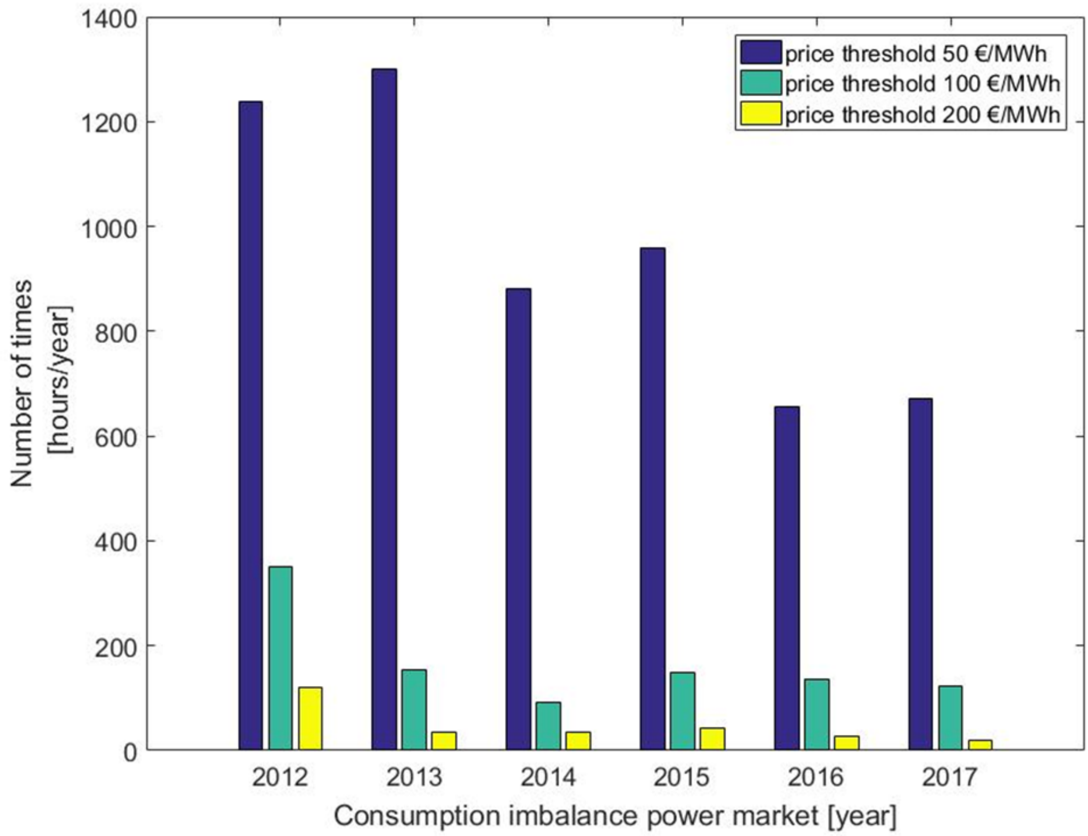

Figure 21: Number of occurrences of the price exceeding a price threshold.

Based on Figure 19, Figure 20 and Figure 21, the following observations can be made:

- The price level in all considered markets is falling from year to year, which means a decreasing earning potential for the participating resources.
- The downward trend of the prices may continue as the number of flexibility resources participating in the markets increase.
- At the same time, the unit price of battery technology and power electronics is going down, which means that also lower prices in the markets may guarantee a profitable operation of the resources.

5.8 Revenue analysis for various electricity market years

A sensitivity analysis has been done for the years from 2012 to 2016 for the hourly FCR-N, FCR-D and balancing power markets. FCR-N market: The fixed parameters had the following values:

- The dead band width is 0.05 Hz, which corresponds to a default case.
- The droop slope is 0.05 Hz, which is the currently used slope. This means that the power

reaches its maximum value by the time the frequency deviation from the dead band is 0.05 Hz, or $f < 49.9$ Hz and $f > 50.01$ Hz.

- The response time was set to be 2 s and the activation time was 180 s.
- The power bid was set to be 1 MW (presently default in the Suvilahti BESS unit).

The varying parameters were:

1. Price bid size [10 30 50] €/MW. The price bid was assumed to be fixed throughout the whole year. The bid was accepted if the market price exceeded the bid price.
2. FCR-N hourly market prices, from year 2012 to year 2016.

The annual energy stored in the BESS was calculated and the revenues obtained.

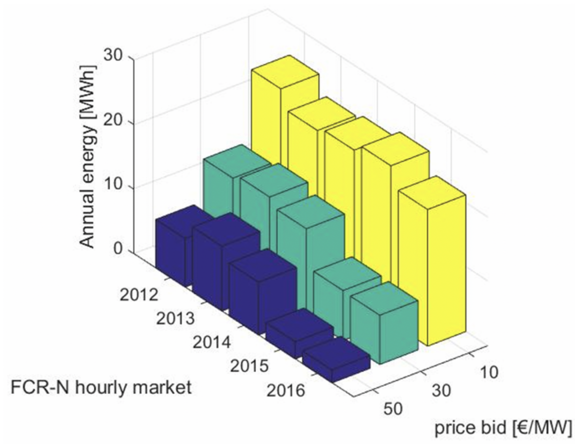

Figure 22: Annual energy stored for frequency regulation with the power bid of 1 MW.

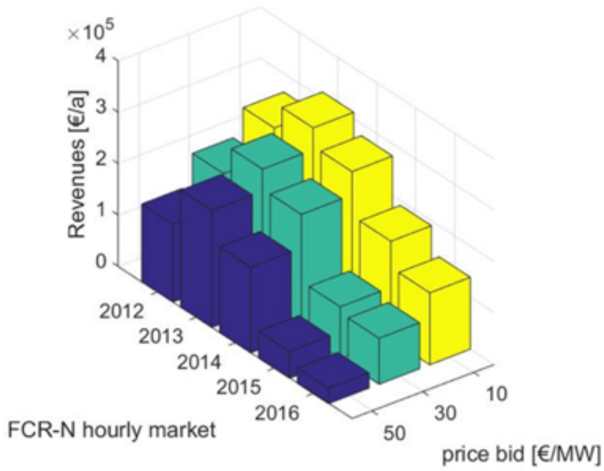

Figure 23: Annual revenues from the FCR-N hourly market.

The calculations show that the changes in the annual energy (Figure 22) and thereby the operational costs are minor from year to year for the same price bid level. The reason for this is that the frequency regulation task is power-intensive by nature, but not energy-intensive. On the other hand, the changes in the annual revenues from year to year are significant (Figure 23). For instance, the change in revenues for the price bid 50€/MW between the years 2013 and 2016 is 19820 €, which is 87 % less than in 2013. Another example from the figure shows that in year 2016 the annual revenue for the price bid 10€/MW was 55 % less than in year 2013. The revenues from the FCR-D market for the 1 MW power bid were calculated for the years from 2012 to 2017. The results are depicted in Figure 24.

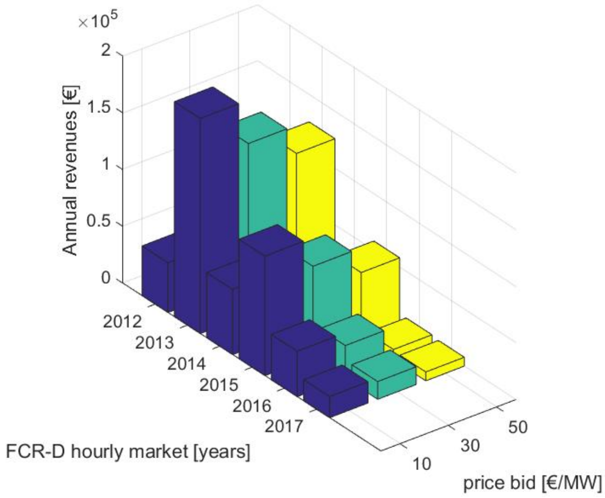

Figure 24: Revenues from FCR-D hourly market in years 2012–2017.

The decrease in annual revenues from year 2013 to 2017 is explained by the decreasing price levels in the FCR-D hourly market. Further, the annual revenue and energy analysis in the balancing power market for the years from 2012 to 2017 is presented in Figure 25 and Figure 26.

Figure 25: Revenues from the BPM market for the 0.5 MWh bid BESS capacity.

Figure 26: Annual energy allocated to the balancing power market.

It can be concluded that the changing price level and volatility in the markets from year to year have a significant impact on the revenues. The price level and thereby the earning potential in all the three markets under consideration have been decreasing from year to year.

5.9 Break-even analysis of BESS operation in electricity markets

This chapter has a twofold goal:

1. Determination of the price threshold in the electricity markets that yields a profitable operation of a BESS unit in a specific number of years.
2. Definition of the unit price of the battery technology that is needed for the BESS operation to become profitable with today's market prices.

5.9.1 Methods

The break-even analysis is carried out using the network present value calculation. The annual revenues are calculated for different BESS operational cases:

1. only FCR-N hourly market
2. only FCR-D hourly market
3. only balancing power market

The revenues from the balancing power market were calculated for the price differences of 50, 100 and 200 €/MWh, and 0.5 MWh of energy capacity was charged and discharged at those price differences:

$$Bt(BPM) = \sum_{1}^{N_{days}} \sum_{t=1}^{24} (Price_{\text{discharge}}(t_{\max})E_{\text{discharge}}(t_{\max}) - Price_{\text{charge}}(t_{\min})E_{\text{charge}}(t_{\min}) \quad (24)$$

The revenues from the FCR-N and FCR-D hourly markets are calculated as

$$Bt(FCR-X) = \sum_{1}^{N_{\text{days}}} \sum_{t=1}^{24} Price_{(}FCR-X)(t) * P_{\text{bid}}(t) \quad (25)$$

Finally, the net present value is calculated as follows:

$$NPV = \sum_{t=1}^{T} \frac{B_t}{1+r}^{t} - C_0, \quad (26)$$

where

*B*t revenues from FCR-N or FCR-D, BPM, €

C_0 initial investments, €

T length of the period, years

r rate of interest, p.u.

The break-even point is obtained when the net present value of the project turns from negative to 0 and becomes positive. This is the time when the initial investments are paid back by the obtained revenues. A payback can be called technical when all cycles are run, and economic when all investments and operational costs are paid back. These two paybacks can be different depending on the revenue size and amount of energy stored for the application in question. The technical payback can roughly be calculated as:

$$Payback(years) = \frac{E_{\text{Total, stored (over lifetime)}}}{E_{\text{Stored (in 1 year)}}} = \frac{N_{\text{cycles}} DOD(\%)}{E_{\text{Stored(1 year}})} \tag{27}$$

The *NPV* is calculated for different revenue values representing different volatilities in prices in the electricity markets.

5.9.2 Results in the markets as independent applications

The break-even analysis is carried out in the example of the Suvilahti BESS, as well as for various unit prices of battery technology; 1000 €/kWh and 500 €/kWh. In Figures 27–29, the calculation results are presented for the FCR-N hourly markets for various battery unit prices.

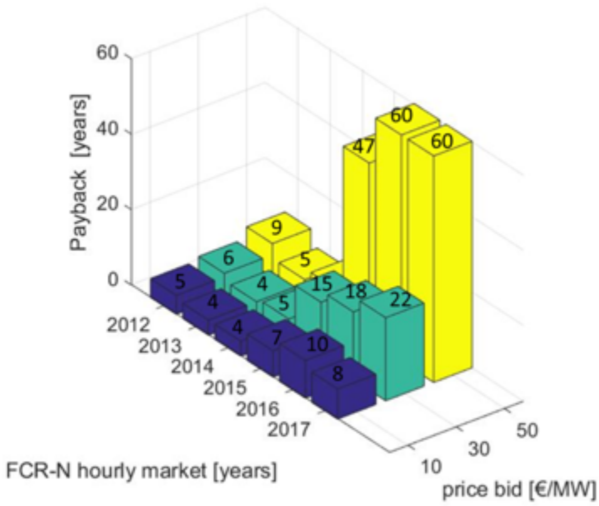

Figure 27: Break-even point when the NPV turns 0 for various price volatilities (battery unit price 2000 €/kWh).

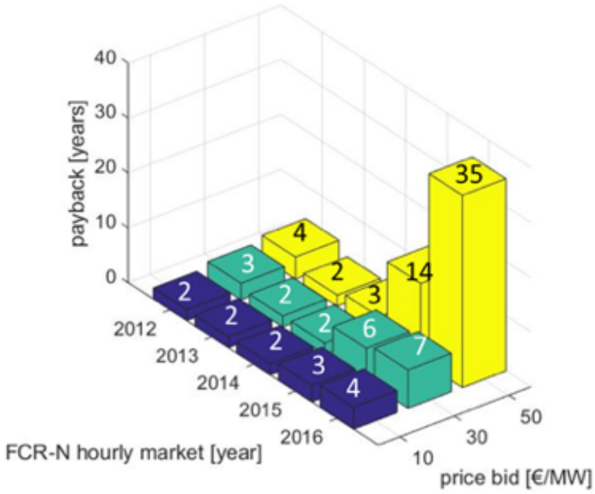

Figure 28: Break-even point when the NPV turns 0 for various price volatilities (battery unit price 1000 €/kWh).

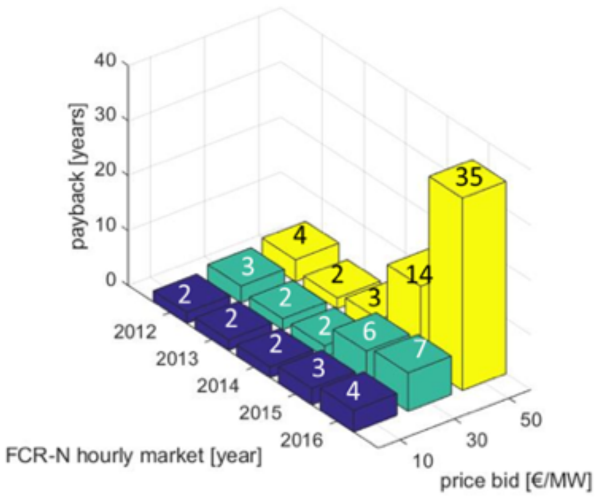

Figure 29: Break-even point when the NPV turns 0 for various price volatilities (battery unit price 500 €/kWh).

The results show that the payback is becoming shorter with the decreasing price of battery unit.

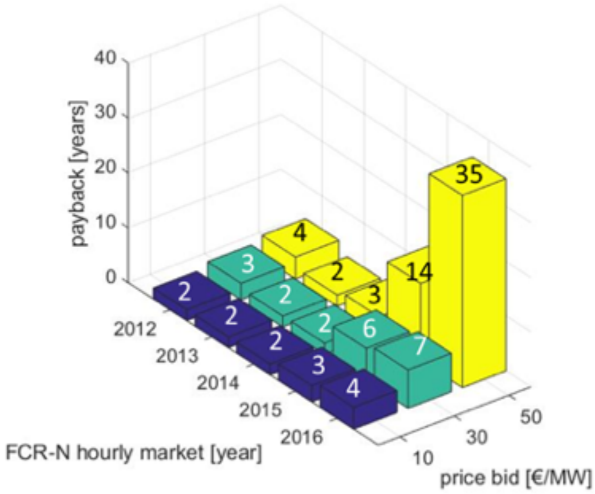

Figure 30: Break-even point when the NPV turns 0 (price of battery 2000 €/kWh).

It can be seen that the break-even point can be achieved in eight years already with the present prices in the FCR-N hourly market at the price bid of 10 €/MW and the battery unit price of 2000 €/kWh. In the FCR-D hourly market, the price level and the frequency of the frequency reserve activation is not enough to be profitable for the BESS (except for year 2013). In the case of the balancing power market, the break-even point was not achieved even in 60 years of observation time. Even though the break-even point can be achieved in ten years in the FCR-N hourly market, the BESS remains heavily underutilized, which is illustrated in Figure 31.

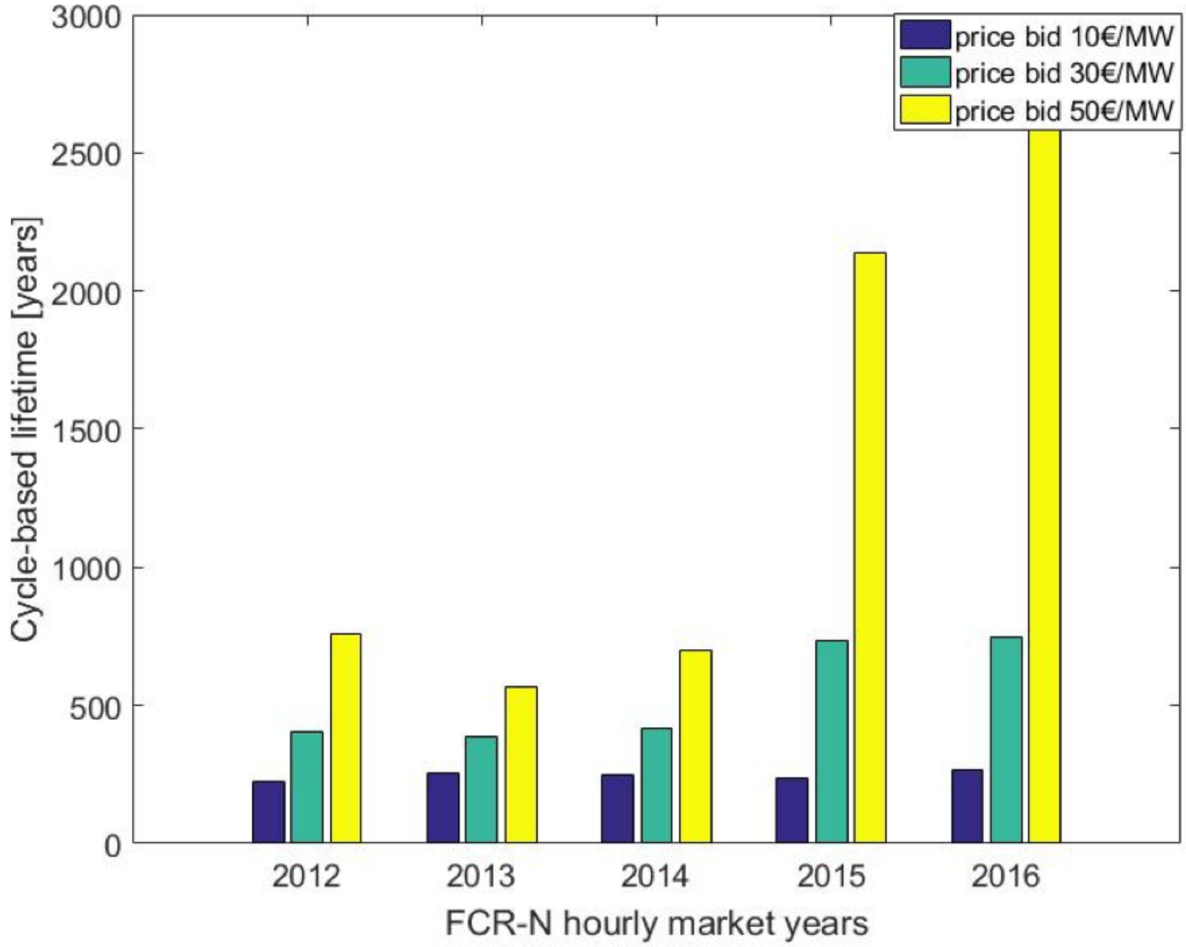

Figure 31: Number of years when all cycles are run if the BESS is operated only in the FCR-N hourly market.

Based on the net present value calculation and the break-even analysis, the answers can be given in response to the two questions set at the beginning of the subsection. First, we determine the price threshold in the electricity markets that yields a profitable operation of a BESS unit in a specific number of years. The profitable operation assumes that the break-even point is achieved within 5–10 years (all initial investments are covered by the revenues obtained). In the FCR-N hourly market, the prices should be above

$$C_0 = N\text{years} * Revenues = N_{\text{years}}(1\text{MW} * X\left[\frac{€}{\text{MW}}\right] * F\left[\frac{times}{year}\right]) \tag{28}$$

$$X\left[\frac{€}{\text{MW}}\right] * F\left[\frac{times}{year}\right] = \frac{C_0}{(N_{\text{years}} * 1MW)} \tag{29}$$

The results were calculated using Eq. (29) and collected into Table 3. Table 3 shows the price level and how often per year it should occur so that the initial investments were paid back in n

years with the 1 MW power bid size.

Table 3: Number of occurrences of the price level in order for the investments to be paid back in 5, 8 and 10 years.

Price level [€/MW]	Payback (number of years, *n*) 5	8	10
10	24 000 (not feasible)	15 000 (not feasible)	12 000 (not feasible)
30	8 000	5 000	4 000
50	4 800	3 000	2400
100	2400	1500	1200

Based on the results, for instance, if the price level in the FCR-N market was 100 €/MW, it would take 2400 times for such a price to be in the market during a year in order to reach the payback in five years. Referring back to Figure 27, in 2016 the payback (or break-even point) would be achieved in ten years if the BESS was operated at the prices higher than 10 €/MW. In 2016, the prices in the FCR-N hourly market exceeded the 10 €/MW threshold 5033 times, and the mean price was 28 €/MW. This also supports the figures in Table 3, which shows, for example, that the price level of 30 €/MW should occur at least 4000 times in order to have the investments paid back in ten years.

Second, we define the unit price of battery technology that is needed for the BESS operation to become profitable with today's market prices. Thanks to the battery technology improvements and a growing market, the price of lithium-ion battery technology is continuously decreasing. At the same time, the market price analyses show a downward market price trend. Yet another fact affecting the profitable operation is the number of revenue streams for the BESS operation. The more tasks a BESS unit is performing and thus obtaining profit, the higher is the chance also for the expensive batteries to be operated in a profitable way. Nevertheless, with the calculations presented above, the battery operation is profitable already today in the power-intensive applications and not profitable in the energy-intensive ones.

5.10 Simultaneous operation in the FCR-N hourly market and the balancing power market

In the preliminary simulation of BESS operation in the balancing power market during the hours free from the frequency regulation task, it has been observed that the high up-regulating prices in the market always occur during the frequency regulation hours and are thus ”missed” by the BESS operator. After this observation, the price correlation was studied using historical market

Table 4: Illustration of price correlation between BPM and FCR-N markets.

Price in BPM	> 50 €/MWh	> 100 €/MWh	> 250 €/MWh	> 350 €/MWh
Year 2012	956 /1237 = 77 %	272/351 = 77 %	54/69 = 78 %	29/39
Year 2013	1021/1300 = 78 %	131/154 = 85 %	11/11	5/5
Year 2014	791/882 = 89 %	79/93 = 85 %	15/15	3/3
Year 2015	916/960 = 95 %	147/149 = 98 %	36/36	11/11

prices, and a positive correlation was obtained. Table 4 illustrates the percentage of hours when the regulation in the FCR-N hourly market is ON during the hours when the balancing power market (BPM) price is higher than 50, 100, 250 and 350 €/MWh.

This observation means that a BESS should be operated for the BPM market during the same hours as the frequency regulation task. The price bid definition to the BPM market can be calculated following the developed logic presented in Figure 32.

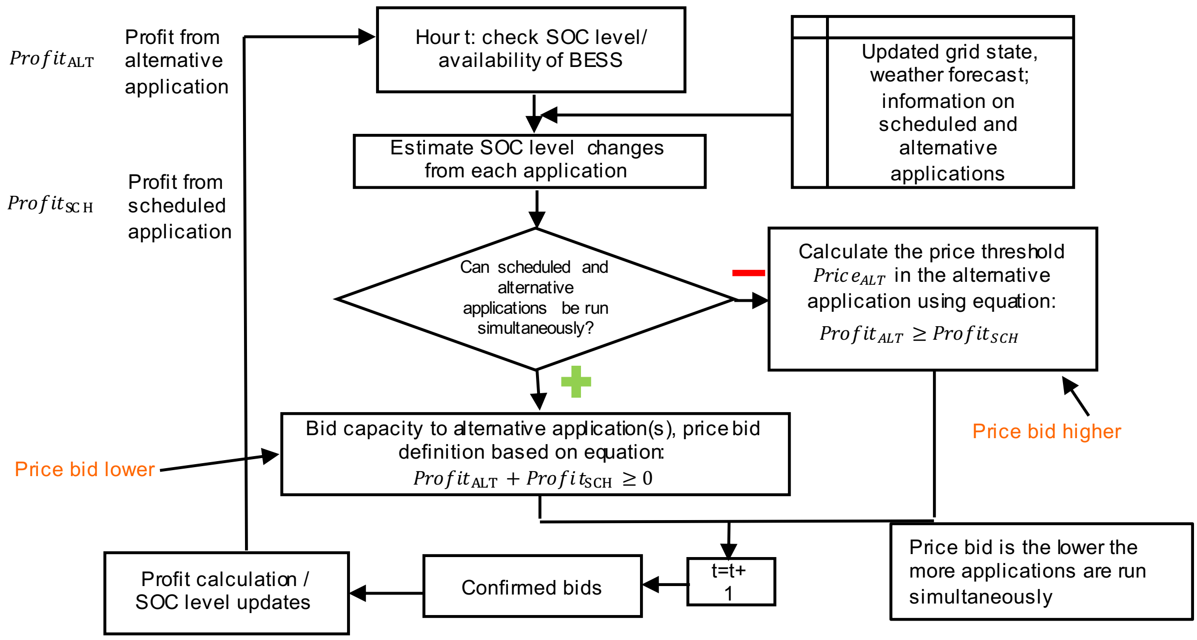

Figure 32: Decision-making logic of the operational phase to define the price bid threshold to the BPM knowing the price in the FCR-N hourly market.

5.11 Results of the sensitivity analyses

1. The droop slope and activation time have a significant impact on the energy required from the BESS to fulfill the frequency regulation. The delay in response, in turn, has only a minor effect on the outcome (because of the small parameter variation). Two highlights:
2. • There is an opportunity to improve the economic performance of the BESS operation in the FCR markets with the current rules

  - The TSO may need to reconsider a remuneration mechanism for the faster performance for the BESS operators to compensate for the large operational energy costs and thus attract faster reserve resources to the market.

3. The BESS requires SOC correction methods when participating in frequency regulation because of the battery efficiency of less than 100 % and owing to the asymmetry in frequency deviation when the regulation is not done in every hour of the year. The SOC correction methods and their consequences are to be considered in the future research.
4. A correlation has been observed between the FCR-N hourly market prices and the BPM prices. BESS operation in the balancing power market (BPM) during the hours ”free” from the frequency regulation task does not bring significant profit because the prices are likely to be low in those hours. High-price hours (higher than 100 €/MWh) in the BPM tend to coincide with the frequency regulation hours in the FCR-N hourly market. Therefore, BESS energy allocation to the BPM should be done during the frequency regulation hours.
5. BESS profitability from simultaneous operation in the BPM and the FCR seems to be more beneficial than using the BESS for the FCR only, as long as charging/discharging energies and price bids are optimized.
6. With the present parameters in the simulation (i.e., response time 2 s, immediate activation time, fixed droop slope) the most optimal operation of the BESS seems to be at the price bid (to the FCR-N market) of 10 €/MW and the highest possible power bid [MW] to the FCR-N hourly market, yielding the highest benefit-cost ratio and the shortest payback time.

6 Conflict of interests between stakeholders

This chapter presents analytical discussion on the interests of multiple stakeholders and their relationship. It is assumed that there is a BESS operator, who may be the BESS owner, an aggregator, a retailer or some other third party. The BESS operator has to apply such an operating strategy that delivers him/her the maximum profit. The operating strategy defines which task(s) are executed, in which priority order, and in which time. The BESS operator serves as a service provider for multiple stakeholders such as the TSO, retailer and the DSO. Each of them has interests of its own, which are developed further into tasks or service requests for the BESS unit. The BESS operator then decides which of those tasks and what kinds of combinations deliver him/her the highest profit. Here, the regulatory framework and the market design will play an important role in the decision-making process of a BESS operator, since it is located between the stakeholders and the BESS operator (see Figure 33) and serves as a trigger to activate the resource to provide the service. The obvious strategy for a BESS operator to maximize the

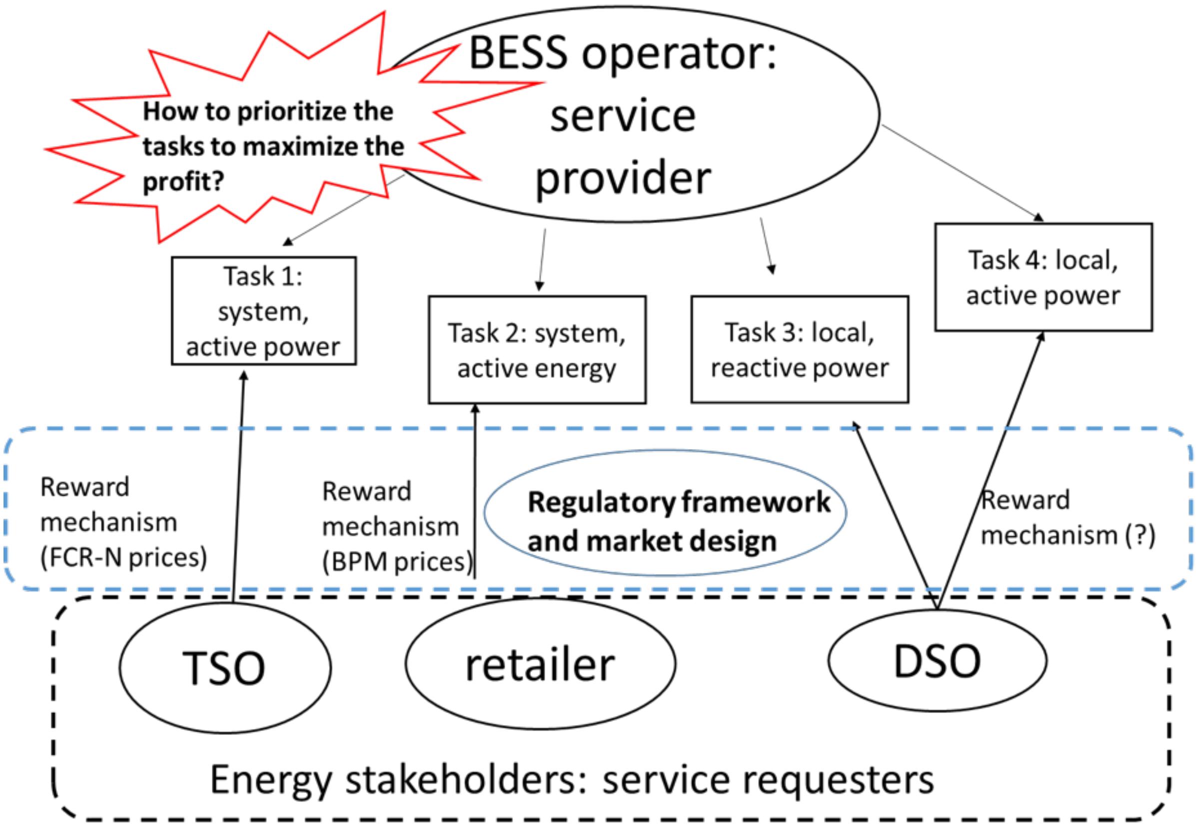

Figure 33: Regulatory framework to meet the interests of the BESS operator and multiple stakeholders.

profit is to prioritize the tasks in the order of the expected reward obtained from them; the first priority task delivers the highest reward and so on. However, in practice, this does not always have a positive impact on the social welfare neither does it serve the long-term objectives of the whole energy sector. Therefore, one of the global objectives of the regulatory framework and the market design is to enable such an operation of a flexible energy resource (BESS, in this case) that will not only meet the interests of the BESS operator, but also the involved stakeholders, and thereby be beneficial from the socio-economic perspective. For example, for the time being, reward mechanisms for the service provider to carry out local tasks are either missing or so insufficient that they are never competitive with the system tasks and will thus never get the first-order priority. The conflict of interests may be either of a technical or economic nature. A technical conflict means that the BESS capacity allocated to a task is limited because of the capacity allocation to the prioritized task. An economic type of conflict means that there is a limitation on providing the service to a task because of its low level of reward. When two or more tasks are executed during the same hour, a conflict may occur depending on the service requested. The relationship between tasks is conflicting or non-conflicting depending on the grid- and system-level state and the reward level. Figure 34 shows that at certain moments of time there occurs a conflict between a system and local tasks when a battery resource is requested to provide a service in opposite directions (for instance, local grid requests a battery to discharge (peak shaving task) while a system operator requests a battery to charge (down-regulation hour in the power system). There can be another case of non-conflicting system and local tasks, when their type of service requires the battery to perform in the same mode (charging or discharging). The conflict of interests between the system tasks is always of a technical nature. This is because

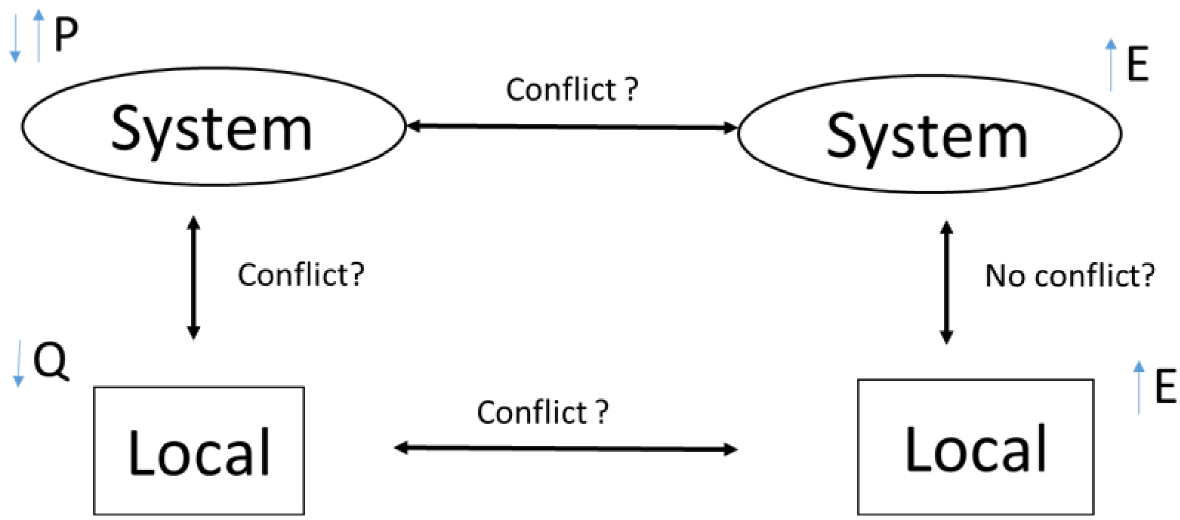

Figure 34: Relationship between the tasks depending on the system and local grid state.

the same capacity cannot be bid simultaneously to multiple markets even if different products, that is, active power- and energy-based ones, are traded. For instance, if the BESS operator bids power capacity to the FCR-N hourly market, he/she cannot bid the full energy capacity to the BPM anymore. Instead, the energy capacity available to the BPM left after operating in the FCR-N market can be calculated as the full energy capacity minus the minimum energy capacity required to provide the bid power in both directions at least for 30 min (preliminary plans of Fingrid). The applications can be classified into market-related and grid-related ones (Figure 35). The market-related applications can be active-power-based (frequency regulation) or energy-based applications (day-ahead and intraday wholesale markets). The grid-related applications can be further divided into active power (peak shaving, interruption management) and reactive power applications (voltage control, reactive power compensation). BESS can be

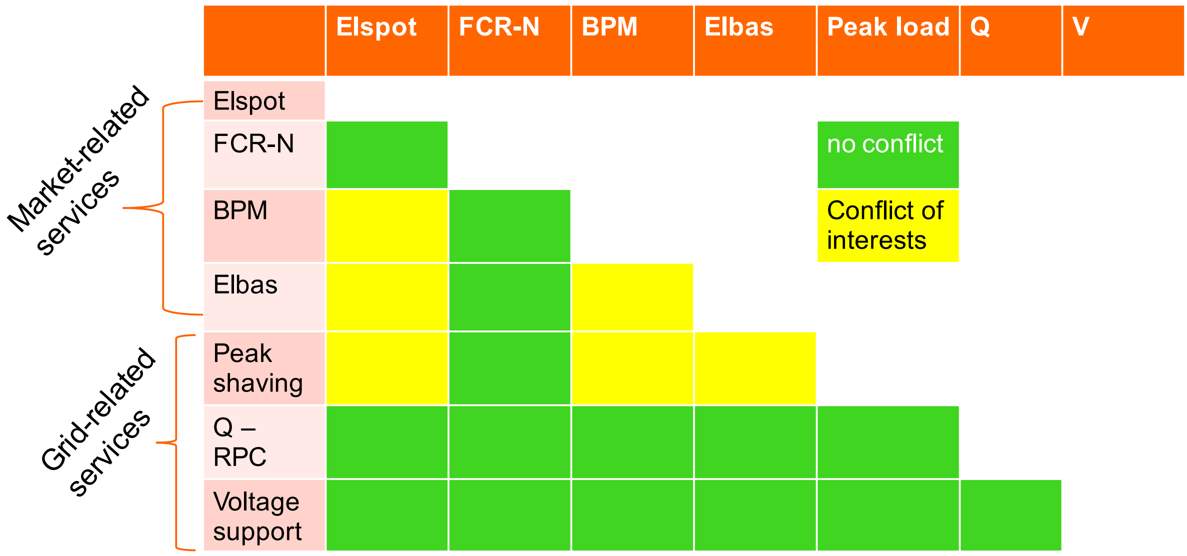

Figure 35: Conflict of interests between applications.

operated simultaneously during the same hour in the energy-based and power-based applications as long as the SOC level is kept within the optimum level. To this end, SOC level correction measures are required. A conflict of interests arises between energy-based applications in the case of energy capacity limitations. The priority is given to the alternative application if the benefit obtained from it is higher taking into account all the costs and penalties caused by not following the scheduled application. The conflict of interests between the system-level tasks can be mitigated by the following issues:

- Keeping the SOC level at the target level in order to make capacity available
- Regulatory framework, market design
- Aggregation of multiple BESS units
- Further investigation of this question is out of scope of this project and is shifted to the further research needs.

In this research project, the conflict of interest is analysed between a system and a local task in the example of the FCR-N hourly market and a reactive power compensation task in the case distribution grid.

6.1 Priority of system-level and grid-level tasks

This section considers two main options:

1. System-level tasks are assigned the first-order priority 1 and grid-level tasks; the second-order priority 2.
2. Grid-level tasks are assigned the first-order priority 1 and system-level tasks; the second-order priority 2.

The task having priority 1 will operate with its determined characteristics. The task having priority 2 receives the services left over of the task with priority 1. Hence, the task with priority 2 may not receive the full service. The consequences of different prioritizations of tasks are analysed in the following section in the example of RPC as a grid task and FCR-N hourly market as a system task. One of these tasks is reactive-power-intensive while the other task is active-power-intensive. The consumption/production of reactive power and active power is fulfilled in accordance with the PQ curve of the power electronic device. The PQ curve of the BESS unit in Suvilahti is illustrated in Figure 36.

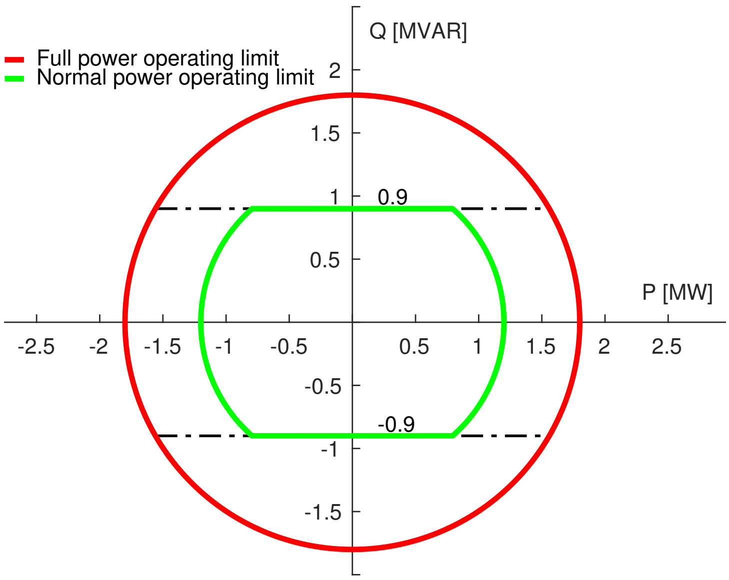

Figure 36: Present PQ curve of the Suvilahti BESS.

The green cut circle represents the normal operation of the BESS and the red circle indicates the maximum operation limit. As it can be seen in Figure 36, during the normal operation, the maximum reactive power consumption/production cannot exceed ±900 kvar. The radius of the green circle is equal to 1.2 MVA. The maximum operation limit allows the battery to exceed the nominal apparent power 1.2 MVA up to 1.8 MVA for 30 s, after which it has to recover in the normal operation mode for at least 10 min. In a case where the reactive power task has priority 1 and the active power task priority 2, the BESS is operating in the areas indicated by the blue line (see Figure 37). In this case, the maximum reactive power capacity will always be available to serve the task (whether it is voltage control or reactive power compensation service) and the active power output will be limited according to the PQ curve. Of course, it is possible that there is no need for the full reactive power output, which will then allow a higher active power output (consumption/production). Then, the operating border shifts from the blue to the yellow line. In the opposite case, when the reactive power task has priority 2 and the active power task priority 1, the BESS is operating in the area indicated by the yellow line. Again, it is possible that there is no need for the maximum active power output (as it often occurs in the frequency regulation task), which allows a larger reactive power output. This means that the operating mode may shift from the yellow to the blue line.

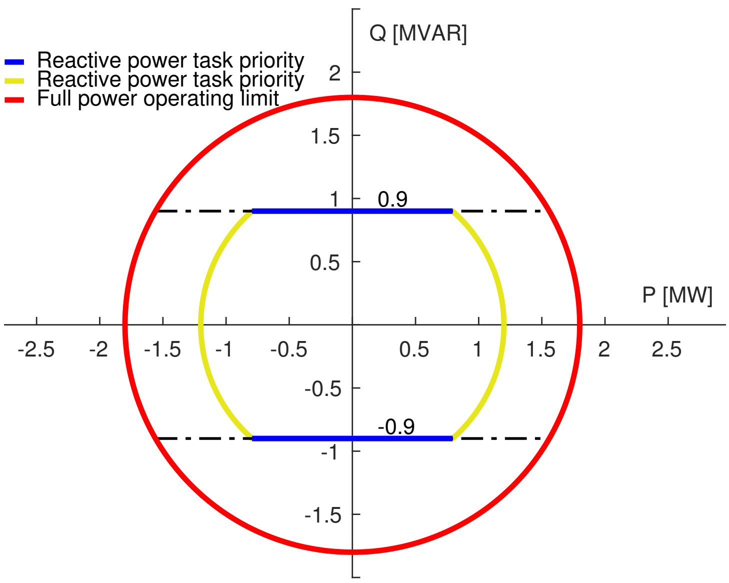

Figure 37: Operating area in the PQ curve according to the priority of the tasks.

This is to say that the blue and yellow lines do not strictly distinguish the operating areas of differently prioritized tasks, but rather, they give an example of where in the PQ curve the operation may happen in the case of reactive-power- or active-power-prioritized task.

6.2 Reactive power compensation as a local task

The reactive power compensation (RPC) in distribution networks has become an important issue since the beginning of 2017 when Fingrid introduced a new reactive power tariff for the companies determined by the P/Q window requirements in the TSO/DSO connection points. The main objectives of the present analysis are:

- Study the relationship between a local RPC task and a system-level task: does it have a conflicting or a non-conflicting (co-existing) nature?
- Define the savings that a BESS unit (on the example of Suvilahti BESS unit) can deliver to a DSO company (in the example of Helen Electricity Network Ltd) by providing an RPC service?

- Analyse the economic and technical impact of the priority of the tasks: 1) the system task priority is 1 and the local task priority is 2; 2) priority is changed vice versa

Limitations of the study:

- The degradation rate of power electronics has not been taken into account in the analysis. It is a complicated question because it depends on many factors, for example the chosen power electronics design (topology, transistors) and symmetrical/unsymmetrical loading of semiconductors [18]. In the further research, this impact can be assessed for instance by adding the cost of replacement of power electronic units to the net present value calculation.
- The analyses are done based on the historical hourly reactive power measurements in year 2016 (see Figure 38) and market prices in the FCR-N hourly market in 2016. Therefore, the conclusions drawn from the analyses are case-specific and further studies should be carried out to validate them.

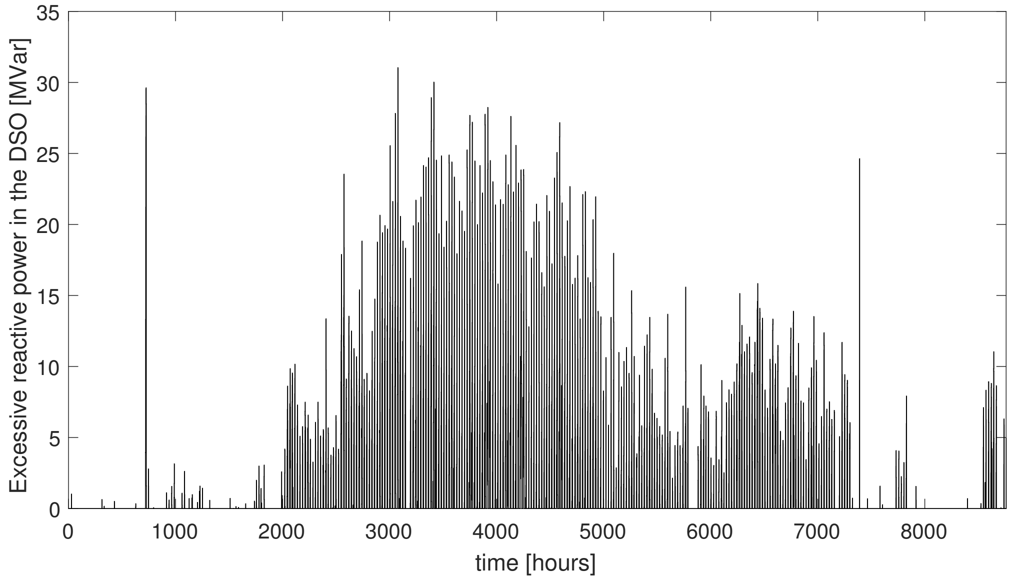

Figure 38: Surplus of reactive power in the DSO's area in year 2016.

According to the reactive power tariff, the fifty highest exceeding hours for each month are excluded in the invoicing of reactive power. Therefore, for each month, the first 50 highest reactive power values were eliminated from the analyses. The reactive power tariff has both reactive power and reactive energy components. The new pricing will be introduced gradually starting from the beginning of 2017:

- In 2017 for reactive power exceeding the reactive power limits, one-third of the unit price will be charged (333 €/Mvar, month), reactive energy 5 €/Mvarh.

- In 2018 for reactive power exceeding the reactive power limits, two-thirds of the unit price will be charged (666 €/Mvar, month), reactive energy 5 €/Mvarh.
- From 2019 onwards, for reactive power exceeding the reactive power limits, a unit price of 1000 €/Mvar, month and a reactive energy fee of 5 €/Mvarh will be charged.

The presented analyses consider all the three tariff options. After eliminating the fifty highest hourly reactive power values in each month, the maximum reactive power has decreased from the 31 Mvar to 18 Mvar. Figure 39 shows that the need for reactive power compensation is around 18 Mvar at the maximum in June, which can be composed of:

- 18 large-scale BESS units of 1 Mvar reactive power capacity
- 1800 small-scale residential BESS units of 10 kWh
- 3600 residential rooftop solar PV systems; 5 kWp
- about 50 solar PV power plants; 350 kWp

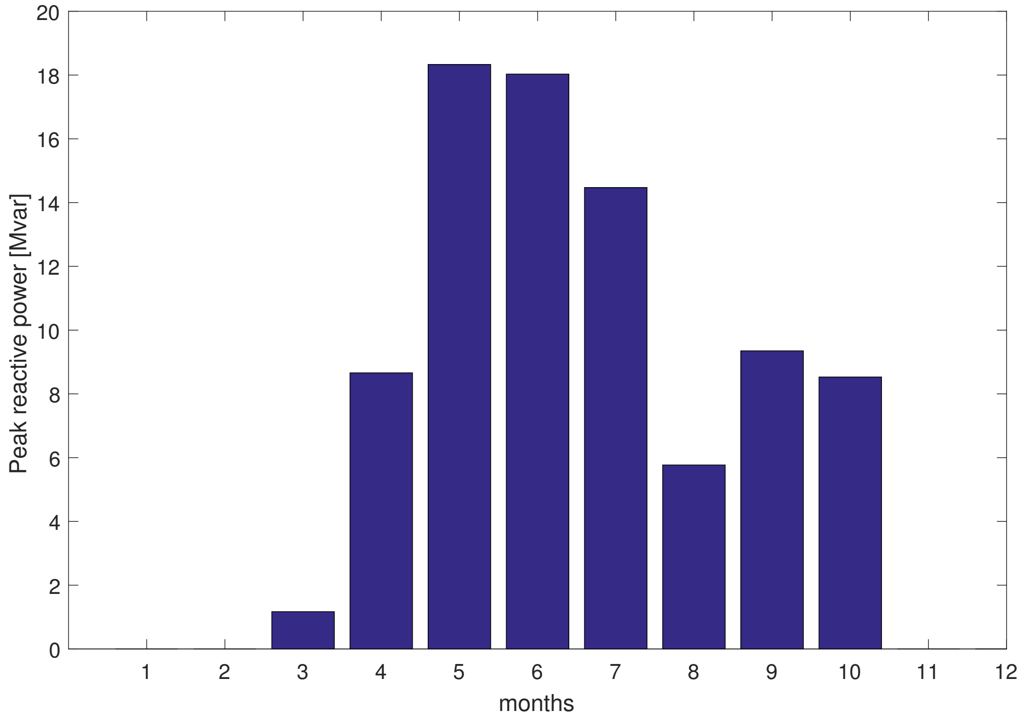

Figure 39: Maximum hourly reactive power compensation needs during 2016.

Next, the priority for the system level and local task has to be set. Two alternatives are considered:

1. Priority 1 is on the RPC task, priority 2 is on the FCR task.
2. Priority 1 is on the frequency regulation task, and priority 2 is on the RPC task.

6.2.1 Case 1: first priority RPC, second priority FCR-N market

In this case, the BESS was consuming reactive power to the full capacity 900 kvar every time there was a need for that in the case distribution network. During those hours, the active power to the frequency regulation task was limited according to the nominal apparent power based on the PQ curve. The difference in the monthly peak reactive power, the monthly reactive energy values and the economic benefit for three tariff options was calculated (Figure 40 and Figure 41).

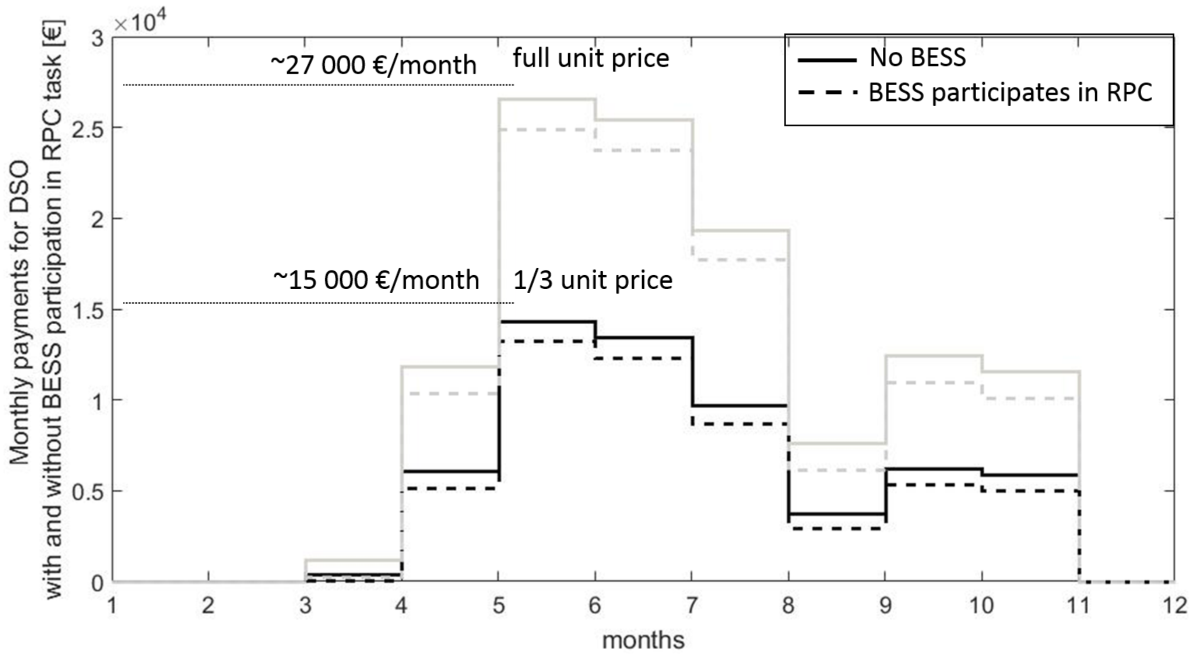

Figure 40: DSO's monthly reactive power payments with and without BESS participating in RPC.

The reactive power compensation tariff fee is becoming more and more expensive in the coming years. This creates strong incentives for DSOs to look actively for RPC resources on the grid. Figure 41 shows the savings calculated as the difference between the payments without and with BESS participation.

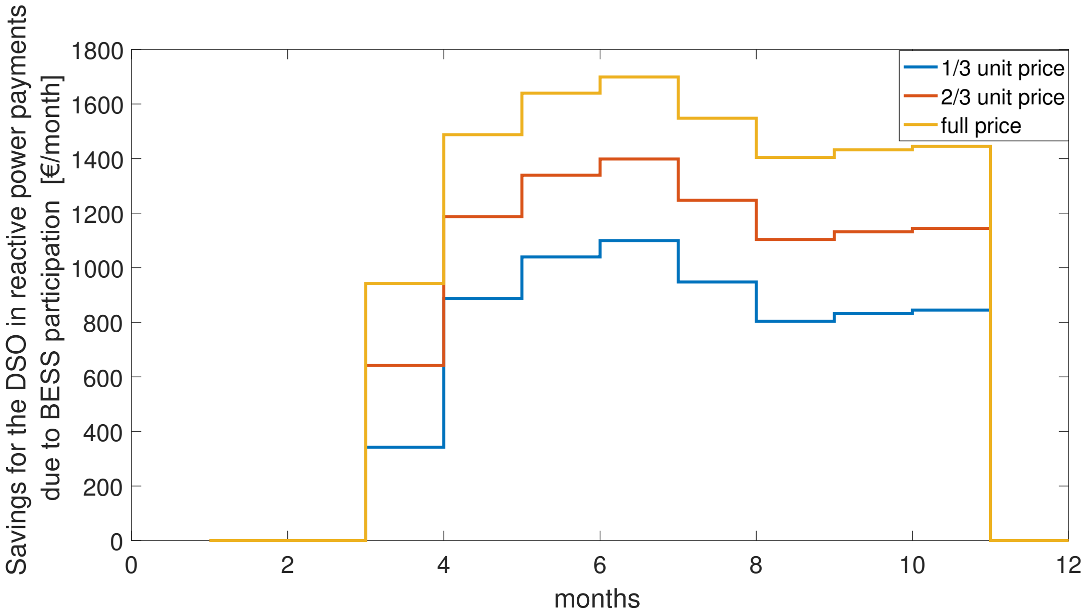

Figure 41: Savings for the DSO due to a BESS participation (900 kvar) in the RPC task.

Next, the limit in revenues from the second-priority frequency regulation task was calculated. The power bid to FCR-N hourly market is 1 MW (presently default). During the reactive power compensation task (±900 kvar) the active power bid was limited to 0.8 MW, according to the equation representing the PQ curve:

$$P = \sqrt{S^2 - Q^2} \tag{30}$$

In the future, various tests can be executed to test other PQ curve shapes and the corresponding effects on the earning potential in the active power tasks. In practice, the active power limitation resulting from the simultaneous participation RPC task does not, in most cases, limit the economic profit from the FCR hourly markets. This is due to the fact that the duration of frequency deviation from the dead band has so far been such that the power does not reach the promised power bid within the 3 min activation time (present market rules). However, this may change in the near future, when the frequency quality may deteriorate (the duration of frequency outside the dead band increases) while the activation time requirements may get tighter for such fast response resources as BESS. The earning potential from the FCR-N hourly market was calculated assuming that there are different price bids, that is, 10, 30 and 50 €/MW. In other words, the BESS was providing frequency regulation only during those hours in which the price was higher than the price bid. In year 2016, there were 4785 hours, 1941 hours and 438 hours when the price exceeded 10, 30 and 50 €/MW, respectively. During those hours, the RPC task was carried out for 407 hours, 168 hours and 101 hours, respectively. The monthly reactive energy consumed by the BESS was calculated. Further, the proportion of reactive energy that was consumed simultaneously during the second-prioritized frequency regulation task was calculated.

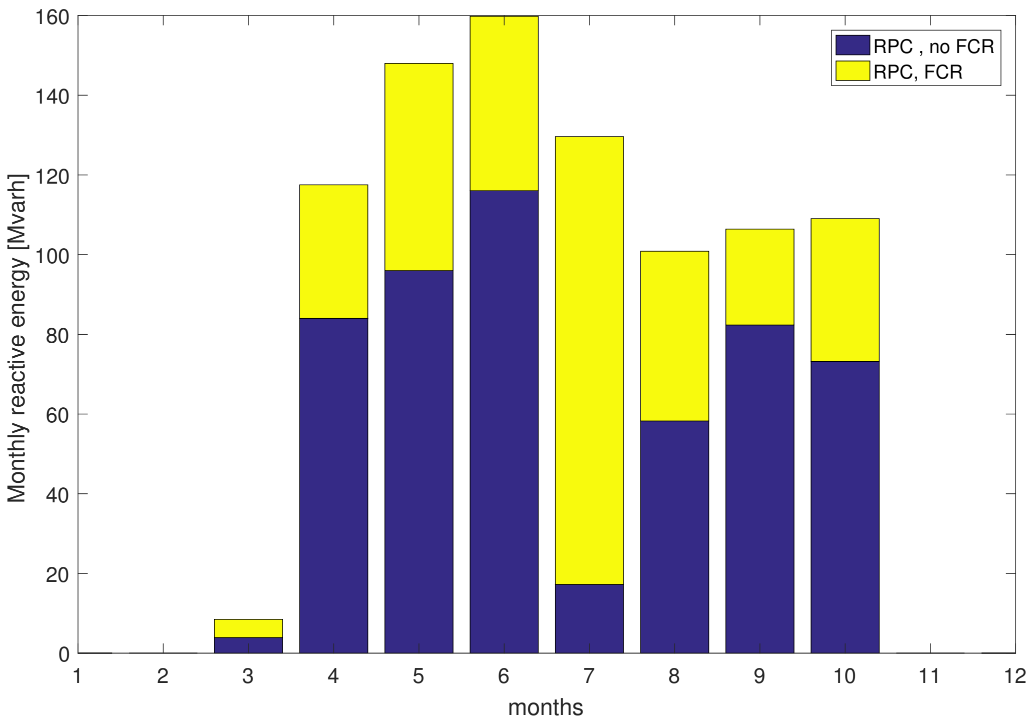

Figure 42: Total monthly reactive energy compensated by the BESS (900 kvar) with a division into a simultaneous FCR task and a purely RPC task (price bid in the FCR-N market 10 €/MW).

As a result, the economic benefit was calculated for the BESS participation in the FCR-N hourly market with and without participation in the RPC task. The limit of the revenues from the FCR-N hourly market because of the RPC task was calculated for each month and presented in Figure 43.

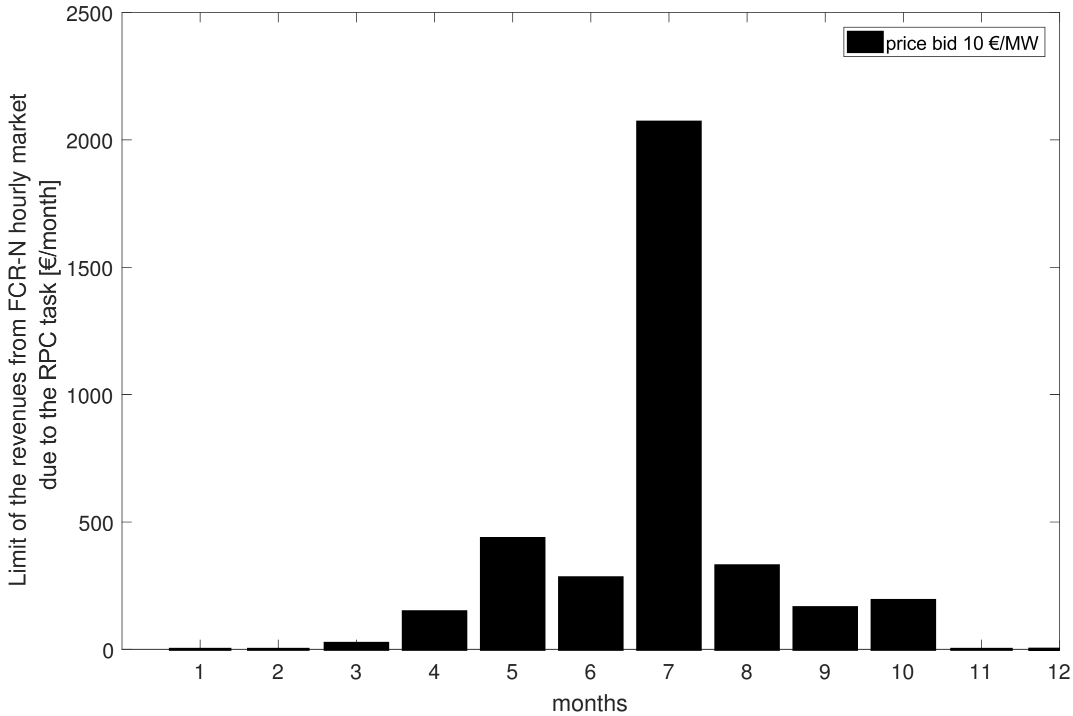

Figure 43: Limit of the revenues from the FCR-N hourly market as a result of the RPC task.

By combining Figure 41 and Figure 43 into Figure 44, it can be concluded that the savings to the DSO that the BESS delivers by consuming 900 kvar of reactive power are higher than the limit in the revenues from the FCR-N hourly market for all months except July. The reason for this is that frequency regulation was activated during many hours in July at the same time when there was a high need for RPC in the grid (see Figure 42)

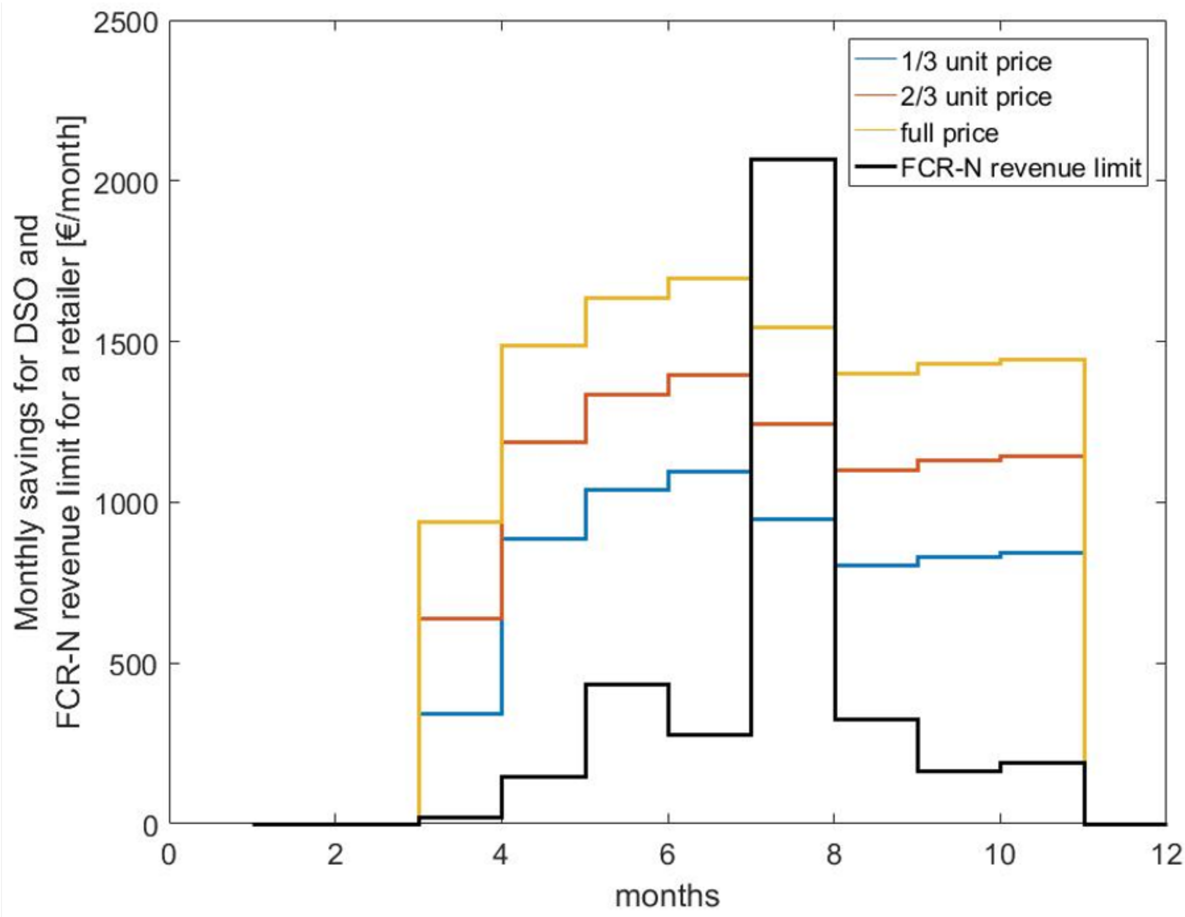

Figure 44: Savings for the DSO vs. revenue limitation to a retailer.

As a result of such a task priority set-up, the DSO company obtains savings and the retailer/BESS operator is losing part of the revenues because of the active power limitation. As it was stated above, the reactive power tariff fee for the DSOs is so high that the savings in money that a relatively small 900 kvar BESS unit can deliver are significant and exceed the limitation in revenues from the power-based tasks such as the FCR-N hourly market that they cause as a result of task prioritization (except for the month of July, when the need for both frequency regulation and RPC was high, see Figure 45 and Figure 46).

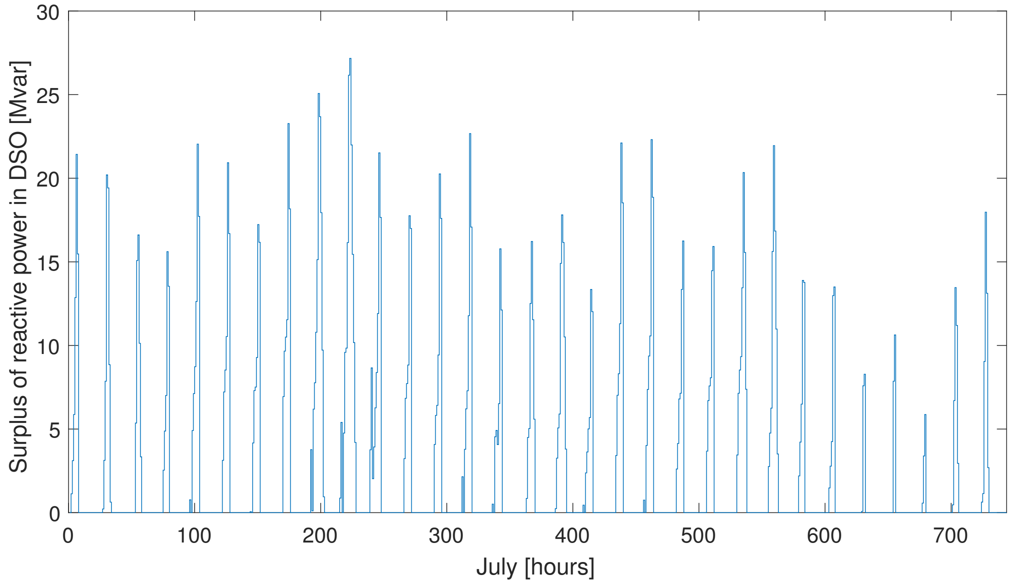

Figure 45: Surplus of reactive power in July 2016.

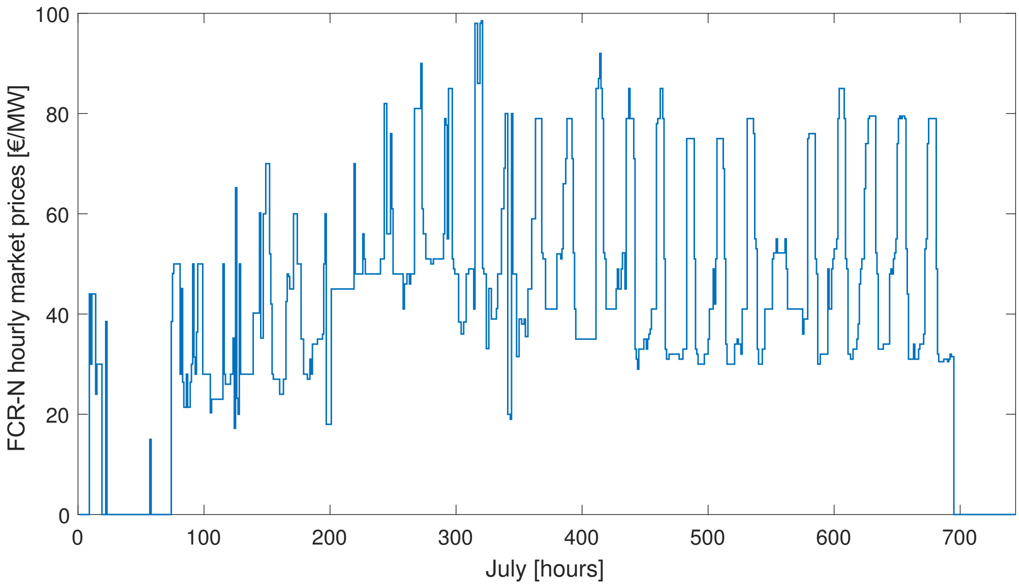

Figure 46: Prices of frequency regulation hours in the FCR-N hourly market in July 2016.

The price per one Mvar that a retailer should get in order to compensate for the limited revenues from the RPC service can be roughly calculated. This can be done by dividing the amount of revenue money that was limited because of the RPC task by the total monthly reactive energy that was consumed during those hours when frequency regulation was carried out. This calculation was done at a monthly resolution. The results are illustrated in Figure 47.

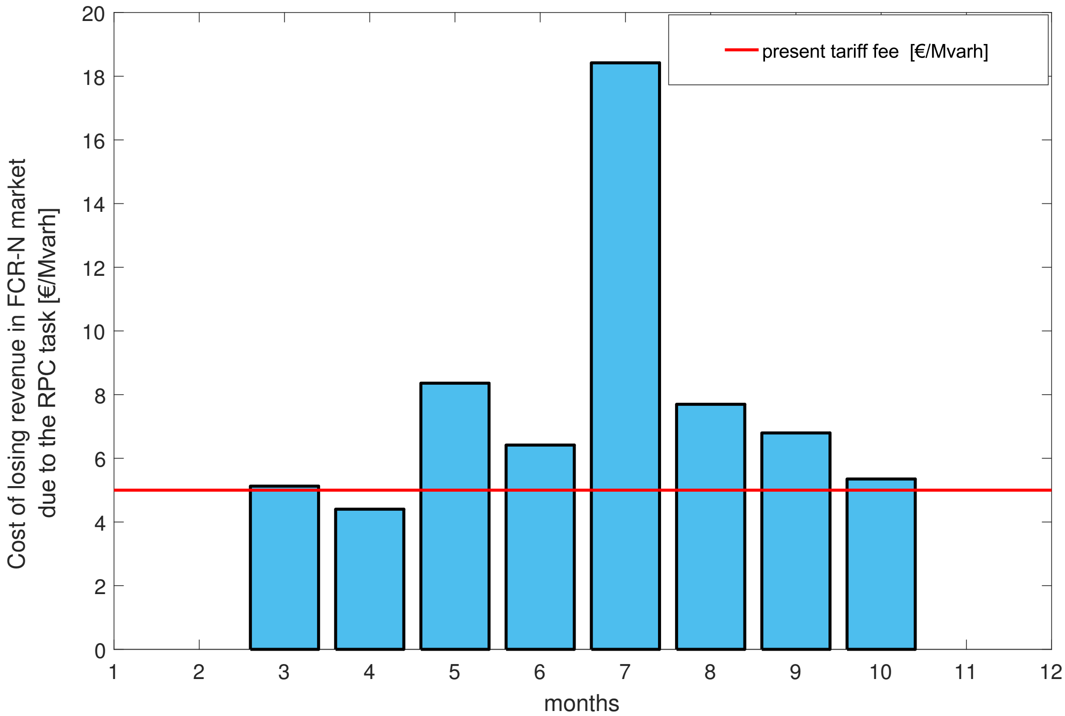

Figure 47: Monthly price of using 1 Mvar of BESS for RPC task to compensate for the profit limitation from the hourly FCR-N market.

The results show that the cost of Mvar to compensate for the revenue limitation is much higher than the present tariff fee for the reactive energy that the TSO Fingrid charges from DSO companies. This leads to a conclusion that with the present tariff structure and market prices, the prioritization of the local reactive power task over the system frequency regulation task is not profitable.

6.2.2 Case 2: first-priority FCR-N, second-priority RPC

This is the default priority currently applied in the Suvilahti BESS unit. The BESS active power offered to the FCR-N hourly market is fixed to 1 MW. The amount of reactive power consumed is defined according to the required active power in the frequency regulation task and the PQ curve. Instead, the limitation on the consumed reactive power by the BESS unit also limits the savings that it brings to the DSO. The changes in the savings to the DSO are calculated for two assumptions:

1. Present default activation time in the FCR-N hourly market, linear active power increase in 3 min
2. Activation time is 0.01 s, which means that full power is achieved almost immediately

According to the presented PQ curve in Figure 37, the reactive power is limited every time when the active power gets below 0.8 MW. In the first assumption, the calculation results showed that the active power exceeds the 0.8 MW value only for 46 h per year, whereas in the second assumption, the active power exceeded the value 0.8 MW 425 h per year, at the price bid of 10 €/MW. This means that a conflict of objectives between the RPC and frequency regulation tasks arises if the activation time becomes shorter. Next, the monthly reactive energy consumed by the BESS is calculated for both assumptions and the savings to the DSO are calculated.

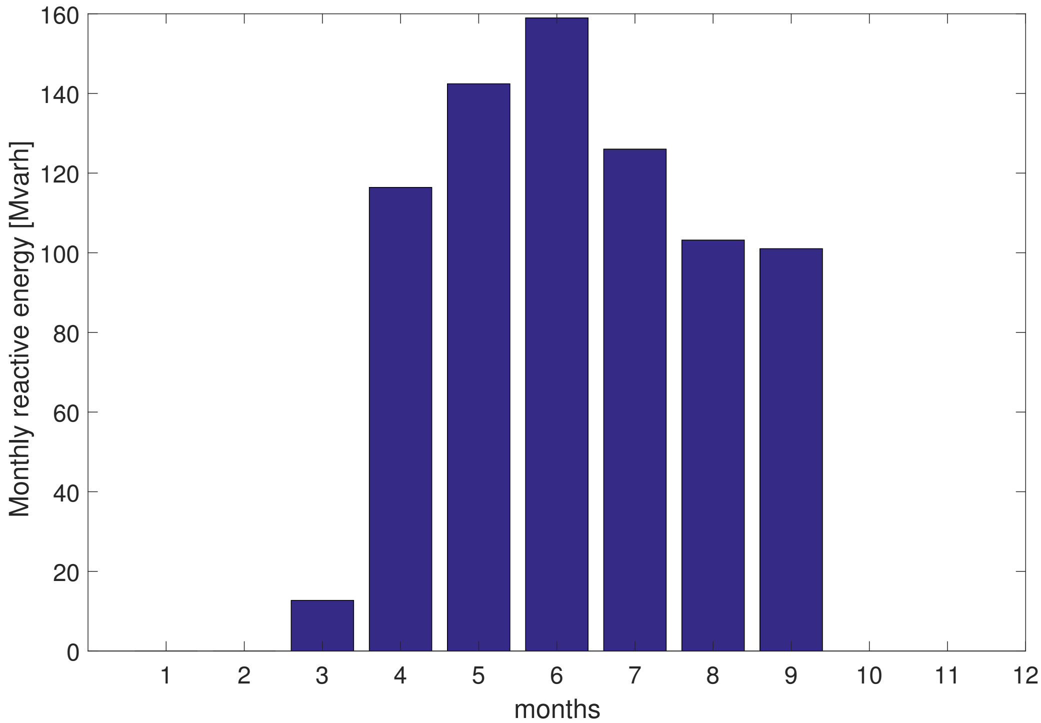

Figure 48: Monthly reactive energy, RPC as a second-priority task.

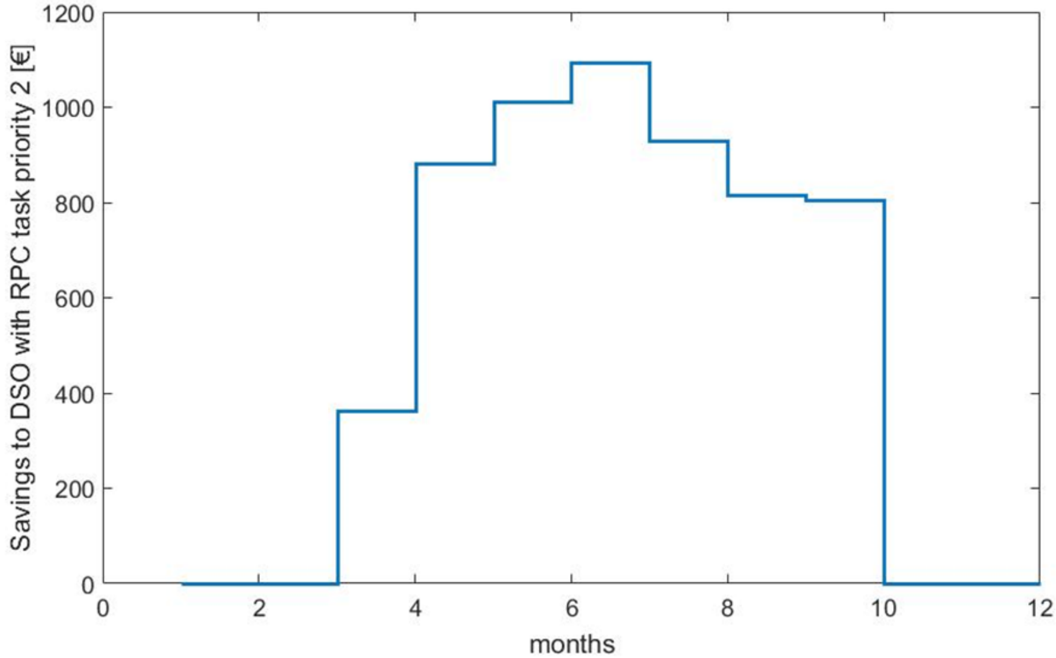

Figure 49: Monthly savings to the DSO as a result of the BESS participation in the RPC task in priority 2.

Figure 48 and Figure 49 show that the monthly reactive energy and thereby the monthly savings to the DSO are almost the same as in case 1 where priority 1 was on the RPC and 2 on the frequency regulation task (see Figure 40 and Figure 41). Even though there are hours when the active power exceeds the 0.8 MW value, this occurs for so few seconds in an hour that it does not have a significant impact on the reactive power output and thereby the reactive energy consumed by the BESS during the frequency regulation hour. This leads to the conclusion that it is not only technically possible but also economically beneficial for a BESS operator to keep the first-order priority for the frequency regulation task and the second-order for the RPC task. This finding supports the present operating mode of the Suvilahti BESS.

6.3 Discussion

The major conclusions of the chapter are:

- The conflict of objectives between the local RPC task and the system-level frequency regulation task has been analysed with different priority settings. The results indicate that the most beneficial operating strategy for a BESS operator is to set the priority of the frequency regulation task over the priority of the RPC task even in the case when the activation time requirement is almost instant (0.01 s).
- Based on the year 2016, there is no or a minor technical conflict when the frequency regulation task is given priority 1 and the RPC task is given priority 2. The RPC task

can be carried out to the full extent except for only a few hours a year when the active power exceeds 0.8 MW. Even during the hours when the active power exceeds the 0.8 MW threshold it has only a minor impact on the hourly reactive power energy consumed by the BESS.

- BESS participation in the RPC task delivers significant savings to the DSO company and in most cases even exceeds the limit of the revenues from the FCR-N hourly market.
- The impact of the reactive power on the active power availability, and vice versa, depends essentially on the PQ curve. Various PQ curve shapes (other than in Figure 36) could be considered in the future research. The impact of the active power on the availability of reactive power depends not only on the PQ shape but also on the frequency quality and the operational parameters in the frequency regulation task (such as activation time).
- The observations are made on the example of the RPC and the frequency regulation task. Further investigation should be carried out between the RPC task and other tasks in order to be able to draw final conclusions on the compatibility of the local task with the other tasks. It will be possible to carry out analyses of this kind by using first the developed simulation tool and then test the findings on the technical platform built within the project.
- There will be more and more technology installed on the grid (such as rooftop solar PV, electric vehicles, small-scale BESS), equipped with power electronics capable of providing RPC.

7 Technical implementation

This chapter describes technical implementation of the control system developed within the project. The decision on the system solution to be developed was made in co-operation with the project partners. The novelty of the proposed system lies in the selected control approach, where the control is distributed at different levels of the system. The master control unit handles the decision-making based on several data sources, while the local control on each resource maintains a varying group of local tasks, some beneficial to the local network and others to the system power system. In the following, the background of the communication protocols available is provided and the selected architectures and implementations are described.

7.1 Communication protocols

Modern power grid installations use various protocols and standards. Some, such as MODBUS and DNP3, are universal SCADA systems, while others, for instance IEC 60870-5-104 and IEC 61850, are standardized protocols, developed for target-specific needs of data communication in power grid installations. Of these four, IEC 61850 is of the most recent development and is not to this day widely adopted by industry [19]. Table 5 presents a comparison of features between the three standards that are commonly used at present. MODBUS, being the oldest of them, only features the basic functionality, a limited set of data types and poor scalability, as the network addressing is limited by mere 255 slave devices. DNP3 was developed slightly earlier and in parallel to IEC104. It is nowadays extremely common in industrial applications. It offered better support for integer and floating point types, which removed the need for manual bitmapping. However, it was not accepted as an IEEE standard until 2010, which suggests that industrial applications do not always implement the same standard in practice, and thus, might be incompatible. Finally, IEC104 provides broader addressing space (24-bit) for functions, supports data flow control procedures and can apply a broad range of encryption methods used with TCP in Ethernet networks. This allows the standard to be scalable, hardened against underlying network faults and secure with up-to-date encryption methods. The major advantage is the ability to use the existing framework of Ethernet networks to provide a reliable data link (owing to the redundancy used in the underlying network).

7.2 System overview

The developed system can be described in three parts: master server, communication links and resources on the sites. The master server is based on purely open source software and runs a Linux operating system, which provides the foundation for the Docker engine platform. Docker engine [20] is an open source containerizing technology that can be used to run containerized applications, virtually on any platform. Containerized applications are extremely easy to deploy on a new server platform providing a Docker engine environment. Communications links

Table 5: Comparison of communication protocols.

	MODBUS	DNP3	IEC 60870-5-104
Year of development	1979	1993	2000
Max controlled addresses	255	65520	65535
Max functions per slave	65535	65535	16777215
Supported IO types	Coil(1 bit), Discrete input (1 bit), Input register (16 bit), Holding register(16 bit)	16/32-bit integer values, 32/64-bit floating point values, Event information contains time structures	Single indication, Double indication, Step position, Integer/floating point measurements and set points, 32-bit bit-strings, Counters, Packed events, Test & reset
Data prioritization	interrogation	3 classes defining groups for polling link layer data flow control	Grouped polling interrogation
Data integrity	one CRC 16-bit	CRC 16-bit every 16 data octets Link control using ACK polling	16-bit one-complement sum in the TCP packet, packet acknowledgement in the TCP, Link integrity control with transmitted/received packet counters
Encryption	None	None, pre-shared key encryption (in 2010 standard)	Optional TLS encryption

are established over the public Internet applying various technologies such as VPN tunnels based on Cisco ASA Series [21], OpenVPN [22], which is a purely software-based VPN solution, corporate LANs, Netcontrol Communication gateway [23] and other TCP/IP network components. The controllable resources are a combination of various pilot, demonstration and commercial implementations built earlier. The LUT battery resources were modified to meet the requirements of IEC 60870-5-104 by using an open source C library [24], the Helen resource was modified by Landis+Gyr with proprietary software resources, and the LUT mobile battery resource (EV charging) used a custom-built communication link between a charging pole and the master server. The geographical location of the system components could have posed challenges, but fortunately, each unit had a good-quality connection to the public network. The measured latencies were rather low even in the worst cases, approximately 50 ms. Figure 50 presents the system units on the map.

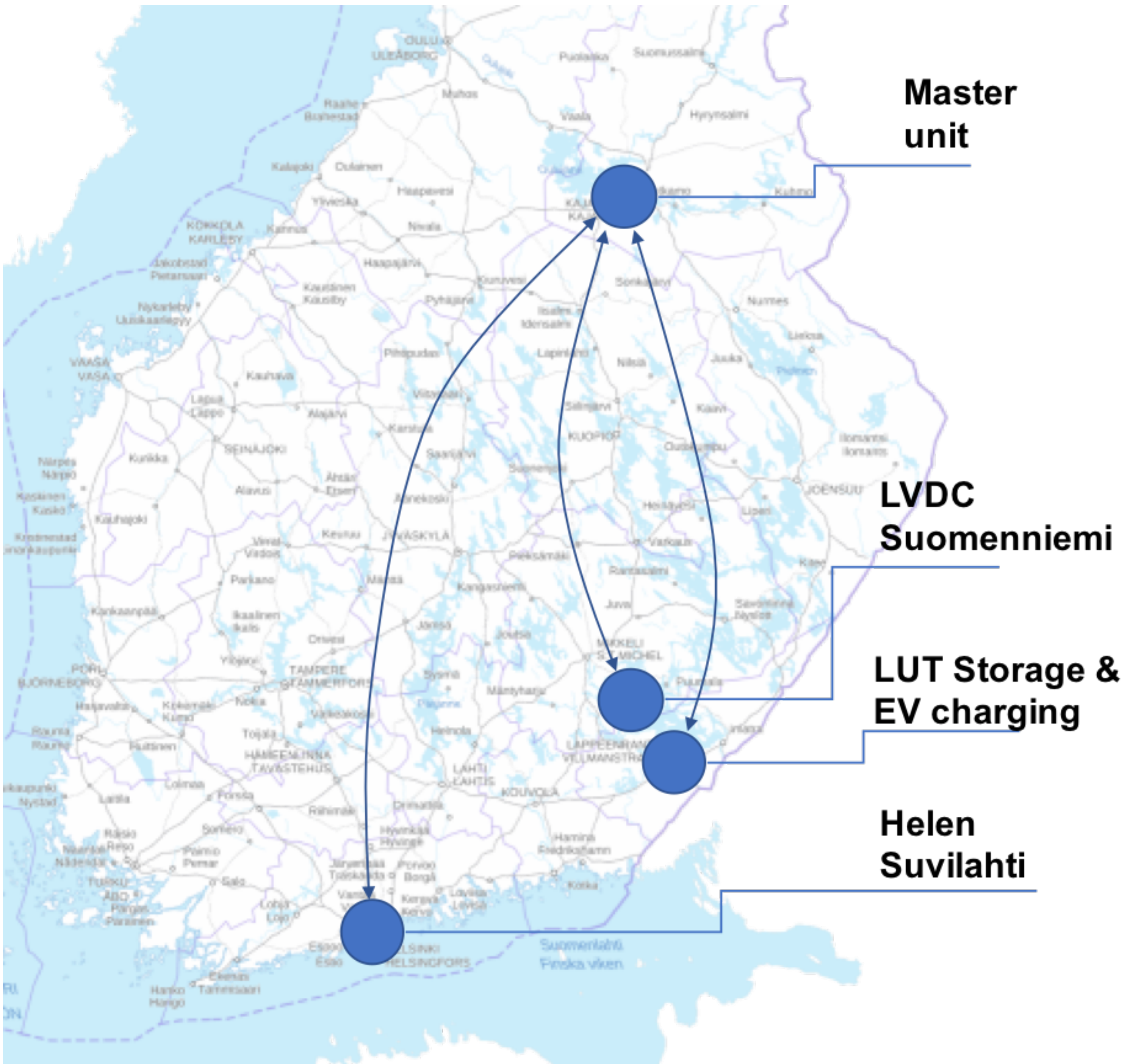

Figure 50: Communication system units on the map.

The master server consists of several applications, some running critical services and others supporting tasks. Figure 51 presents the application structure of the master server. The most fundamental part of the application stack is the communication module that handles the TCP/IP connections to the resources while keeping the IEC 104 protocol communications alive. The communication module serves the optimization module that handles the decision-making based on several data resources. On top of the stack there is a visualization module, which is used to visualize data stored in the database. The visualization module also provides monitoring and alerting tools to maintain secure operation of the resources and the control system. The

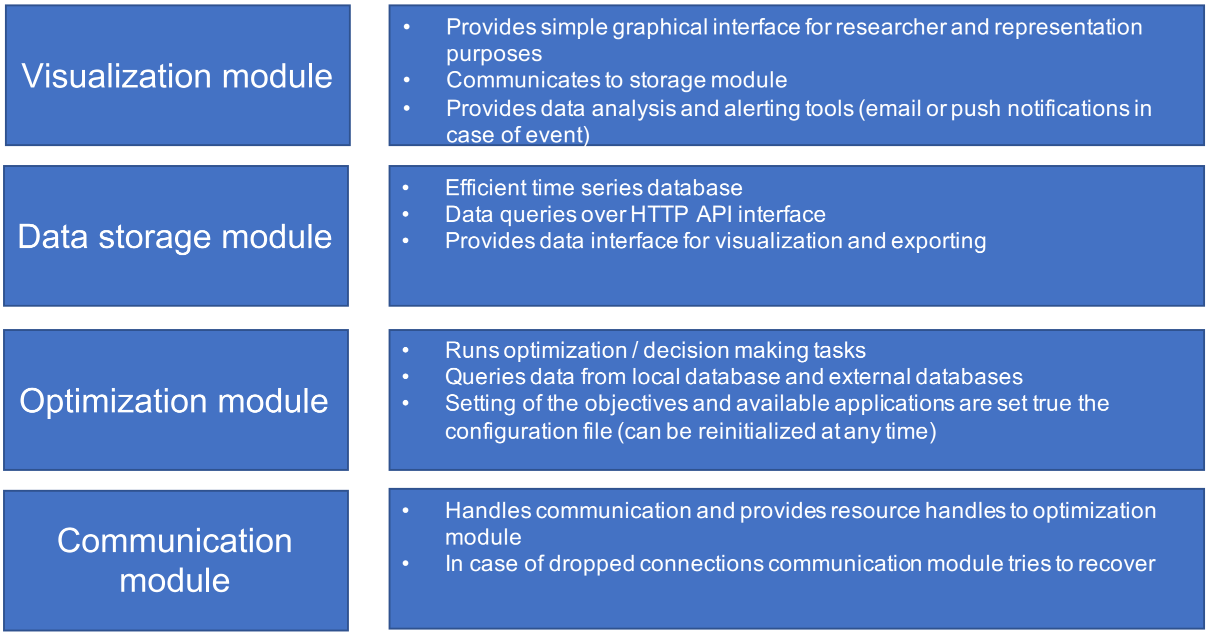

Figure 51: Master server application structure.

communication module of the master server is based on the custom implementation of the IEC 104 library by the Python [25] programming language. The implementation relies on several open source Python packages such as Scapy [26] and several Python standard libraries. The database module uses an open source time series database InfluxDB [27], which is a highly efficient database for storing and processing time series. The database software is running on a Docker engine as a separate database container. The visualization module is based on the open source Grafana project [28]. Grafana provides flexible UI to illustrate database data in dynamic graphs and single values. Alerting is also implemented on the Grafana platform so that each abnormal event will trigger an email alert to the maintainer. Grafana is also run as a Docker container on the master server. The optimization module is implemented in the same Docker container as the communication module as those are highly dependent on each other. Within the container, the processes are divided into independent process threads to maintain secure operation of the communication links in the case of a communication error in some resource link. Process threading is implemented with the Python standard threading library. The control structure of the system follows a traditional layer design, where different control and decision-making tasks are distributed on different layers. Some of the controls are centralized and some are distributed on the local control of each site. Figure 52 illustrates the control system structure applied in the project. The bottom layer represents the hardware control on the power

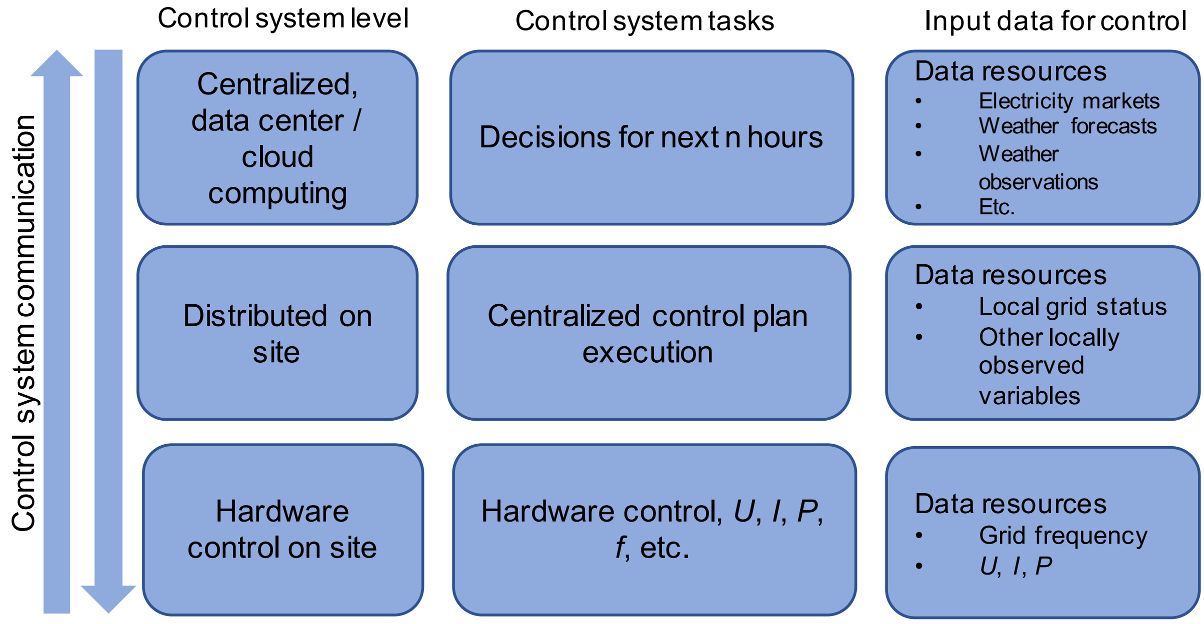

Figure 52: Control system stucture illustrated as layers.

converter between the grid and the battery. The middle layer contains the local control on the site that handles local tasks requiring local data resources. The local control also acts as a failsafe control if the communication link to the master device is lost. On the top layer there is the master control that is a purely centralized control system making decisions for the next hours or days. The centralized decision-making layer uses a wide array of external data sources such as market signals, weather forecasts and weather observations.

7.3 Resource-side implementation

In this section, the technical implementation of the distributed energy resource (DER) side is described. The main document giving the technical specification of the resource-side interfaces is provided separately.

7.3.1 LUT resources

The controlled DERs are the LVDC research site owned by Suur-Savon Sähkö Oy and the Green Campus BESS at LUT. The energy storage of Suur-Savon Sähkö Oy is directly connected (without an interface converter) to a low-voltage direct current (LVDC) public electricity distribution network [6]. Thus, the LVDC distribution network comprises two controllable resources, an MVDC grid interface rectifier and an LVDC-network-connected battery energy storage system

(BESS). The Green Campus BESS is a single energy storage connected to the LUT LVAC laboratory network. Both systems integrate ABB converters and a control and monitoring system developed at LUT. The BESS control system is described in [8]. In this project, an M2M interface for remote control of resources was developed. In the development, a protocol was selected, an interface specification was generated and documented, and an interconnection concept was developed. The interface was implemented according to the specification on both the LUT controllable resources, the LVDC BESS and the Green Campus BESS. The control is based on the communication protocol IEC 60870-5-104, and the communication channel is secured by a virtual private network (VPN) technique (Figure 53).

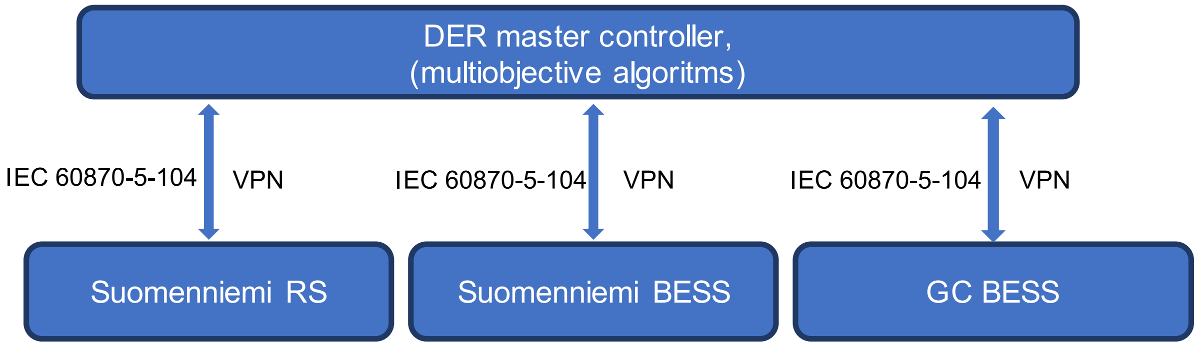

Figure 53: High-level control system.

LUT resources are illustrated in Figure 54 and Figure 55. The schematic diagrams of the systems are illustrated in Figure 57 and Figure 56.

Figure 54: LVDC BESS.

Figure 55: Green Campus (GC) BESS.

7.3.2 Functionalities in BESS EMS

In this section, the requirements for the BESS energy management system (EMS) functionalities and on-site restrictions are described. The DER is required to operate in different markets as described in the previous sections. In the BESS, the following tasks are provided:

- reactive power compensation (RPC)

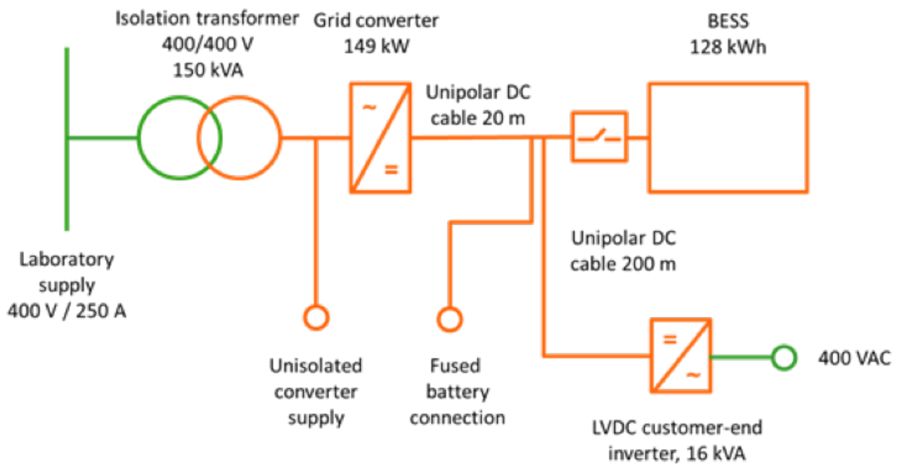

Figure 56: Schematic diagram of the GC BESS.

- voltage regulation (VR)
- frequency containment reserve for normal operation (FCR-N)
- frequency containment reserve for disturbances (FCR-D)
- power balancing market operation (ELBAS)
- energy market operation (ELSPOT)

Figure 58 demonstrates how different tasks are generated from the market optimization algorithms for the execution. The systems have different power and energy capacities and capabilities, and therefore, at the control level, the following aspects should be taken into consideration:

- Restrictions by the power ratings of the BESS power electronics and transformers
- Restrictions by the energy storage (cells) performance (charge and discharge power, operational capacity)

The following system tasks are defined, and conflicts and system capabilities are addressed:

- Reactive power compensation (RPC) and voltage regulation (VR) tasks (reactive power)
  - independent of other tasks
  - possible restrictions by the maximum apparent power/maximum reactive power of the power electronics
  - low priority, allow sleep & stand-by
- Peak shaving (predictable) tasks (active power and energy)
  - requires energy storage capacity and charging power band (PB)
  - affects only the BESS interface power flow, not visible in the point of common coupling (PCC) power flow (a common PCC with generation/loads)
- FCR-N and FCR-D tasks (active power)
  - both cannot be run simultaneously (active power)
  - peak shaving: restricted (a PCC on the BESS network interface), allowed (a common

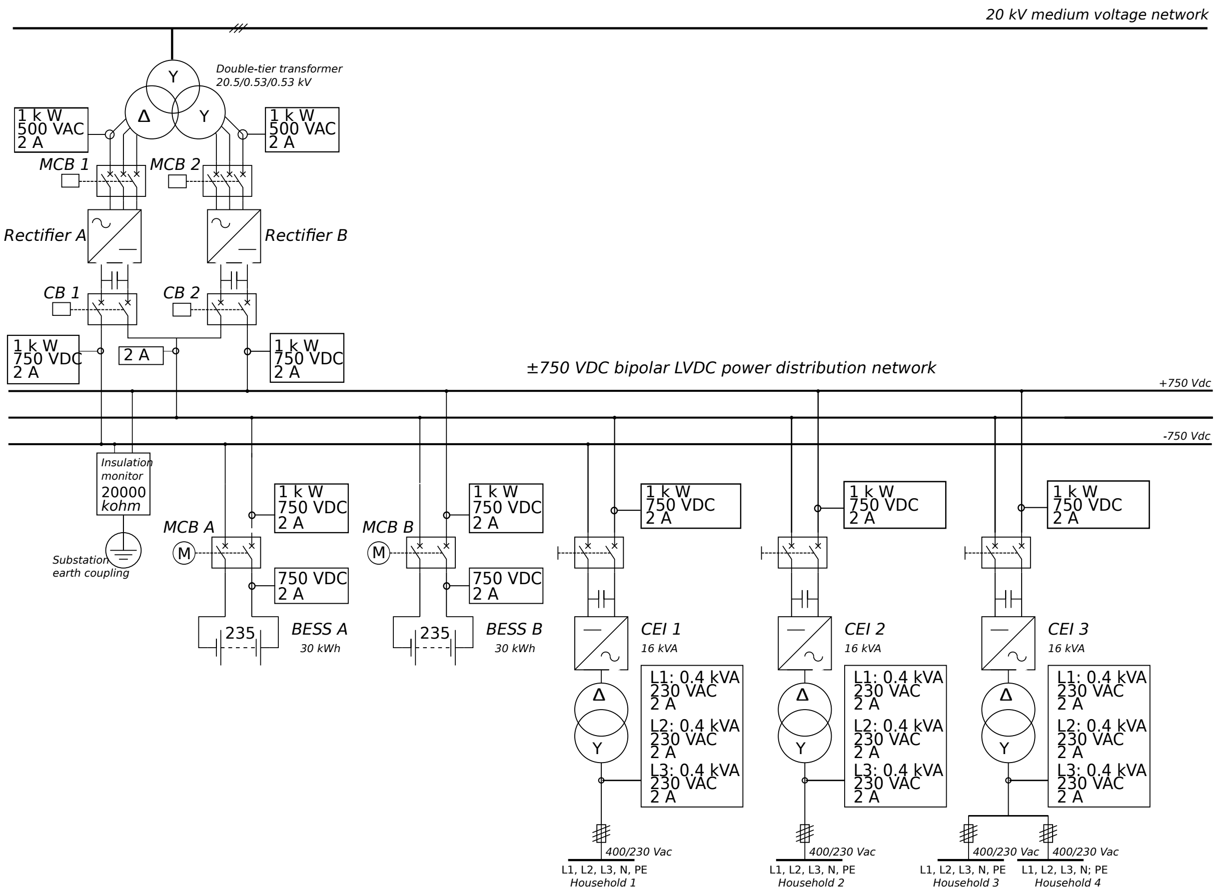

Figure 57: Schematic diagram of the LVDC network integrating the BESS.

  PCC with generation/loads)
  - restricts running of ELBAS, ELSPOT tasks (running on top of the ELBAS, ELSPOT tasks (power offset) is not allowed)
- ELBAS task (energy)
  - hour-ahead planning
  - peak shaving: restricted (a PCC on the BESS network interface), allowed (a common PCC with generation/loads)
  - restricts running of the ELSPOT, FCR-N and FCR-D tasks
- ELSPOT task (energy)
  - day-ahead planning
  - peak shaving: restricted (a PCC on the BESS network interface), allowed (a common PCC with generation/loads)
  - restricts running of ELBAS, FCR-N and FCR-D tasks

During execution of the task, the task is setting a reference (active/reactive power, voltage), which next set to the end-device (Figure 59).

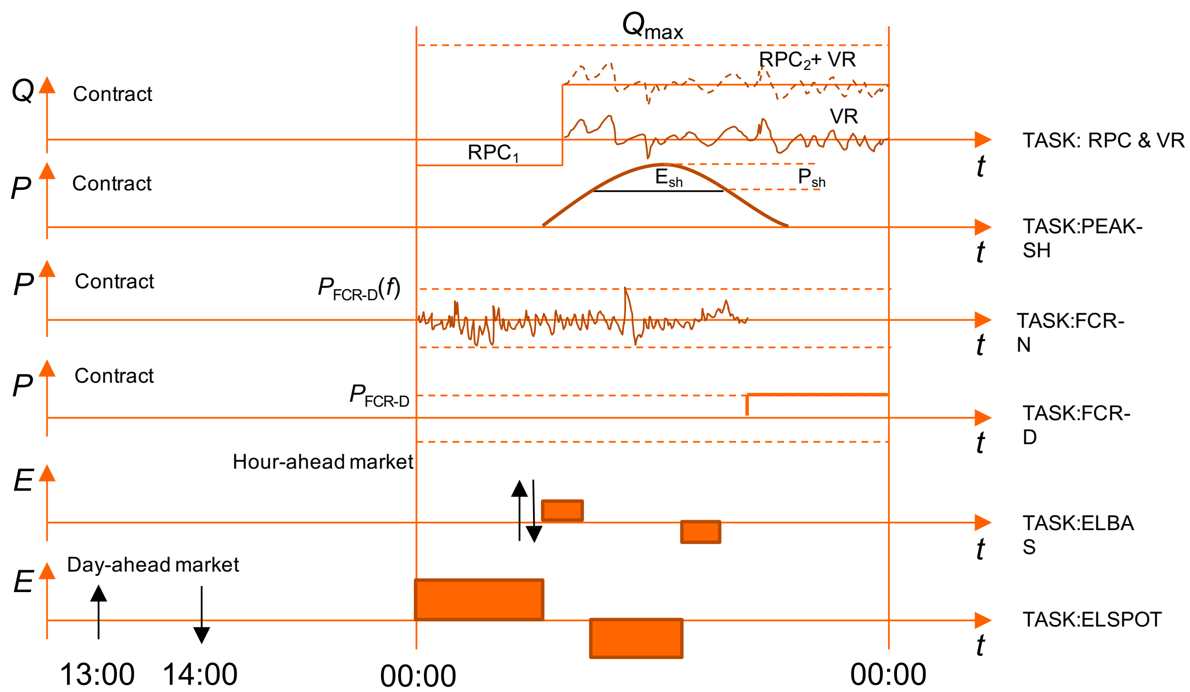

Figure 58: BESS tasks.

7.3.3 Low-level control in pseudo language

Two-level polling cycles, scheduling and real time, are running in the BESS system and interconnecting the high-level IEC-104 interface with the BESS control system. Implementation of the low-level interconnection of systems is following a pseudo-language description given in Figure 60 and Figure 61.

```
# Scheduling cycle
begin
repeat in 15 minute intervals
read control registers (IEC 104 mapping)
check parameters, apply rate limiters and saturation
assign RPC and VR tasks parameters
if VREF = 0 set QREF else set VREF
assign PS, FCR-N, FCR-D, ELBAS, ELSPOT parameters
switch current task to highest priority task
set PREF(t) / Set PREF(f)
report state of BESS to informational registers (IEC 104 mapping)
end
```

Figure 60: Scheduling cycle.

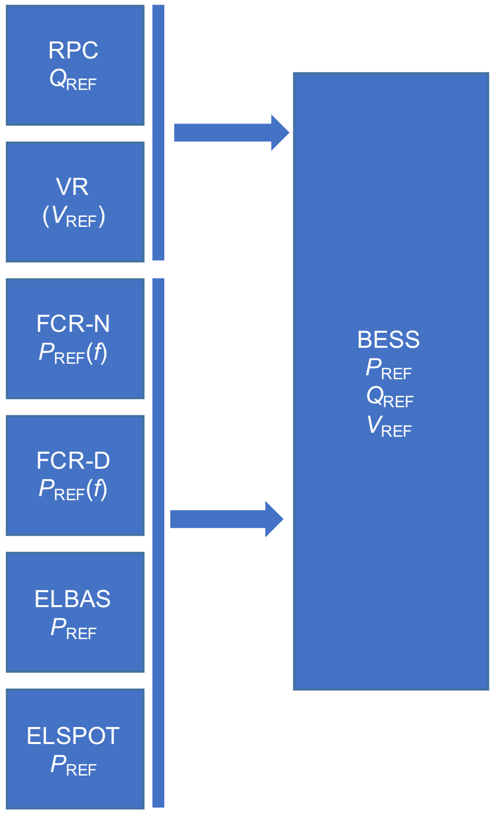

Figure 59: Task and converter control.

```
#Real time cycle
begin
repeat in 1 second interval
updates to informational registers (IEC 104 mapping)
power control task (if active)
Read of active power references, reactive power references in power control task
Check parameters, apply rate limiters and saturation
Set PREF / QREF
end
```

Figure 61: Scheduling cycle.

7.3.4 Communication between the battery storages and the centralized control system

This section describes the IEC 60870-5-104 communication between the battery storages and the centralized control system in brief. The majority of the data traffic is implemented by the cyclic parameters of the slave/server units sent upon connection to the control station (master/client). The control unit may request parameters by calling an interrogation command from the BESS. This is needed to identify local changes in the slave or BESS task configuration, which are then considered as inputs in multi-objective algorithms (run in the control master station). In reply to the interrogation command, the BESS identification, description, parameters and restriction of the controlled BESS are sent by the controlled station to the master station. The control station manages distributed battery resources by scheduling and prioritizing tasks implemented in the server/client units. The optimization master runs task optimization functions based on the information from the BESS, resources from energy markets and resources from other sources. Information from the BESS is divided into description (parameters are received during interrogation) and periodically monitored measurements (parameters received in cycles). Monitoring is divided into two time bases, 1-second and 1-minute cycle reporting. The control station optimization loop is run (with the time cycle required by the optimization algorithms) and new control parameters are sent to the BESS upon priority/task change in the master task scheduler (when the priority of the task should be changed). The client/server runs tasks (applications) by the priority table as long as the master station revokes new parameters. The functions implemented on the BESS interface are:

- Interrogation
- Changing of task priority
- Control of power flow tasks
- Cyclic reporting in the monitoring direction
- Monitoring messages (cycle: 1 min, monitored station $\rightarrow$ master)
- Monitoring messages (cycle 1000 ms, monitored station $\rightarrow$ master)

The main document containing a detailed IEC 60870-5-104 technical specification of the resource-side interfaces is provided separately.

7.3.5 Helen Suvilahti

This report does not provide a detailed description of the technical implementation of the Helen Suvilahti battery systems; further information of the systems can be requested from Helen Oy [29].

7.4 Control system implementation and experiences

The following section offers insights into the system implementation process. The system structure and protocols chosen for the project implementation were more or less all standard protocols or common industrial approaches. The insights presented in this section are objective observations gathered by the research organization and should be interpreted as such. The companies involved in the project had very little impact on the flow of the implementation process. Some challenges were encountered in the implementation owing to communication issues with the subcontractors. Nevertheless, the skills and experience of the subcontractors were definitely supreme, and the personnel were well qualified for the tasks under consideration.

The integration process begun with the communication network implementation. Traffic was routed through corporate networks to suitable connection points for VPN tunnels. The VPN tunnel between LUT and Helen caused several problems in the deployment phase. The reasons for these issues were not completely identified in the process. The OpenVPN tunnels between LUT and the LVDC research site were configured by the ”simplest set-up” approach using static keys. The deployment went as planned even though the VPN host device was a highly customized Linux system dedicated to run industrial processes. However, it is emphasized that this was only one example case and cannot be used to compare a corporate VPN solution with commercial solutions. The IEC 104 protocol implementation used different approaches in every device in the network. The LUT resources were mostly deployed by the open-source software, while the Helen Suvilahti BESS was deployed by the proprietary software. The open-source alternative was in this case more error tolerant and even allowed communication that was not explicitly by the standard. Such properties of the communication protocols caused lots of debugging hours on the resources that were implemented by the open-source approach. The main issue was that the message exchange was not following a standard approach. The lack of documentation of the proprietary side also caused a lot of guessing in the resource configuring phase. Still, it can be stated that there are open-source libraries that can be used in the IEC 104 communication, but it is essential to have proper documentation of each device connected to the messaging link.

7.4.1 Communication

Communication between the participants in the integration process plays a key role in any project. Typically, there are several subsystems that follow standards but are still allowed to be configured and used in several alternative ways. This calls for comprehensive documentation and information sharing between the participating subcontractors. Within the project, the lack of sufficient communication with subcontractors caused a lot of delays in the integration project.

8 Operation of multiple BESS units

This chapter presents an analytical discussion on the operation of multiple BESS units, and the value and challenges it creates to the involved stakeholders, to the electricity market, the power system and a distribution grid. The established interconnection IEC 104 between the multiple BESS units enables the exchange of parameters related to a single BESS unit. Yet, it does not allow the exchange of power flows between the batteries. Several studies regarding the operation of multiple BESS units have been carried out worldwide. For instance, in [30], the impact of the control of multiple dispersed BESS units has been considered from the network operators' perspective. In [31], the benefits of a virtual energy storage system to the frequency response task are discussed. However, to the knowledge of the authors, the implementation and control of such a virtual energy storage system in the objectives of multiple stakeholders has not been discussed before in the literature. This chapter discusses the main advantages and challenges of such a system in brief. The main advantages are related to the possibility of dynamically changing the priority order of the tasks on the premises of each BESS unit. For instance, if there is a disturbance in a local distribution grid, the BESS located in that grid can shift the priority from the system to the local task in order to fully meet the request of the DSO (for instance, discharge energy to the grid). The energy/power that was undelivered to the system level task can be collected from the other BESS units. As a result, having multiple BESS units under operation and control can result into a higher capacity utilization rate for both the system- and local-level tasks. Another advantage of such a virtual energy storage system is the opportunity to affect the lifetime of each BESS unit. This can be done by implementing a multi-string operating algorithm [32], when a part of the BESS units are working in the charging mode and another part in the discharging mode. After the SOC level saturation on the BESS unit premises, the switching of the roles takes place. The consistent charging/discharging direction reduces the battery ageing and is beneficial for their lifetime.

At the same time, the following challenges arise when a single operator/aggregator remotely controls multiple BESS units:

- Optimal control against system-level tasks taking into account the local owner's preferences, grid constraints and market rules
- Verification of power flows to the pre-defined task, especially if a BESS unit can simultaneously execute multiple local and system power-based tasks
- Cost-benefit sharing mechanism between the BESS owners
- Compensation of the costs related to the imbalance power that is caused to the balance responsible party when a BESS is controlled by a third party (aggregator)
- Cyber security and scalability of the communication protocols

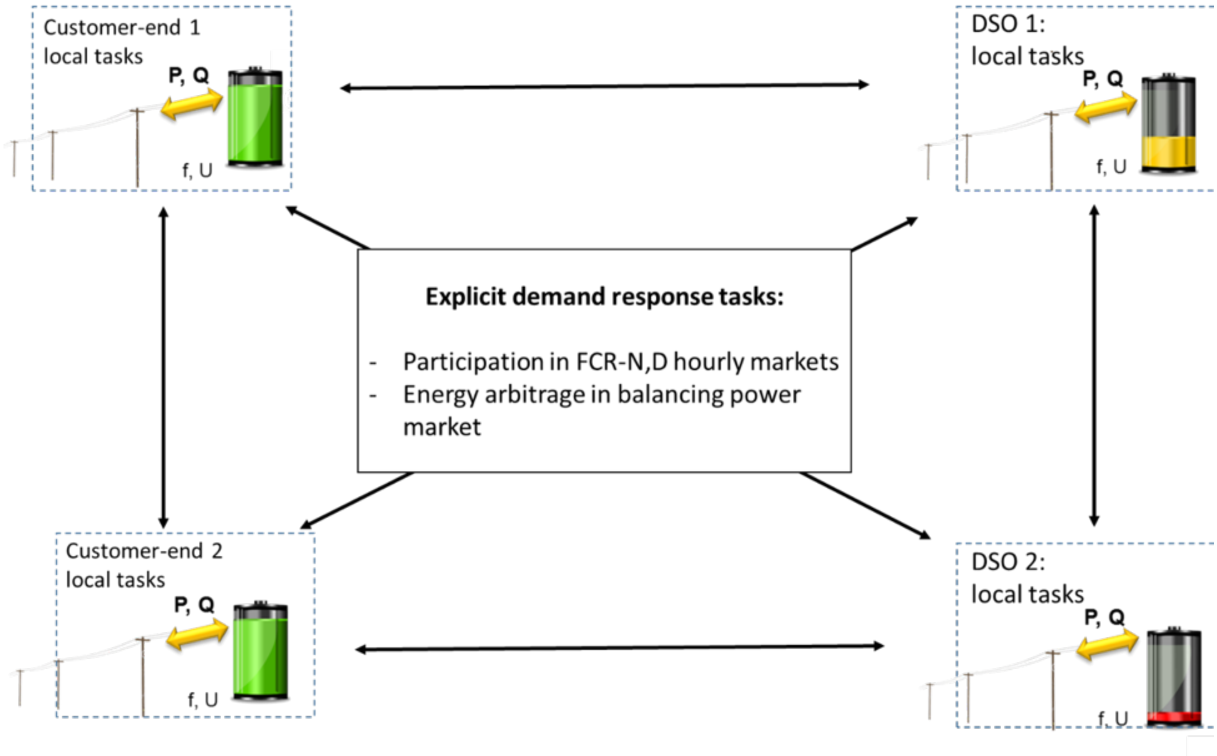

Figure 62: Aggregation of multiple BESS units to perform explicit (system level) demand response (DR) tasks.

9 Results from the test period

The chapter describes test data gathered during the test period and provides analyses based on the data. Further, the applied control methods and observations made during the operation are described. The system was implemented along with the analyses executed in the project. The integration process of the Helen BESS and the master unit started in the summer 2017. After several delays in the integration project, the control functionality of the test set-ups was activated in early November 2017. The testing of all the four battery systems begun on the 3th of November 2017 and ended on the 2nd of January 2018. The testing period can divided into three parts. Firstly, in the beginning of the test period, the controllable resources of the system were tested to see if the control signals were obeyed correctly. In the first testing period, the control system was also refined. Secondly, the control logic was defined separately for each controllable resource. Thirdly, control signalling aiming at a mutual benefit of the whole system was tested. In the following, the applied control signalling and recorded events are described in more detail.

9.1 First testing period, from 3 November 2017 to 1 December 2017

During the first test period, the primary focus was on refining the control system and system integration. The major concern was the IEC 104 communication interoperability between the commercial approach in the Helen battery resource and the open source implementation in the master unit. The main issue in the integration was the loose interpretation of the IEC 104 communication protocol standard. The problem was tackled by using several network monitoring tools, such as tcpdump [33] and Wireshark [34]. At the end of the first test period, the system was observed to operate as intended. All controllable resources were confirmed to obey the control signals that the master device sent. The local tasks were also confirmed to operate as designed. All resources were then set to run frequency containment reserves as the highest-priority applications at the end of the first test period. Figure 63 illustrates an example data capture over the first test period. The data show that the LVDC test site SOC has been kept in 100 % almost over the whole test period. The Helen BESS was tested with an application that caused the SOC to vary over the whole test period. The testing of the Green Campus BESS began in the latter half of the first test period.

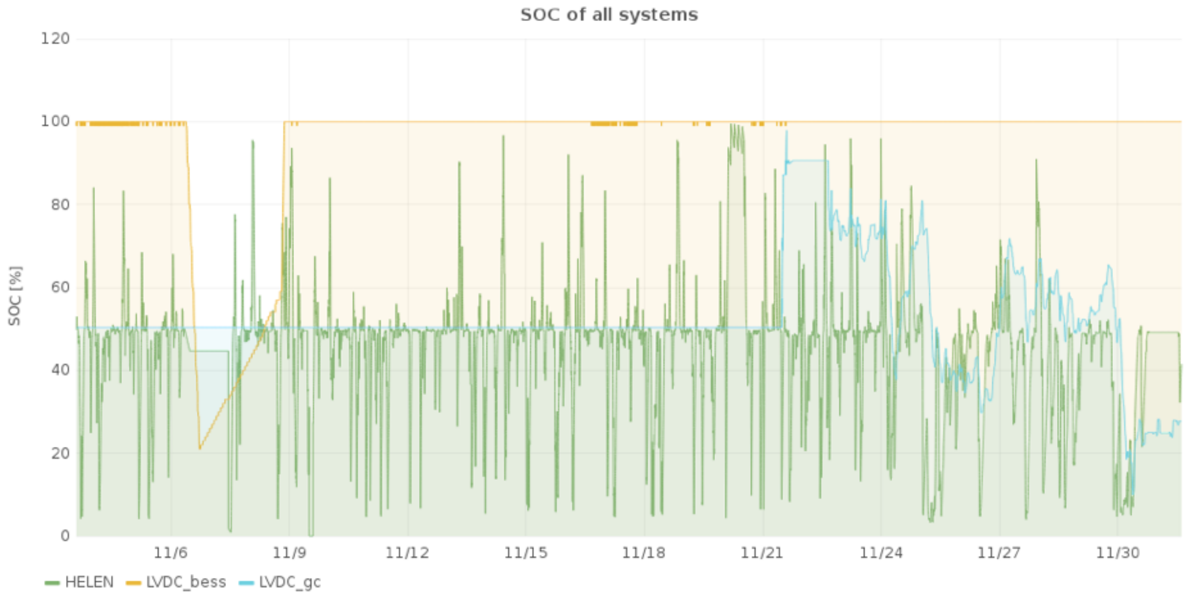

Figure 63: Example data illustration captured from the Grafana UI during the first test period. Figure shows the relative state of charge over the testing time period.

9.2 Second testing period, from 1 December 2017 to 22 December 2017

The second testing period consisted of individual operation testing with single units. Each BESS had a purpose of its own regardless of the status of the whole system. The primary task in each unit was set to the FCR according to the analyses performed during the process. The SOC correction was implemented by a unique technique with each unit. The FCR operation was set to react to frequency changes immediately without any additional delays. The Helen BESS was set to correct the SOC level every time it reached the dead band set in the FCR-N task. The dead band correction power was set to 100 kW and the target SOC to 50 %. In practice, if the SOC is below 50 % and the grid frequency is measured to be within the dead band, the battery is charged towards the 50 % SOC. If the SOC is over 50 %, the direction of operation is the opposite. The FCR-N task had parameters according to Figure 64. The active power takes a positive value when the frequency is below the lower range of the dead band 49.95 Hz. In this case, the battery is discharging. In case the frequency is above 50.05 Hz, the battery is charging and the active power takes a negative value. The SOC level was also corrected by the energy application if the SOC saturated on the edges of the operation area. Charging and discharging was initiated at the beginning of the hour and continued for the whole hour until the 50 % SOC was reached. The charging and discharging power was calculated according to the present SOC value in the beginning of each hour. Operation was initiated if the state of charge was within 15 % of each SOC edge (0–100 %). The operation simulated controlled energy market participation. As the secondary application, the Helen BESS was set to operate in the RPC task with a constant 600 kVar set-point value.

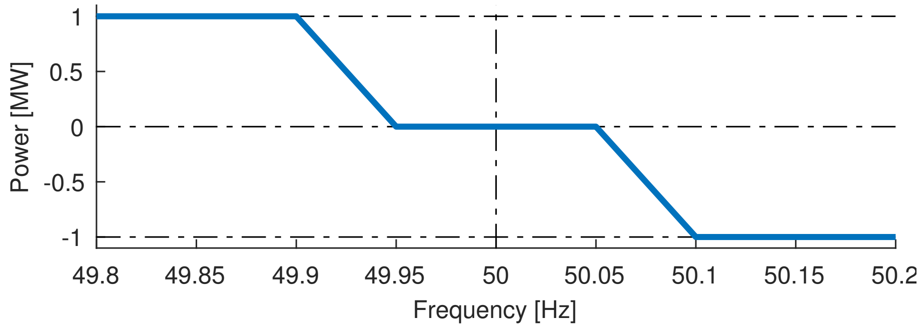

Figure 64: FCR-N droop curve in the Helen Suvilahti BESS during the testing period.

The Green Campus BESS was set to similar FCR-N operation as the Helen BESS but without the SOC correction functionality in the dead band. A secondary application was set to VR to support the laboratory voltage level. Figure 65 presents the droop curve of the FCR-N application and Figure 66 the VR droop curve.

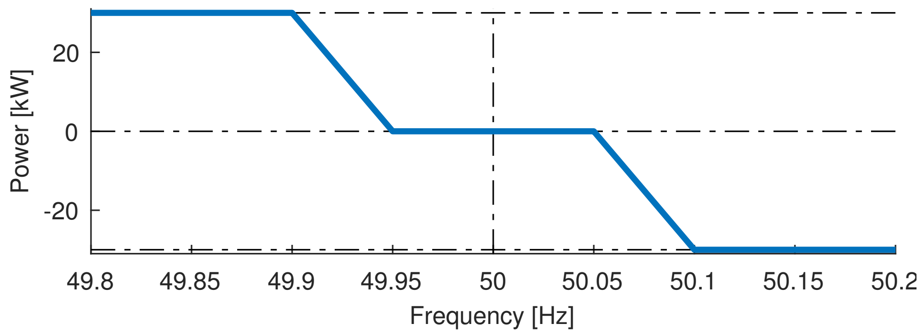

Figure 65: FCR-N droop curve in the Green Campus BESS during the testing period.

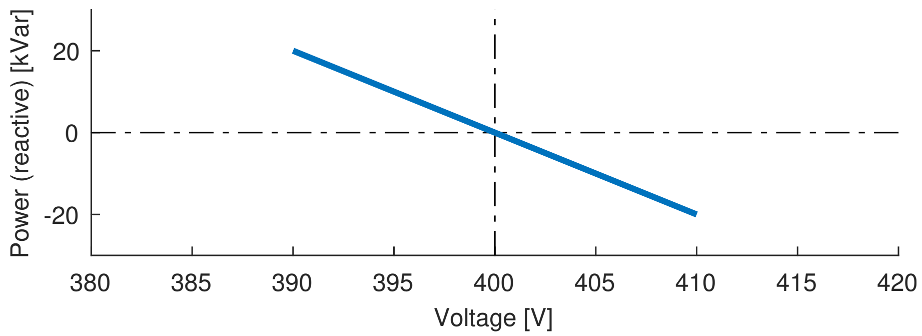

Figure 66: VR droop curve in the Green Campus BESS during the testing period.

The BESS of the LVDC research site had also an FCR and primary task that was controlled by the master control unit, but it also had a UPS functionality set to local control. If the UPS task were to be activated locally, it would run over any task that was set by the master control unit. In the FCR-N application, the SOC operation boundaries were thus set to be rather strict from

70 % to 90 %, meaning that the SOC correction will initiate whenever the SOC reaches each one of the limits. The initial point of the FCR-N operation was considered to be at 90 %. The control system also had an ability to set a lower SOC correction limit dynamically according to the estimated power demand within the operating area of the UPS application. The estimation was based on the local weather forecast acquired by the master control unit. The BESS had balancing issues with the battery cells, and thus, a decision was made not to use dynamic FCR-N SOC boundaries. The reactive power application in the LVDC research site was in a separate power electronic module. The present status and agreements with the local DSO required no use of the reactive power task on the site, and thus, the secondary application was neglected. Figure 67 presents the FCR-N droop curve used in the case of the LVDC research site BESS.

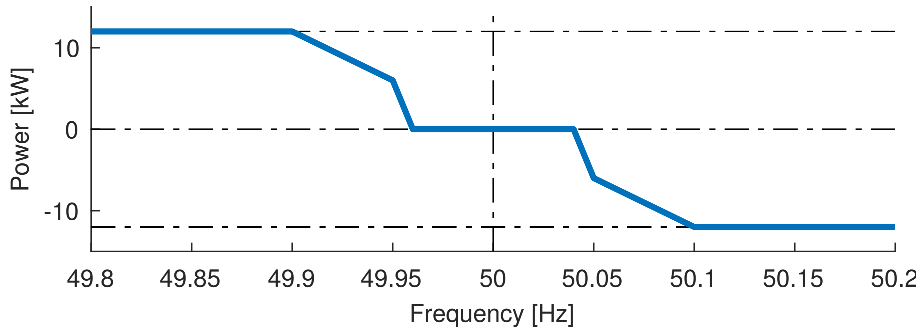

Figure 67: FCR-N droop curve in the LVDC Suomenniemi BESS during the testing period.

9.3 Third testing period, from 22 December 2017 to 2 January 2018

The final testing stage focused on testing of the collaborative operation of multiple units. As stated previously, the most beneficial application is FCR-N, and therefore, the operation logic was set to aim at the availability of the FCR-N application. In order to ensure that at least one of the units can participate in the FCR-N application there has to be either a logic that is based on the forecast frequency behaviour or a logic that is based purely on the expectation values. The latter approach was selected for the implementation. Because it is difficult to estimate in which direction the frequency will next deviate, an assumption was made that the battery resource pool has to contain resources with varying SOC levels. With that assumption, each resource reaches the SOC edges in the FCR-N operation at different times. Such an operation logic increases the probability of the FCR-N application availability of the battery resource pool. In practice, this behaviour was implemented in the Green Campus BESS logic in the master control unit. The SOC correction of the Green Campus BESS was set to operate based on the present SOC state of the Helen BESS. If the Helen BESS has a SOC level higher than 50 % of the Green Campus BESS, the SOC correction is set to aim at a 40 % SOC level, and vice versa, if the Helen BESS SOC is lower than 50 % of the Green Campus BESS, the correction is set to aim at a 60 % SOC level. Secondary applications are included in a similar set-up as in the second test period. The

LVDC research test site was also operated with the same logic as in the second test period.

9.4 Measurement data

The market data and measurement results are presented in Figures 68–69. The FCR-N price volatility was similar to the price data observed earlier during the past year. The real-time FCR-N price data were not available during the testing period, and therefore, the resources were operated in the FCR-N task every hour excluding the hours when the battery SOC level was saturated to the lower or upper limit. The balancing power market price data in Figure 69 represent a typical pattern. The price peaked at 200 €/MWh at the beginning of December.

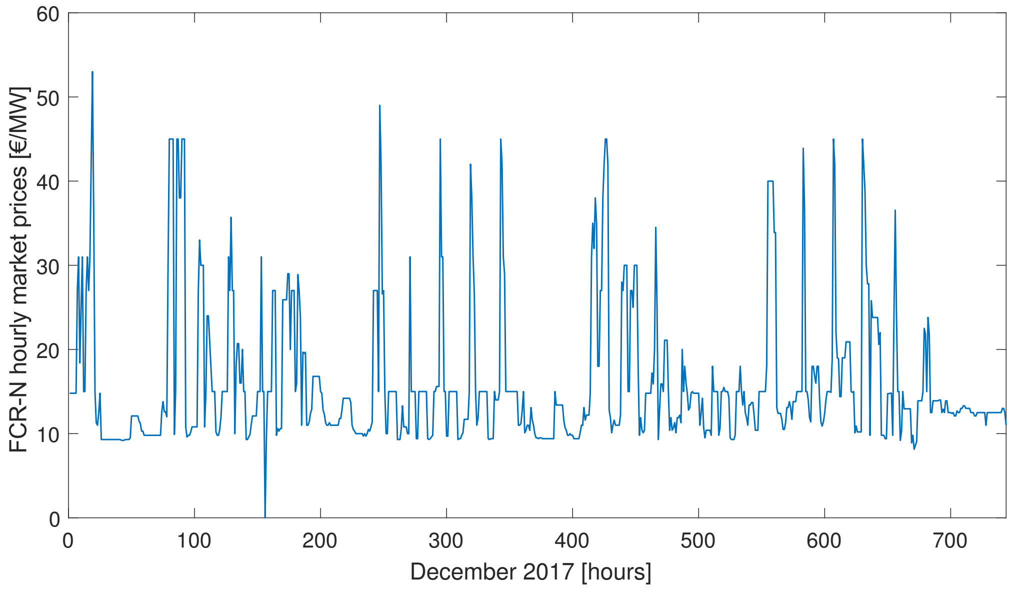

Figure 68: FCR-N hourly market prices in December 2017.

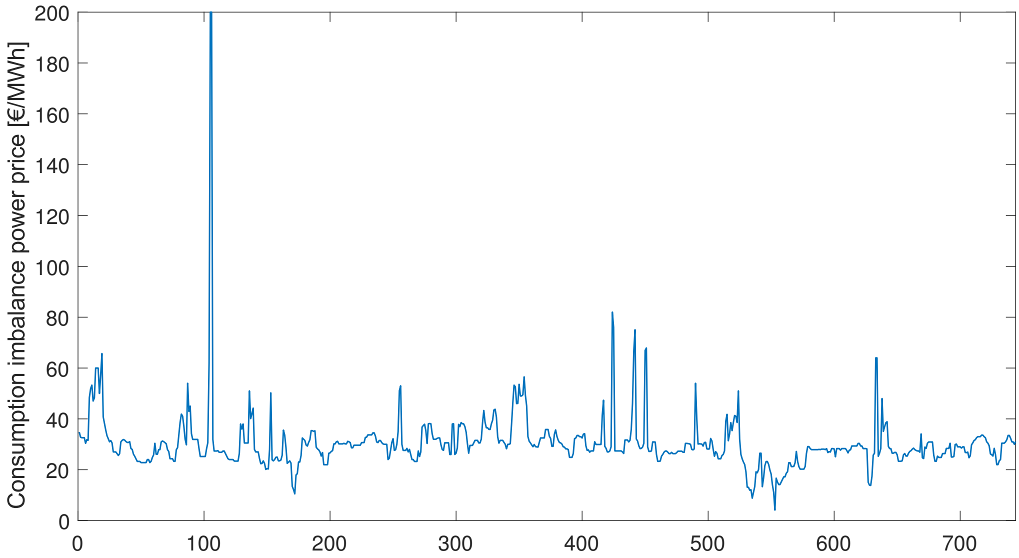

Figure 69: Balancing power market prices in December 2017.

Figures 70–71 illustrate the battery SOC level and active power values during a randomly selected 24-hour period.

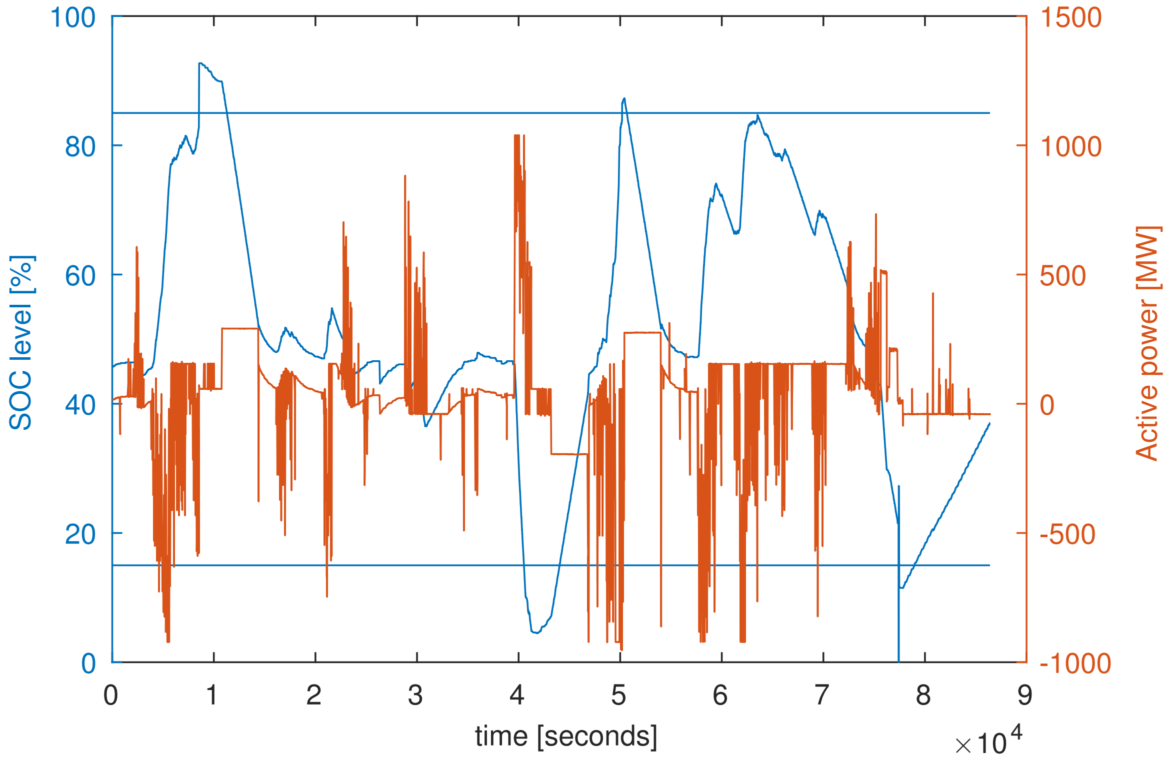

Figure 70: Illustration of the SOC level and active power values in the period of 24 hours.

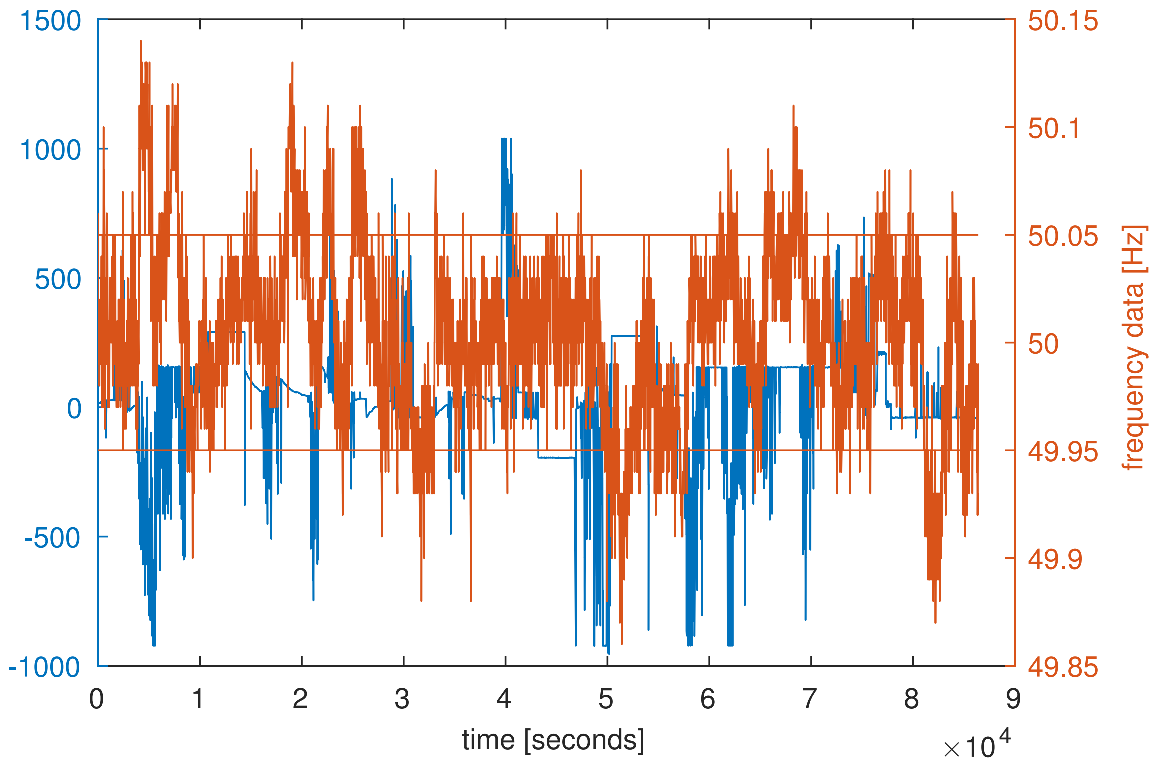

Figure 71: Frequency measurement data and active power of the BESS in the period of 24 hours.

9.5 Discussion

The results indicate that the battery resource behaves as the analyses showed. However, the statistical certainty of the results can be questioned as the testing period lasted only one and a half months. Still, valuable observations can be made regarding the recorded data during the testing period.

The first observation of the analysed data shows that the SOC level tends to saturate to the lower limit more often that to the upper limit. This is explained by the unefficiency of the battery (the charging power is always less than the discharging power) and supports the findings obtained during the simulations.

The second noteworthy characteristic of the data is that if the resources are not coordinated mutually the probability of the undelivered services increases significantly. In the second testing period there were several occasions when none of the three battery resources was able to fulfill the FCR-N service request that was set to the first-order priority. Figure 72 illustrated an example of such an event when two battery resources were saturated to the edge of the operating area. The LVDC research site BESS has been reserved for the full capacity UPS service because of the weather conditions on the site.

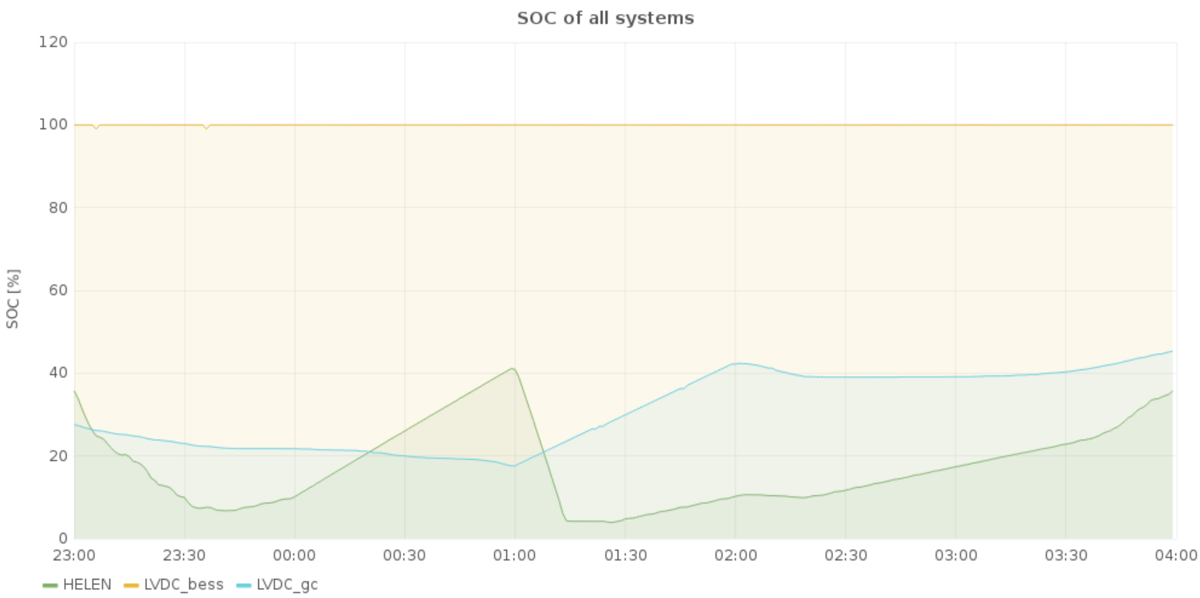

Figure 72: SOC of all the three battery resources. The graph begins from the 24th of December and ends five hours later on the 25th of December.

The third observation made during the third testing period (mutual control) was that the service availability of the FCR-N service increased as expected. The SOC correction events seemed to activate at concurrent hours rather than within the same hour. In other words, the SOC correction did not take place in an overlapping manner among the resources. Nevertheless, the testing period was extremely short, and thus, any definitive conclusions cannot be made regarding the increased service level of the FCR-N task.

10 Conclusions and further research

In the final chapter, the key highlights of the results obtained within the project are given. One of the main objectives of the research was to define a strategy to operate a BESS in the most cost-effective way. The following observations were made in the course of the project:

- At the present moment, the most rewarding application is a power-intensive one such as the FCR-N hourly market. BESS operation in the FCR-N hourly market can be paid back in ten years with the present market prices with the price bid of 10 €/MW.
- However, the main challenge of the operation for the frequency regulation task is underutilization of the battery, if operated with the 3 min activation requirement. If the BESS is operated with the instant activation time, the cycles may run out before the investments are paid back with the present prices in the FCR-N hourly market and the frequency quality.
- The challenge of underutilization can be turned into an opportunity for a BESS operator to allocate the BESS capacity to the other application(s).
- The system-level tasks can be carried out simultaneously as long as the SOC level is kept within the target level, which increases the capacity availability for multiple applications.
- The SOC level correction method requires further investigation: what is a reasonable way to do it.
- The system- and local-level tasks can be carried out simultaneously thereby delivering the maximum profit with the right prioritization of the tasks. With the present frequency market prices, frequency quality and the considered case distribution network, the priority should be given to the system-level task, which has only a minor impact on the local RPC task.
- When a BESS operator maximizes the profit by prioritizing multiple tasks, the conflict of objectives between the stakeholders can be mitigated by a) setting the right priority of the tasks and 2) aggregating multiple BESS units and dynamically changing the priority of tasks on their premises.
- The right priority of the tasks that delivers the maximum profit to a BESS operator is sensitive to the system market prices and rules as well as the needs of the local distribution grid. More analyses should be carried out to define the optimum priority of the tasks.
- The control architecture does not scale up well for a large number of resources. Static VPN tunnels are not feasible for the job, and therefore, communication protocols with strong encryption have to be considered.

Further research needs can be categorized as

1. Further development of a simulation tool
    - Simulating various types and sizes of a BESS
    - Considering the impacts of different operating strategies on the lifetime of a BESS

- Incorporating optimization of the operating parameters of the BESS in various marketplaces (both system and local)
- Enabling the analysis of the impact of various operating strategies on a distribution grid (power quality, reliability in various disturbance scenarios) with different penetration rates of BESS
- Implementing various alternatives for SOC correction methods

2. Regulation, energy market design and business aspects
    - Impact of the regulation and market design on the operation of various types and sizes of BESS, and influences on the owners/operators of the BESS, as well their needs and experiences
    - Novel remuneration mechanisms for BESS resources (e.g. development of the ancillary market rules and compensation mechanisms)
    - Development of the cost-benefit sharing mechanisms in the multi-use of the BESS, that is, for instance, combining the DSO's and the retailer's actions in a reasonable way, both technically and economically, especially considering the cases when the DSO's and the retailer's activities are in conflict with each other
    - Specifying the conflict of objectives in different operating strategies: a) Who is responsible for selecting a priority order? b) What is the benefit and/or risks for the stakeholders involved? c) How to solve the case when a BESS operator causes imbalance power to a balance responsible party (BRP)?
    - Investigating operating strategies (priority order) of the BESS at various voltage levels of the grid (LV, MV, HV)
    - Impact of the shift from the energy-based to the power-based tariff on the operating strategy of the BESS
    - Development of the economic regulation of the electricity distribution business and related legislation to provide the DSOs with opportunities and incentives for using BESS for the needs of the distribution network (e.g. peak cutting and reliability improvement)
    - Regulatory rules for using BESS in energy communities
3. Developing optimization methods
    - Simple optimization algorithms for individual subtasks (local optimization) and complex algorithms for the whole problem (global optimization)
    - Learning algorithms for a BESS operating strategy to behave close-to-optimally
4. Scenarios in the future energy systems
    - Market impact of the increased BESS participation (e.g. possible saturation of the ancillary markets)
    - More detailed forecasts for loads and generation in the power system, for optimal

BESS sizing and operating strategies; for instance, which capacity should be available for the local tasks and how much should be allocated to the needs of the energy system

- Studying the commercial opportunities of BESS in the scenario of large-scale penetration of BESS (e.g. what would be the added value from flexibility, if flexibility markets are saturated)

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