Graduate thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Shirin Sadullaeva

Valuation of energy storage technologies in the Nordic power systems and markets context with growing wind power penetration

Graduate thesis in Electric Power Engineering
Supervisor: Prof., Dr. Olimpo Anaya-Lara
Co-supervisor: Dr. Raymundo E.Torres-Olguin
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Preface

I would like to express my heartfelt thanks to my supervisor Prof., Dr. Olimpo Anaya-Lara and co-supervisor Dr. Raymundo E.Torres-Olguin for their trust in my abilities, allowing me the autonomy to explore my research interests while providing the necessary guidance and supervision. This journey would not have been possible without their supervision and guidance.

I am sincerely grateful for their guidance, availability for the weekly meetings, and assistance throughout this research endeavor. Their mentorship has been invaluable, and I am truly honored to have had the opportunity to work under their supervision.

Thank you very much.

Shirin Sadullaeva

Abstract

Despite the Nordic region's extensive experience in operating power systems (PS) with high wind farm (WF) penetration, there are ongoing and emerging technical challenges. The increasing demand for flexible power systems and grid stability has emphasized the need to address key problems linked to variable renewable energy sources (VRE). The signs of inflexibility in the Nordic markets include increasing demand for power ramping capacities, risk of frequency excursions, volatility of market prices, and cases of negative market prices. Additionally, the uneven distribution of flexible resources across bidding zones in the Nordic region makes Sweden and Denmark more prone to price volatility. Energy storage systems (ESS) have garnered significant interest due to their ability to provide multiple grid-associated services and the declining cost of storage components. However, the property of storage systems to deliver a wide range of energy and power services, while being heavily impacted by the external electricity market factors, poses difficulties in quantifying their possible values and monetizing them.

The main research question that framed this Master's Thesis is: **"Is there a value and a niche for energy storage systems at the utility scale to support the Nordic power systems and markets in the context of growing wind power penetration?"**

The research evaluates the value of commercially mature and emerging storage technologies within the Nordic power systems and markets. Specifically, Battery Energy Storage Systems (BESS), Flywheel Energy Storage Systems (FESS), and Diabatic Compressed Air Energy Storage Systems (D-CAES) are examined across various Nordic ancillary and energy markets, including Frequency Containment Reserves for Normal Operation (FCR-N), Fast Frequency Reserves (FFR), manual Frequency Restoration Reserves (mFRR), and energy arbitrage in a Day-Ahead (DA) Elspot market. Listed frequency services are procured by the Nordic Transmission System Operators (TSOs) to maintain equilibrium and stable operation in the grid.

A literature review has revealed tendencies related to a disproportional focus on BESS, while FESS and CAES were underrepresented. Also, the studies of storage opportunities in the Nordic electricity markets are predominantly dedicated to FCR-N with fewer studies valuating FFR or other services.

The contribution of this Master's thesis is the detailed assessment of the potential of mature and emerging storage technologies to address challenges in the Nordic power systems while benefiting storage project owners in the studied Nordic markets. This thesis attempts to enhance the understanding of storage value in Nordic systems by evaluating the feasibility and economic viability of these technologies through the establishment of a storage technology-Nordic market matching framework and simulation models. A second-by-second and hourly annual simulations are implemented in Matlab *de novo* for frequency and energy services on real Nordic PS grid data and recent market prices from Nord Pool, Energinet, and Statnett to ensure the relevancy of the results. Where the optimization of operation based on the profit maximization is allowed by the Nordic market rules (mFRR Energy Activation Market and Energy Arbitrage in Elspot), the Convex (CVX) -tool in Matlab is used to solve a linear deterministic optimization problem. Activation of other services (FCR-N, FFR, mFRR capacity market + EAM) is based on the grid frequency profile or orders from the Nordic system operator.

The results are presented for 3 study cases, 11 scenarios, and 82 sub-scenarios covering selected storage technology types, Nordic market services, and different energy-to-power (E:P) ratios. The results are provided for each technology and market/ combination of markets separately, after which they are cross-compared by utilizing the best-achieved revenues and net present values (NPV).

Findings indicate that BESS, despite cycles-related lifetime limitations, can achieve positive profits in all analyzed markets if sized accordingly. At the same time, FESS is primarily suitable for FCR-N due to its low E:P ratio. CAES, although having high capital expenditure (CAPEX) costs and low efficiency, can be valuable for energy arbitrage and mFRR services with optimized duration. Recommended sizes and ratios for each technology are determined based on revenue potential and economic viability. For automatic frequency service (FCR-N, FFR) E:P of 1 with the size 5MW/5MWh is recommended for the BESS. FESS, having the E:P ratio limit of 0.25, demonstrated the best market performance in FCR-N with the size of 5MW/1MWh. For energy

arbitrage in Elspot markets, a longer storage duration is required. Economic value calculations suggest 1MW/4MWh for the BESS, and 5MW/25MWh for CAES. In mFRR market, which has shown to be the most energy-demanding, 5MW/ 75MWh CAES yielded the highest NPV.

The value of BESS in FCR-N is evaluated to be about 610 USD/kW/year based on the revenue from recommended 5MW/5MWh BESS with NPV totaling at 3,247.73 at the end of a BESS lifetime (12 years). The thesis showed that it is possible to yield a revenue of above 300 USD/kW/year of installed BESS capacity in Elspot market. If storage is already participating in FFR market, then its value can be increased by combining it with FCR-N (estimated value is 399.13 USD/kW/year) or Elspot day-ahead market (249.88 USD/kW/year). This is mostly because FFR is procured only seasonally and therefore would otherwise sit idle if not sequentially stacked with other services. In the case of FESS technology, only FCR-N market has the potential of providing a positive business case according to the thesis conclusions. FFR requires 100% FFR committed capacity activation when the frequency is at its threshold, and therefore FESS is inherently bound to be penalized as maximum power output is less than installed power capacity due to energy constraints associated with low E:P. An alternative strategy was tested for FESS in FFR when only a fourth of the installed capacity is nominated at FFR market to match energy and power capacity limits, but an analysis demonstrated that with the current rules and prices in the Nordic FFR market, obtained revenue failed to offset high FESS' CAPEX costs, and negative NPV is yielded for the alternative strategy. The value of FESS that can be potentially obtained from FCR-N market, is evaluated to be 599.5 USD/kW/year based on the revenue values from 5MW/1MWh FESS with NPV totaling at 2,897.74 USD/kW at the end of a FESS lifetime (20 years). For CAES, all studied markets also allowed yielding positive cases. The analysis has shown that it is possible to yield a revenue of above 300 USD/kW/year of installed CAES capacity in Elspot market. The highest revenue contributor in mFRR market is energy payment EP which CAES receives for the activated capacity in EUR/MWh. mFRR is procured throughout the year. It is stated to be a symmetrical service. However, historical data indicates that Nordic TSOs mostly procure up-ward regulation. Therefore, CAES operators should adopt a certain strategy for recharging CAES. In the thesis, this was done by recharging the CAES from the grid and compensating at up-ward energy regulation prices. The highest value of CAES can be obtained from mFRR service when CAES is bidding into both capacity and energy markets, and evaluated to be 950.73 USD/kW per year based on the revenue from 5MW/75MWh CAES with NPV totaling at 4,774.61 USD/ kW at the end of a CAES lifetime (30 years). If CAES operator for some reason wants to bid in an Elspot market then combining it with mFRR EAM (estimated value is 536 USD/kW/year) can allow increasing the total revenue. This is because CAES would have a wider selection of prices to choose from and can optimize its operation accordingly. Participation of CAES in an Elspot only provides almost four times less revenue of mFRR generated.

Highlights of research gaps, assumptions and limitations of the work and models, and discussions of advantages/ disadvantages and applicability of the used methods were presented in a critical manner. Validation of model behaviors and study conclusions was performed to ensure the adequacy and relevancy of the obtained results.

Suggested future work includes incorporating the remaining markets (FCR-Dynamic, automatic FRR) that were initially disregarded based on recommendations from the literature, exploring the potential for hybrid operation of storage with WF or other VRE plants, and examining the impact of future Nordic balancing market plans on the value of storage, among other avenues of research.

The paper titled "Valuation of mature and emerging storage technologies in the context of Nordic power systems", is under development and is planned for submission to the "Energies" journal in October. The paper is based on the works and conclusions from this Master's thesis.

Sammendrag

Tross omfattende erfaring i Norden med å operere kraftsystemer med høy andel vindkraft, står vi fortsatt overfor tekniske utfordringer. Økt etterspørsel etter fleksible kraftsystemer og stabilitet i strømnettet har understreket behovet for å håndtere problemene knyttet til variable fornybare energikilder. Tegn på manglende fleksibilitet i de nordiske markedene inkluderer økende behov for kraftøkning, risiko for frekvenstap, volatilitet i markedspriser og tilfeller med negative markedspriser. I tillegg fører den ulike fordelingen av fleksible ressurser mellom budsonene i Norden til økt prisvolatilitet i Sverige og Danmark. Energilagringssystemer (ESS) har vakt betydelig interesse på grunn av deres evne til å levere flere tjenester knyttet til strømnettet og den fallende kostnaden for lagringskomponenter. Imidlertid fører egenskapene til lagringssystemer til å levere et bredt spekter av energi- og effektjenester, samtidig som de påvirkes av eksterne faktorer i elektrisitetsmarkedet, til vanskeligheter med å kvantifisere deres mulige verdi og omsette den til økonomisk gevinst.

Hovedspørsmålet som ligger til grunn for denne masteroppgaven er: "Har energilagringssystemer på nytteverdi og en egen plass i det nordiske kraftsystemet med økende penetrering av vindkraft?"

Forskningen vurderer verdien av modne og fremvoksende lagringsteknologier i de nordiske kraftsystemene og markedene. Spesifikt blir batterilagringssystemer (BESS), svinghjullagringssystemer (FESS) og diabatiske komprimerte luftenergilagringssystemer (D-CAES) undersøkt i ulike nordiske markeder for frekvensregulering (FCR-N), hurtigfrekvenstjenester (FFR), manuell frekvenstjenester (mFRR) og energiutnyttelse i Day-Ahead Elspot-markedet. Frekvensreguleringstjenester blir anskaffet av de nordiske overføringsnettoperatørene (TSO) for å opprettholde balanse og stabil drift i strømnettet.

En litteraturgjennomgang har avdekket tendenser knyttet til en uforholdsmessig fokus på BESS, mens FESS og D-CAES var underrepresentert. Videre er studier av lagringsmuligheter i de nordiske elektrisitetsmarkedene hovedsakelig dedikert til FCR-N, med færre studier som vurderer FFR eller andre tjenester.

Bidraget fra denne masteroppgaven er den detaljerte vurderingen av potensialet til modne og fremvoksende lagringsteknologier for å takle utfordringene i de nordiske kraftsystemene og samtidig gi fordeler for lagringsprosjekteiere i de nordiske markedene som er undersøkt. Oppgaven forsøker å forbedre forståelsen av verdien av lagringssystemer i de nordiske systemene ved å vurdere gjennomførbarheten og økonomisk bærekraft av disse teknologiene gjennom etablering av en ramme for sammenkobling mellom lagringsteknologi og nordiske markeder, samt simulering av disse med modeller. Simuleringene utføres på sekundbasis og timelig basis ved hjelp av reelle data fra nordiske kraftsystemer og nylige markedspriser fra Nord Pool, Energinet og Statnett for å sikre relevansen av resultatene.

Resultatene presenteres for tre forskningstilfeller, elleve scenarier og 82 under-scenarier som dekker ulike lagringsteknologier, nordiske markeder og ulike energi-til-effekt (E:P) forhold. Resultatene presenteres for hver teknologi og marked/kombinasjon av markeder separat, etterfulgt av en sammenligning basert på oppnådde inntekter og netto nåverdi (NPV).

Funnet indikerer at BESS, til tross for begrensninger knyttet til syklusvarighet, kan oppnå positiv lønnsomhet i alle analyserte markeder dersom dimensjonert riktig. FESS er primært egnet for FCR-N på grunn av sitt lave E:P-forhold. D-CAES, til tross for høye kapitalkostnader (CAPEX) og lav effektivitet, kan være verdifullt for energiutnyttelse og mFRR-tjenester med optimal varighet. Anbefalte størrelser og forhold for hver teknologi bestemmes basert på potensialet for inntekter og økonomisk bærekraft.

Verdien av BESS i FCR-N vurderes til omtrent 610 USD/kW/år basert på inntekter fra anbefalt 5MW/5MWh BESS, med en NPV på totalt 3 247,73 ved slutten av levetiden (12 år). Oppgaven viser at det er mulig å oppnå inntekter på over 300 USD/kW/år for installert BESS-kapasitet i Elspot-markedet. Hvis lagring allerede deltar i FFR-markedet, kan verdien økes ved å kombinere det med FCR-N (estimert verdi på 399,13 USD/kW/år) eller Elspot day-ahead-markedet (249,88 USD/kW/år). Dette skyldes hovedsakelig at FFR anskaffes bare sesongmessig og ville ellers ikke være i bruk hvis det ikke ble kombinert med andre tjenester. For FESS-teknologi har kun FCR-N-markedet potensial til å gi en positiv forretningscase ifølge konklusjonene i oppgaven. FFR krever

at 100% av den tildelte kapasiteten aktiveres når frekvensen er på terskelnivå, og derfor blir FESS i utgangspunktet straffet siden maksimal effekt er mindre enn installert effektkapasitet på grunn av energibegrensninger knyttet til lavt E:P-forhold. En alternativ strategi ble testet for FESS i FFR der bare en fjerdedel av den installerte kapasiteten er nominert i FFR-markedet for å matche energi- og effektkapasitetsgrenser, men analysen viste at med dagens regler og priser i det nordiske FFR-markedet ble oppnådd inntekt ikke dekket høye CAPEX-kostnader for FESS, og negativ NPV ble oppnådd for den alternative strategien. Verdien av FESS som potensielt kan oppnås fra FCR-N-markedet vurderes til 599,5 USD/kW/år basert på inntektsverdier fra 5MW/1MWh FESS, med en NPV på totalt 2 897,74 USD/kW ved slutten av levetiden (20 år). For D-CAES tillater alle studerte markeder positive resultater. Analyser har vist at det er mulig å oppnå inntekter på over 300 USD/kW/år for installert D-CAES-kapasitet i Elspot-markedet. Den høyeste inntektsbidragsyteren i mFRR-markedet er energibetalingen (EP) som D-CAES mottar for aktivert kapasitet i EUR/MWh. mFRR anskaffes gjennom hele året og betraktes som en symmetrisk tjeneste. Imidlertid indikerer historiske data at nordiske TSO-er hovedsakelig anskaffer oppoverregulering. Derfor bør D-CAES-operatører vedta en strategi for å lade opp D-CAES. I oppgaven ble dette gjort ved å lade opp D-CAES fra strømnettet og kompensere det til oppoverreguleringspriser. Den høyeste verdien av D-CAES kan oppnås fra mFRR-tjenesten når D-CAES byr inn i både kapasitets- og energimarkeder, og vurderes til 950,73 USD/kW/år basert på inntekter fra 5MW/75MWh D-CAES, med en NPV på totalt 4 774,61 USD/kW ved slutten av levetiden (30 år). Hvis D-CAES-operatør av en eller annen grunn ønsker å by inn i Elspot-markedet, kan kombinasjonen med mFRR EAM (estimert verdi på 536 USD/kW/år) øke den totale inntekten. Dette skyldes at D-CAES da har et bredere utvalg av priser å velge mellom og kan optimalisere driften deretter. Deltakelse i Elspot gir bare nesten en fjerdedel av inntektene som genereres i mFRR-markedet.

Forskningsgap, antagelser og begrensninger i arbeidet og modellene, samt fordeler/ulemper og anvendelighet av metodene som er brukt, ble kritisk diskutert. Validering av modellatferd og konklusjoner fra studien ble utført for å sikre adekvatthet og relevans av resultatene.

Forslag til fremtidig arbeid inkluderer å inkludere de gjenværende markedene (FCR-Dynamic, automatisk FRR) som opprinnelig ble utelatt basert på anbefalinger fra litteraturen, utforske mulighetene for hybriddrift av lagring med vindkraftverk eller andre fornybare energianlegg, og undersøke virkningen av fremtidige planer for balansering av det nordiske markedet på lagringsverdien, blant andre forskningsområder.

Artikkelen med tittelen "Vurdering av modne og fremvoksende lagringsteknologier i konteksten av nordiske kraftsystemer" er under utvikling og planlegges sendt til tidsskriftet "Energies" i oktober. Artikkelen er basert på arbeidet og konklusjonene fra denne masteroppgaven.

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Abbreviations and Glossary of Terms

ABBREVIATIONS

AC - Alternating Current

A-CAES- Adiabatic Compressed Air Energy Storage

aFRR - Automatic Frequency Restoration Reserves

AP - Availability Payment

BESS - Battery Energy Storage Systems

BP - Back Pressure of CAES

BT - Back Temperature of CAES

CAES - Compressed Air Energy Storage

CAPEX - Capital Expenditure

CCGT - Combined Cycle Gas Turbine

CCR -Capacity Calculation Region

CEOG - Centrale Electrique de l'Ouest Guyanais

CNS - Carbon Neutral Scenario

CVX - Matlab-based modeling system for convex optimization

DA - A day-ahead market also known as Elspot

DC- Direct Current

DER - Distribution Energy Resources

DI - Dimensioning Incident

DLC - Double-Layer Capacitor

DoD - Depth of Discharge

EAM - Energy Activation Market

EDF - Électricité de France

Ei- the Swedish Energy Markets Inspectorate

EIFS - Secondary Legislation for connection of generators in Sweden

EMS - Energy Management System of a Storage

EP - Energy Payment

ESS - Energy Storage Systems

EV - Electric Vehicles

FB - Flow Battery

FCR-D - Frequency Containment Reserve - Disturbance

FCR-N - Frequency Containment Reserves for Normal Operation

FES - Flywheel Energy Storage

FFR - Fast Frequency Response

FR - Frequency Response

D-1 - One day before the day of operation

D-2- Two days before the day of operation

D-CAES - Diabatic CAES

E:P - Energy-to-power ratio

Elbas - Intraday Market in Nordic Pool

Elspot - Day-ahead market in Nordic Pool

EPRI - Electric Power Research Institute

ESS - Energy Storage Systems

GAMS - General Algebraic Modeling Language

GT - Gas Turbine

HP - High Pressure of CAES

HT - High Temperature of CAES

HVDC - High Voltage Direct Current

IEEE - the Institute of Electrical and Electronics Engineers

IRENA - International Renewable Energy Agency

LAES - Liquid Air Energy Storage

Li-ion - Lithium Ion battery

LP - Linear Programming

MARI - Manually Activated Reserves Initiative

Me-air - Metal-air batteries

mFRR - Manual Frequency Restoration Reserves

min - minutes

NAN - Not Measured Values

NANiC - Sodium nickel chloride batteries

NaS - Sodium sulfur battery

NiCd - Nickel-cadmium battery

NiMH - Nickel metal hydride battery

NPV - Net Present Values

NPSM - Nordic power systems and markets

NREL - National Renewable Energy Laboratory

NSA - Nordic Synchronous Area

O& M - Operation and Maintenance

OPEX - Operational Expenditures

OWF - Offshore Wind Farm

PHS - Pumped Hydro-power Storage

PICASSO - Platform for the International Coordination of the Automatic frequency restoration process and Stable System Operation

PM - Permanent magnet machine

PP - Penalty Payment

PPP Public-Private Partnership

PS - Power Systems

Q - Quarter

QP - Quadratic Programming

RE - Renewable Energy

RfG - Requirements for Generators

RT - Roundtrip efficiency

SA - Synchronous Area

sec - seconds

SEI - Solid Electrolyte Interphase

SMES - Superconducting Magnetic Energy Storage

SoC - State of Charge

SOCP - Second-order cone programs

SOGL - System Operation Guidelines

SoH - State of Health

SvK - Svenska Kraftnät

ths - thousand

TLBO - Teaching-learning-based optimization

TMS - Thermal Management System of battery

TSO - Transmission System Operator

VC-CAES - Variable configuration CAES

VRE - Variable Renewable Energy

WF - Wind Farm

GLOSSARY of TERMS

Emerging Energy Storage Technology - in this Master's Thesis refers to Li-ion BESS

Grid Code - A Technical Specification for Interconnecting a facility to a public grid

Grid Exchange - Storage Exports (discharging) to and Imports (charging) from the utility grid

Mature Energy Storage Technology - in this Master's Thesis refers to D-CAES and FESS

Net Present Value - Indicator that accounts for the present value of all cash flows over the project's lifetime

Niche for Storage - A specific market segment or service where storage technologies gain benefits and fill a particular need of a market/ service

Nordic Transmission System Operators - Five system operators of Nordic Power Systems (Stattnet in Norway, Svenska Kraftnat in Sweden, Fingrid in Finland, Energinet in Denmark)

Optimal/ Recommended Size - The size of a storage system that yields the highest positive net present value given the market rules and technology constraints

Utility Scale - Storage Capacities 1 MW and above

Value of Storage - A ratio between the total generated revenue that corresponds to the highest positive net present value and installed capacity of a storage system

Value Stacking - The practice of leveraging multiple revenue streams or value sources from a single storage system simultaneously or sequentially

Chapter 1

Introduction

1.1 Background

Wind power integration was highlighted as one of the main pillars in the Nordic power sector development roadmap [1]. Despite possessing extensive expertise in operating power systems (PS) with a high share of wind farms (WF), challenges and technical issues continue to emerge in these systems. The growing demand for flexible power systems and grid stability has emphasized the key problems associated with operating grids reliant on variable renewable energy (VRE) sources [2]. Due to the ability to provide multiple grid-associated services and the decreasing cost of storage components, energy storage systems (ESS) are attracting increasing interest among scientific and industrial communities [3].

Pumped hydro-power storage (PHS) was one of the earliest types of storage used for grid services [4]. Other technologically mature ESS implemented at the utility-scale include Diabatic Compressed Air Energy Storage (D-CAES) and Flywheel Energy Storage Systems (FESS) [5]. The development of ancillary electricity markets, coupled with the increased role of volatile power production, has created new opportunities for energy storage [6]. Battery Energy Storage Systems (BESS) have rapidly emerged as ESS with installed capacities exceeding 15 GW in the past 5 years [7]. However, a property of storage systems to deliver a wide range of energy and power services poses challenges in quantifying their possible values and monetizing them [8]. Several factors contribute to the potential of storage technologies, including the structure of the electricity market, limitations and costs of storage technologies, and the availability of alternative flexibility options in the market [9].

This Master's Thesis evaluates the value and performance of the selected storage technologies in the Nordic power systems and markets (NPSM) and provides insights into NPSM's constraints, opportunities, sizing suggestions, possible revenue streams, and Net Present Values (NPV).

1.2 Research Questions and Objectives

The main research question that framed this Master's Thesis is:

Is there a value and a niche for energy storage systems at the utility scale to support the Nordic power systems and markets context of growing wind power penetration?

The sub-questions that helped in addressing the main research question are:

1. Which of the mature or emerging storage technologies demonstrated or have the potential to render services to the grid?
2. What are the common classifications of storage applications/ services?

3. What are the issues with high penetration levels of wind power and what are the strategies of the Nordic Transmission System Operator (TSO) in handling them?
4. Do the Nordic Grid Codes or Nordic Market Structure provide conditions for yielding economic benefits from storage?
5. How is the Nordic Ancillary services market organized?
6. How to evaluate and valuate storage technologies?
7. How to select and what could be the optimal sizes of energy storage in a given context?
8. What is the potential of the Nordic market (s) to generate a positive business case and how much value it is possible to obtain from each of the selected ESS?

The above questions were addressed through the followings objectives:

- Present literature review and analysis of the (a) selected storage technologies; (b) services provided by the storage systems; (c) Nordic TSO's strategies in managing and developing wind power; (d) Nordic Grid Code requirements imposed to WF operation; (e) Nordic Balancing markets; (f) Optimal sizing methods for storage systems.
- Development of storage evaluation framework based on gained theoretical knowledge.
- Selection of methods and implementation of storage sizing and valuation models.
- Formulation of the business cases for testing the models above.
- Calculation of revenue streams and NPVs from storage for different Energy to Power (E:P) combinations and markets.

1.3 Scope of Work, Limitations, and Assumptions

This Master's Thesis aims to evaluate the value and the niche of commercially available and emerging storage technologies within the context of the Nordic power systems and markets, which are experiencing increasing wind penetration. **The value of storage technology will be quantified by a ratio between the total generated revenue that corresponds to the highest positive net present value levels and the installed capacity of a storage system. The niche of storage will be presented in the form of discussions of the specific energy storage technology relevancy for studied markets. The strategy of value stacking and profit maximization where possible and/or feasible will be applied in order to evaluate the potentially highest achievable value. Utility-scale in the research question implies that storage sizes of 1 MW and above will be tested in the studies for the provision of grid services.**

Battery Energy Storage Systems, Flywheel Energy Storage Systems, and Diabatic Compressed Air Energy Storage Systems will be examined across multiple Nordic ancillary and energy markets, such as Frequency Containment Reserves for Normal Operation (FCR-N), Fast Frequency Reserves (FFR), manual Frequency Restoration Reserves (mFRR), and energy arbitrage in a Day-Ahead (DA) Elspot. Storage technologies will be evaluated based on the developed grading scale associated with critical technical and non-technical ESS' parameters. Recommendations will be provided regarding the appropriate optimum sizes of the studied storage systems for the specific markets and their combinations where relevant. The optimum sizing is guided by the revenue potential and economic viability of ESS. The findings will also provide insight into the constraints and opportunities of Nordic markets for storage deployment. The valuation of storage technologies will be done through quantification of revenue streams and the resulting Net Present Values (NPV) will be presented and compared with existing literature. Matlab scripting and CVX tool will be utilized to implement time-domain models of Nordic market rules and storage electrical representation.

Simulations will be conducted on a second-by-second basis for automatic frequency services (FCR-N, FFR) and on an hourly basis for energy (Elspot) and manual frequency markets (mFRR).

Hydro-power pumped storage is out of the scope of this thesis as it has been extensively researched in the context of Nordic energy systems including under the "HydroBalance" project led by the Centre of Environmental Design for Renewable Energy [10], which has drawn conclusions of potential future uses of Norwegian hydropower flexibility and storage for Nordic and European market up to 2050.

The following limitations were accepted to deliver the objectives and reply to the questions described under Section 1.2:

1. Valuation of ESS will be performed in the context of Nordic power systems and markets;
2. Studied markets will be limited to FCR-N, FFR, Elspot, and mFRR.
3. Focus will be on the mature or rapidly emerging ESS such as Li-ion BESS, FESS, and D-CAES.
4. The storage project will be a standalone and connected to the utility grid, as such restoration of a state of charge (SoC) of storage will be performed by charging from the grid (if needed) and compensated accordingly.
5. Degradation of ESS is not accounted for in revenues and NPV's calculation over a storage lifetime;
6. Representation of storage systems in the models will be electrical, with parameters such as SoC, Depth of discharge (DoD), round trip (RT) efficiency, self-discharge losses, maximum energy capacity, maximum, and minimum charging and discharging power.
7. Distribution grid storage services are out of the scope of this thesis.
8. Analysis of grid hosting capacity is out of the scope of this project meaning that it will be assumed that all power discharged by storage can be accommodated by the grid.
9. Studying the impact of planned enhancements in the Nordic balancing market (plans to join European Manually Activated Reserves Initiative and Platform for the International Coordination of the Automatic frequency restoration process and Stable System Operation) on the procured/ required volumes of storage are not included in the scope.

The following assumptions were accepted to deliver the objectives and reply to the questions described under Section 1.2:

- It is assumed that the pattern of price violation and price levels over the operational time of storage will follow current trends in the studied markets. Justification of the approach was given in Section 4.3 when discussing input data;
- It is assumed that the grid can absorb all energy produced by the storage implying that no transmission congestion was considered;
- It is assumed that a storage has access to the availability payment which might not necessarily correspond to the real-life operation.
- FFR is procured on a seasonal basis during summer-autumn months with a procurement period being announced yearly by the Nordic TSOs. It is assumed that FFR will be procured between May to October.

Discussion of the impacts of the accepted assumptions on the model results is provided in section 4.10.

1.4 Methods

Methods employed in the thesis work are presented in a stand-alone Chapter 3. Methods cover:

1. Evaluation Framework of ESS.
2. Modelling of ESS and Stacking Revenues.
3. Valuation of ESS.

Readers are referred to section 3.4 for the discussion of the limitations of used methods.

1.5 Research Gap and Thesis Contribution

The attempt to identify research gaps in the studied area was made based on the literature review in order to understand the potential contribution of this Master's thesis. The points below are based on the personal observations of the author of this Master's thesis, and as such might not fully reflect research gaps in the studied area. Also, the readers are invited to confirm the identified research gaps every three months from the thesis publication date as the storage topic is being actively discussed and researched in both scientific and industrial societies.

In the reviewed literature body the following tendencies were revealed:

1. Evaluation of the economic value of storage technologies to provide grid services is disproportionately focused on BESS. CAES' limited assessment is mostly performed in the context of the US or Canadian markets while very few FESS evaluations are published for Great Britain. For Nordic systems, the majority of published literature is dedicated to PHP for long-term services and to BESS for frequency services. Another noted gap was in the scope of the techno-economic evaluation of storage systems. It was usually performed for a single technology category, whereas comparison across technologies was mostly based on the technical parameters and/or capital expenditures (CAPEX)/ operational expenditures (OPEX) data;
2. Representation of Nordic market opportunities for storage systems in the literature was narrowed down to frequency containment reserve normal and disturbance (FCR-N and FCR-D) with fewer papers highlighting FFR. Valuation of these opportunities was also performed on the example of BESS. Also, assumptions were made in studies making penalties flat (a fixed percentage of penalty payment from the total cash inflow of storage).

The contribution of this thesis is in the detailed assessment of the potential of mature and emerging storage technologies in order to address challenges in the Nordic power systems while benefiting storage project owners in the studied Nordic markets. By examining the feasibility and economic viability of storage technologies through the development of a storage evaluation framework and technology-market simulation models, this research contributes to the broader knowledge and understanding of storage applications in Nordic systems. A second-by-second and hourly annual simulation was performed for frequency and energy services on real Nordic PS grid data and recent market prices from Nord Pool, Energinet, and Statnett to ensure the relevancy of the results. Additionally, the identified research limitations, conclusions, and recommendations for further work pave the way for future studies in this field.

1.6 List of Publications

The paper below, which is based on the works performed within the scope of this Master's thesis, is in progress and will be submitted to Energies scientific journal with an impact score of 5.5:

1. "Valuation of mature and emerging storage technologies in the context of Nordic power systems", Shirin Sadullaeva (3), Dr. Raymundo E.Torres – Olquin (2), Prof. Olimpo Anaya-Lara(1, 2, 3), *Energies.*

*Affiliation:*1 – Electronic and Electrical Engineering, University of Strathclyde Glasgow, 2 – Energy Systems, Sintef Energy Research, 3 – Department of Electric Energy, Norwegian University of Science and Technology (NTNU).

Full Paper Planned Submission Date: 30.10.2023

1.7 Report Structure

The Project Report is divided into six (6) Chapters:

Chapter 1 of the thesis is the Introduction, which provides background information on the thesis topic and establishes the relevance of evaluating storage technologies in the Nordic power systems and markets. It also presents the research questions, objectives, scope of work, methods, limitations and assumptions, research gap, and publications, offering an overview of the study.

Chapter 2 presents the theoretical and analytical framework of existing research, developments and discussions pertaining to the research area. It begins by providing an overview of the most common categories of energy storage systems and their technical details, specifically focusing on BESS, FESS, and CAES. It then discusses power and energy services, examining the suitability of these storage types for grid services. The chapter also addresses challenges related to wind farm integration in the Nordic context and highlights the potential relevance of storage services in the Nordic power system and market, balancing services. Finally, existing optimization methods and tools are explored, along with a review of the literature on sizing problems in energy storage.

Chapter 3 explains methods adopted in the Master's thesis. It also provides a review and discussion of the employed methods.

Chapter 4 elaborates on the framework for the implementation of storage sizing and valuation models. It explains the rationale when matching the storage system with a specific market, selecting study cases, and how value stacking was performed given the constraints of the Nordic balancing market rules along with input data values. Afterward, the explanation of Matlab scripts and definition of model notations are given. The chapter is concluded with an overview of the model constraints.

Chapter 5 summarizes key results and findings of the Master's thesis. The chapter starts with an overview of the tested business cases and explains which performance indicators were used to draw conclusions. The results are presented for 3 study cases, 10 scenarios, and 74 sub-scenarios which cover selected storage technology types, Nordic market services, and different E:P ratios accordingly. The results are provided for each technology and market/ combination of markets separately, after which they are cross-compared by utilizing the best-achieved revenue and NPV values. Results validations are also captured in this Chapter.

Finally, Chapter 6 summarizes the conclusions of the Master's Thesis by grouping them into four categories. Suggestions for future work are also presented in this Chapter.

A short summary of each subsequent Chapter is given in italic font at the beginning of Chapter. Conclusions are presented at the end of sections where relevant for the convenience of readers to navigate the thesis.

Chapter 2

Energy Storage and Grid Services in the Nordic Power Systems and Markets: Theory Analysis and Literature Review

Chapter 2 presents the theoretical and analytical framework of existing research, developments, and discussions pertaining to energy storage, grid services, and optimization aspects while introducing WF's challenges along with the Nordic PS/ Nordic power market context.

Given that the deploying storage at utility scale is a relatively new area and there are many developments and plans in this sphere, two criteria were followed for literature review:

- *Criteria 1. Use recent references;*
- *Criteria 2. Use reliable sources (IEEE Xplore, Springer, Science Direct, national TSOs strategies, NREL, IRENA) with a decent number of citations. A number of citations were checked through Google Scholar.*

Chapter 2 first provides the most adopted categories of energy storage systems such as the form of energy that is stored and other available classifications. It then gives a concise review of the technicalities of selected storage technologies (BESS, FES, CAES) which, inter alia, cover common issues with the particular storage type, common groups, main equations, status quo, and their operational principles. Discussion after that shifts to the power and energy services in order to understand what classifications exist, and the suitability of described storage types to perform grid services. The analysis is then followed by an overview of the current challenges of WF integration in the Nordic context. The potential relevance of storage services in the Nordic power system/ power market is explained by highlighting the signals indicating issues with WFs in the Nordic power market (e.g., the correlation between wind volatility and increased export levels in the Nordic system or negative pricing), Nordic countries' Grid Code requirements, and structure of Nord Pool and Nordic Balancing markets. Conclusions are made about the possible values, storage services, and markets in the Nordic power system that might be relevant for yielding benefits from implementing energy storage. Finally, existing optimization methods and tools are highlighted and the analysis of literature on storage optimal sizing problems is performed.

The motivation to include the specific sections in this Chapter is explained in Fig. 2.1.

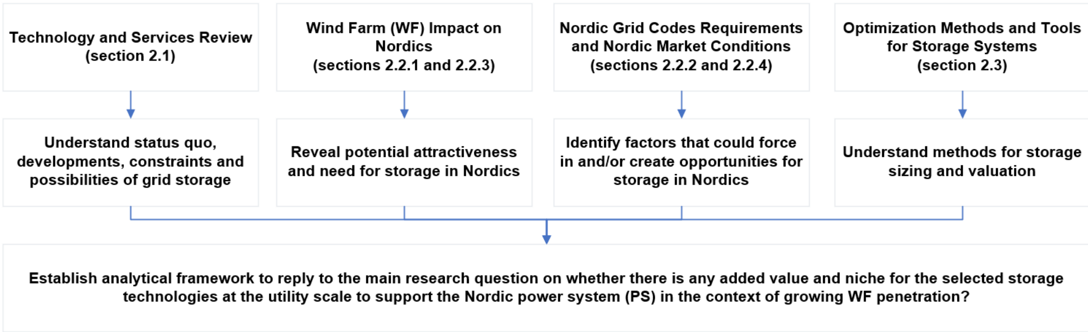


Figure 2.1: Explanation of the reasoning behind the presented Chapter 2 structure.

Source: Self-made

As the Master's Thesis is a logical continuation of my Specialization Project [11], certain subsections were directly extracted from it. Sections 2.1.1, 2.2.1, 2.2.2, and 2.3.2 are reused from the Specialization Project [11]. Section 2.1.3 was extended with the papers review related to the tendencies in E:P ratios in the existing storage projects for different services, Section 2.2.3 was extended with the comparison of study cases from Denmark and Finland on how increased wind farm penetration is escalating market problems, Section 2.3.3 was extended with greater details associated with optimization of specific technologies such as BESS, FESS, and CAES. Finally, Sections 2.1.2, 2.2.4, and 2.3.1 are newly added.

2.1 Storage Technologies and Utility Level Storage Services

2.1.1 Classification of storage systems

The classification of energy systems is provided to establish the understanding of the taxonomy of ESSs to which the selected storage technologies belong. The most widely adopted classification of energy storage systems is based on the form of energy they store (Fig 2.2[12]).

Other classifications include [13]:

- Classification according to the needs of the grid;
- Classification according to the supply time of the storage system;
- Classification as single-and multipurpose storage systems;
- Classification according to the position in the grid.

Thermal energy storage (TES)	Sensible Heat Storage (SHS) • Liquid • Solid Latent heat storage (LHS) or phase change materials (PCM) Thermochemical energy storage (TCES) Pumped thermal energy storage (PTES)
Mechanical energy storage (MES)	Pumped hydro energy storage (PHES) Gravity energy storage (GES) Compressed air energy storage (CAES) Flywheel energy storage (FES)
Chemical energy storage (CES)	Hydrogen energy storage Synthetic natural gas (SNG) Storage Solar fuel
Electrochemical energy storage (EcES)	Battery energy storage (BES) • Lead-acid • Lithium-ion • Nickel-Cadmium • Sodium-sulphur • Sodium ion • Metal Air • Solid-state batteries Flow battery energy storage (FBES) • Vanadium redox battery (VRB) • Polysulfide bromide battery (PSB) • Zinc-bromine (ZnBr) battery Paper battery Flexible battery
Electrical energy storage (ESS)	Electrostatic energy storage • Capacitors • Supercapacitors Magnetic energy storage • Superconducting magnetic energy storage (SMES)
Others	Hybrid energy storage

Figure 2.2: Classification of ESS technologies.

Source: Figure taken from [12]

2.1.2 Status quo and main equations of shortlisted storage systems

This work focuses on three promising energy storage technologies that reached technological and commercial maturity or have been rapidly emerging over the past years, and represent both short-term and long-term duration storage categories, such as Lithium-ion (Li-ion) BESS, FESS, and diabatic CAES.

Battery Energy Storage Systems

BESS consists of two large technology groups: (I) conventional secondary such as lead-acid (PbA), nickel-cadmium (NiCd), nickel metal hydrate (NiMH), lithium-ion (Li-ion), metal air (Me-air), sodium sulfur (Nas) and sodium nickel chloride (NANiCl); (II) flow batteries (FBs) such as vanadium redox (VR) and hybrid FBs [14]. The common issue with all batteries is their degradation. The aging process can be however reduced by controlling the following parameters [15]:

- The depth of each cycle is known as Depth-of-Discharge (DoD);
- The ambient temperature of the battery cells;

- Energy stored at any given time which is the State-of-Charge (SoC);
- The current circulating throughout the BESS;
- Number of usage cycles.

Battery performance can be measured by the State-of-Health (SoH) indicator (Eqn.2.1) [16]:

$$SoH = \frac{C_{av}}{C_{nom}} \tag{2.1}$$

where C_{av} (MWh or MW) and C_{nom} (MWh and MW) are available and rated capacity of BESS respectively.

The evaluation of the effect of a degradation process on the available battery capacity could be performed by applying the so-called superposition principle, i.e., aggregation of capacity losses (C_{faded}^{total}) due to different processes in a battery [17] such as calendric and cyclic denoted as $C_{faded}^{calendric}$ and C_{faded}^{cyclic} in the Eqn. (2.2) respectively:

$$C_{faded}^{total} \approx= C_{faded}^{calendric} + C_{faded}^{cyclic} \tag{2.2}$$

The focus of this thesis is on Li-ion BESS which is the most widely utilized utility-scale storage technology at the moment. A detailed explanation of the chemistry of rechargeable ion batteries can be found in [18]. The overview of components and principles of a typical state-of-art Li-ion BESS is given in Fig.2.3. It employs a graphite anode and a metal-oxide cathode that intercalate lithium ions through an organic liquid electrolyte. The electrodes are equipped with aluminum and copper current collectors, respectively, which have desirable stability and oxidation potentials. The organic electrolyte and electrode materials are not thermodynamically stable, so during the initial charge-discharge cycles, a Solid Electrolyte Interphase (SEI) layer is formed on the graphite anode side. This SEI layer acts as a protective barrier against direct electrolyte exposure, as it is electronically non-conductive. However, the SEI layer is not an ideal insulator and may gradually grow during subsequent operation, leading to a loss of active lithium. This process is often associated with decreased battery capacity and increased resistance [19].

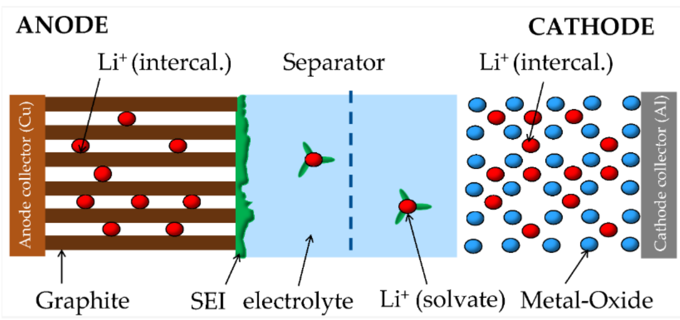


Figure 2.3: Components and principles of a typical state-of-art Li-ion BESS.

Source: Figure taken from [19]

Depending on the selected size, application, and voltage connection level, battery storage might consist of multiple battery modules or packs, a DC/AC inverter link, and potentially grid coupling through a transformer[19]. Battery integrity is ensured by its thermal (TMS) and energy management (EMS) systems (Fig.2.4).

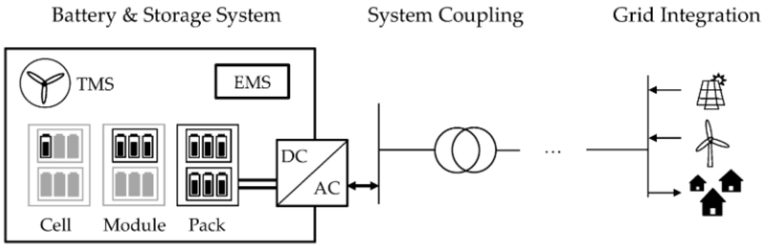


Figure 2.4: BESS components and grid integration.

Source: Figure adapted from [19]

Flywheel

FESSs use the kinetic energy of a rotating mass for electrical energy storing [14]. "The amount of energy that can be stored in the flywheel is a function of the moment of inertia of the rotor and the speed at which it can be rotated along with its tensile strength and stress restrictions (Eqn. 2.3)" [20]. Based on this, FESS systems with speeds up to 10,000 revolutions per minute and high-speed FESS systems with speeds up to 60,000 rotations per minute.

Table 2.1: Comparison of low and high-speed FESS.

Specifications	**Low speed FESS**	**High speed FESS**
Material	Steel	Composite
Electrical Machine	Induction, PM, SM, reluctance machine	PM, SM, reluctance machine
Placement Atmosphere	Partial vacuum and partial gas	Absolute vacuum
Field of Application	Power Systems	Aerospace and traction

$$E = \frac{1}{2} \cdot m \cdot r^2 \cdot (w_{max}^2 - w_{min}^2) \tag{2.3}$$

where E is a useful energy ("state of charge") of the flywheel in the range of maximum ($wmax$) and minimum angular speed ($wmin$) accordingly. Masses of flywheel concentrated at rim and radius are given by m and r respectively. The usable energy of FES is represented by the difference between the energy amounts at these two speeds and is limited to ca. 95% of rated energy depending on the FES design. A comprehensive overview of possible design variations for FES is given in Fig.2.5.

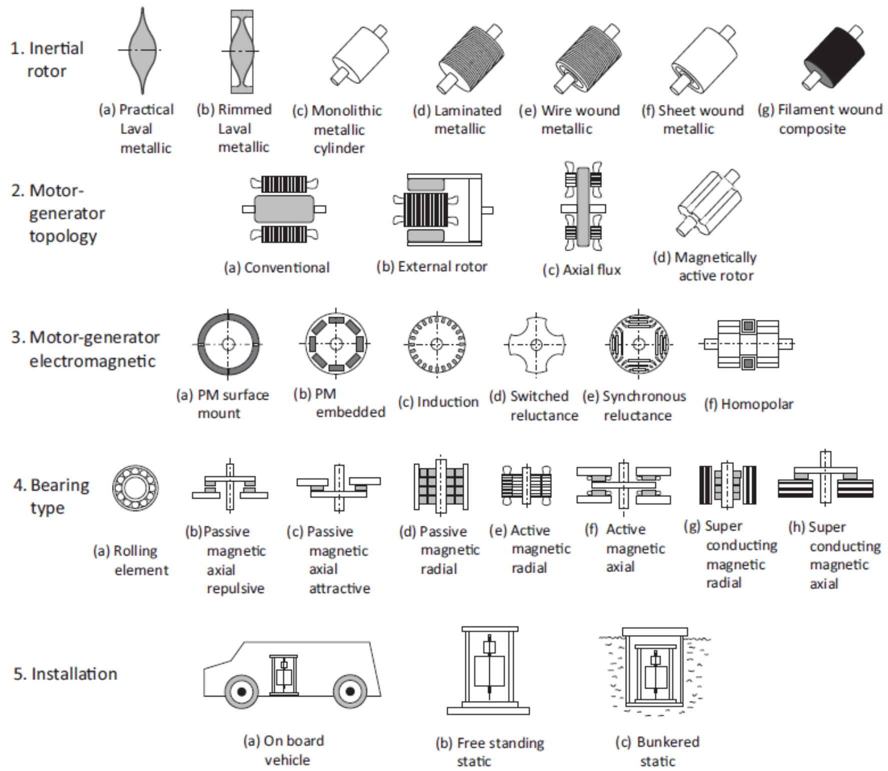


Figure 2.5: Morphological chart of the FESS design options.

Source: Figure taken from [21]

The model for the energy stored is as follows [22]:

$$\frac{dE}{dt} = \eta_{eff} \cdot P_{in} \tag{2.4}$$

$$\eta_{eff} = \begin{cases} e_c, if P_{in} \geqslant 0 \\ e_d, if P_{in} \leqslant 0 \end{cases} \tag{2.5}$$

where P_{in} and η_{eff} denote the input/output power and charging (e_{c})/ discharging (e_{d}) efficiency, respectively. It is suggested that P_{in} should be less or equal to the rated power of FESS. FESS use motor generators for electromechanical conversion of energy in/ out of the flywheel. Motor-generators are designed to operate at efficiencies in the range between 90% - 95 %. However, flywheels have a drawback of higher leakage rates due to losses from friction and windage in the bearing and motor-generator components, as well as magnetic losses. The differential equation 2.4 will be expanded in the modeling part to factor in frictional windage and lamination core losses from the bearing and motor-generator components and represented as standby losses.

The windage loss P_{w} is proportional to the square of flywheel angular speed w and coefficient K [21]. The constant K depends on the chamber pressure, flow regime, and geometry of the flywheel. The equation for windage losses is as follows:

$$P_w \sim K \cdot \omega^2 \tag{2.6}$$

Lamination core losses consist of magnetic hysteresis and eddy current losses:

$$P_c = K_h \cdot f_e \cdot B^n + K_e \cdot f_e \cdot B^2 \tag{2.7}$$

where, B denotes operating peak magnetic flux density, f_e - electrical frequency. K_h, K_e hysteresis and eddy coefficients and n depend on the lamination material, conductivity and thickness [22].

Similar to the BESS, flywheel grid connection is realized through a DC/AC link and transformer coupling (Fig. 2.6):

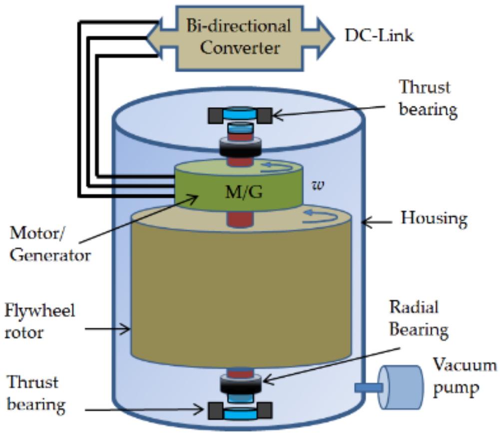


Figure 2.6: FESS components and grid integration.

Source: Figure taken from [23]

FESS can charge/discharge within a few minutes and is least affected by the temperatures and DoD in comparison to the BESS for example. However, as explained above they suffer from high self-discharge levels associated with standby losses, and are also prone to mechanical failures [24].

Compressed Air Energy Storage

CAES represents commercialized mechanical storage technology with high technological maturity and capability to store capacities above 100 MW per unit [14].

Existing commercial scale CAES storage plants are based on a so-called diabatic method which can be broadly compared to the conventional gas turbines but with using lower cost excess energy for compressing the air instead of gas [25].

CAES type such as adiabatic energy storage is under development. The difference of conventional CAES is that the heat in diabatic plants is wasted and energy is stored only in the cool pressurized air. Whereas A-CAES integrates a thermal energy storage system by removing the heat from compressed air and storing it separately in thermal storage which is then recombined with the compressed air for producing hot, high-pressure air for turbine rotation. The process for A-CAES does not involve any combustion and as such, results in a zero-emission of carbon dioxide[26].

It should be understood that D-CAES is a hybrid technology of storage collocated with electricity generation. Discharging diabatic CAES requires additional heat which is usually provided by the combustion of oil or natural gas. As such there are two energy input streams - electrical energy for compressor driving $E_\mathrm{in,el}$ and thermal energy for heating up the air before expander $E_\mathrm{in,th}$ [27].

$$\eta_{cycl,eff} = \frac{E_{out,el}}{E_{in,el} + E_{in,th}} \tag{2.8}$$

For example, the industrially operating McIntosh plant has an efficiency of 54% [27], and producing (discharging) 1 kWh of electrical energy requires 0.69 kWh of electrical energy $E_\mathrm{in,el}$ to drive the air compressor and 1.17 kWh of thermal energy $E_\mathrm{in,th}$ to heat up the air before expansion. Therefore, it is clear that at D-CAES more electricity can be generated (discharged) $E_\mathrm{out,el}$ than needed for charging $E_{\text{in,el}}$. **These reference numbers will be used when modelling CAES in the implementation part of this thesis.**

The scheme of a diabatic CAES is well presented in Fig. 2.7. Where BP/BT and HP/HT denote back pressure/ back temperature and high pressure/ high temperature accordingly.

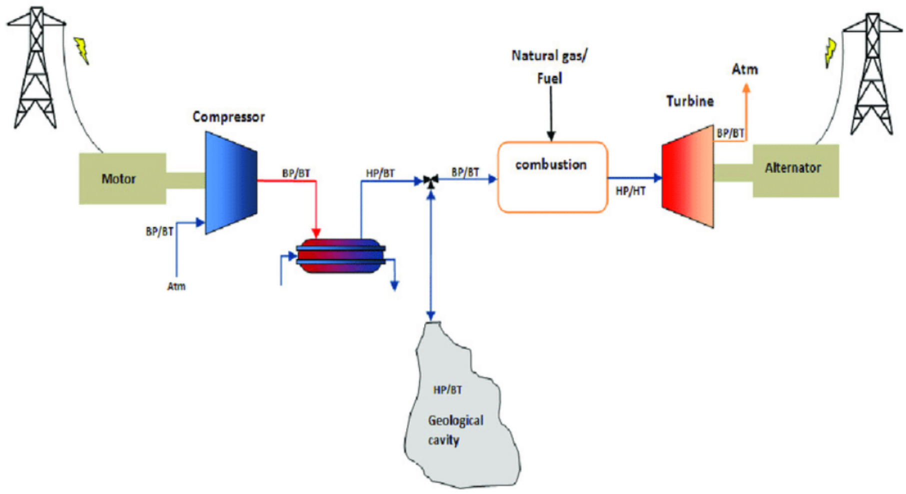


Figure 2.7: Scheme of a diabatic CAES.

Source: Figure taken from [28]

The power of diabatic CAES is in 100 MWs with an energy rating in the range between 100 MWh - 10 GWh [29]. Discharge time is from an hour to 10 hours and a lifetime above 30 years which makes them a good fit for long-duration services, unlike FES. Even though it is possible to discharge D-CAES to 100 %, in order to maintain efficiency at the rated levels it is recommended to operate CAES at 30%-50% of its energy capacity. The relationship between the efficiency and depth of discharge of CAES is based on the principles of thermodynamics and energy conversion. When the system is discharged to a higher level, more energy is required to compress the air, and more energy is lost during the expansion process due to increased friction and other inefficiencies. A detailed explanation of the thermodynamics of CAES is given in [21] and [27].

Another alternative CAES technology is liquid air energy storage (LAES) which is based on the concept that liquidizing and storing air for its later use in electricity production [30]. The main benefit of LAES compared to other CAES is its high energy density which allows for reducing storage volumes by around six times but higher exergy losses and a lower round-trip efficiency of only 70%-80%.

One can see that each type of storage comes with technical limitations and possibilities which could be decisive when selecting the relevance for certain types of applications and project conditions. A comparison of storage technologies is performed in Chapter 4.1.

2.1.3 Services provided by storage systems

The focus of this project is on utility-scale grid-connected storage applications.

The author in [31] highlights 4 possible applications for utility-grid-connected ESS:

1. Smoothing power fluctuations. The charge/ discharge of energy storage can control excessive ramps from renewable energy generation by smoothing/ levelling down/up ramps that are above the threshold set by the TSO or the country Grid Code.
2. Reducing power system's demand for peak capacity. Energy storage can store excessive

energy when the system is at a low load followed by releasing stored energy during the peak hours and as such, reducing the system demand in spare peak generation.

3. Tracing new energy power schedule output. When the difference between the real-time renewable energy (RE) generation and scheduled output power (predicted power) exceeds the permissible error, the energy storage system can absorb or release power to bridge the difference and maximize its ability to trace new energy schedule output.

4. Regulating power system's frequency and voltage. Storage technologies with fast response can support the grid in maintaining frequency and voltage stability during disturbances by quickly absorbing or releasing active or reactive power.

Another classification of storage applications is provided in Fig. 2.8 [32]:

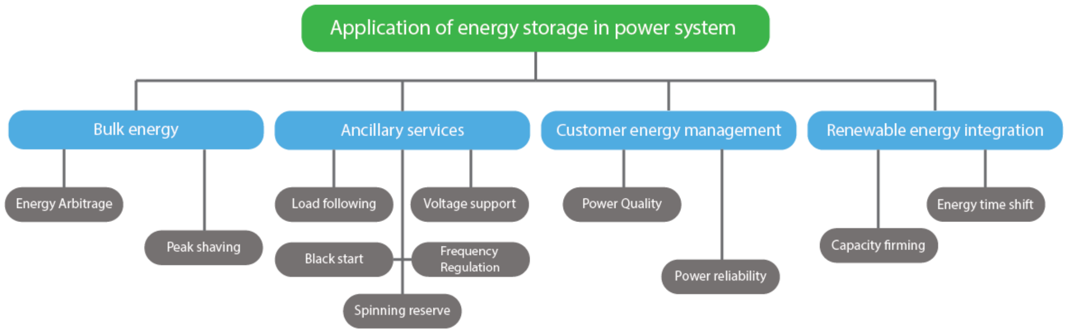


Figure 2.8: Classification of ESS applications.

Source: Figure adapted from [32]

Bulk energy applications are represented by two services which are energy arbitrage and peak shaving.

According to [33] energy arbitrage is "the practice of taking advantage of a price difference by buying energy from the grid at a low price and selling it back to the grid at a higher price". Peak shaving has the same principle as energy arbitrage with the difference in end target where the peak shaving is used to support peak demand [32]. Bulk applications can be compared to the reducing demand for peak capacity service explained by the previous classification.

Ancillary services comprise flexible reserves in the grid that are activated to maintain system stability or re-start the system after a blackout. Authors in [34] suggest that fast responsive energy storage technologies such as battery energy storage, supercapacitor storage technology, flywheel energy storage, and superconducting magnetic energy storage are viable technologies in providing frequency response (FR) in power systems with high penetration of RE generation.

Spinning reserve application on the contrary requires a discharge capacity over longer periods [35].

Every storage application can be characterized by certain parameters which dictate the most suitable technology type depending on storage capacity, duration, response time, and available cycles per operational lifetime (Fig. 2.9) [32]:

Applications			Storage power (MW)	Response time	Discharge time	Cycle	Desired life time (years)
Bulk energy	Energy arbitrage		≤500	minutes	≤10 h	300–400/yr	≤20
	Peak shaving		≤500		≤6 h	50–250/yr	≤20
Ancillary service	Load following		≤100		≤4 h	N/A	≤20
	Spinning reserve		≤100	≤4 h	≤5 h	N/A	≤20
	Voltage support		≤10	≤100 ms	≤1 h	5000/yr	≤20
	Black start		≤50	≤2 h	≤16 h	10–20/yr	≤25
	Frequency regulation	Primary	≤40	Instantaneous	30 min ≥ t ≥ 15 min	8000/yr	≤15
		Secondary	≤40	minute	1 h ≥ t ≥ 30 min		
		Tertiary	≤100		≥1 h		
Customer energy management	Power quality		≤10	≤200 ms	≤2 h	50/yr	≤10
	Power reliability		≤10	minutes	≤4 h	≤400/yr	≤15
Renewable energy integration	Time shift		≤500	≤30 min	≤5 h	≤4000/yr	≤15
	Capacity firming		≤500	≤30 min	≤4 h	300–500/yr	≤20

Figure 2.9: Characteristics of ESS applications.

Source: Figure taken from [32]

An interesting analysis was conducted by authors in [19] to reveal the relations (patterns) between the E:P ratio of storage systems and the services they are rendering. BESS was used to conduct the analysis. Results are shown in Fig. 2.10. It is speculated that for frequency regulation most projects have capacities above 1 MW with an E:P ratio of 1:1 which is justified by the technical requirements imposed on frequency service and market conditions. For peak shaving this ratio is higher and in the range of 4:1 which matches daily variations of load profiles and time windows (morning and evening peak) when the service is required by the dispatchers. E:P ratios will be tested in the implementation part of this thesis.

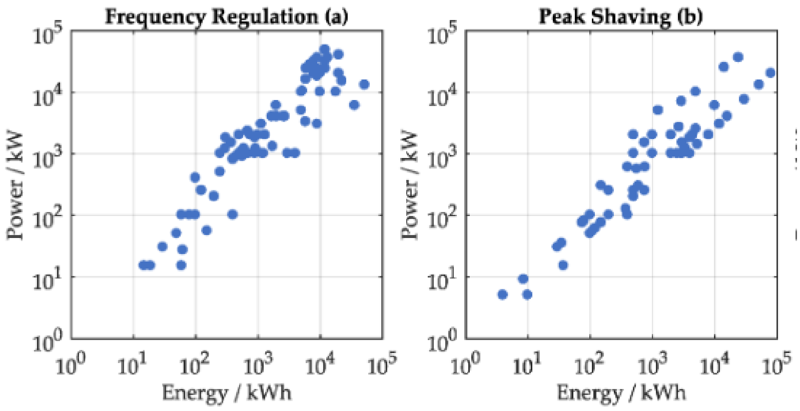


Figure 2.10: Energy to power ratio analysis for frequency (a) and peak shaving (b) services.

Source: Figure taken from[19]

Described services are further analyzed for suitability for Norwegian/ Nordic conditions in Section 2.2.

It appears that even though there is no agreed classification of ESS services/ applications, broadly two big application groups were identified after a literature review such as (1) power services (ancillary services); (2) energy services (bulk services). The former category normally requires a fast response for a limited time (between seconds to minutes) while the latter category requires longer discharge times over continuous periods. Flywheel due to its technical characteristics comprises a short-duration storage group whereas CAES represents a long-duration storage. BESS is used for both groups even though it is more suitable for the former category.

2.2 Managing Wind Farm Integration Challenges in the Nordic Power System/ Power Market

2.2.1 Challenges with WF integration and Nordic TSO strategies on wind power development

Issues studied and experienced with wind integration and associated with the following impacts on power systems vary and evolve over time [36], [37]:

- The need for coordinated balancing in different timescales: short-term reserves or ramping requirements, accurate scheduling, efficient utilization of conventional power plants, peak load balancing.
- The need for grid reinforcement.
- Re-considering market structure and imbalanced energy pricing.

The expected technical challenges in the Nordic power system are given in [38]. They consider planned developments and current system conditions. Tripling WF capacities is highlighted as the main trigger of potential technical issues after 2025 (Fig. 2.11). Data on Nordic PS is given in Appendix A.

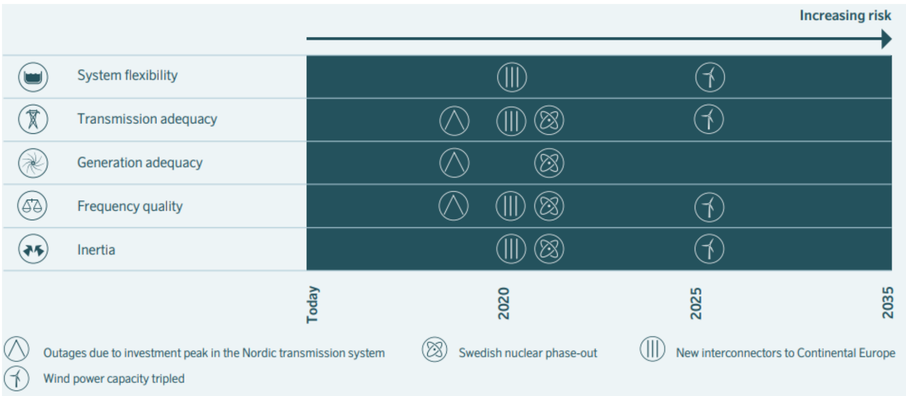


Figure 2.11: Timeline for the identified challenges in the Nordic power system. The figure includes four triggers (changes) that will exacerbate the highlighted challenges.

Source: Figure taken from [38]

Wind power resources can be managed by proper grid connection rules (Grid Codes), increasing transmission capacities and interconnectivity, enabling flexibility in power systems by means of maneuver generation plants, demand side management, and storage systems [36].

There is already a valuable experience in operating grids with high penetration of wind power in both interconnected and more isolated power systems. Wind generation in Danish power system covered close to 50% of annual load in 2020 [2]. Some real-life examples of how wind generation emergencies were handled in the Nordic region have been discussed in Appendix B.

Technical challenges caused by WF have a direct impact on how exports and imports are managed. Fig.2.12 shows the correlation between export levels in Denmark and wind farm production variations. It can be noticed that around 80 % of hourly export variations were caused by the volatility of wind generation. It does not necessarily mean that the Danish power system would not have been able to do the balancing itself but rather it was cost-efficient balancing. However, it can mean that areas with initially lower prices might have been indirectly affected by these variations.

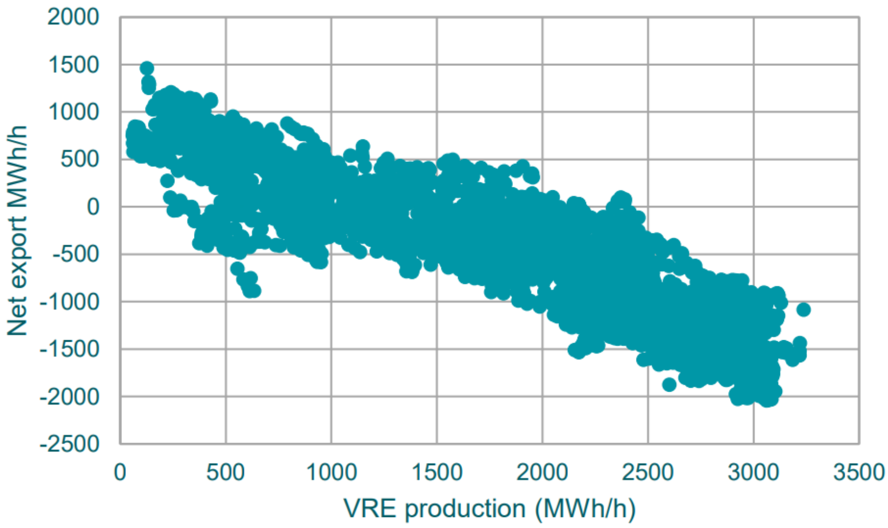


Figure 2.12: Correlation between export and wind power production volatility in Denmark, December 2015.

Source: Figure taken from [2]

An interesting example of how a change in wind production can impact needs in ramping capacities in another Nordic country, Sweden is discussed in [39]. Fig. 2.13 shows how the ramping-up capacity needs for covering net load in Sweden between 5 a.m. and 6 a.m. on a winter day have changed between 2011 and 2018 starting from 2200 MW and ending at 2500 MW should wind power be unavailable. This trend is expected to increase.

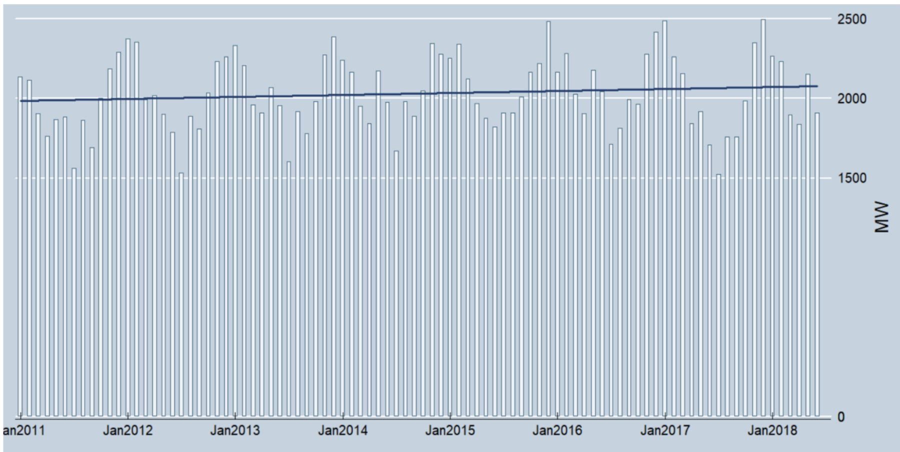


Figure 2.13: Monthly maximum need for ramping-up capabilities to meet net load between 5am and 6am in case of wind unavailability.

Source: Figure taken from [39]

The growing share of VRE/ WF coupled with increasingly deregulated wholesale electricity markets is also known to threaten grid frequency [40]. In the Nordic power systems the frequency deviations are followed up weekly by Statnett and the frequency statistics report is then forwarded to other TSOs [41]. It can be seen from Fig. 2.14 that so far events of frequency excursions (minutes per year) in the Nordic power system are within the maximum values recommended by the System Operation Guideline (SOGL). This is possible because of the structure of the Nordic balancing market (more details on the market are discussed in Section 2.2.4).

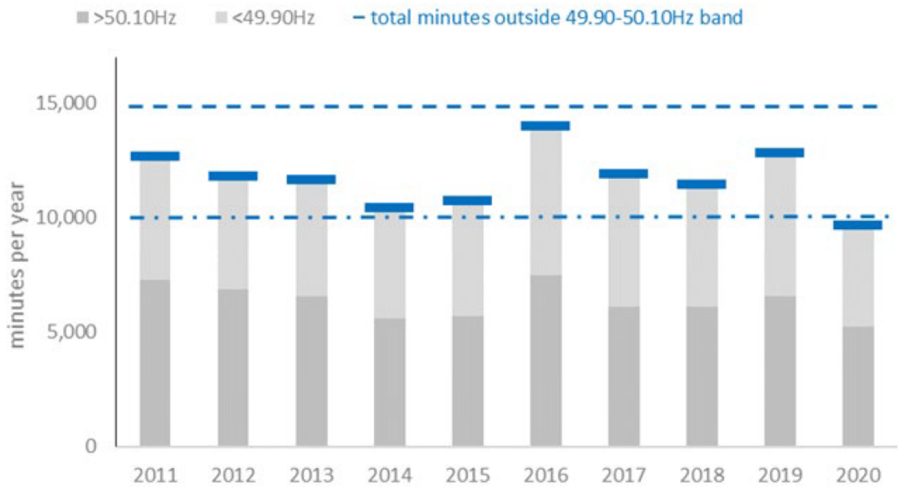


Figure 2.14: The minutes outside the standard frequency range VS maximum value of 15000 min/year in SOGL and the target of not more than 10000 min/year, 2011-2020, Nordic PS.

Source: Figure taken from [39]

In the autumn of 2020, the four Nordic TSOs launched work in drafting an updated common strategy for meeting the expectations for wind power development and sector integration until 2030 [1]. According to the strategy, electrification, wind power, flexibility, and sector integration were highlighted as the success elements for the joint Nordic operation. The roadmap for wind power integration consists of four workstreams (Fig. 2.15):

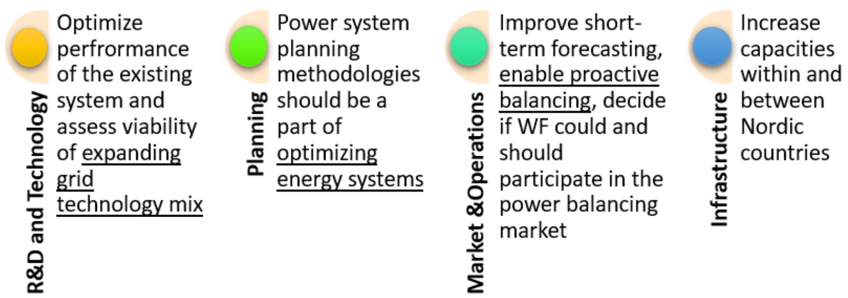


Figure 2.15: Roadmap for wind power development in the Nordic grid.

Source: Self-made based on[1]

It can be concluded that the role of flexibility and needs for balancing has been recognized by Nordic TSOs amid growing VRE/WF penetration.

2.2.2 Nordic Grid Codes requirements to WF for enabling storage deployment

The purpose of this section is to examine the Nordic Grid Codes on the presence of specific operational requirements imposed on utility-scale wind farms. This should help in understanding if ESS could assist wind farm owners in meeting those restrictions.

Several national grid codes introduced ramp rate requirements for wind farms in order to prevent large frequency deviations as a result of large wind production ramps. "A ramp event is identified when the ratio of wind power deviation and time interval is larger than a given power ramp rate threshold value" [42]. Depending on whether the limit is on a ramp-up or ramp-down event, the ramp violation that can not be met by wind farms could be offset by storage systems [43]. In Ireland, EirGrid limits positive ramp events up to 30 MW/min, in Germany the requirement is imposed on ramp-up events at 10% of rated power per minute. In India, the limitation is 10% per minute for plants with a capacity greater than 10 MW connected at 33 kV [43]. The revenue might be generated from avoiding the penalty imposed for failing the requirements or the amount of curtailed wind power that could have been stored otherwise.

Another niche for ESS collocated with wind farms is to deal with forecast errors. In South Africa, wind farm projects under the Public-Private Partnership (PPP) modality have been requested to provide weekly and daily forecast updates. After that, forecast penalty schemes were tested to illustrate the impact of different penalty implementation approaches. The results demonstrated that owner-operators of wind farms would see a material impact on their revenue and the accuracy of forecasting or mitigation of forecast errors will be an important aspect to consider during operations [44].

In Norway, grid requirements are specified in Functional requirements in the power system [45] and in Norwegian National Guideline for functional requirements for electric power systems [46].

Statnett requirements for wind farms apply for capacities above 10 MVA. They include:

- Low/high voltage/ frequency ride through and fault ride through;
- Reactive power control operational mode;
- Active power control operational mode: ramp rate limitations and participation in frequency control;
- Verification of wind farm characteristics on the system model

Even though Statnett reviews installations and retains the right to reject their acceptance, the requirements for the wind farms are **the guidelines** and therefore are optional to follow.

The connection of large wind farms (to the voltage levels above 100 kV) ***in Denmark*** should follow Technical Guidelines TG 3.2.5 [47]. These requirements deal with WF control capabilities, the output of reactive power, tolerance to voltage and frequency deviations, gradient limitations, electrical simulation models requirements, and the contents of operation agreements. The ramp rate requirements state that the ramp rate should be between 20% and 1% of the maximum capacity of the plant and always below 60 MW/min.

In ***Sweden***, power generating facilities should comply with the European regulation RfG [48], the Swedish Electricity Act [49] and the Swedish secondary regulation EIFS 2018:2, issued by Ei. In terms of active power control requirements for wind generation, SvK has no specific limitations to WF except for making available the option to allow reduction to <20% of maximum power (by individual control of each wind turbine) in 5 sec based on the orders received from the system operator.

The Grid Code Specifications for Power Generating Facilities in ***Finish*** grid are also based on the European regulation [48] with national additions and clarifications [50]. Fingrid requires the power generating facility to be capable of maintaining active power according to the target value, regardless of changes in the frequency, except when any frequency control mode is active. However, if the facility's primary energy production decreases rapidly (e.g. when wind velocity decreases), there is no need to maintain active power with a separate energy reserve.

From the above analysis it is possible to conclude that wind farm operators are not particularly "motivated" or forced to equip volatile wind production with storage facilities in the majority of Nordic countries. As such the value of ESS in enabling wind farms will be analyzed in the broader context of the Nordic Market. Additional value in Denmark from storage can be yielded from collocating storage with WF for levelling ramps to the required 60MW/min.

2.2.3 Impact of Wind Farms on the Nordic Power Market

The Nordic power market (Fig. 2.16) is represented by five system operators (Stattnet in Norway, Svenska Kraftnät in Sweden, Fingrid in Finland, Energinet in Denmark) and a single market operator known as Nord Pool [51].

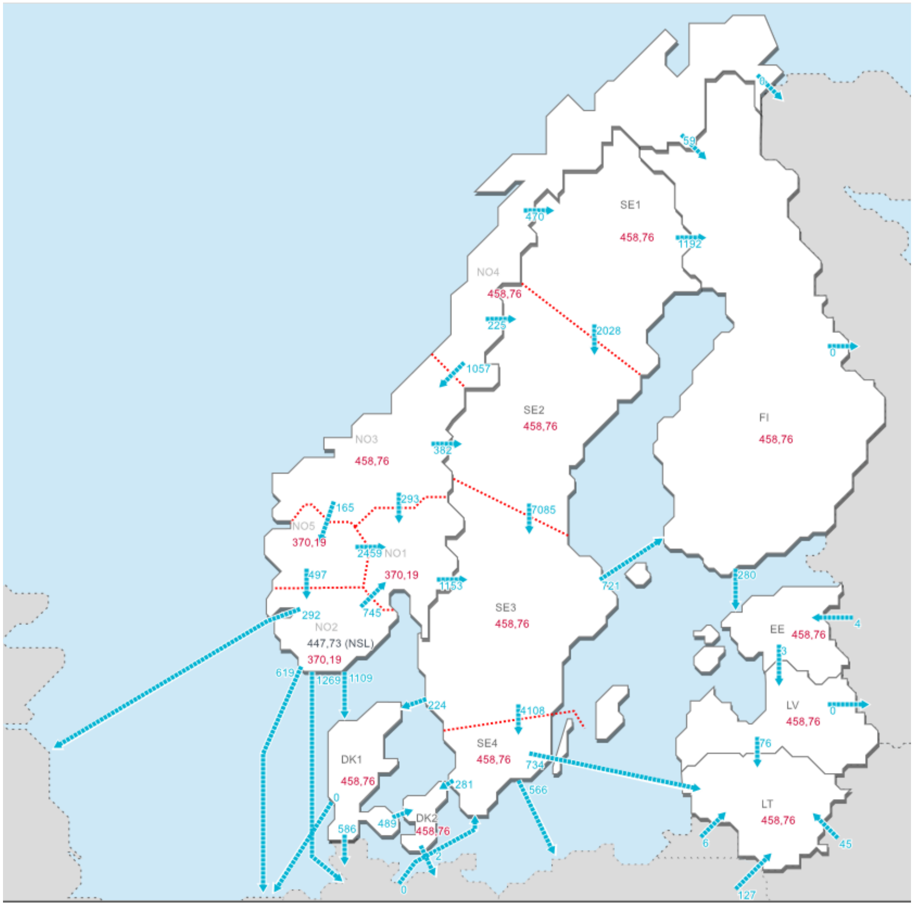


Figure 2.16: Nordic Power Market. Power Flows on 30 December 2022, 04:00 PM.

Source: Figure retrieved from [52]

Hydro, nuclear, and wind power make up the main generation fleet in this market. The data on production both real-time and archive can be accessed through [53].

Electricity trading in the Nordic power market (Fig 2.17) is realized within the different "time windows". The majority of trading happens in a day-ahead market (Elspot). The intraday market (Elbas) serves as a "correction market" where market participants can trade to adjust generation and consumption levels into a balance. Elbas closes one hour before the delivery hour. Finally, the balancing market allows trading of automatic and manual reserves used in order to maintain power balance during the hour of operation. Nord Pool Spot is responsible for the Elspot and Elbas markets, while the national Nordic transmission system operators (TSOs) operate the balancing market [54].

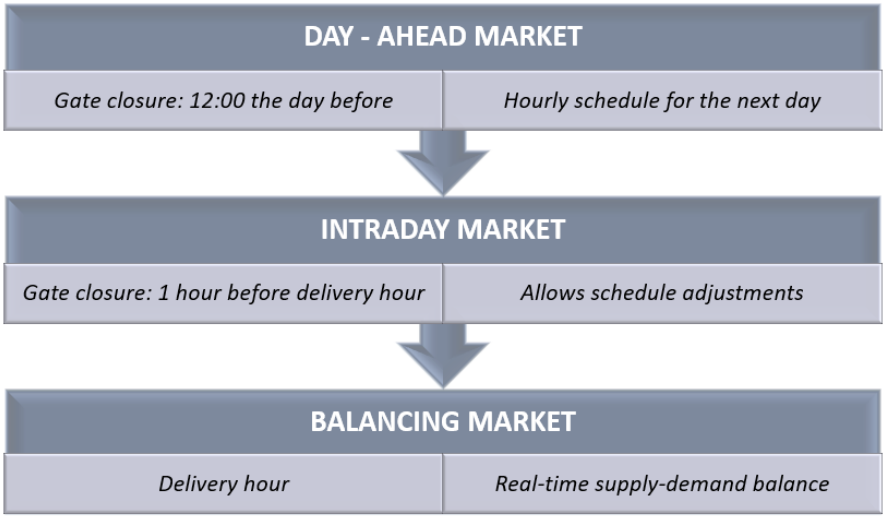


Figure 2.17: Nordic Power Market Structure.

Source: Self-made

Earlier last year (October 2022) the Nordic TSOs published the Evaluation Report [55] on the implementation of a common Nordic aFRR capacity market with cross-zonal capacity reservations. The market is expected to deliver annual net benefits for the Nordic region of approximately 50 million euros. The launch of the market is planned for December 7, 2022. Finland is expected to join after receiving the clearance for the amended national terms and conditions from the Finnish regulator. A common mFRR capacity market development is planned for the later stages.

There are twelve (12) bidding zones in the Nordic Capacity Calculation Region (5 in Norway, 4 in Sweden, 1 in Finland, 2 within Denmark) with unevenly distributed flexible resources [56]. The Norwegian bidding zones such as NO2, NO3, and NO5 and Swedish bidding zones SE1 and SE2 enjoy good availability of flexible hydro-based generation. The bidding zones NO1, SE3, SE4, and DK2 (Norway, Sweden, Denmark) are deficit areas where currently national capacity procurement schemes are deployed to ensure available balancing.

With an influx of wind power and volatile consumer behaviour intermittency in the Nordic grid has increased over the past decade by pressuring electricity prices and making balancing more expensive.

In [39] authors explore the correlation of intermittency and market pricing on the example of the Swedish grid. They highlight three signs of inflexibility in the Swedish market which could further escalate with the increasing role of VRE in the market:

1. Increasing demand for **power ramping capacities** in light of increasing **wind farms penetration**;
2. **Frequency excursions** in the grid due to difficulties in balancing demand and production;
3. **Volatility of the market prices** and cases of **negativity of market prics**.

The impact of penetration levels of wind farms on price convergence and market splitting behaviour was studied in [57] on the example of the Denmark system. The probability of market splitting was concluded to be sensitive to wind power and excess wind generations which are 1.5 times higher than the demand (volume estimated in line with wind expansion plans) require for additional interconnectors.

Another study case on the example of Denmark was provided in [58] where authors investigated the feasibility of hydrogen electrolysis/ hydrogen storage given the increasing levels of wind electricity.

Fig.2.18 demonstrates an escalating trend of excessive offshore and onshore wind energy production that is causing negative energy prices which instead of exporting can be either stored or channeled for hydrogen production.

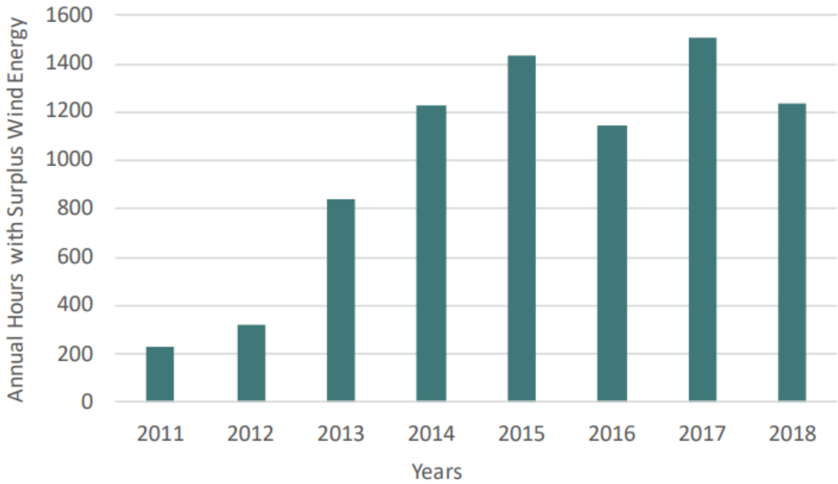


Figure 2.18: Hours of excess wind production (both offshore and onshore) in Denmark from 2011 to 2018.

Source: Figure taken from [58]

The authors in [59] concluded that increased systems costs due to increased wind penetration of wind farms in Finland are not comparable (less) than imbalance payments from wind power producers.

Similar to Sweden and Denmark, electricity prices in Finland for example in 2020 went below zero for a total of nine hours over three days which was directly correlated to wind overproduction.

Even though according to the knowledge gained from the literature review, there are neither special incentive mechanisms nor specific requirements imposed on VRE/WF generators to facilitate the provision of flexible power in the Nordic market context, the issues above potentially create favorable conditions for deploying various ESS technologies which could be either a stand-alone or collocated with VRE/WF projects.

There are very few comparative investigations of benefits from storage in the Nordic market mostly due to the interconnectivity of Nordic systems and reliance on Norwegian hydropower flexibility.

According to the study [60] produced by Sintef, CAES, PHS were concluded as the most suitable for providing bulk power at a lower cost while BESS was considered for energy balancing services in the context of the implementation of the North Sea grid.

In [61] authors concluded that the EES in the conditions of the Nordic Power Market would generate the highest benefits from price arbitrage in Elspot (day ahead) if aggregated with ancillary services from participating in the balancing market. For the Elbas (intraday) market, only Denmark and Sweden's prices offered high profitability due to the stability of prices within the day in other bidding areas.

The following conclusions were drawn from the above analysis:

- *Up until now hydro-power plants were deployed in the Nordic region to cope with balancing requirements;*
- *Flexible resources are not evenly distributed across bidding zones in the Nordic region making Sweden and Denmark more prone to price volatility and grid issues with increasing injection of intermittent sources;*

- *A day ahead and balancing markets might represent profitable opportunities in the Nordic market for ESS if values from several revenue streams such as energy arbitrage/ energy shifting and ancillary services (frequency regulation) are stacked together.*

2.2.4 Nordic Balancing Markets

The Nordic TSOs have a duty of maintaining equilibrium between production and consumption constantly, which they achieve by operating balancing markets. The N-1 criterion governs the amount of reserve acquired in each market, with the ability to manage the Dimensioning Incident (DI), which results in a violation in system frequency. To minimize the effect on system frequency, the TSOs handle a set of frequency reserves. Additionally, Nordic TSOs can exchange and trade reserves with one another. The Nordic Balancing rules are explained in [62]. Fig. 2.19 displays the reserve products employed within the Nordic power system and their technical specification.

Ancillary Services	**FFR** Fast Frequency Response	**FCR** Fast Containment Reserve		**FRR** Fast Restoration Reserve	
Automatic Products	**FFR**	**FCR-D**	**FCR-N**	**aFRR**	
Manual Products					**mFRR**
Activation	Stepwise 49.7 Hz 49.6 Hz 49.5 Hz	Automatically at frequency < 49.9 Hz	Automatically at frequency deviation 49.9-50.1 Hz	Automatically if frequency deviates 50.0 Hz	Manual upon TSO request
Volume	200-300 MW	1450 MW split between Nordic systems based on a Dimensioning Incident	600 MW split between Nordic systems on the basis of annual consumption	Capacity can be exchanged between synchronous systems subject to reserving grid capacity	Shall be sufficient to handle imbalances for each area separated by congestions
Activation time	***Seconds***	***Seconds***	***Minutes***	***Minutes (faster than mFRR)***	***15 Minutes***

Figure 2.19: Nordic Balancing Products.

Source: Figure adapted from [62]

Since the pricing and procurement rules might differ for each Nordic country, *FCR* and *FRR* products will be explained in the example of *Denmark* DK2 zone that operates synchronously with Nordic PS, while *FFR* will be detailed for *Norway*. *This selection is made for readers' comprehensive understanding of the implemented study cases.* The respective information on other Nordic countries is summarized in Fig. 2.21. Table 2.2 provides volumes of automatic balancing capacities required by the Nordic TSOs for 2022 [63].

Table 2.2: Share of balancing power requirements between the Nordic TSOs in 2022 [63].

Nordic TSO	**Share/ Volumes of Balancing Products between the Nordic TSOs**							
	FFR [MW]		**FCR-N** [MW]		**FCR-D** [MW]		**aFRR** [MW]	
Energinet (DK2)	8%	24	2.74%	17	3%	43	10%	30
Svenska kraftnät	35%	105	38.33%	230	40%	580	35%	105
Statnett	39%	117	39.04%	234	37%	537	35%	105
Fingrid	18%	54	19.88%	119	20%	290	20%	60
Total, MW	**100%**	**300**	**100%**	**600**	**100%**	**1450**	**100%**	**300**

While FCR-N can be easily distinguished from other types of services as it is designed to correct the balance between production and consumption continuously, deployment of other services is illustrated in Fig.2.20 on the example of a hypothetical outage of a large component in a power system. FFR serves to slow down a frequency collapse, followed by FCR-D which stops the frequency drop and brings it to a new balance level. aFRR then stabilizes frequency back to the normal band (49.9 Hz - 50.1 Hz). mFRR releases aFRR and ensures equilibrium is maintained until a new balance is achieved in the energy market.

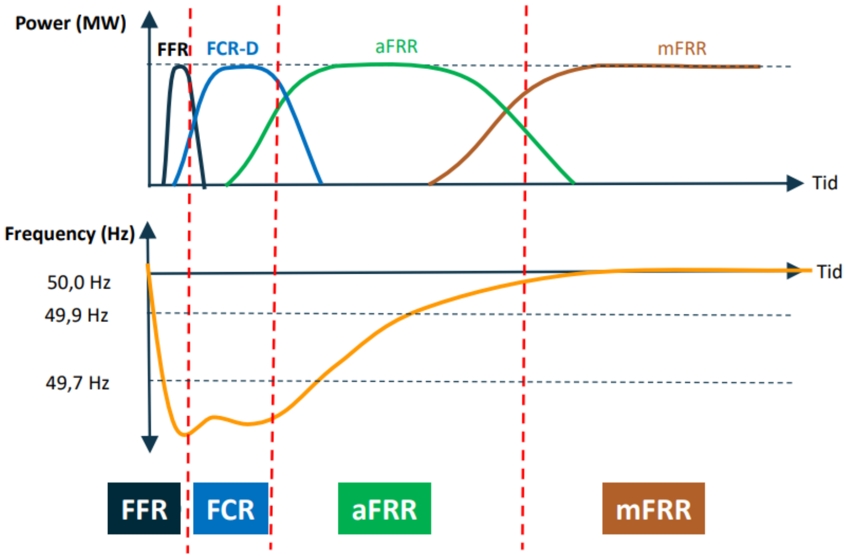


Figure 2.20: Activation of Nordic reserve products during a hypothetical power system incident.

Source: Figure taken from [64]

Analysis of Denmark balancing services details is based on the recently published by Energinet tender conditions for ancillary services [65].

FCR-N and FCR-D

Primary reserves referred to as frequency containment reserves (FCR) are designed to maintain the system operating within the standard frequency range during normal operation (FCR-N) and in the event of disturbance (FCR-D). They are activated automatically through local controllers.

In collaboration with Svenska Kraftnät, Energinet purchases symmetrical frequency-controlled normal operation reserves (FCR-N), which require the suppliers to provide both upward regulation (in case of under-frequency) and downward regulation power (in case of over-frequency). The combined required volume for Energinet and Svenska kraftnät was 258 MW in 2021. FCR can be procured two days before the day of operation (D-2) and one day before the day of operation (D-1). Suppliers can submit bids hourly or as block bids, with block bids submitted at the D-2 auction being able to last up to six hours and block bids submitted at the D-1 auction being able to last up to three hours. The market participant can decide when the block bid begins, but it must end on the day of operation. The usual practice is to sort bids for FCR-N based on their price per MW. Energinet and Svenska Kraftnät select bids with increasing prices to meet their combined required volume, ensuring that the TSOs bear minimal costs. Bids are either accepted in full or rejected altogether. Each approved bid for FCR-N is compensated with an availability payment equivalent to the bidding price of the market participant known as a pay-as-bid. The energy provided by FCR-N upward regulation reserves is settled based on the regulating power price for upward regulation per MWh. Likewise, the energy supplied by FCR-N downward is settled per MWh with the regulating power price for downward regulation.

Following substantial frequency drops FCR-D shall be activated for regulating frequency. It is sized based on DI which is the largest generation outage or HVDC deducted by 200 MW for frequency-dependent load [62]. FCR-D is an upward regulation reserve and is activated automatically. It is triggered when the frequency drops suddenly below 49.9 Hz and remains in operation until the frequency is restored or until the manual reserve takes over the power supply. Similarly to FCR-N, FCR-D can be procured in D-2 and the remaining required volumes in D-1 markets. Blocks in D-2 can have up to 6 hours duration with blocks in D-1 with a maximum of 3 hours duration. When FCR-D upward bids are accepted, the market participants are compensated with an availability payment based on their bidding price using a pay-as-bid approach. However, energy volumes provided by frequency-controlled disturbance reserves are not calculated. Instead, the market participants with balance responsibility for the respective units must settle the energy supplies from FCR-D reserves as standard imbalances.

aFRR and mFRR

aFRR are secondary reserves activated automatically to release primary reserves and bring the system back to a balanced operation. aFRR can be also deployed to achieve the agreed exchange schedules through the interconnectors. Normally, it should be possible to supply the reserve within 5 minutes. aFRR activation is centralized and based on the signal received online in the form of a power rating from Energinet to the balance-responsible party with reference to the relevant bid. aFRR is procured through Nordic Market Management System (MMS) whose optimization algorithm is to minimize the socio-economic costs. Each approved bid is compensated with an availability payment equivalent to the highest accepted bid for the bidding area known as a pay-as-cleared approach. The energy supplied from activation of aFRR is compensated to the highest of the electricity spot price and regulating power price for up-regulation.

Tertiary reserves called mFRR are activated manually by the control center to maintain the balance in the system until a new balance is reached or to manage grid bottlenecks. mFRR replaces the remaining FCR and aFRR. mFRR concerns both upward and downward regulation and is procured through regulating the power market. The activation time of full mFRR capacity should be within 15 minutes. All bids for upward and downward regulation accepted will receive an availability payment corresponding to the price of the highest bid for accepted upward and downward regulation accordingly. **Similar to other frequency markets, mFRR has 2 parts: capacity market and energy activation market (EAM). Participation in mFRR EAM does not require bidding to the capacity market [66].**

FFR

FFR service explanation for the Norwegian power system is based on [67] and [68].

Statnett has established a seasonal market for FFR and conducted a demonstration project for the procurement of FFR in 2020 and 2021. In 2022, a commercial market was established for the acquisition of FFR, which providers can offer for the entire season or specific periods. To ensure adequate FFR capacity during low inertia periods, reserve capacity bids are accepted based on merit order, with the final bid setting the price for the FFR market using marginal-cost pricing. The Norwegian FFR market compensates providers for both FFR capacity and activation, with "pay-as-bid" used for the latter. Bid prices must reflect actual costs for the provider and cannot be arbitrarily chosen. Currently, there are two types of contracts for FFR with Statnett both seasonal (May to October) but with different requirements for delivery. FFR Profile is procured at predefined time windows, while FFR Flex is ordered whenever necessary.

According to the Nordic TSOs, it is not allowed to make the same reserve available in several overlapping markets. Also, the reserve shall be activated in response to either grid frequency violations or signals from the TSO depending on the balancing service, and not based on the profit maximization considerations.

	Product Details	Norway (Statnett)	Denmark (Energinet)	Sweden (Svenska kraftnät)	Finland (Fingrid)
FFR	Procurement is done through	National Seasonal Market	National hourly market	Interim solution – seasonal market; Long-term – hourly market	National hourly market
	Minimum bid capacity	1 MM for FFR Profile; 5 MW for FFR Flex	0.3 MW	Not specified	1.0 MW
	Capacity Provider (s)	Generators, Loads	Generators, Batteries, Loads	Information not available	Generators, Batteries, Loads
	Pricing Rules	Marginal-cost pricing for capacity payment and pay-as-bid for activation	Marginal-cost pricing	Marginal -cost pricing	Marginal-cost pricing
	Gate Closure Time	Q1 of the concerned year	D-1 15.00	Long-term plan – D-1	D-1 18.00
FCR-N, FCR-D	Procurement is done through	Partially mandatory and partially market based	Market	Market	Market
	Minimum bid capacity	0.1 MW	0.1 MW	0.1 MW	0.1 MW
	Capacity Provider (s)	Generators	Generators, Batteries, Loads	Generators	Generators
	Pricing Rules	Regulated pricing	Pay as bid for availability payment and Regulating Power pricing for energy supplied (for FCR-N); Availability payment for FCR-D	Pay as bid for availability payment and Regulating Power pricing for energy supplied (for FCR-N); Availability payment for FCR-D	Regulated pricing
	Gate Closure Time	D-2 16:00 D-1 18:30	D-2 16:00 D-1 20:00	D-2 16:00 D-1 20:00	Yearly D-18:30
aFRR	Procurement is done through	Market	Market	Market	Market
	Minimum bid capacity	5.0 MW	1.0 MW	5.0 MW	1.0 MW
	Capacity Provider (s)	Generators	Generators, Batteries, Loads	Generators	Generators
	Pricing Rules	Pay-as-cleared	Pay-as-cleared	Pay-as-cleared	Pay-as-cleared
	Gate Closure Time		D-1 07:30		
mFRR	Procurement is done through	Market	Market	Market	Market
	Minimum bid capacity	1.0 MW	5.0 MW	10.0 MW	10z.0 MW
	Capacity Provider (s)	Generators, Loads	Generators, Loads	Generators, Loads	Generators, Loads
	Pricing Rules	Marginal pricing	Pay-as-cleared	Marginal pricing	Pay-as-bid
	Gate Closure Time	45 min before deliver	D-1 09:00	One hour ahead	D-1 13:00

Figure 2.21: Nordic Balancing Market Specification.

Source: Figure from [69] is updated based on the rules from [62], [67] and[65]

Planned Developments in Nordic Balancing Market

Further developments are planned in the Nordic balancing philosophy in 2023 - 2024 which could create further opportunities for storage facilities [69], [70]. Such plans include:

1. Creation of a Nordic aFRR capacity market - went live on December 7, 2023;
2. Shifting to 15 minutes imbalance settlement period (ISP) instead of the existing 60 minutes - planned for Q2 of 2023;
3. Replacement of manual Nordic regulating power market to automated mFRR to introduce automatic activation of mFRR bids, market clearing every 15 minutes, and area control error

(ACE) based balancing - planned for Q4 of 2023;

4. Development of a new FRR dimensioning methodology in accordance with EU System Operation Guideline (SOGL) to prepare for implementation of the Manually Activated Reserves Initiative (Mari) and Platform for the International Coordination of the Automatic frequency restoration process and Stable System Operation (Picasso) Nordic initiatives;

5. Connection of a Nordic aFRR to the common European platform PICASSO - planned for Q2 2024;

6. Connection of a Nordic mFRR to the common European platform Mari- planned for Q2 2024.

More details can be found through [71]. The roadmap is provided in Fig.2.22

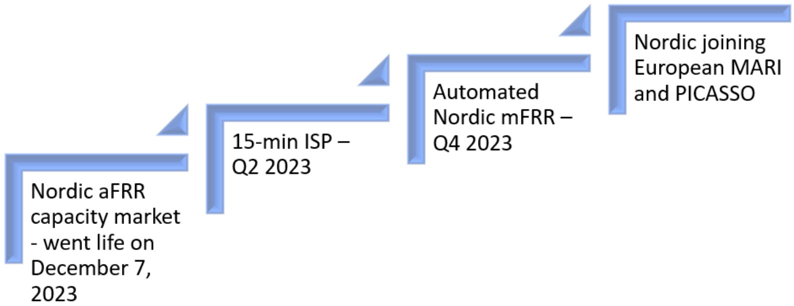


Figure 2.22: Nordic Balancing Model Roadmap.

Source: Figure adapted from [71]

2.3 Optimization Strategies

The analysis of market rules in Section 2.2.4 revealed certain constraints that hinder the optimization of balance providers from the revenue maximization perspective. In the frequency ancillary markets, that provide capacity and energy payments, participation of nominated by balance providers capacities, should be guided (triggered) by the grid frequency profiles or signals from the Nordic TSO. Optimization based on the profit is allowed in energy arbitrage and mFRR energy activation markets. Optimization of storage participation in other services will be based on the seasonal value stacking and is elaborated in Chapter 4. Section 2.3 was nevertheless introduced to obtain an understanding of the storage size and operation optimization developments.

2.3.1 Optimization in energy systems

According to [72] optimization in energy systems can be categorized into three (3) levels:

Level 1. Synthesis optimization. "Synthesis optimization" in energy systems refers to the process of finding the optimal design and operation of an energy system, taking into account various factors such as efficiency (maximizing), cost (minimizing), reliability (maximizing), and environmental impact (minimizing);

Level 2. Design optimization. In the context of energy systems, "Design optimization" involves improving the technical characteristics and properties of the system components, as well as the substances that flow through them under typical operating conditions, in order to achieve desired performance goals. It can be argued that design optimization also encompasses the synthesis of the overall energy system.

Level 3. Operation optimization. "Operation optimization" refers to the process of finding the optimal operating point of a known energy system under specific conditions, where the synthesis and design have already been determined. This optimal point is defined by the operating properties of the system's components and substances, including factors such as speed of rotation, power output, charging and discharging cycles, etc.

Another aspect to consider is the party interested in energy systems optimization. Those usually include:

1. Energy system owners: these are individuals or organizations who own the energy systems and are interested in optimizing their performance to improve efficiency, reduce costs, and increase profitability;
2. Energy system users: these are individuals or organizations who use energy systems and are interested in optimizing their energy consumption to reduce costs and environmental impact;
3. Energy technology manufacturers: these are companies that develop and produce energy technology components, such as solar panels, wind turbines, and batteries, and are interested in optimizing the performance of their products;
4. Energy system operators: These are professionals who operate and maintain the energy system, ensuring that it operates efficiently and reliably;
5. Energy policymakers: These are government officials responsible for developing energy policies and regulations that support the optimization of energy systems to achieve national energy goals.

In the framework of this thesis value evaluation and sizing is performed on behalf of the storage owner implying that the objective function is to increase profitability in energy markets while selecting the most profitable bidding periods in frequency markets.

Several mathematical programming techniques have been developed for solving various types of optimization problems which are also applied in energy systems optimization. The most exhaustive taxonomy of analytical and simulation models is provided by Massachusetts Institute of Technology [73] and summarized in Fig. 2.23

Category	Certainty	Uncertainty
Strategy Evaluation	Deterministic simulation Econometric models Systems of simultaneous equations Input-output models	Monte Carlo simulation Econometric models Stochastic processes Queueing theory Reliability theory
Strategy Generation	Linear programming Network models Integer and mixed-integer programming Nonlinear programming Control theory	Decision theory Dynamic programming Inventory theory Stochastic programming Stochastic control theory

Figure 2.23: Classification of Analytical and Simulation Models.

Source: Figure adapted from [73]

2.3.2 Optimal sizing software

Table 2.3 below provides a non-exhaustive list of existing optimization software/ tools also used for storage optimization. Plexos is a very robust powerful optimization tool [74], however high annual costs make it inaccessible to academia. PSSDE, Homer Pro are mostly designed for distribution-level grids. REopt capability is based upon a mixed-integer linear program optimization to find the optimal mix, sizes, and dispatch of different generators and loads to minimize cost. Similar to Homer Pro it is more widely used for distribution grids applications [75]. Antares Simulator was initially developed by the French transmission operator for its own use and then made publicly available [76]. Currently only available storage model in Antares is hydro storage therefore other storage technologies could be only represented as virtual nodes with power plants and loads.

Table 2.3: Overview of commercial software for optimization.

Name of the optimization software/tool	**Developer**	**Cost**	**Areas of application**
Plexos[74]	Energy Exemplar	USD 80,000 annual per single license	Economic Dispatch Studies; Portfolio Risk Assessment; Battery optimization; Hybrid Resource optimization; Emission modelling
Antares Simulator[76]	RTE	Free	Generation dispatch; Unit commitment; Hydro energy management; Reserve requirements determination
PSSDE[77]	Siemens	Subscription-based fee. Amount not available publicly	Optimization of DER operation including with storage, EV
Homer PRO[78]	NREL, HOMER energy	Between USD 125 to USD 379 monthly	Optimization of microgrids
REopt[79]	NREL	License-based fee. Amount not available publicly	Techno-economic optimization of generation mix (RE, conventional generation, storage systems)

Motivation to study storage and markets modeling techniques and algorithms applicable led to the decision to develop own tools in Matlab.

2.3.3 ESS optimal sizing approaches

The optimal ESS sizing problem is characterized by its power (MW) and energy capacities (MWh) which should justify ESS capital expenditure (CAPEX) by its operational benefits. Generally, the methods for optimal sizing of ESS depend on the market conditions where a project is being implemented, technology type, and selected applications. Considering the uncertain nature of grid load, renewable energy generation, and prices, stochastic programming was proposed by a large amount of reviewed literature. In [80] authors develop a stochastic model for sizing ESS in power systems with intermittent wind generation. The proposed model simultaneously considers expected generation fuels costs and amortized ESS daily capital costs. Another example of stochastic optimization can be found in [81]. The objective of the proposed algorithm is to maximize battery capacity exploitation in the context of variable and stochastic energy and power requirements.

An analytical method is presented in [82] where an evaluation of a hybrid energy storage system for grid services was performed by developing a two-step analytical techno-economic approach. Firstly, the minimal total capacity of the system was calculated by factoring in TSO requirements and the system parameters. Secondly, the optimal capacity of each of the storage components was defined which enables maximization of the economic benefit from the enhanced frequency reserve provision for the UK market. Many researchers have tried to present methods for location, size, and ESS operation regimes optimization. In [83] particle swarm-based algorithm is proposed with the BESS size optimization strategy to maximize the net present value of the project at the end of a contract year. The case is based on the UK market where storage is mostly targeting firm and enhanced frequency services. In [84] optimization is proposed for the energy arbitrage function and tested on the Western Electricity Coordinating Council interconnection. The location and sizing of ESS were approached from the centralized perspective such that selected parameters minimize the expected daily operational costs, renewable energy spillage, and investments.

Several articles reviewed the BESS optimization in the framework of a bidding strategy in electricity markets. Different control reserve market scenarios were built in [85] to develop optimal strategies for battery bidding in Germany's secondary balancing market for yielding maximum economic revenues. Time series forecasting-based auto-regressive integrated moving average models were used by authors to analyze the possibility of generating revenues from the selected cases and different energy-to-power ratios of the BESS. A number of research efforts have been made for studying BESS optimization as a component of microgrids' reliable operation. [86] proposes a novel double-stage framework for the BESS optimization on the basis of failure (outage) forecasting. The first stage involves forecasting the location of faults or other failures in the grid followed by the second stage of teaching-learning-based optimization (TLBO) combined with quadratic programming for minimizing the total microgrid operational costs. Another noticeable trend in the storage optimal sizing discussions is anchored in deploying single storage for multiple services to maximize profit. In [87] authors analyzed the techno-economic performance of a given storage size for single- and multiple-usage cases demonstrating that a multi-use strategy allows yielding maximum profit by utilizing the given battery size.

When it comes to a size optimization of a mechanical storage technology, a literature review has revealed that a focus is often shifted to finding an optimal combination of design, material selection, and geometry modification of a storage system to maximize the overall storing capacity rather than focusing on a sizing aspect only. In [88] authors employed Design of Experiments along with Finite Element Analysis to choose optimum FESS on the basis of weight, energy density, energy storing capacity, and specific energy of a flywheel. Moreover, parameters and size optimization are further combined with the tuning of controller gainers. The study presented in [89] suggests optimizing FESS around fixed power storage while considering angular (rotational) speed and inertia of the flywheel for energy capacity optimization by using a particle swarm technique. Additionally, particle swarm optimization is used to select an optimal value of the inertia and controller gain to achieve a precise system response to the change in power output from the wind energy system. FESS optimization in [90] was performed as a part of the bigger power system's economic dispatch model where other components such as non-linear loads, wind turbines, and synchronous generators were modeled using General Algebraic Modeling Language (GAMS) and standard Interior Point algorithm then applied to solve it. The optimization function was to minimize the generation costs while ensuring transient and frequency stability by providing an adequate dynamic response from the flywheel.

To optimize and broaden the operational range of CAES, authors in [91] proposed variable configuration CAES (VC-CAES) to cope with wind farm fluctuations. Moving to a multi-stage compressor and a multi-stage expander allowed increasing in wind power utilization coefficient from 26.29% to 71.02%. Due to CAES properties to store energy long-term, multiple papers studied CAES optimization in combination with RE plants. In [92] authors studied how integrated optimization of diabatic CAES and solar photovoltaic (SPV) plants can reduce simple payback period and greenhouse gas emissions through performing a Pareto multi-objective optimization and so-called brute-force search. Another example of hybrid CAES optimization where RE utilization rates above 70% were achieved is given in [93]. The paper proposes to use CAES in the construction of an environmentally friendly energy park in North-West China and uses an improved swarm optimization algorithm to solve the model.

As discussed above, the ESS sizing problem can be solved by different methods with the common denominator in the most of reviewed literature of ESS energy and power capacity being treated as decision variables and the economic-financial benefits becoming objective functions to be maximized. The methodology and implementation of valuation, sizing, and optimization (where applicable) are discussed in Chapter 3 and Chapter 4 of this Master's thesis.

Chapter 3

Methods for Storage Modelling and Valuation

The methodology adopted in the Master thesis considers three (3) phases as shown in Fig.3.1.

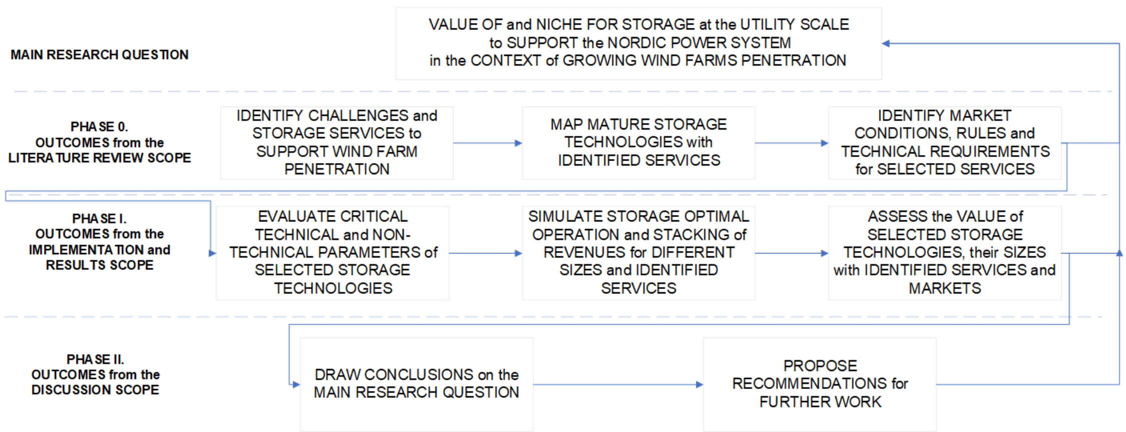


Figure 3.1: Phases of the Master thesis organization.

Source: Self-made

Chapter 3 focuses on the first phase of the structure presented in Fig.3.1, and elucidates methods used in this thesis in order to achieve the objectives described under Section 1.2 and to answer the main research question. Methods include (I) the Establishment of a storage technology evaluation framework for matching the selected ESS with relevant markets, (II) Modelling of the Storage Technologies and Stacking Revenues approach, (III) a Storage economic assessment that illustrates the value of storage. It also provides a critical review and discussion of the employed scientific methods.

3.1 Approach for Evaluation of Storage Technologies

There is no agreed international or regional framework for the evaluation of different storage technologies. Reviewed papers focus on quantifying and cross-comparing technical and economic parameters for various storage types ([94], [95]). The evaluation of ESS was performed within the Thesis in order to match the selected storage technologies with the potential electricity markets/ service.

The proposed storage technology evaluation method involves assigning numerical scores to each important parameter on a grading scale of 0 to 5, with higher scores indicating better performance. It employs systematic literature analysis in order to reveal critical technical and non-technical parameters when considering storage and to assign appropriate weights to each parameter. From the literature review (Section 2.1.3), it was found that requirements for certain parameters such as response time, energy storage duration, and self-discharge vary depending on the service type, and therefore, storage evaluation was tailored and performed for bulk (energy) and fast response ancillary (power) services separately.

The proposed storage technology grading criteria are as follows:

Grade 0: Performance is not Possible

Criteria: The parameter falls outside of the range of compliance and therefore fails to fulfill the minimum requirements.

Grade 1: Poor or Not Relevant Performance

Criteria: The parameter shows significant weaknesses or limitations. It has a negative impact on overall storage performance and may hinder its effectiveness or feasibility in fulfilling the desired requirements.

Grade 2: Below Average Performance

Criteria: The parameter has some weaknesses or limitations, but they are not as pronounced as in Grade 1. The parameter may have a moderate impact on storage performance and might require improvement or intervention for optimal functionality.

Grade 3: Average Performance

Criteria: The parameter demonstrates average performance without any significant strengths or weaknesses. It contributes reasonably to storage functionality/feasibility but does not excel in any particular aspect.

Grade 4: Above Average Performance

Criteria: The parameter exhibits above-average performance, showcasing notable strengths and advantages. It positively impacts storage effectiveness and contributes significantly to fulfilling the desired requirements/ feasibility.

Grade 5: Excellent Performance

Criteria: The parameter demonstrates outstanding performance with exceptional strengths and advantages. It significantly enhances storage functionality making it highly desirable for optimal performance.

Grading of non-technical parameters should be adapted to the local context of a project depending on the merit of a certain project aspect(s).

The details of the established framework and assessment results are presented in Section 4.1.

3.2 Approach for Modelling of Storage Technologies and Stacking Revenues

Modelling of participation of storage technologies in the selected markets will be performed in Matlab. Matlab models will represent the electrical parameters of storage systems and market rules. Deterministic linear modelling with CVX-tool (which is a convex optimization in Matlab) was used for implementing the optimization algorithm in a day-ahead and mFRR EA markets. Logical operators were used in Matlab for frequency services. Models validation was done by analyzing that the implemented algorithms are behaving as expected and comparing results from the models with findings from the available literature. Detailed formulation of analytical problems for each studied case is provided in Chapter 4.

The value stacking and optimization of storage systems will follow the Nordic market rules explained in Section 2.2.4. The market design of balancing services in the Nordic market does not allow units that have access to the availability payment, participate simultaneously in several markets, or choose a bidding strategy based on a maximization of profit value principle. Activation of purchased frequency services, depending on the reserve type, should be based on either frequency settings for FFR, or FCR, or signals from dispatchers for mFRR depending on the selected service type. Furthermore, certain frequency services such as FFR are procured only seasonally. mFRR service allows bidding into only the energy market implying that balance providers can bid in multiple markets if mFRR EA has been selected. It is also possible to perform optimization of bidding strategy for energy services such as energy arbitrage in a day-ahead market. Based on the listed market design constraints, value stacking from multiple services can be performed by taking advantage of the seasonality of frequency markets and daily electricity price variations of energy markets.

Therefore, diversification of market participation of selected storage technologies was performed on a seasonal basis, i.e. taking part in the frequency regulation markets when market prices are expected to be on a higher side or when certain frequency service is being procured, and exercising arbitrage in the energy-only markets at any other time to increase the storage value. Different E:P ratios are tested for the selected business cases to evaluate which storage size and business case allow to yield higher profit while minimizing penalties. As such, the proposed approach consists of the following stages:

1. Analyze seasonal price variation trends of frequency regulation and energy markets in Nordic countries based on historical data to formulate positive business cases.
2. Collect input data for simulations.
3. Build and run Matlab models to calculate ESS' energy content change, charged, discharged power, cycles, revenue streams, and penalties for each selected storage technology type, different E:P ratios, and market services.
4. Build model for NPV calculation to evaluate storage value, recommend optimal sizes, and cross-compare studied cases and storage types.

Selected business cases and other modelling details are provided in Chapter 4. Results are discussed in Chapter 5.

3.3 Net Present Value Approach for Assessment of Storage Value

NPV method was used to compare different sizes (energy-to-power ratios) of the selected storage types and market combinations. The input values to the NPV model are retrieved from Matlab simulations. In essence, the NPV method allows us to conclude the profitability of the project by taking into account the "present value of all cash flows over the project lifetime" [96]. If the difference between the present value of cash flows and the initial investment is positive, one can conclude that the project is potentially profitable. The following equation was employed for the NPV assessment (Eqn. 3.1):

$$NPV = -CAPEX_{Storage} - \sum_{n}^{N} \frac{C_{O\&Mn}}{(1+r)^n} + \frac{Profit_n}{(1+r)^n} \tag{3.1}$$

where r is the discount rate for the project evaluation. $C_{O\&Mn}$ refers to the operation and maintenance costs consisting of fixed and variable costs. Fixed O&M are required for the regular maintenance of storage and variable costs depend on the storage charging and discharging cycles. Charging and discharging cycles are taken from the output of Matlab code. $Profit_n$ refers to the total net profit obtained in the year n. N is the number of years under evaluation (operational lifetime). $CAPEX_{Storage}$ is the total capital expenditure of the storage including engineering, license, and permitting. The Data used for the analysis are provided in Section 4.3.

Input values in the NPV model include:

1. Power and energy capacities based on the selected business case;
2. Project CAPEX in USD (USD);
3. Project fixed (USD/MW) and variable (USD/MWh) operation and maintenance costs;
4. Project discount rate in %;
5. Operational lifetime (in years);
6. Total number of cycles (in charge and discharge process) over a planning horizon (output from Matlab model plots);
7. Total energy trade (in charge and discharge process) in MWh (output from Matlab model);
8. Total Revenue in EUR and USD that also considers total penalties for failing to perform frequency services due to SoC constraints (output from Matlab model));

The NPV amount and sign (positive or negative) allow us to conclude the profitability of selected BESS sizes, E:P ratios, and services.

The interaction between different approach stages is provided in the block diagram in Fig.3.2.

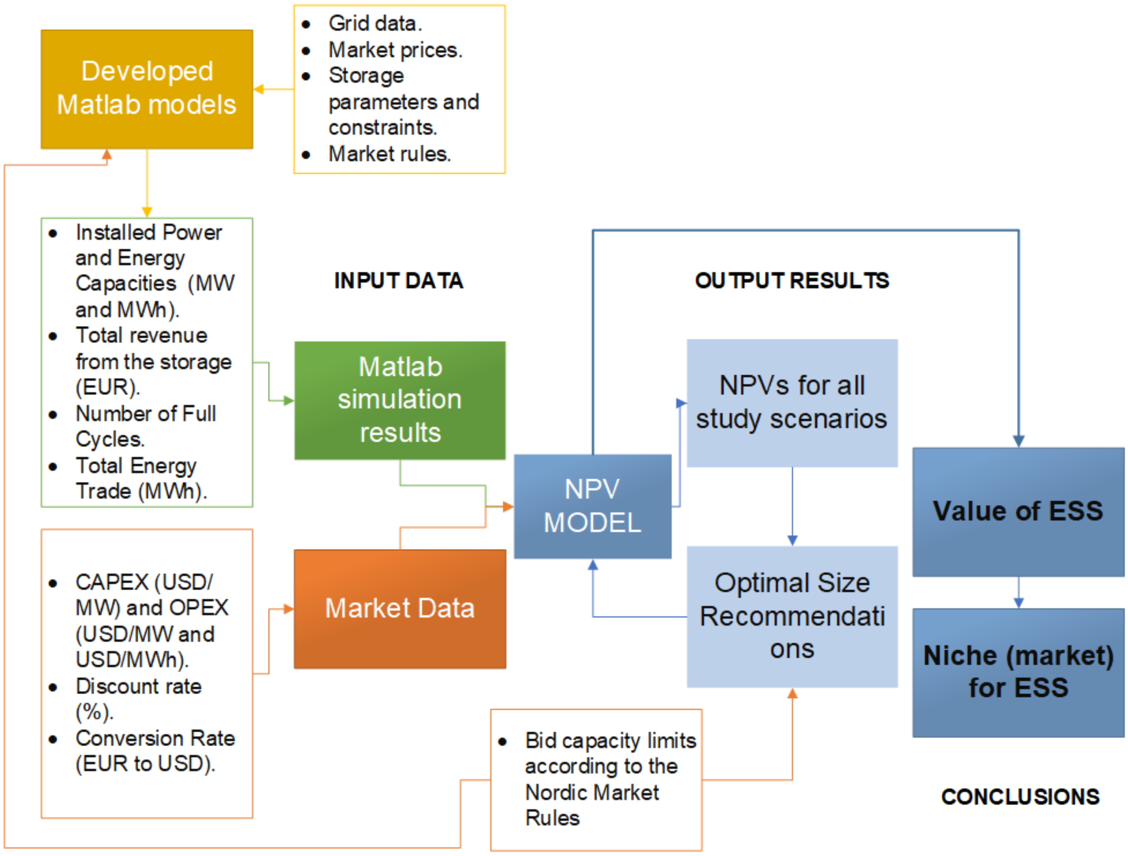


Figure 3.2: Interaction between different approach stages in the Thesis.

Source: Self-made

3.4 Limitations of Used Methods

In Sections 3.1, 3.2, 3.3 methods used in the thesis were explained such as systematic literature review and establishing grading scale for storage evaluation, deterministic linear programming and convex optimization for storage optimization in energy markets, and the NPV approach for the economic assessment. While these methods represent powerful mathematical tools for engineers and provide a reasonable approximation of decision variables one should be aware of their limitations.

The evaluation of critical ESS parameters through systematic literature review may face criticism due to the subjectivity involved in assigning weights to these parameters. However, this concern can be mitigated when applied to the evaluation of storage parameters. This is because the causal relationships between technology performance indicators and their applicability to specific projects or grid services categories are generally objective and straightforward to interpret. Furthermore, the reasonableness of the evaluation conclusions can be supported by simulation results.

In terms of the selection of the mathematical optimization technique, as energy and power systems are characterized by a high level of uncertainty due to volatility of RE generation, continuous load patterns change, and market prices fluctuations, applying stochastic programming (SP) might seem as a more intuitive choice to make, as SP is designed to handle uncertainties. However, the quality of its solutions requires high accuracy of probability distributions of input data [97]. Forecasts of expected grid needs in storage, price change, and wind generation form independent research topics by themselves. The main research interest of this thesis was to evaluate storage in the framework of the Nordic system/market, and therefore, deterministic linear programming was applied as the mathematical modelling tool. Linear programming is actively used for decision support including in engineering problems [98]. For example, in [99] Energinet evaluated storage potential for Denmark while using a deterministic approach.

Convex optimization tool CVX was employed through Matlab to solve the problems formulated in Section 4.4 and in Section 4.5. Convex optimization is the mathematical problem of finding a vector that minimizes or maximizes the function subject to non-linear inequality constraints, linear inequality, equality constraints, and bound constraints [100]. Convex optimization problems include least-square problems, linear programming (LP), quadratic programming (QP), and conic optimization problems. They can be represented as second-order cone programs (SOCP), and as such could be efficiently solved by convex optimization methods. An explanation of convex optimization problems, their applications, and algorithms can be found in [101].

The limitations of the CVX tool in Matlab are explained below. More details about Matlab-based CVX syntax are provided in [102].

- CVX tool could not check if the problem is convex therefore properties of convex optimization should be checked first before using this tool;
- CVX tool is not designed for very large problems (e.g., image processing or machine learning);
- Problem formulation, if possible, should be written in an efficient way by avoiding slow commands in Matlab.

Finally, the selection of NPV for storage economic assessment could be argued due to simplifications used in NPV such as for example assumption about the fixed discount rate or lack of consideration of external factors (e.g., the impact of governmental regulations on the economy of scales of storage technology). However, it is still a comprehensive tool that accounts for all costs and benefits integrated over time value of money for performing sensitivities [96] (e.g., storage sizes, different markets, different technologies) which fit the purpose of the research question.

In conclusion, Chapter 3 delves into the details of the methods utilized in the thesis and proves their relevance to the thesis objectives. Further details on the results from evaluation and modeling frameworks could be found in Chapter 4.

Chapter 4

Implementation of Storage Modelling and Valuation Models

This Chapter presents the framework for the implementation of storage modelling and valuation models. Storage evaluation is performed to assess the relevance of the selected storage technologies for the respective markets. It explains the rationale when selecting study cases while providing thorough information on input data. Chapter also explains how the value stacking was performed for increasing ESS' revenues given the constraints of the Nordic balancing market rules. As introduced in Section 1.3, implementation is focused on the BESS, FESS, and CAES. The formulation of problems for energy arbitrage, FCR-N, FFR, mFRR is presented in great detail. Afterward, the explanation of Matlab scripts and definition of models' notations are given. The chapter is concluded with an overview of the model constraints.

The approach explained in Chapter 3, which is employed for the implementation of storage sizing and valuation models, is summarized below in steps for the readers' convenience:

1. Match the selected storage technology with selected markets.
2. Analyze seasonal price variation trends of frequency regulation and energy markets in Nordic countries based on historical data to formulate positive business cases.
3. Collect input data for simulations.
4. Build and run Matlab models to calculate ESS' energy content change, charged, discharged power, cycles, revenue streams, and penalties for each selected storage technology type, different E:P ratios, and market services.
5. Build model for NPV calculation to evaluate storage value, recommend optimal sizes, and cross-compare studied cases and storage types.

4.1 Matching selected energy storage technologies with the markets

The purpose of Section 4.1 is to summarize the key technical and non-technical parameters of storage technologies. Evaluation will allow us to match the selected storage technologies and selected markets and therefore contribute to a formulation of positive business cases in Section 4.2. The evaluation approach is explained in Chapter 3.1. Storage metrics are split into technical and non-technical indicators and shall be factored in during the storage selection process. Evaluation is performed for two groups of services: bulk (energy) and ancillary (power). Radar charts are made to present multidimensional data related to storage indicators.

A systematic review of storage-related literature was used to reveal and synthesize the critical parameters when considering certain storage types.

Two groups of metrics are proposed: (I) Technical Parameters (Table 4.1 and Table 4.2); (II) Non-technical Parameters (Table 4.3 and Table 4.4). Parameters are synthesized based on [5], [103], [104], [105].

Table 4.1: Comparison of ESS technologies: technical parameters.

Shortlisted ESS technology	**Technical Indicators**			
	Typical power rating [MW]	Typical energy rating [MWh]	Response time	Efficiency [%]
D-CAES	5-300	580-2860	min	40-55
Flywheel	Up to 20	Up to 5	<s	80-95
Li-ion BESS	0.1-100	0.0016-126	<s	65-95

[1] *ESS' parameters used in the simulations are captured in Table 4.6*

Table 4.2: Comparison of ESS technologies: technical parameters: continuation.

Shortlisted ESS technology	**Technical Indicators: continuation**			
	Specific Power [W/kg]	Specific Energy [Wh/kg]	Lifetime/ cycles	Self discharge [%/day]
D-CAES	-	3.2 – 5.5	20-40 years	Negligible
Flywheel	11900	5-100	20,000-175,000 cycles	100
Li-ion BESS	245-2000	80-200	10,000-12,000 cycles	0.1-5

Parameters presented in Table 4.1 and Table 4.2 demonstrate that BESS and FESS are capable of fast response (in seconds) which corresponds to the requirements of both FFR and FCR markets. The biggest constraint of FESS is its low energy-to-power ratios (up to 0.25) and high self-discharge losses (up to 100%). These parameters, are taking FESS out of consideration for long-duration storage services such as, for example, mFRR or energy arbitrage. CAES, with its large capacity and energy ratings, can be a good fit for energy services while having the possibility to participate in slower response frequency services such as aFRR.

Higher specific energy parameter allows for compact and lightweight energy storage systems, which is crucial for applications with space constraints. It does not directly impact the compliance of ESS with market rules but contributes to the overall decision-making process during real-life projects. Higher specific power enables quick energy delivery, which is why BESS and FESS can provide a rapid power response as discussed above, and as such participate in frequency regulation and/or grid stabilization. The limited cycling resource of BESS makes it less attractive for highly cyclic applications. The impact of this parameter on BESS performance in different markets will be discussed in section 5.2.6.

The non-technical parameters have been also included in the analysis, to present other considerations that might have a substantial impact during a storage technology selection process. It is evident that market rules impose no specific constraints for non-technical rules. Yet, they are important when adhering to the project budget, target revenue indicators, environmental and site requirements.

Table 4.3: Comparison of ESS technologies: non-technical parameters.

Shortlisted ESS technology	**Other Indicators**			
	Capital cost [USD/ kW]	Construction timeline [years]	Technological maturity	Location requirements
D-CAES	400-2000	3-5	Mature	The storage site must be in a stable geologic formation that is well sealed and can withstand the repeated pressure cycles required for a CAES system
Flywheel	600-2880	2-4	Mature	Flexible
Li-ion BESS	400-2500	1-3	Mature	Sensitive to temperatures

Table 4.4: Comparison of ESS technologies: non-technical parameters: continuation.

Shortlisted ESS technology	**Other indicators: continuation**	
	Environmental impact	Explanation
D-CAES	Negative	Air pollutant emissions, water consumption and discharge, land use, fuel consumption, and noise. Also affects the local meteorology, terrestrial and aquatic ecology, and geology
Flywheel	Negligible	No greenhouse emission or toxic material produced when flywheels are working
Li-ion BESS	Negative	Metals like cobalt, nickel, and manganese possess toxicity and have the potential to contaminate water supplies and ecosystems if they seep out from landfills.

Based on the values of technical and other parameters, evaluation scores between 0 to 5 were assigned to each parameter, with 5 representing the best score and 0 representing the failure to comply with the requirement of a specific service.

For some parameters, such as efficiency, lifetime, capital costs, and environmental impact, relative merits are not difficult to evaluate. Thus, a 5 can be awarded to the technology that is most efficient or has the lowest capital costs, or longest operational lifetime. Requirements for other parameters, such as response time, and E:P ratio depend on the service type. In essence, bulk energy services require longer response times but higher energy-to-power ratio and lower self-discharge levels whereas ancillary services need fast response and higher power capacities. Therefore, it was decided to present the ranking of selected technologies separately for bulk and fast-response ancillary services as shown in Fig. 4.1 and Fig. 4.2.

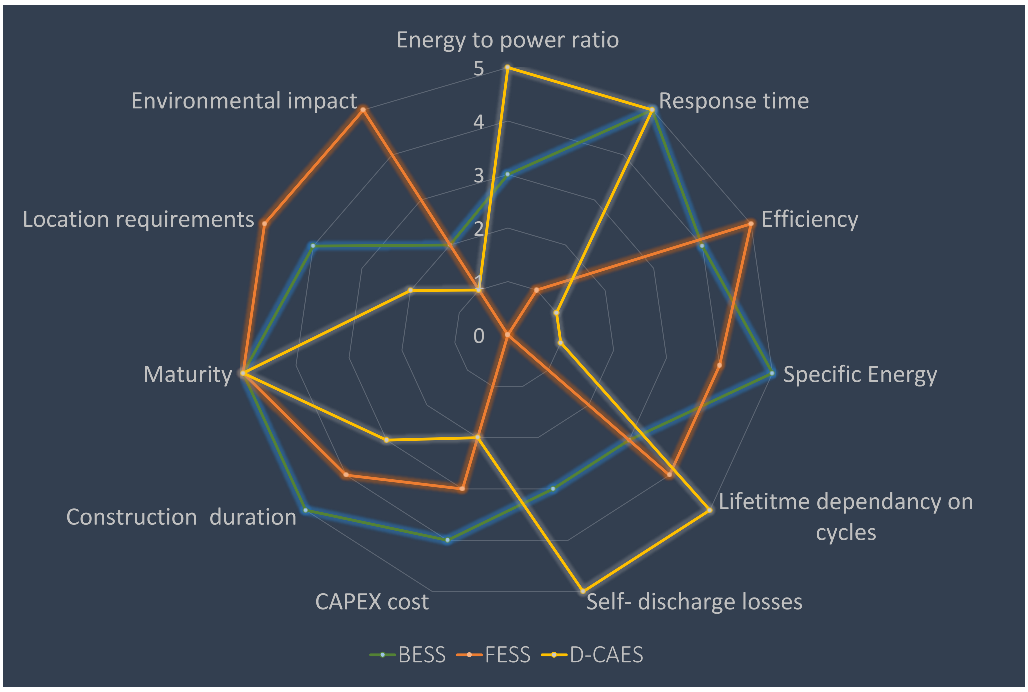


Figure 4.1: Evaluation of selected ESS against the requirements of bulk energy services.

Source: self-made

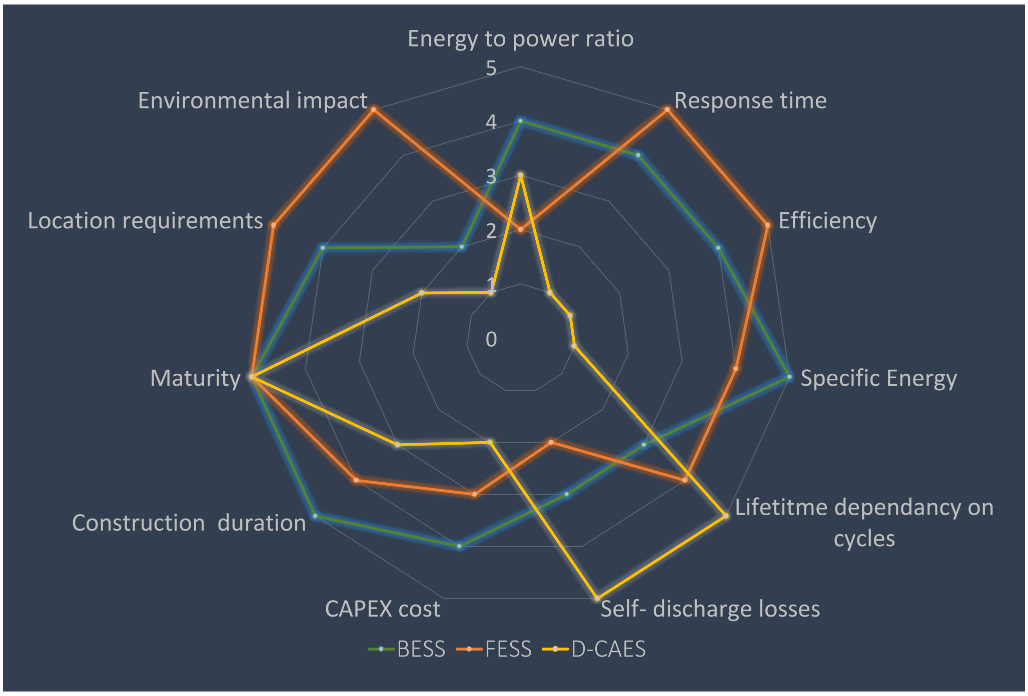


Figure 4.2: Evaluation of selected ESS against the requirements of fast-response ancillary power services.

Source: self-made

Based on the analysis of matching storage technologies with relevant markets, conclusions can be drawn as presented below.

Battery Energy Storage Systems (BESS):

- *Relevance for Grid Services*: BESS is highly relevant for grid services due to its fast response time and ability to provide both power and medium-duration energy services. It is well-suited for applications such as frequency regulation, peak shaving, and energy time-shifting.
- *Limitations*: The main constraints of BESS are limited energy capacity and cycling capabilities. BESS may not be suitable for applications that require very long-duration energy discharge or extensive cycling, as this can impact its lifespan and economic viability.
- *Test markets*: FCR-N, FFR, Energy Arbitrage in Elspot, and their combinations.

Flywheel Energy Storage Systems (FESS):

- *Relevance for Grid Services*: FESS is primarily relevant for power services that require fast response and short-duration energy discharge. It can be utilized for applications such as frequency regulation, and short-term backup power.
- *Limitations*: FESS has limited energy capacity, which restricts its ability to provide extended energy discharge. It is not suitable for applications that require continuous power delivery over extended periods.
- *Test markets*: FCR-N, FFR,

Compressed Air Energy Storage (CAES):

- *Relevance for Grid Services*: CAES is relevant for both power and energy services, with a particular focus on long-duration energy storage. It is suitable for applications such as bulk energy shifting, peak shaving, and supporting intermittent renewable generation.
- *Limitations*: CAES requires suitable geological conditions for the construction of underground storage caverns. CAES systems have lower round-trip efficiency compared to other storage technologies.
- *Test markets*: mFRR, Energy Arbitrage in Elspot, and their combination.

In summary, BESS, FESS, and CAES each have their strengths and limitations when it comes to grid services. BESS excels in providing a fast response and flexibility, FESS is well-suited for short-duration fast response power services, and CAES offers large-scale, long-duration energy storage capabilities.

4.2 Study Cases

The study cases selected are based on the analysis carried out in Chapter 2 and conclusions of the Specialization project [11]. The main criteria when selecting relevant study cases were:

1. Storage technology is applicable for the selected service/market;
2. Selected market can potentially provide a positive business case;
3. Data (price, bidding volumes, recorded frequency profiles) is available for the selected market.

A summary of the selected Study Cases with a concise Balancing markets' pricing rules explanation, which will be further implemented in the models, is given in Fig. 4.3. Selection of a specific Nordic Market is based on recommendations from [99] which concluded that aFRR and FCR-D are less attractive, and as such aFRR and FCR-D are not studied within this thesis scope, but recommended as a possibility for future works in section 6.2.

Valuation of FESS and BESS will be done for their participation in FCR-N and FFR ancillary markets, individually as well as in combinations. CAES, which represents long-term storage, will be tested in the mFRR market. Additionally, BESS and CAES will engage in energy arbitrage by participating in the Day Ahead market to potentially optimize their operational utilization/increase value, and avoid idle operation. While value stacking for BESS will be performed sequentially on a seasonal basis due to constraints imposed by automatic frequency balancing markets, the mFRR Energy Activation (EA) service will be combined with energy arbitrage in the day-ahead market during the same operational period. This is because participation in mFRR EA markets does not require bidding or commitment to the mFRR capacity market [66]. Further details will be elaborated in section 4.5. Multiple energy arbitrage cases were pre-examined for FESS, but due to its inherently low E:P ratio, all NPVs were negative. Therefore, FESS will not be tested in energy arbitrage in the day-ahead market. This is further explained in section 5.3.

Denmarks' DK2 zone (part of Nordic bidding zones) was chosen as a test market for FCR-N, mFRR, and DA given the conclusions from Section 2.2.3 that DK2 is more prone to imbalances and price violations due to a high share of wind farms in the country's energy mix.

For FFR Profile, Norway's NO5 (part of Nordic bidding zones) was selected as a test market due to the availability of the detailed information, technical specifications, and test data implemented by Statnett for FFR.

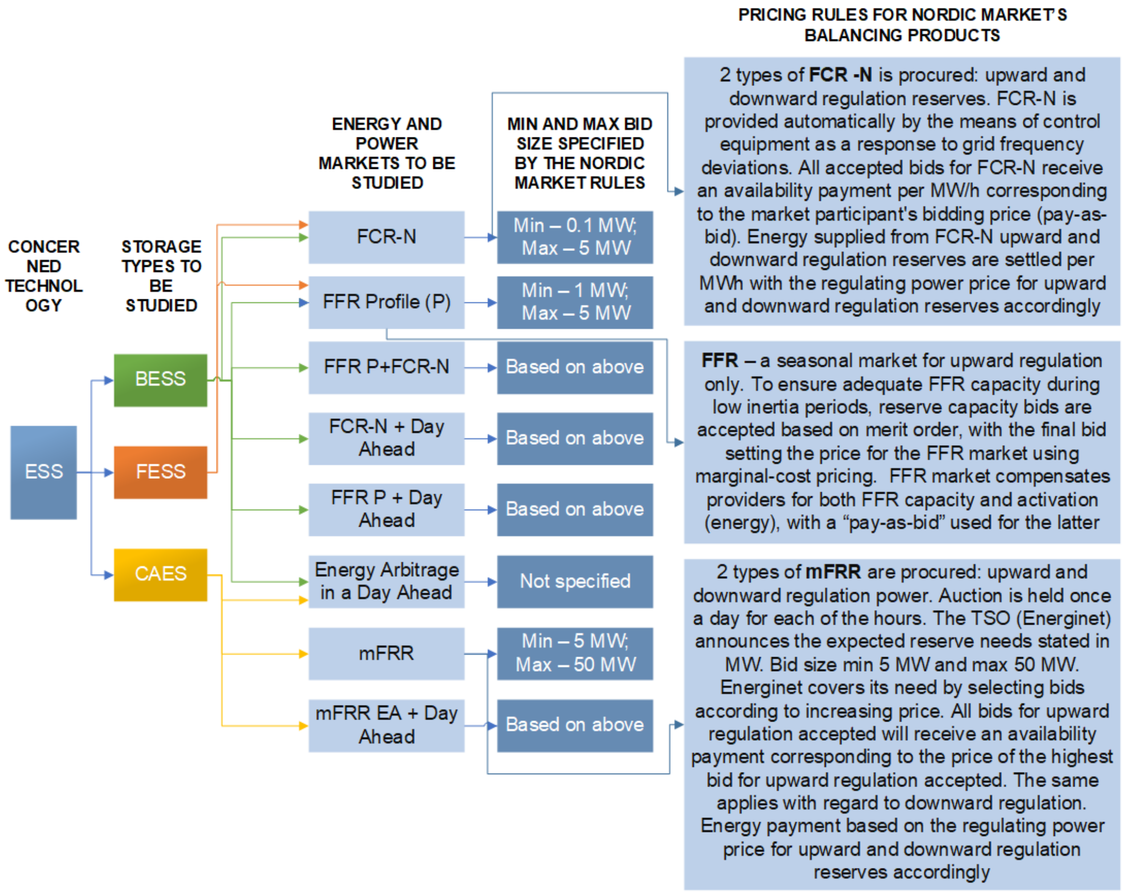


Figure 4.3: Selected Study Cases.

Source: Self-made

The 2021 year's average prices for the different types of balancing reserves for DK1 and DK2 are presented in Fig. 4.4. In 2021, Energinet spent 183 million EUR on purchasing reserve capacity [106]. The prices were affected by the fuel costs, levels in hydro reservoirs, and CO_2 prices. The general trend for FCR-N in DK2 is that it is higher during the summer months (May-July) and throughout December and January. For mFRR, more profitable periods are in April and May.

Prices on a Day Ahead market in the DK2 zone between 2017 and 2020 demonstrated an even pattern throughout the year with more fluctuations within the day (Fig. 4.5). However, between 2021 and 2023, spikes were observed in December 2021, March 2022, and March 2023 with the highest price of 449.77 EUR per MWh in August 2022. The reasons for baseline market price skyrocketing are explained by the European Commission in their Quarterly Report [107] and tied to a war-energy crisis but generally, those surges are far beyond their year ahead-peers and as such, cannot be recognized as a general pattern for monthly price fluctuations in a Day Ahead market.

For the FFR market in Norway, the procurement period is specified by Statnett [68], and it is between May to October for FFR Profile.

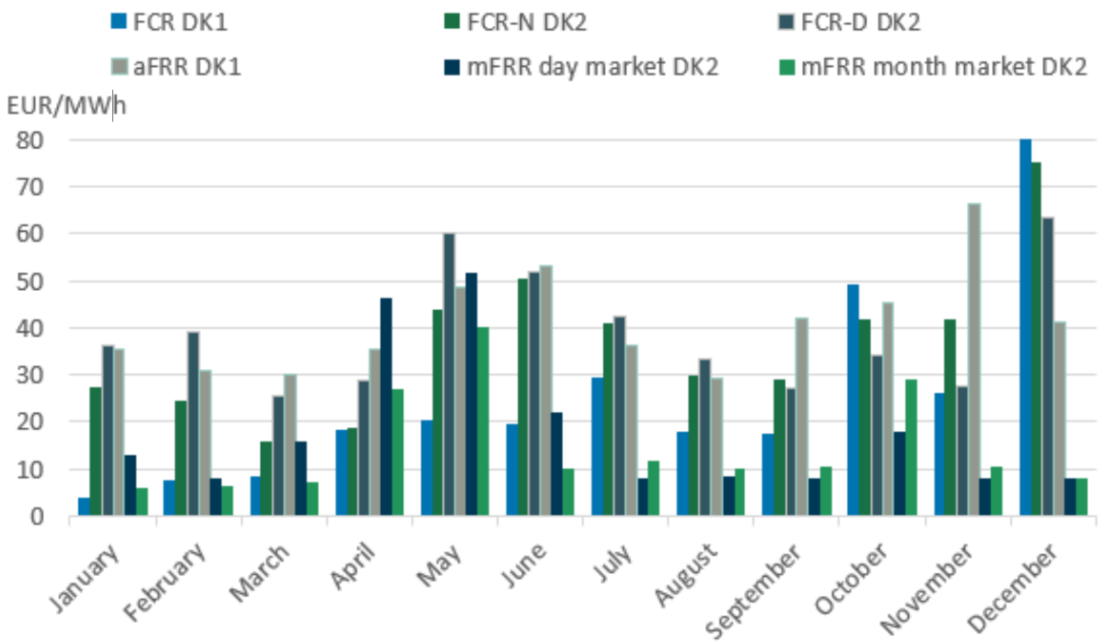


Figure 4.4: 2021 monthly averages (EUR/MW/h) for balancing reserve capacities in Denmark bidding zones.

Source: Figure taken from [106]

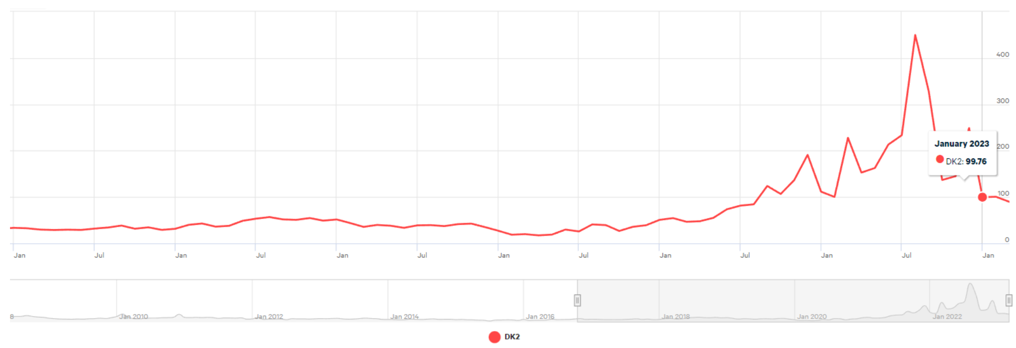


Figure 4.5: January 2017 - March 2023 monthly averages (EUR/MWh) for a Day Ahead market in DK2.

Source: Figure retrieved from [108]

The selected time frames for storage bidding in a specific market in order to provide potentially profitable cases are based on the analysis above, and presented in Table 4.5:

Table 4.5: Selected bidding periods for individual market participation and value stacking.

Services combination for value stacking	**Bidding Period**	**Service Activation**
DA only	Throughout the year	Optimization based on the maximization of revenue
FCR-N only	Throughout the year	FCR- N - frequency settings
DA+FCR-N	FCR-N - May - December; DA- remaining period	FCR- N - frequency settings; DA - optimization based on the maximization of revenue
DA+FFR	FFR - May - October; DA- remaining period	FFR - frequency settings; DA - optimization based on the maximization of revenue
FFR + FCR-N	FFR - May-October; FCR-N - remaining period	FFR - frequency settings
FFR only	May-October	FFR - frequency settings
DA+ mFRR EAM	mFRR +DA; concurrently	Optimization based on the maximization of revenue
mFRR only	Throughout the year	mFRR - signals from the TSO

The results for the study cases explained in Fig. 4.3 and Table 4.5 will be organized around a technology type in the following manner:

- Case 1. Participation of the BESS in FCR-N (scenario A), DA (scenario B), DA+FCR-N (scenario C), FFR (scenario D), DA+FFR (scenario E); FFR+FCR-N (scenario F);
- Case 2. Participation of the FES in FCR-N (scenario A), FFR (scenario B);
- Case 3. Participation of the CAES in mFRR (scenario A), DA (scenario B), DA+ mFRR (scenario C).

Multiple E:P ratios will be analyzed for each scenario while applying Nordic market bid size limitations and typically employed storage sizes in commercial markets. The objective is to find the "bending point" and optimum E:P ratio when NPV turns negative/ drops after reaching its maximum value despite possible revenue growth:

- BESS - E:P from 1:5, 7.5, and 10 with 1 MW power capacity, and E:P of 1 for 5MW power capacity.
- FESS - E:P of 0.25, 0.2, 0.15, 0.1 with 1 MW power capacity and E:P of 0.25 with 20 MW power capacity.
- CAES - E:P of 4, 5, 6, 7, 10 15, 90, and 100 with 5 MW power capacity.

As such, 3 study cases, 11 scenarios, and 82 sub-scenarios will be analysed. Simulations for automatic frequency markets (FCR-N, FFR) were performed on a second-by-second basis, and simulations for energy (Elspot) and manual frequency markets (mFRR) are done on an hourly basis.

The framework and explanation above will be further used to implement storage models, study scenarios, and evaluate storage's potential value on the proposed markets.

4.3 Input Data

Input data for the implemented models consist of:

- Technical parameters and cost information for the selected storage technologies;
- Market data related to energy and availability payment components of a Day Ahead, FCR-N, FFR, mFRR services;
- Grid data related to frequency profiles, droop settings, and technical specifications for minimum and maximum MW requirements for the balancing power.

Technical parameters of storage were discussed and presented in Sections 2.1.2 and 4.1. Storage parameters used in the simulations are summarized in Table 4.6.

Table 4.6: Technical parameters of selected storage technologies used in the modeling.

Parameter	**Technology**		
	BESS	FES	CAES
Roundtrip Efficiency	90%	95%	55%
Self- discharge	5% a day	100% a day	negligible
Minimum SoC	20%	0%	30%
Maximum Charging Power, MW	Power Capacity	Power Capacity	Power Capacity
Maximum Discharging Power, MW	Power Capacity	Power Capacity	0.00117*Power Capacity +Power Capacity
Lifetime	12,000 cycles	175,000 cycles	30 years (cycles independent)

As explained in Section 2.1.2 the diabatic CAES can be reviewed as a hybrid plant (air storage collocated with electricity generation), and discharged power is higher than charged power due to the extra heating of the compressed air usually by means of combustion of natural gas before it is channeled to the turbine. The reference number of proportion between the thermal energy required per kW of discharged electrical power is taken from the McIntosh plant [27].

The minimum depth of discharge of CAES of 30% considers optimal operational principles based on thermodynamics discussed in Section 2.1.2.

BESS integrity is maintained by keeping its state of charge at 20% as recommended by the BESS manufacturers (see Section 4.1 for the details). For NPV calculation, the number of years under evaluation (N) was calculated as the ratio between the total number of life cycles of the BESS to the BESS cycles over a year n. Battery charging and discharging cycles n are taken from the output of the Matlab code. The Lifetime (N) of CAES and FESS is independent of operational cycles.

High windage and lamination core losses of FESS are represented as the self-discharge efficiency.

The power capacities range in the simulations will be based on the minimum and maximum power limits for a specific balancing product (see Fig. 2.21).

The discount rate for the project evaluation in NPV calculation r is assumed as 10% [109].

Variable operation and maintenance costs which depend on the charging and discharging cycles vary from technology to technology. For the BESS variable costs are assumed to be 0.3 USD/MWh [110]. Fixed O&M costs for the BESS are between 6-12 USD per kW installed per year [94]. Operation and maintenance costs for CAES are not provided in great detail in the reviewed literature. The typical range for the total fixed O&M costs of CAES is estimated to be between 12.3 USD and 20.1 USD per kW installed per year, while the variable O&M costs are estimated to be in the range of 1.7 USD to 2.5 USD per MWh [111]. Fixed operation and maintenance for FES is between 4.8

and 6.7 USD per kW installed per year according to [94]. Variable FES costs are between 0.22-4.3 USD per MWh [112].

The total capital expenditure $CAPEX_{Storage}$ includes engineering, license, and permitting and was accepted as 448,000.00 USD/MW for the BESS. FESS and CAES capital costs are between 600-2,880.00 and 400- 2,500.00 USD/kW, respectively [112]. In [111] CAES capital expenditure was estimated at 1,218.00 USD per kW for 2020. Further cost reduction can be expected especially in the BESS market due to a phenomenon known as the economy of scale [113]. Costs used in the evaluation are displayed in Table 4.7.

Table 4.7: Cost of the selected energy storage technologies used in the modelling.

Technology	**Capital Costs (USD/MW)**	**Fixed O&M (USD/kW/yr)**	**Variable O&M (USD/MWh)**
Li-Ion BESS	448,000.00*	6	0.3
Diabatic CAES	1,000,000.00**	12.3	1.7
FESS	1,200,000.00***	4.8	0.8

**The BESS' CAPEX costs in Table 4.7 are indicated per 1MW/1MWh size. Increasing the energy capacity of BESS will entail CAPEX prices going up. The numerical relation between energy capacity increase and CAPEX levels is retrieved from Rystad battery market analysis report [114]. CAPEX cost increase coefficient varies with energy size and is between 1.25 for E:P equal to 2 and 6.25 for E:P equal to 10.*

*** The FESS' CAPEX costs in Table 4.7 are indicated per 1MW/0.15MWh size. Depending on energy capacity, CAPEX increase can vary between 1.5 for 1MW/0.2MWh FESS to 2 for 1 MW/0.25 MWh FESS [112].*

**** The CAES' CAPEX costs in Table 4.7 are given for 1MW/1MWH size. Extra added energy storage capacity entails a cost increase of 200,000.0 USD per added MWh [115].*

The above CAPEX - Energy capacity coefficients were considered in NPV calculations.

When applying price data in a linear deterministic programming model, the data should have pre-defined values and originate from historical values to ensure that tested scenarios are realistic. Market data was extracted from the Nord Pool [116] for day-ahead prices and up-ward and down-ward energy regulation prices for a specific zone, Energinet's Energy Data Service [117] and Statnett [68] on-line platforms for capacity (availability) payments. Datasets for prices have an hourly resolution.

An example of hourly Availability payment for FCR-N market in DK2 from 01 January 2018 to 31 December 2022 is plotted in Fig. 4.6. The Y-axis reflects hourly availability payment in DKK/MW/hour, and X-axis is a logarithmic representation of 35040 hours counting from 01:00 of 01 January 2018 for 4 years onward.

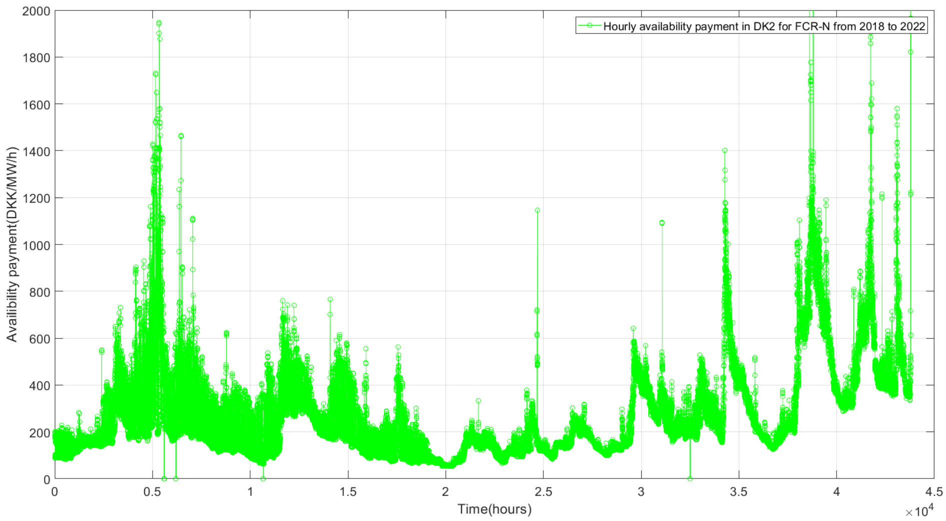


Figure 4.6: Hourly availability payment for FCR-N market in DK2 from 01 January 2018 to 31 December 2022 (DKK/MW/h).

Source: Self-made in Matlab based on data from [118]

The hourly price pattern for FCR-N Availability payment shows higher values from 0:00 to 06:00, after which it begins to fall until 13:00. The analysis indicates that FCR-N availability payment for 2022 is not necessarily similar to the prices of the preceding years and is on a higher side. However, generalizations will be made in this regard for storage evaluation, and hourly data for 2022 will be utilized in the analysis. A similar approach will be used for other services' payments. According to [119], hourly power prices are expected to stabilize from 2030 to 2050 in the Nordic market and be slightly above the past 10 years' historical averages. Therefore, price levels of 2022 are assumed to be representative given the expected increasing needs for flexible power but also deployment of demand side management and electrolyzers which should contribute to the electricity price stabilization [119].

According to Statnett [68], FFR is procured between May to October. Based on this the procurement period between May to October including these border months will be used for FFR PRofile market analysis.

The most recent grid frequency measurements data for the Nordic power system is for 2018 and were made available by [120]. It is measured in Zealand, Denmark (DK-2), as a part of the Nordic power system. The dataset has a sample time of 1 second with values that are not measured (for 16.9 days) replaced as NaN. Measurements were performed by DEIF MTR-3 (336.4 days) and Schneider PM800 (11.7 days) with an accuracy of 10 mHz which corresponds to the Nordic TSOs requirements. NaN values were replaced by the reference frequency (50 Hz) in the analysis. There were, however, no occasions recorded when the frequency went to 49.7 Hz or below which is the setting for FFR service activation. They could have been omitted as a part of NaN set. Therefore, an additional check was performed on frequency quality in the measured year (2018) from Statnett's and Fingrid's Frequency Quality reports [121]. According to it, the total duration of the frequency drop to 49.7 Hz and below totaling at 58 seconds for the studied year. These drop events were generated in the frequency input data for FFR analysis.

Droop settings for individual storage plants are specified in the Danish Grid Code. It is 4% for DK2 and 5% for DK1 [122]. Other Nordic countries' general recommendation for droop is in the range of 2% to 12 %. The droop settings used for the FCR-N and FFR services are explained in Sections 4.6 and 4.7, respectively.

Finally, the signals from the TSO (Energinet) for mFRR activation were retrieved from 2022 datasets [123].

4.4 Formulation of an optimization problem for energy arbitrage in Elspot (a day ahead) market

As explained in Section 4.2, value stacking and market diversification of BESS in the Nordic markets for increasing its value will be performed by bidding in several markets with exercising arbitrage in a day ahead market during the low-profit periods for ancillary services (see Table 4.5).

As a Day Ahead market has no availability payment part, storage is allowed to optimize its operational cycles unlike in the ancillary services balancing market.

The optimization tool is developed in Matlab for the energy arbitrage service for a standalone BESS connected to the transmission utility grid.

The optimization model is adapted from [110], and [124], where the objective function is to maximize revenue generated by storage from buying and selling power over the planning horizon. The objective function and constraints are detailed below. A self-explanatory illustration of the storage participation process in the Nordic's Elspot market to exercise energy arbitrage implemented in Matlab is given in Fig. 4.7. Every single component of the optimization will be explained as follows.

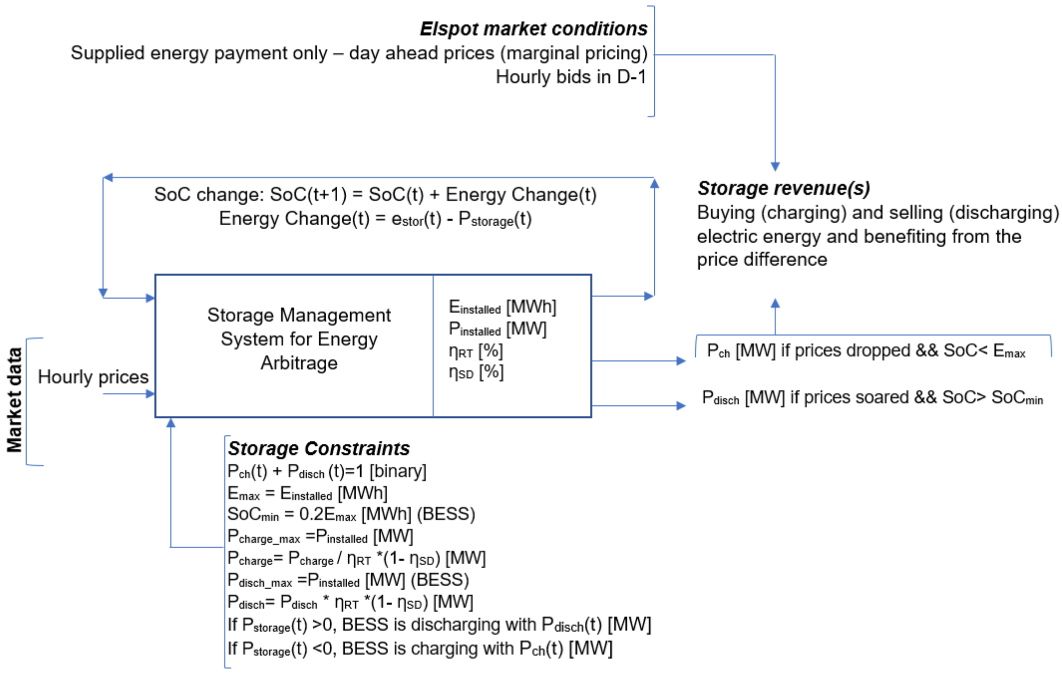


Figure 4.7: Storage participation process in energy arbitrage in Nordic's Elspot market implemented in the model.

Source: Self-made

Objective function

The selected objective function implemented in the optimization tool is to maximize revenue generated by storage throughout the concerned planning period. Profit from energy arbitrage consists of buying (charging) and selling (discharging) electric energy and benefiting from the price difference in the market which is associated with volatile generation from renewable sources and consumers' behaviour. Thus, the objective function can be described by the following Eqn. 4.1:

$$Max \sum_{t}^{T} mcost \cdot p_t^{storage} \cdot \Delta t \tag{4.1}$$

If $p_t^{storage} > 0$ the BESS is exporting power to the grid (discharging) with $p_t^{discharge}$;

If $p_t^{storage} < 0$ the BESS is importing power from the grid (charging) with p_t^{charge};

t refers to the time periods, Δt is an absolute time interval between periods (e.g., 1 hour), T overall simulation period, $mcost$ - energy price at time t in Elspot in EUR/MWh, $p_t^{storage}$ is the power exchange between the BESS and grid at time t, p_t^{disch} is power discharge to the grid at time t, and p_t^{charge} is power charge from the grid at time t accordingly.

The outputs from the model are the amount of charging/discharging p_t^{charge}/p_t^{disch} energy over a planning horizon T and total income in EUR (*optimal value*).

Constraints

In order to obtain a model that resembles the operation of a real BESS the following constraints were introduced:

$$p_t^{charge} + p_t^{disch} = 1 \tag{4.2}$$

$$p_t^{storage} \leq p_{installed} \tag{4.3}$$

$$p_t^{storage} \geq -(p_{installed}) \tag{4.4}$$

$$e_t^{stor} \leq e_{max} \cdot SOC_{max} \tag{4.5}$$

$$e_t^{stor}(1) = 0.5 \cdot e_{max} \tag{4.6}$$

$$e_t^{stor}(24) = 0.5 \cdot e_{max} \tag{4.7}$$

$$e_{t+1}^{stor} \geq e_{max} \cdot SOC_{min} \tag{4.8}$$

$$e_{t+1}^{stor} = e_t^{stor} - p_t^{storage} \tag{4.9}$$

$$p_t^{charge} = p_t^{charge} / \eta_{RT} \cdot (1 - \eta_{SD}) \tag{4.10}$$

$$p_t^{discharge} = p_t^{discharge} \cdot \eta_{RT} \cdot (1 - \eta_{SD}) \tag{4.11}$$

where e_t^{stor} refers to the energy stored in storage at a given time t (Eqn. 4.9), e_{max} is a maximum energy capacity equal to the installed capacity of storage, $p_{installed}$ represents an installed power capacity, η_{RT} is a roundtrip efficiency of storage, η_{SD} is the self-discharge efficiency of storage, SOC_{max} maximum state of charge of storage, SOC_{min} is minimum state of charge of storage. The model does not consider storage degradation, and therefore e_{max} and $p_{installed}$ are constant over the complete operational period because degradation of storage is not considered.

Eqn. 4.2 represents the binary constraint implying that BESS cannot charge and discharge simultaneously. Eqn. 4.3 and Eqn. 4.4 limit charging and charging power capacities of storage to its installed capacity $p_{installed}$; Eqn. 4.5 and Eqn. 4.8 were introduced to maintain battery integrity by controlling its maximum and minimum state of charge. Eqn. 4.6 and Eqn. 4.7 are special cases of SoC constraints to force BESS to start and end its operational period (24 hours) at 50% state of charge for allowing flexibility in grid power exchange in both directions. Eqn. 4.9 is introduced to show the update of BESS energy content at each simulation time-step t. Finally, Eqn. 4.10 and Eqn. 4.11 are ensuring that BESS charging and discharging capacities at a given time t are adjusted to its round trip η_{RT} and self-discharge η_{SD} efficiencies (losses encountered during charging, discharging, and operation of storage).

Implemented optimization algorithm is shown in Fig. 4.8:

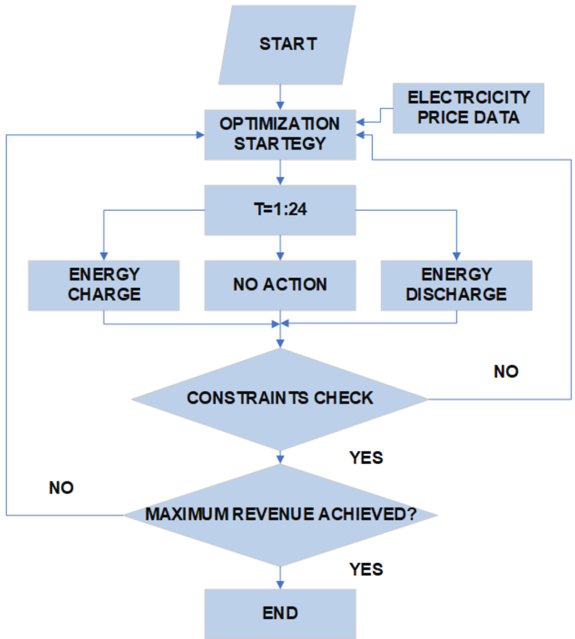


Figure 4.8: Implemented optimization algorithm for energy markets.

Source: self-made

4.5 Formulation of an optimization problem for combined mFRR EA and energy arbitrage in Elspot (a day ahead) market

While value stacking for BESS will be performed sequentially on a seasonal basis due to constraints imposed by automatic frequency balancing markets, the mFRR Energy Activation (EA) service will be combined with energy arbitrage in the day-ahead market during the same operational period. This is because participation in mFRR EA markets does not require bidding or commitment to the mFRR capacity market [66]. Therefore, the optimization function for maximizing the revenue will also factor in the possibility to exchange power at mFRR EA market.

The difference from equations introduced in section 4.4 will be therefore in the objective function. Also, as the power discharging of CAES is higher than its charging capacity as was explained in section 2.1.2, the power discharging constraint will be revised accordingly.

A self-explanatory illustration of the storage combined participation process in the Nordic's Elspot and mFRR EA markets to exercise energy arbitrage and provide manual frequency power implemented in Matlab is given in Fig. 4.9. Every single component of the optimization will be explained as follows.

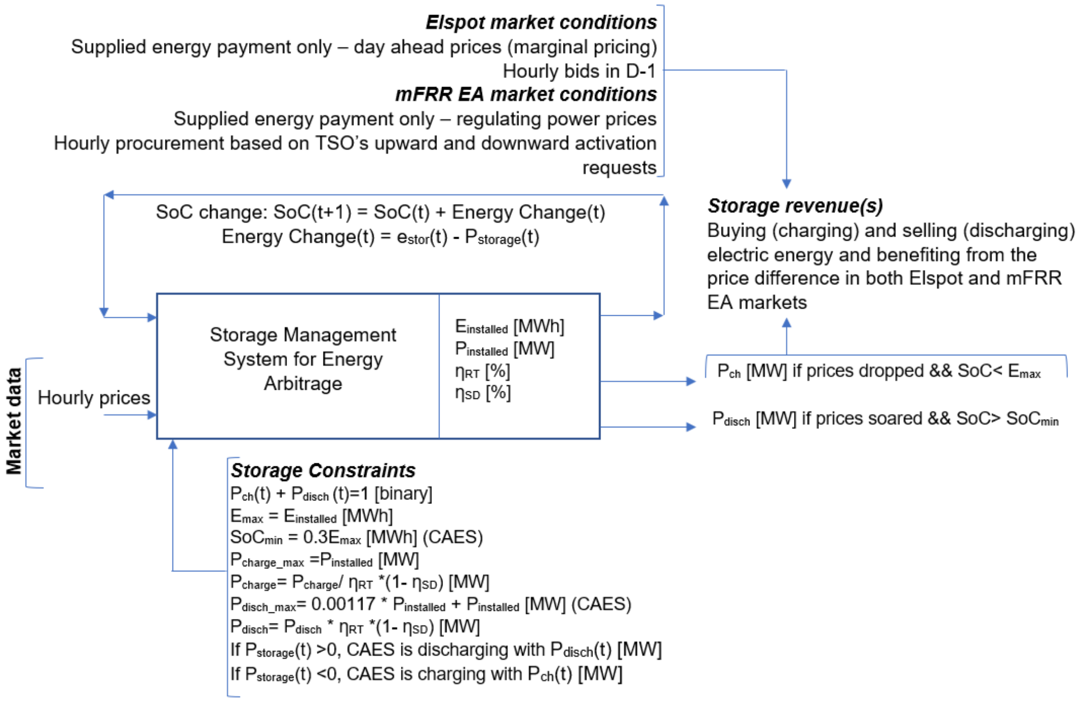


Figure 4.9: Storage combined participation process in energy arbitrage in Nordic's Elspot market and mFRR EA markets to exercise energy arbitrage and provide manual frequency power, implemented in the model.

Source: Self-made

Objective function

In the case when combined participation in Elspot and mFRR EA is analyzed, profit consists of buying (charging) and selling (discharging) electric energy and benefiting from the price difference in Elspot or mFRR EA market. Thus, the objective function can be described by the following Eqn. 4.12:

$$Max \sum_{t}^{T} mcost \cdot p_t^{storage} \cdot \Delta t + ecost \cdot p_t^{storage} \cdot \Delta t \tag{4.12}$$

If $p_t^{storage} > 0$ the CAES is exporting power to the grid (discharging) with $p_t^{discharge}$;

If $p_t^{storage} < 0$ the CAES is importing power from the grid (charging) with p_t^{charge};

t refers to the time periods, Δt is an absolute time interval between periods (e.g., 1 hour), T overall simulation period, $mcost$ - energy price at time t in Elspot in EUR/MWh, $ecost$ - energy price at regulating market mFRR EA time t in EUR/MWh, $p_t^{storage}$ is the power exchange between the BESS and grid at time t, p_t^{disch} is power discharge to the grid at time t, and p_t^{charge} is power charge from the grid at time t accordingly.

The outputs from the model are the amount of charging/discharging p_t^{charge}/p_t^{disch} energy over a planning horizon T and total income in EUR (*optimal value*).

Constraints

Constraints of CAES operation correspond to those introduced in section 4.4 except for the equation that limits maximum power discharge:

$$p_t^{storage} \leq 0.00117 \cdot p_{installed} + p_{installed} \tag{4.13}$$

Eqn. 4.13 is a special case for power discharging constraint introduced for a diabatic CAES due to its specifics of operation associated with the fact that CAES can provide more discharging power, produced due to air reheating at the output, as discussed in section 2.1.2.

4.6 Formulation of an analytical problem for FCR-N in Nordic balancing market

An illustration of the storage participation process in the Nordic's balancing market to provide FCR-N service implemented in Matlab is given in Fig. 4.10.

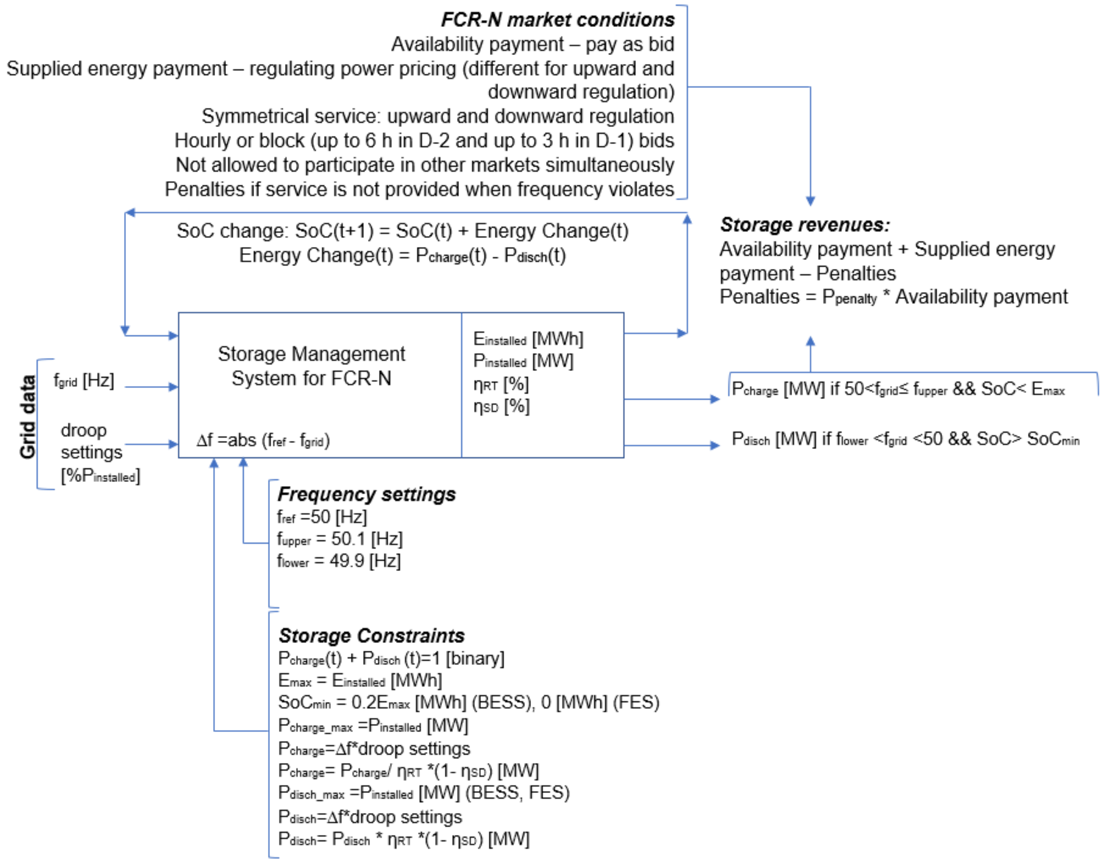


Figure 4.10: Storage participation process in FCR-N in Nordic's balancing market implemented in the model

Source: Self-made

In the Nordic PS when the frequency falls within the range of 49.9-50.1 Hz, FCR-N shall be activated automatically. An example of FCR-N desired response is provided in the document "Technical Requirements for Frequency Containment Reserve Provision in the Nordic Synchronous Area" [125] and reproduced in Fig. 4.11.

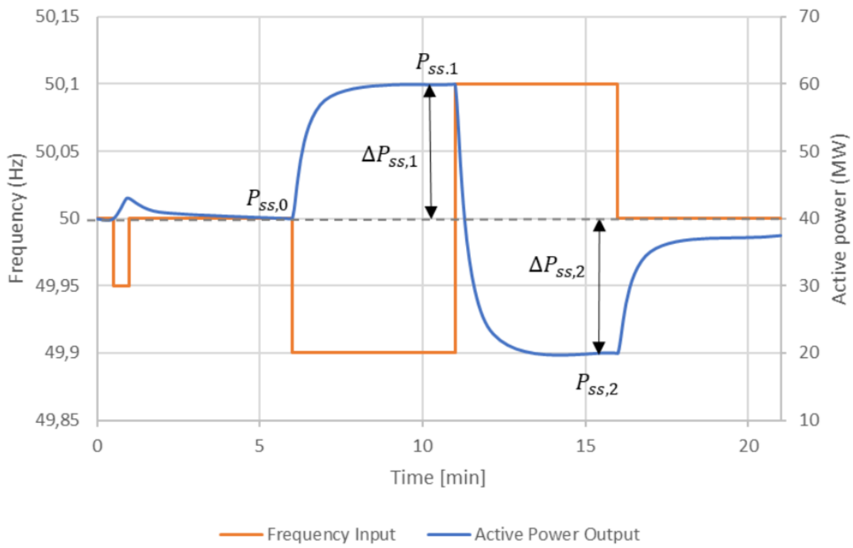


Figure 4.11: Example of FCR-N step-response sequence. Input frequency (orange) and example response (blue).

Source: Figure taken from [125]

where $P_{ss,0}$ is the steady-state power at f_{ref}=50 Hz, $P_{ss,1}$ is the steady-state power at f_{lower}=49.9 Hz and $P_{ss,2}$ is the steady-state power at f_{upper} =50.1 Hz. The support duration time for the storage facilities was revised and decreased from indefinite support to 75 minutes. The new revision will be enacted from September 2023.

For storage facilities $P_{ss,0} = 0$ meaning that they are not allowed to charge or discharge when the grid frequency is 50 Hz. The contractual power that the storage makes available for FCR-N depends on its rated power and droop setting. Droop setting refers to the slope of the frequency-power characteristic curve of a generator/ storage facility. The amount of power injected/ absorbed to/from the grid is defined by the Eqn. 4.14. The specification of FCR-N service requires that at frequency deviations between 0 and 100 mHz, FCR-N reserves must be provided linearly by the storage units. At frequencies equal to 50.1 Hz, 100 % of FCR-N downward capacity must be activated by recharging the storage units, whereas at frequencies equal to 49.9 Hz, 100 % of FCR-N upward capacity must be activated by discharging of storage units.

$$P_t^{storage} = \begin{cases} p_t^{discharge} = \Delta f \cdot droop \; if \; 49.9Hz \leq f_{grid} < 50Hz \; and \; SoC > SoC_{min} \\ p_t^{charge} = \Delta f \cdot droop \; if \; 50Hz < f_{grid} \leq 50.1Hz \; and \; SoC < E_{max} \end{cases} \tag{4.14}$$

The frequency deviation Δf is calculated using a classical approach as the near-instantaneous deviation of the frequency f_{grid} from the desired frequency f_{ref} (Eqn. 4.15).

$$\Delta f = f_{ref} - f_{grid} \tag{4.15}$$

For the frequency f_{grid}=49.9 Hz $p_t^{discharge}$ corresponds to the maximum discharging power as defined in the table 4.6. For the frequency f_{grid}=50.1 Hz p_t^{charge} corresponds to the maximum charging power as defined in the table 4.6. This is ensured by calculating droop for FCR-N according to the Eqn. 4.16:

$$droop = p_{installed}/0.09 \tag{4.16}$$

0.09 Hz is the maximum frequency deviation according to the FCR-N specification.

The storage parametric constraints are the same as explained in Section 4.4.

For the revenue calculation gained from FCR-N, it is assumed that the storage bids are submitted for each hour of the profitable period (see Table 4.5 for the selected bidding time windows), and all submitted bids are accepted, and as such, have an access to the availability payment AP_t^{FCR-N}. NPV is calculated over the complete operational period N. Charging p_t^{charge} and discharging $p_t^{discharge}$ power of the storage for FCR-N is modelled for each second of the selected profitable period since the timestamp of measured grid frequency is given on a second basis. Since FCR-N should be capable of both upward and downward regulation (symmetrical service) but there are more recorded over-frequency events at the beginning of the studied year, it is assumed that storage starts its operation at $e_t^{stor} = 30\%$ of its rated energy e_{max}. At every second there is a change in the energy content of the storage (Eqn. 4.9). The profit calculation was performed according to the Eqn. 4.17:

$$Profit_{FCR-N} = \sum_t^T AP_h^{FCR} + \sum_t^T EP_h^{FCR} - \sum_t^T PP_h^{FCR} \tag{4.17}$$

Where AP_t^{FCR-N} is the hourly availability payment from FCR-N market (Eqn.4.18) and $cost_h^{availability}$ hourly capacity market prices (DKK/ MW/h):

$$AP_h^{FCR-N} = p_{installed}^{FCR-N} \cdot cost_h^{availability} \tag{4.18}$$

EP_t^{FCR-N} is the hourly energy payment received for the actually activated FCR-N reserves E_h^{FCR-N} based on the upward $cost_h^{reg-upward}$ and downward $cost_h^{reg-downward}$ hourly regulating energy prices (DKK/ MWh) (Eqn. 4.19), and triggered by the grid frequency violation (Eqn. 4.14 and 4.15).

$$EP_h^{FCR-N} = E_{charging}^{FCR-N} \cdot cost_h^{reg-downward} \cdot \frac{1}{3600} + E_{discharging}^{FCR-N} \cdot cost_h^{reg-upward} \cdot \frac{1}{3600} \tag{4.19}$$

Here $E_{charging}^{FCR-N}$ and $E_{discharging}^{FCR-N}$ are calculated as incremental sum of per second charging p_t^{charge} and discharging $p_t^{discharge}$ power values over every 3600 second (Eqn. 4.20 and Eqn. 4.21). 3600 in the denominator is required for the conversion of price units given in EUR/MWh and aggregated charging energies in $MW \cdot s$.

$$E_{charging}^{FCR-N} = \sum_t^{3600} p_t^{charge} \tag{4.20}$$

$$E_{discharging}^{FCR-N} = \sum_t^{3600} p_t^{discharge} \tag{4.21}$$

PP_t^{FCR-N} is the penalty payment for failing the service due to SoC or other technical constraints. The penalty payment is calculated as the following (Eqn. 4.22).

$$PP_h^{FCR-N} = P_{penalty} \cdot AP_t^{FCR-N} \cdot \frac{1}{3600} \tag{4.22}$$

$P_{penalty}$ is the penalty power and consists of up-ward regulation penalty $P_{penaltyup}$ and downward regulation penalty $P_{penaltydown}$. The penalty is assigned when the storage unit breaches the committed power during frequency violation events as per FCR-N specification. Breach events cover non-provision of committed power or reduced provision of required power. Up-direction refers to breaching discharging commitments, while down-direction refers to breaching charging commitments. 3600 in the denominator is required for the conversion of availability price units given in EUR/MWh and aggregated penalty energies in $MW \cdot s$. Penalty power, cannot exceed committed capacity for a one-time step. Simulations are on a second-by-second-basis, therefore $p_t^{penalty} \leq (p_{installed}/3600)$. Penalty powers are accumulated over every hour and are calculated as follows (Eqn. 4.23, Eqn. 4.24, Eqn. 4.25):

$$P_{penalty}^{FCR} = \sum_{t}^{3600} p_t^{penaltyup} + \sum_{t}^{3600} p_t^{penaltydown} \tag{4.23}$$

$$p_t^{penaltyup} = min((droop \cdot \Delta f \cdot \eta_{RT} \cdot (1 - \eta_{SD})),\ p_{installed}/3600) \tag{4.24}$$

$$p_t^{penaltydown} = min((droop \cdot \Delta f / \eta_{RT} \cdot (1 - \eta_{SD})),\ p_{installed}/3600) \tag{4.25}$$

4.7 Formulation of an analytical problem for FFR in Nordic balancing market

An illustration of the storage participation process in the Nordic's balancing market to provide FFR service implemented in Matlab, is given in Fig. 4.13. Unlike FCR-N, FFR is an asymmetrical service procured in under-frequency events and provides only upward (discharging) regulation to the grid automatically based on the frequency settings. In essence, it ensures that the loss of a large generation unit or HVDC link will not cause considerable frequency excursions during low inertia periods, and is supplemental to FCR-Dynamic. There are 3 alternative frequency levels for the activation of FFR f_{lower1}=49.7 Hz, f_{lower2}=49.6 Hz, and f_{lower3}=49.5 Hz, and the storage might choose one of those settings. 49.7 Hz was used in the simulations. The maximum activation time is 1.30 sec, 1.0 sec and 0.7 sec for the above-specified frequencies respectively (Fig. 4.12). The implemented model does not consider any time delays as modelling the controller's gainers was not in the scope of this thesis, and therefore storage is activated immediately. Different minimum support duration times are allowed: 5.0 s (for short support duration) and 30 s (for a long support duration).

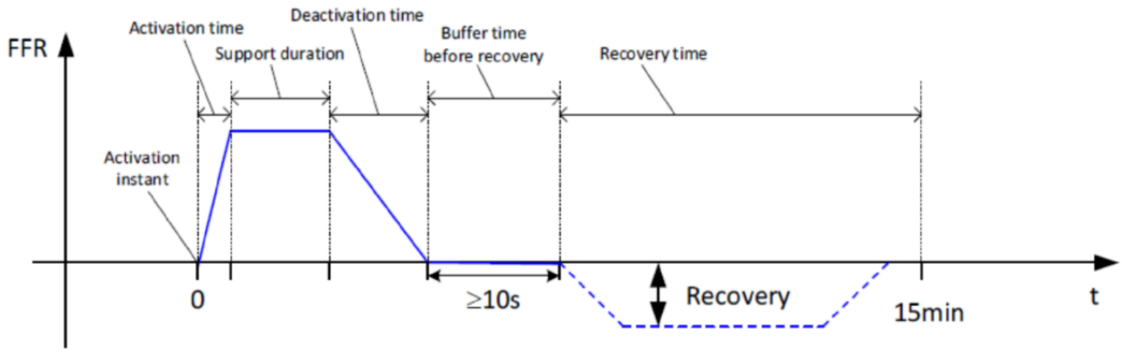


Figure 4.12: FFR activation sequential diagram.

Source: Figure taken from [126]

As FFR only provides discharging, storage's SoC recovery was implemented by its charging from the grid in case SoC is at its minimum level and given the grid frequency is equal to or above the lower threshold of a deadband range (49.99 Hz - 50.01 Hz).

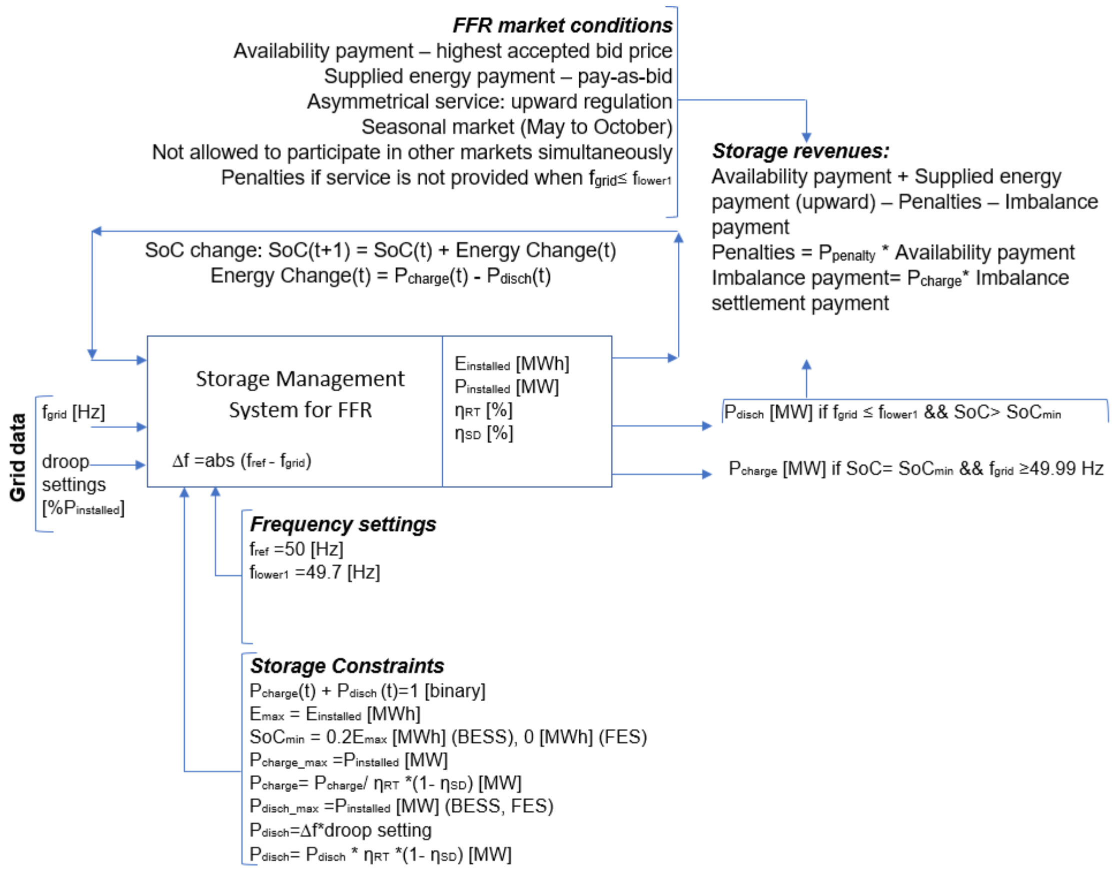


Figure 4.13: Storage participation process in FFR in Nordic's balancing market implemented in the model.

Source: Self-made

For FFR, full capacity activation depending on the chosen frequency settings, should correspond to 49.7 Hz or 49.6 Hz, or 49,5 Hz. Considering these, the amount of power injected/ absorbed to/from the grid is defined by the Eqn. 4.26.

$$P_t^{storage} = \begin{cases} p_t^{discharge} = p_{installed} \; if \; f_{grid} \leq 49.7Hz \; and \; SoC > SoC_{min} \\ p_t^{charge} = E_{max} \; if \; SoC(t) = SoC_{min} \; and \; f_{grid} \geq 49.99Hz \end{cases} \tag{4.26}$$

The frequency deviation Δf is calculated according to the Eqn. 4.15.

The storage parametric constraints are the same as explained in Section 4.4.

For the revenue calculation gained from FFR, it is assumed that the storage bids are submitted for each hour of the period specified by Statnett (see Table 4.5 for the selected bidding time windows), and all submitted bids are accepted, and as such have an access to the availability payment AP_t^{FFR}. AP_t^{FFR} for FFR is uniform and specified in NOK/MW/hour (see Section 4.3 for the details). NPV is calculated over the complete operational period N. Discharging $p_t^{discharge}$ power of the storage for FFR is modelled for each second of the selected period since the timestamp of measured grid frequency is given on a second basis. Since FFR should be capable of upward regulation only, it is assumed that storage starts its operation at $e_t^{stor} = 100\%$ of its rated energy e_{max}. At each second there is a change in the energy content of the storage (Eqn. 4.9). When the energy content of storage reaches its minimum SoC, charging p_t^{charge} of the storage is performed from the grid. Therefore, the profit calculation has an additional deduction term for imbalance settlement IS_t^{FFR} related to storage charging from the grid at the intraday market prices. Profit calculation is performed according to the Eqn. 4.27:

$$Profit_{FFR} = \sum_{t}^{T} AP_h^{FFR} + \sum_{t}^{T} EP_h^{FFR} - \sum_{t}^{T} PP_h^{FFR} - \sum_{t}^{T} IS_h^{FFR} \tag{4.27}$$

where AP_t^{FFR} is the hourly availability payment from FFR market and $cost_h^{availability}$ hourly capacity market prices for FFR (DKK/ MW/h), and calculated according Eqn. 4.28:

$$AP_h^{FFR} = p_{installed}^{FFR} \cdot cost_h^{availability} \tag{4.28}$$

EP_t^{FFR} is the hourly energy payment received for the actually activated FFR reserves E_h^{FFR} based on the upward $cost_h^{reg-upward}$ regulating pay-as-bid power prices (NOK/ MWh) (Eqn. 4.29) and triggered by the grid frequency violation (Eqn. 4.26 and 4.15). IS_t^{FFR} is the hourly imbalance settlement payment, compensated by the storage based on up-ward regulation prices, for recovering its state of charge by absorbing power from the grid (Eqn. 4.30).

$$EP_h^{FFR} = E_{discharging}^{FFR} \cdot cost_h^{reg-upward} \cdot \frac{1}{3600} \tag{4.29}$$

$$IS_h^{FFR} = E_{recovery\ charging}^{FFR} \cdot cost_h^{reg-upward\ market} \cdot \frac{1}{3600} \tag{4.30}$$

Here $E_{charging}^{FFR}$ and $E_{discharging}^{FFR}$ are calculated as incremental sum of per second charging p_t^{charge} and discharging $p_t^{discharge}$ power values over every 3600 second (Eqn. 4.31 and Eqn. 4.32). 3600 in the denominator is required for the conversion of price units given in EUR/MWh and aggregated charging energies in $MW \cdot s$.

$$E_{recovery\ charging}^{FFR} = \sum_{t}^{3600} p_t^{charge} \tag{4.31}$$

$$E_{discharging}^{FFR} = \sum_{t}^{3600} p_t^{discharge} \tag{4.32}$$

PP_t^{FFR} is the penalty payment for failing the service due to SoC or other technical constraints. The penalty payment for FFR is calculated in the same way as for FCR-N (Eqn. 4.33).

$$PP_h^{FFR} = P_{penalty} \cdot AP_t^{FFR} \tag{4.33}$$

$P_{penalty}$ is the penalty power and consists of up-ward regulation penalty $P_{penaltyup}$ a only. This is because FFR is only procured for grid discharging. The penalty is assigned when the storage unit breaches the committed power during under-frequency events as per FFR specification. Breach events cover non-provision of committed power or reduced provision of required power. Up-direction refers to breaching discharging commitments. 3600 in the denominator is required for the conversion of availability price units given in EUR/MWh and aggregated penalty energies in $MW \cdot s$. Penalty power, cannot exceed committed capacity for a one-time step. Simulations are on a second-by-second-basis, therefore $p_t^{penalty} \leq (p_{installed}/3600)$. Penalty powers are accumulated over every hour and are calculated as follows (Eqn. 4.34, Eqn. 4.35):

$$P_{penalty}^{FFR} = \sum_{t}^{3600} p_t^{penaltyup} \tag{4.34}$$

$$p_t^{penaltyup} = min((droop \cdot \Delta f \cdot \eta_{RT} \cdot (1 - \eta_{SD})),\ p_{installed}/3600) \tag{4.35}$$

4.8 Formulation of an analytical problem for mFRR in Nordic balancing market

An illustration of the storage participation process in the Nordic's balancing market to provide mFRR service implemented in Matlab is given in Fig. 4.14. mFRR which is also known as a tertiary reserve should be activated upon the TSO's request fully within 15 minutes and be able to deliver at least 1 hour. mFRR is used as a supplemental regulating power service to cover slow imbalances within the normal frequency range (49.9 Hz - 50.1 Hz) after FCR-N and aFRR have acted to limit frequency deviations until a new balance is reached. The capacity volume requirements per a bidding zone are defined by the TSOs and employ the market-based capacity procurement optimization function based on the available cross-zonal capacities for the common mFRR capacity market [127].

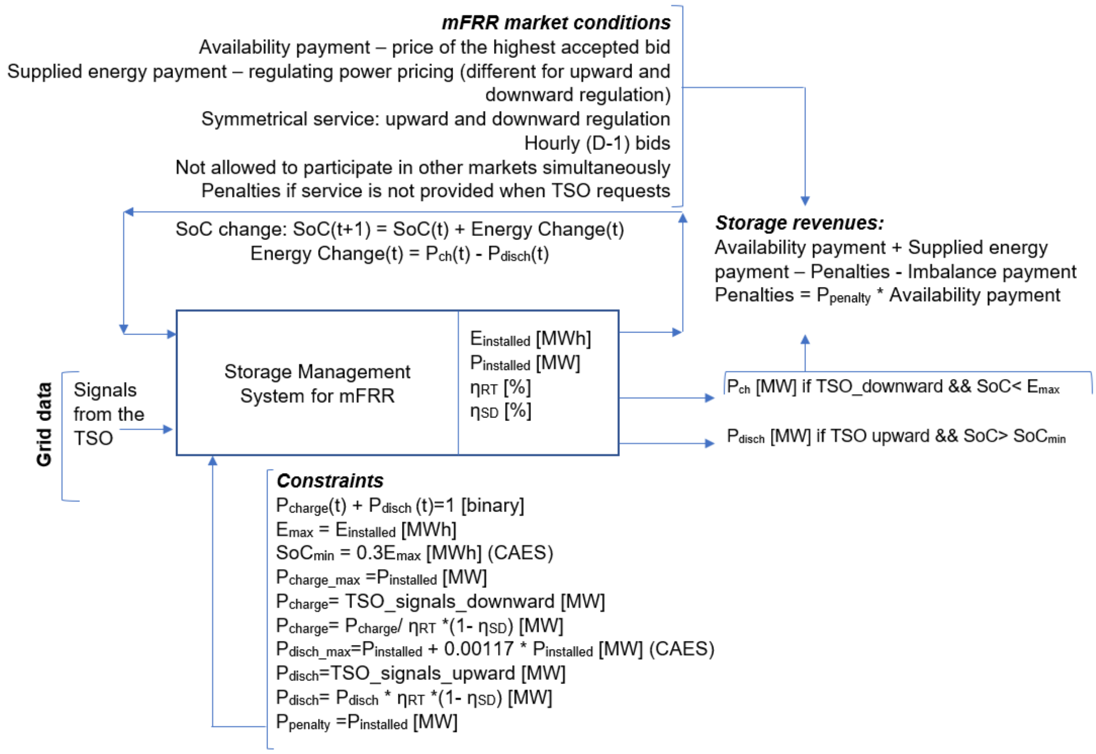


Figure 4.14: Storage participation process in mFRR in Nordic's balancing market implemented in the model.

Source: Self-made

Charging and discharging of storage, therefore, follows the TSO commands for downward and upward regulation accordingly. The volumes and power direction for the mFRR model testing are taken from historical data as explained in section 4.3. The market time unit for mFRR is an hour. The amount of power injected/ absorbed to/from the grid is defined by the Eqn. 4.36.

$$P_t^{storage} = \begin{cases} p_t^{discharge} = TSO's\ signal\ p_t^{discharge}\ and\ SoC > SoC_{min} \\ p_t^{charge} = TSO's\ signal\ p_t^{charge}\ and\ if\ SoC < E_{max} \end{cases} \tag{4.36}$$

The storage parametric constraints are the same as explained in Section 4.4.

For the revenue calculation gained from mFRR, it is assumed that the storage bids are submitted for each hour of the profitable period (see Table 4.5 for the selected bidding time windows), and all submitted bids are accepted, and as such have an access to the availability payment AP_t^{mFRR}. NPV is calculated over the complete operational period N. Charging p_t^{charge} and discharging $p_t^{discharge}$

power of the storage for mFRR is modelled for each hour of the selected profitable period since historical data on mFRR volumes is given on an hourly basis. Since mFRR is employed for upward regulation more often despite being a symmetrical service, it is assumed that storage starts its operation at $e_t^{stor} = 100\%$ of its rated energy e_{max}. Additionally, procured mFRR datasets have shown that in the studied year no downward mFRR regulation was purchased. Therefore, recovery of the state of charge was done from the grid and compensated based on the up-regulation prices. At each hour there is a change in the energy content of the storage (Eqn. 4.9). The profit calculation was performed according to the Eqn. 4.37:

$$Profit_{mFRR} = \sum_{t}^{T} AP_h^{mFRR} + \sum_{t}^{T} EP_h^{mFRR} - \sum_{t}^{T} PP_h^{mFRR} - \sum_{t}^{T} IS_h^{mFRR} \tag{4.37}$$

Where AP_t^{mFRR} is the hourly availability payment from mFRR market and $cost_h^{availability}$ hourly capacity market prices for mFRR (DKK/ MW/h), and calculated according to Eqn. 4.38:

$$AP_h^{FFR} = p_{installed}^{mFRR} \cdot cost_h^{availability} \tag{4.38}$$

EP_t^{mFRR} is the hourly energy payment received for the actually activated mFRR reserves E_h^{mFRR} based on the upward $cost_h^{reg-upward}$ and downward $cost_h^{reg-downward}$ regulating power prices (DKK/ MWh) (Eqn. 4.39) and activated based on the TSO's instructions (Eqn. 4.36).

$$EP_h^{mFRR} = E_{charging}^{mFRR} \cdot cost_h^{reg-downward} + E_{discharging}^{mFRR} \cdot cost_h^{reg-upward} \tag{4.39}$$

Here $E_{charging}^{mFRR}$ and $E_{discharging}^{mFRR}$ are calculated on an hourly basis following the TSO's volumes for downward and upward regulation.

IS_t^{mFRR} is the hourly imbalance settlement payment, compensated by the storage based on upward regulation prices, for recovering its state of charge by absorbing power from the grid (Eqn. 4.40) due to absence of down-ward regulation signals from the TSO.

$$IS_h^{mFRR} = E_{recovery\ charging}^{mFRR} \cdot cost_h^{reg-upward\ market} \tag{4.40}$$

PP_t^{mFRR} is the penalty payment for failing the service due to SoC or other technical constraints. The penalty payment for mFRR is calculated in the same way as for FCR-N and FFR (Eqn. 4.41).

$$PP_h^{mFRR} = P_{penalty} \cdot AP_t^{mFRR} \tag{4.41}$$

$P_{penalty}$ is the penalty power and consists of up-ward regulation penalty $P_{penaltyup}$ and downward regulation penalty $P_{penaltydown}$. The penalty is assigned when the storage unit breaches the committed power and does not follow TSO's signals as per mFRR specification. Breach events cover non-provision of committed power or reduced provision of required power. Up-direction refers to breaching discharging commitments, while down-direction refers to breaching charging commitments. Penalty power, cannot exceed committed capacity for a one-time step. Simulations in mFRR are on an hourly basis, therefore $p_t^{penalty} \leq (p_{installed})$. Penalty powers are calculated as follows (Eqn. 4.42, Eqn. 4.43, Eqn. 4.44):

$$P_{penalty}^{mFRR} = p_t^{penaltyup} + p_t^{penaltydown} \tag{4.42}$$

$$p_t^{penaltyup} = min(TSO_{upwardsignal},\ p_{installed}) \tag{4.43}$$

$$p_t^{penaltydown} = min(TSO_{downwardsignal},\ p_{installed}) \tag{4.44}$$

4.9 Matlab implementation

Problems formulated in Sections 4.4, 4.5, 4.6, 4.7 and 4.8 were developed *de novo* in the Matlab scripts. Scripts follow the logic explained in Fig. 4.7, Fig. 4.9, Fig. 4.10, Fig. 4.13 and Fig. 4.14.

The thesis scripts are given in Appendix C, Appendix D, Appendix E, Appendix F and Appendix G.

The Elspot script for an energy arbitrage is an optimization program for determining the optimal energy storage plan along with charging and discharging power cycles for the storage systems (BESS, FESS, CAES) over a 24-hour period. The script uses historical energy price data retrieved from Nord Pool to maximize the cash flow of the system by taking advantage of price variations in a day-ahead market. The program begins by importing the energy price data from the Excel file and setting storage parameters such as the maximum power capacity, maximum energy storage capacity, absolute time between periods, and constraints such as minimum and maximum state of charge limits, roundtrip efficiency, and self-discharge rate of the storage. Next, the program formulates the objective function to maximize the cash flow over a planning horizon of one day. It defines three decision variables to represent the discharging power, charging power, and energy storage levels, respectively. It then forces constraints on these variables to ensure that they remain within the limits set earlier to represent storage systems' behaviour. The script then uses the CVX optimization solver as discussed in Sections 3.2 and 3.4. to find the optimal values for the decision variables. After the optimization is completed, the program calculates the total charging power, and discharging power, and displays the optimal values for the charging power, discharging power, and energy storage levels. It also plots graphs to demonstrate these variables in correlation to a day-ahead market value. The optimal value is the total revenue generates by the storage.

The FCR-N script is an implementation of a simulation of the BESS and FESS systems participating in FCR-N service in Denmarks's DK2 bidding zone. FCR-N is a reserve service that continuously supports the grid frequency within 49.9-49.99 Hz and 50.01-50.1 Hz by responding to frequency deviations in the form of charging and discharging power. The FCR-N service has a two-part payment structure: an availability payment (capacity payment) and an energy payment from up-or down-regulation deducted by the penalty for failing to activate the FCR-N due to technical constraints.

The script begins by defining the parameters of the battery or flywheel, the FCR-N service specification, and the payment structure. The frequency data for the year 2018 is then loaded from a CSV file and contains 31536000 values (rows). ISNAN (non-measured) values are replaced by reference grid frequency (50 Hz). Availability payment is retrieved from the Energinet database for 2022 and contains 8760 values (rows). The energy payment for up- and down-regulation (discharging/ charging) are extracted from Nord Pool balancing prices database for DK2 which contains 8760 values. The storages' state of charge and full cycle count are initialized. The script then loops through each time step and calculates the charging and discharging power based on the frequency and the state of charge of the battery, flywheel, or CAES. The charging and discharging power are adjusted for efficiency and self-discharge, and the energy change is calculated and used to update the state of charge of the battery, flywheel, or CAES. The script then checks if the state of charge and energy capacity are within the limits and if the charging and discharging power are within the capacity limits. Afterward, the script loops through each hourly interval to accumulate the hourly charging and discharging power and calculates the hourly energy payment and penalty payment. The profit for the hour is then calculated by adding the availability payment, energy payment, and penalty payment (if applicable), and the hourly profit is added to the total profit. Finally, the output values are displayed, and the results are plotted. The script also calculates the number of frequency violation events, the number of storage triggering events and failing duties, and full cycles. The results show the total profit, energy payment, availability payment, penalty amount, charging, discharging, and penalty power. The plots show the storage state of charge, grid frequency, charging power, discharging power, and penalty power as a function of time.

The FFR script is an implementation of a simulation of the BESS and FESS systems participating in FFR service in Norway's NO5 bidding zone. FFR is a reserve service that supports the stability of the grid frequency when it drops to 49.7 Hz and below by rapidly providing power to the grid in response to frequency deviations. Storage absorbs power from the grid when SoC is at its minimum level. The FFR service has a two-part payment structure: an availability payment (capacity payment) and an energy payment deducted by a penalty for failing to activate the FFR due to technical constraints along with compensation paid to the grid by storage for restoring its energy content.

The script begins by defining the parameters of the battery or flywheel storage, the FFR service specification, and the payment structure. The frequency data for the year 2018 for the months from May to October, is then loaded from a CSV file and contains 15897600 values (rows). Availability payment is uniform and specified per hour of the FFR procurement season. The energy payment for up-regulation (discharging) and compensation to the grid for restoring a state of charge, is extracted from Nord Pool balancing prices database for the NO5 zone that contains 4416 values. The storage's state of charge and full cycle count are initialized. The script then loops through each time step and calculates the charging and discharging power based on the frequency and the state of charge of the battery or flywheel. The charging and discharging power are adjusted for efficiency and self-discharge, and the energy change is calculated and used to update the state of charge of the battery or flywheel. The script then checks if the state of charge and energy capacity are within the limits and if the charging and discharging power are within the capacity limits. Afterward, the script loops through each hourly interval to accumulate the hourly charging and discharging power and calculates the hourly energy payment and penalty payment. The profit for the hour is then calculated by adding the availability payment, energy payment, and penalty payment (if applicable), and the hourly profit is added to the total profit. Finally, the output values are displayed, and the results are plotted. The script also calculates the number of under-frequency events, the number of storage triggering events and failing duties, and full cycles. The results show the total profit, energy payment, availability payment, penalty amount, charging, discharging, and penalty power. The plots show the storage state of charge, grid frequency, charging power, discharging power, and penalty power as a function of time.

The mFRR script is an implementation of a simulation of the CAES system participating in mFRR service in Denmark's DK2 bidding zone. The mFRR service payment's structure has two parts: an availability payment and an energy payment minus a penalty for failing to activate mFRR. The script begins by setting the CAES parameters such as the power capacity, maximum power discharging capacity, energy capacity, round-trip efficiency, and self-discharge rate. It then reads the capacity payment, energy payment, and the upward and downward regulation signal data from two Excel files retrieved from Energinet and Nord Pool databases. Data is for a year with an hourly resolution, i.e. with 8760 total number of rows. Next, the program initializes the state of charge to 100% of its energy capacity and profit to zero and sets the penalty and penalty payment to zero. It then loops through each time step and calculates the charging and discharging power for that time step based on the upward and downward regulation signals and the state of charge. It then adjusts the charging and discharging power for efficiency and self-discharge and computes the energy change and updates the state of charge. It also checks if the state of charge and energy capacity are within the limits and if the charging and discharging power are within the capacity limits. The program then calculates the penalty amount should the CAES fail to activate the mFRR reserves in line with the dispatchers' instructions and updates the profit for the time step. After the loop ends, the program displays the total profit, revenue streams, total penalty, total charging power, and total discharging power. The program also includes code for plotting the battery state of charge, upward and downward regulation signals, charging power, discharging power, and penalty power as subplots.

Notation in the models

Below the sets, parameters and variables used in the implemented models are declared.

Sets

T - overall simulation period, indexed by t

Parameters

mcost - energy price in a day ahead market at time t [EUR/MWh]

ecost - energy price in mFRR EA market at time t [EUR/MWh]

$p_t^{storage}$ - power exchange between grid and a storage [MW]

p_t^{charge} - charging power of a storage [MW]

p_t^{disch} - discharging power of a storage [MW]

$p_{installed}$ - installed power capacity of a storage [MW]

e_{max} - maximum energy capacity of a storage [MW]

SOC_{max} - maximum state of charge of a storage [pu]

SOC_{min} - minimum state of charge of a storage [pu]

η_{RT} - roundtrip efficiency of a storage [pu]

η_{SD} - self-discharge efficiency of a storage [pu]

f_{grid} - measured grid frequency at time t [Hz]

f_{ref} -reference grid frequency equal to 50 [Hz]

f_{upper} -upper threshold grid frequency setting for FCR-N equal to 50.1 [Hz]

f_{lower} -lower threshold grid frequency setting for FCR-N equal to 49.9 [Hz]; for FFR equal to 49.7 [Hz]; for SoC recovery during the FFR service equal to 49.99 [Hz]

droop - droop settings of a storage [%]

$cost_{availability}^{FCR,FFR,mFRR}$ - hourly availability payment of a storage from FCR, FFR and mFRR markets, respectively [DKK/MW/hour] or [NOK/MW/hour] converted to [EUR/MW/hour]

$cost_h^{reg-upward}$ - upward regulating power prices in [EUR/MWh]

$cost_h^{down-upward}$ - downward regulating power prices in [EUR/MWh]

TSO's signals upward - activation of mFRR discharge capacity [MW]

TSO's signals downward - activation of mFRR charge capacity [MW]

Variables

p_t^{charge} - storage charging capacity at time t (buying electricity in Energy arbitrage or mFRR EA) from the grid) [MW]

p_t^{disch} - storage discharging capacity at time t (selling electricity to the grid in Energy arbitrage or mFRR EA) [MW]

e_{t+1}^{stor} - energy stored in the battery at a time t+1

$P_{penalty}^{FCR,FFR,mFRR}$ - penalty power of a storage from failing FCR, FFR and mFRR markets accordingly [MW]

Δf - the frequency deviation between the reference and grid frequencies [Hz]

$E_{charging}^{FCR-N,mFRR}$ - actually activated FCR-N and mFRR downward reserves [MW] accumulated over an hourly basis [MWh]

$E_{recovery\ charging}^{FFR}$ - energy drawn from a grid for storage recovery when performing FFR service [MWh]

$E_{discharging}^{FCR-N,FFR,mFRR}$ - actually activated FCR-N, FFR and mFRR upward reserves [MW] accumulated over an hourly basis [MWh]

Output Values

cvx _ optvalue - total profit generated by storage in a day ahead market from energy arbitrage over a planning horizon T

$AP_h^{FCR-N,FFR,mFRR}$ - availability payment generated by a storage from participating in a capacity market of FCR, FFR and mFRR accordingly [EUR]

$EP_h^{FCR-N,FFR,mFRR}$ - energy payment generated by a storage from participating in FCR, FFR and mFRR markets accordingly [EUR]

$PP_h^{FCR-N,FFR,mFRR}$ - penalty payment incurred by a storage from failing to provide declared capacity in FCR, FFR and mFRR markets accordingly due to SoC or other technical constraints [EUR]

$IS_h^{FFR,mFRR}$ - imbalance settlement payment incurred by a storage for charging from the grid to recover SoC when performing FFR or mFRR service [EUR]

$Profit_{FCR-N,FFR,mFRR}$ - total revenue generated by a storage from participating in FCR-N, FFR and mFRR markets accordingly over a planning horizon T.

4.10 Restrictions of the implemented models

Implemented models have the following restrictions:

- Energy and power capacity are set to be constant for the complete operational period. That means the algorithm does not consider the degradation of storage. While FESS and CAES are not significantly affected by the degradation and have an operational lifetime of 20 - 30 years as discussed in Section 2.1.2, BESS facilities have a correlation between the degradation levels and a number of full cycles. However, as the models respect the depth of discharge and state of charge limits, and consider operational lifetime dependency n the maximum number of cycles for the BESS in NPV calculation, this constraint should have a subtle effect on the final results.
- Thermodynamic properties of CAES, mechanical properties of FES, and chemical properties of BESS are represented indirectly as the electric parameters' constraints in the models. As the scope of the thesis is limited to the size optimization of the selected storage technologies for participation in the Nordic energy and power markets rather than design optimization of storage, selected electric representation provides reasonable models to simulate the real behavior of storage facilities.
- It is assumed that the pattern of price violation and price levels over the operational time of storage will follow current trends in studied markets. Justification of the approach was given in Section 4.3 when discussing input data.
- It is assumed that the grid can absorb all energy produced by the storage implying that no transmission congestion was considered. However, the caps for the maximum bidding capacities provided in the market specifications were considered to ensure the adequacy of the studied storage sizes.
- It is assumed that storage has access to the availability payment which might not necessarily correspond to the real-life operation. However, as the historical market prices, measured frequencies, and volumes after the bids clearing were used in the simulations, declared capacities and prices give a reasonable approximation and suffice the thesis' objectives.

Brief conclusions of Chapter 4

Chapter 4 focuses on the implementation of storage modelling and valuation models, providing detailed explanations of storage-market matching criteria, study cases, input data, and the formulation of analytical frameworks for Matlab scripting.

Optimization of storage based on the revenue maximization objective function is only possible in Elspot and Elspot + mFRR EA markets. This is because Nordic TSOs prohibit concurrent bidding of the same capacities in multiple markets as long as they have access to the availability payment. All services except energy arbitrage, have access to the capacity payments. mFRR however, does not force to participate in a capacity market, making it possible to optimize operation in the mFRR EA market. Market properties will be further discussed in Chapter 5. Chapter 4 finishes with explaining Matlab scripts and introduces restrictions of the implemented models while discussing their impact on the results. The results are presented in Chapter 5 with Thesis' Conclusions summed in Chapter 6.

Chapter 5

Results

This Chapter summarizes key results and findings of the Master's thesis. The chapter starts with an overview of the tested business cases and explains which performance indicators were used to draw conclusions. Results are presented for 3 study cases, 11 scenarios, and 82 sub-scenarios which cover selected storage technology types, Nordic market services, and different E:P ratios accordingly. Results are first presented for each technology and market/ combination of markets separately and then they are cross-compared by utilizing the best-achieved revenue and NPV values. A summary analysis of the results for each technology is provided in sections 5.2.6, 5.3.4, and 5.4.5. This is followed by the overall comparison across studied technologies and markets performances, along with recommending the optimal storage sizes in section 5.5. Conclusions are validated by comparing them with relevant papers' conclusions (if available) in section 5.6. Matlab models' behaviour is demonstrated through plotting and discussions of storage operational cycles, penalty powers, and state-of-charge change as a response to the costs or frequency violations depending on the service.

5.1 Overview of study cases and performance indicators

As elaborated in Section 4.2 results are organized around a technology type in the following manner:

- Case 1. Participation of the BESS in FCR-N (scenario A), DA (scenario B), DA+FCR-N (scenario C), FFR (scenario D), DA+FFR (scenario E); FFR+FCR-N (scenario F)
- Case 2. Participation of the FES in FCR-N (scenario A), FFR (scenario B);
- Case 3. Participation of the CAES in mFRR (scenario A), DA (scenario B), DA+ mFRR (scenario C).

DA refers to exercising energy arbitrage in the Elspot market.

Information on input data can be found in Section 4.3. The power capacity of the BESS and FES for frequency services is fixed at 1 MW. The power capacity of the CAES is fixed at 5 MW. This is in line with the Nordic technical specification on the minimum and maximum sizes of the bids (Fig. 2.21). The minimum bid size for FCR-N is 0.1 MW and the maximum bid size for the same is 5 MW [128]. The minimum bid size for FFR Profile is 1 MW and the maximum bid size is 5 MW behind the single point of failure [68]. The minimum bid size for mFRR varies within Nordics and is 5 MW for Denmark and the maximum bid size is 50 MW [129]. The CAES power capacity was fixed to the minimum bid size of mFRR (5 MW).

As stated above, multiple E:P ratios were checked for each scenario, while applying Nordic market bid size limitations and/or typically employed storage sizes in commercial markets. The objective was to find the "bending point" and optimum E:P ratio when NPV turns negative/ drops after reaching its maximum value:

- BESS - E:P from 1:5, 7.5, and 10 with 1 MW power capacity, and E:P of 1 for 5MW power capacity;
- FES - E:P of 0.25, 0.2, 0.15, 0.1 with 1 MW power capacity and E:P of 0.25 with 20 MW power capacity;
- CAES - E:P of 4, 5, 6, 7, 10 15, 90, and 100 with 5 MW power capacity

As such, 3 study cases, 11 scenarios, and 82 sub-scenarios were analyzed. Simulations for automatic frequency markets (FCR-N, FFR) were performed on a second basis, and simulations for energy (Elspot) and manual frequency markets (mFRR) are done on an hourly basis.

The following storage performance indicators have been adopted to conduct an analysis of the results:

- Change of energy content of the storage (MWh), price change (EUR/MWh), frequency violations (mHz), storage cycles (MW), and penalty powers (MW) throughout the selected simulation periods at each time step to demonstrate the mutual impact of storage technical constraints and market rules. Matlab plots are used for this purpose;
- Revenue streams (availability payment, energy payment, penalty payment) in USD for each study case, scenario, and sub-scenario for comparison of the impact of different E:P ratios on the storage financial performance, and market relevance for the specific technology. Bar charts are used for this purpose;
- NPV values (USD and USD/kW), CAPEX (USD), Fixed and Variable Operation and Maintenance costs (USD) for each study case, scenario, and sub-scenario for comparison of the impact of different E:P ratios on the storage financial performance, and demonstration of the trade-off between cash inflow (revenue streams) into and cash outflow from the projects (CAPEX, fixed a variable OPEX). Combo diagrams (a combination of stack and line graphs) and tables are used for this purpose;
- Value (USD/kW/year) of technology for a certain market, calculated as a ratio between the yielded revenue that corresponds to the highest NPV and installed capacity, to analyze a technology potential in a studied market. Bar and area charts are used for this purpose.

Conclusions on applicable/ recommended sizes, revenues, and NPVs will reply to the first part of the research question related to the valuation of storage whereas the conclusions on the relevancy of studied markets/ services should address the second part of the research question which is related to niche identification.

5.2 Case 1: BESS Technology - results interpretation

Case 1 is concerned with BESS technology. Participation of the BESS is evaluated in multiple Nordic frequency ancillary markets such as FCR-N and FFR, energy markets such as Elspot, and their combinations. Technical and financial metrics of the BESS performance adopted for the analysis are explained in section 5.1. The analytical formulation and requirements of the above markets are detailed in Sections 4.4, 4.6, and 4.7. Input data utilized in simulations is provided in Section 4.3.

5.2.1 BESS participation in the Nordic FCR-N

FCR-N, which is a normal operating reserve to handle frequency violations within the normal band, requires balance providers to activate the committed resources automatically as a response to the local frequency deviations. The profile of frequency violations in mHz for the studied year is given in Fig. 5.1 and is on a second basis.

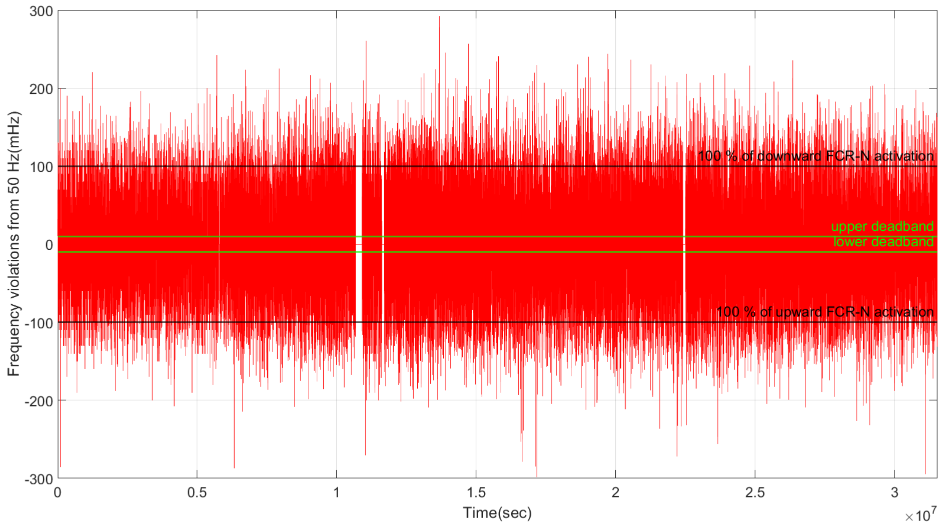


Figure 5.1: Instantaneous measured Nordic power system frequency violations in mHz from the reference frequency for the studied year.

Source: Self-made based on data set from [120], Matlab

From Fig. 5.1 it can be observed that frequency fluctuations in Nordic power systems within the range of 49.9 - 50.1 Hz are continuous throughout the year. Horizontal green lines on the graph represent the dead band zone of +/-10 mHz, and horizontal black lines of +/- 100 mHz represent the frequency thresholds for downward and upward activation of 100% committed FCR-N reserves respectively. White patches show the periods when the grid frequency was exactly 50 Hz. Ca.75% of the period frequency was in the range for FCR-N activation.

Simulations were conducted for the complete year on a 1-second basis. To demonstrate how BESS operates during both over- and under-frequency events in FCR-N market, the period between 887691-st and 887841-st seconds was picked and battery cycles, along with SoC and penalty power were plotted for 5 MW/ 5 MWh battery system (please see Fig. 5.2 and Fig. 5.3).

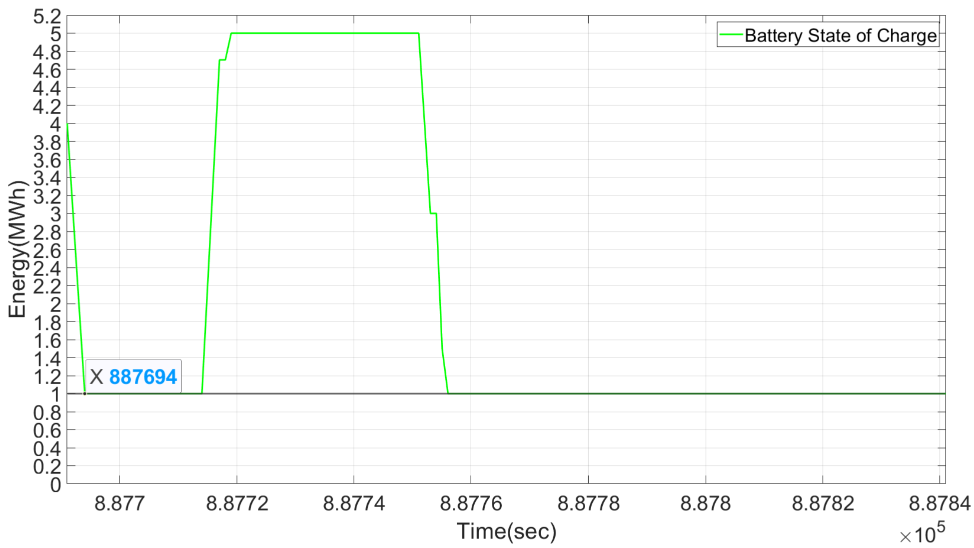


Figure 5.2: SoC of 5MW/5MWh BESS operating in FCR-N market.

Source: Self-made, Matlab

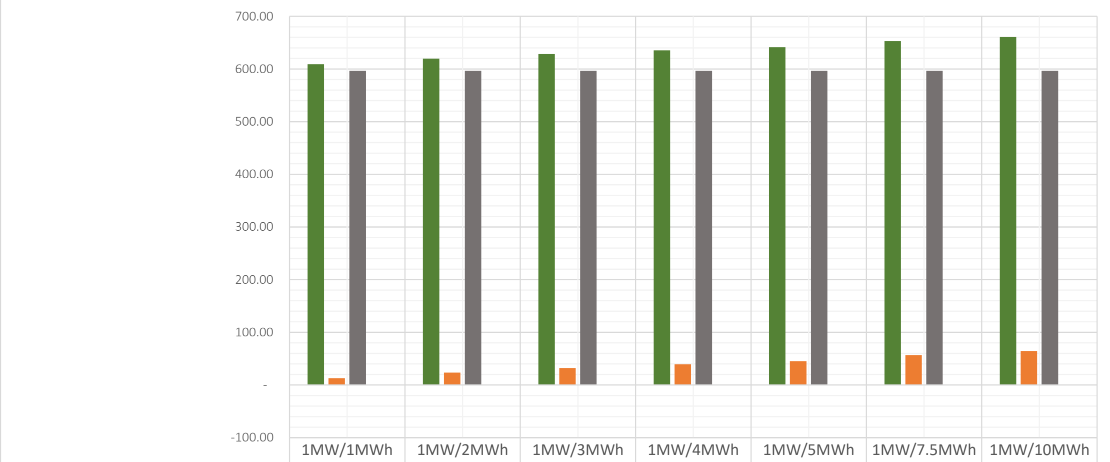
Figure 5.3: Operation of 5MW/5MWh BESS in FCR-N market.

Source: Self-made, Matlab

SoC in Fig. 5.2 is limited by the maximum energy capacity of the BESS e_{max}=5 MWh and SoC_{min}=20% or 1MWh for the given size. Fig. 5.3 captures measured grid frequency in Hz (top blue line), battery charging and discharging cycles for up- and down-regulation accordingly in MW (second and third red lines), and down - and up penalty powers due to the BESS breaching its committed grid exchange power obligations in MW (two last blue lines). BESS charging is plotted with a reverse sign to show that the battery is acting as a load as seen from the grid. It can be noted from the graph that under-frequency in the grid below the dead band 49.99 and above 49.9 Hz (FCR-N upward activation zone) is occurring until 8877000-th second. However, the BESS can only discharge until 887694-th second due to the fact that SoC reaches its minimum depth of 20%. The mismatch between the required power from the battery and SoC constraints triggers up-ward penalty power (last blue line on Fig. 5.3) that is used for penalty payment calculation. Penalty power counting halts when grid frequency normalizes and enters a dead-band zone. Similarly, when over-frequency occurs above 50.01 Hz and below 50.1 Hz (FCR-N downward activation zone) battery charging starts (second red line in the graph) which leads the energy content of the BESS to its maximum limit of 5 MWh. A mismatch between the required battery charging and SoC constraints triggers downward penalty power (third blue line on Fig. 5.3) that is used for penalty payment calculation. The calculation formulas of charging p_t^{charge}, discharging p_t^{disch} and penalty power $P_{FCR}^{penalty}$ are given in Eqn. 4.14 and Eqn. 4.22.

The outputs from the Matlab model are further used to analyze financial indicators for the given constraints and conditions.

The BESS capacity $p_{installed}$ is defined by the Nordic market specification as explained in Section 5.1. The BESS' E:P ratios used in the analysis correspond to the available sizes in the market based on the findings from Chapter 4.1. BESS projects price data such as capital and operation expenditure used in NPV calculation is provided in Table 4.7. The NPV method itself is explained in Section 3.3.



	1MW/1MWh	1MW/2MWh	1MW/3MWh	1MW/4MWh	1MW/5MWh	1MW/7.5MWh	1MW/10MWh
Total revenue, ths USD	608.98	619.58	628.26	635.47	641.52	652.94	660.77
Total enery payment, ths USD	12.90	23.49	32.16	39.36	45.40	56.81	64.64
Total availability payment, ths USD	596.47	596.47	596.47	596.47	596.47	596.47	596.47
Total penalty payment, ths USD	-0.3897	-0.3782	-0.3699	-0.3634	-0.3581	-0.3484	-0.3418

Figure 5.4: Comparison of annual revenue streams of BESS in FCR-N market, ths USD.

Source: Self-made

Based on the equations discussed in Section 4.6, results on various revenue streams obtained from the Matlab model are summarized in Fig. 5.4. BESS bidding in FCR-N market earns revenue from the availability payment AP_{FCR} by being present in the FCR-N capacity market regardless of whether the storage was activated or not. BESS receives additional energy payment EP_{FCR} from triggered-by-frequency-violations grid energy exchange based on the activation market prices. The total revenue $Profit_{FCR-N}$ is reduced by the penalty payment PP_{FCR-N} which is applied when a battery breaches its obligations and does not respond with committed power to grid frequency changes due to SoC or other constraints. Availability payment is the main source of revenue for the BESS in FCR-N market. The value is the same for all cases as the power capacity $p_{installed}$ is fixed to 1 MW while energy capacity increased from 1 to 5, 7.5, and 10. Energy payment of FCR-N are increasing with the increased energy capacity and are 2.12% of the total revenue for E:P 1 (1 MW/ 1 MWh) and 9.78% for E:P of 10 (1 MW/10 MWh). The correlation coefficient between the E:P ratio of the BESS and yielded revenue is 0.97 which suggests a strong positive correlation between revenue and E:P parameter. Predictably, the total penalty payment is decreasing with increased energy capacity. However, for all cases, the penalty payment constitutes less than 1% of the total revenue. This is because FCR-N is a continuous service with both up- and down-ramps and frequency fluctuations of lower magnitude, and as such BESS' SoC constraints do not impose financial losses.

A conclusion on the recommended size for generating higher positive income can be only made after comparing NPV indicator which accounts for the time value of money and costs incurred during project development and operation until the end of a lifetime. NPV for the BESS is calculated for 12 years of operation which is a conservative approach given that the total cycles of available BESS technologies are between 10000-12000 cycles whereas for FCR-N cycles per year were below 800. NPVs for studied sizes of the BESS in FCR-N are provided in Fig. 5.5.

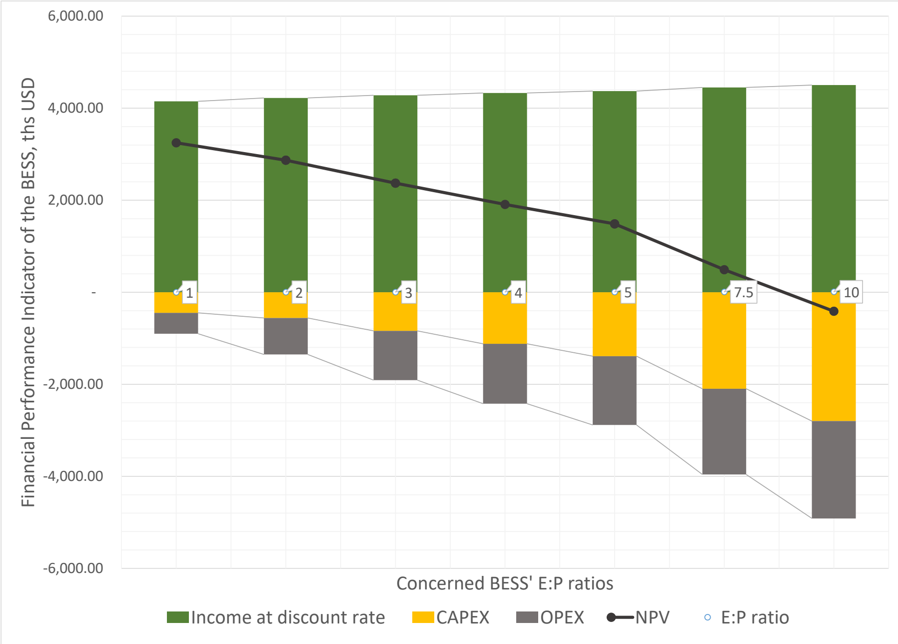


Figure 5.5: Comparison of NPV at the the end of a lifetime of BESS in FCR-N market, ths USD.

Source: Self-made

CAPEX and OPEX costs are shown in Fig. 5.5 with a negative sign as an indication of cash flowing out of the project. NPV is shown as black dots for studied sizes. Contrary to revenue increase with the greater E:P ratios, NPV exhibits a declining trend. This is due to increased capital, operation, and maintenance costs for greater energy capacities.

Based on the analysis above, an E:P ratio of 1 is recommended for BESS which participates in the FCR-N market. Considering that FCR is a power market obtained conclusion is aligned with general size recommendations for storage power applications. Conclusions will be further validated in Section 5.6.

The recommended E:P ratio was applied to the maximum allowable bid size (5 MW) in the FCR-N market to calculate the value of BESS in FCR-N. The value of the BESS in FCR-N is calculated as a ratio between the total generated revenue $Profit_{FCR}$ and installed capacity $p_{installed}$ and will be provided in Section 5.5 for comparison of studied markets. Financial performance indicators for the recommended 5 MW/ 5 MWh BESS are summarized in Table 5.1.

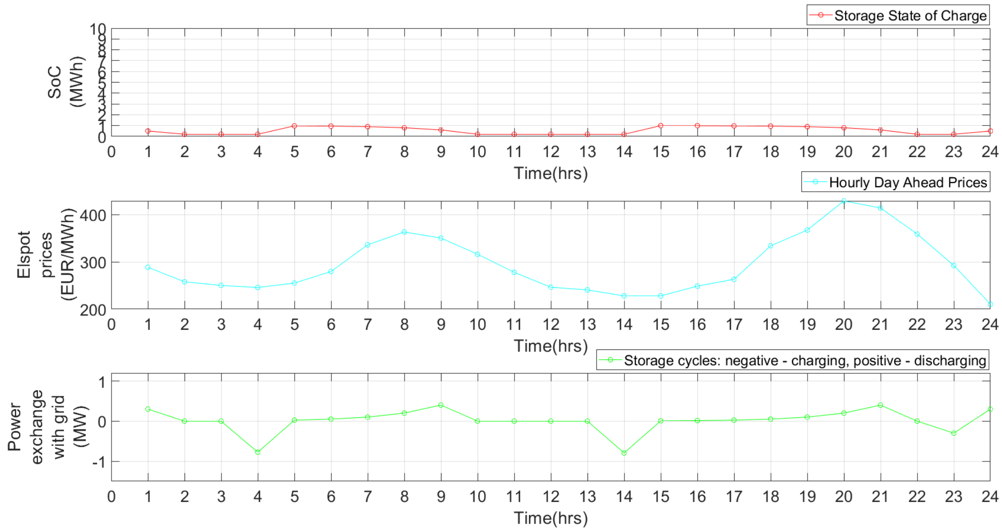
Table 5.1: Financial indicators of the recommended 5 MW/ 5 MWh BESS participating in FCR-N.

Recommended 5 MW/ 5 MWh BESS in FCR-N market	
Financial Indicator	**Value**
Total annual revenue, ths USD	3,044.92
Total annual energy payment, ths USD	64.5
Total annual availability payment, ths USD	2,982.36
Total annual penalty payment, ths USD	- 1.949
Project CAPEX, ths USD	2,240.00
Total O&M costs at the end of a lifetime, ths USD	2,268.45
Income at discount rate at the end of a lifetime, ths USD	20,747.12
NPV, ths USD	**16,238.66**

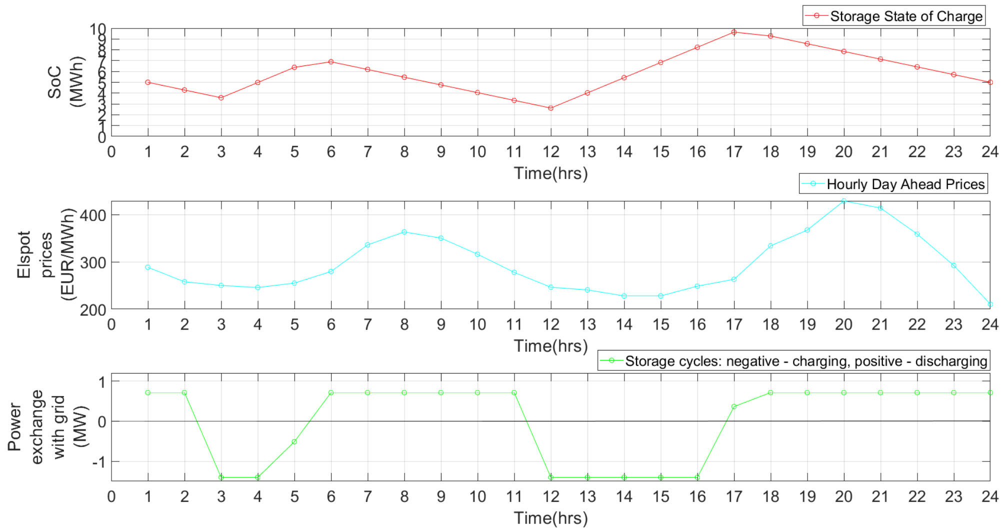
5.2.2 BESS participation in the Nordic Elspot

The strategy of exercising energy arbitrage in a Day Ahead Elspot market was explained in Section 4.4. BESS tracks price change in a day ahead market and makes a decision of buying or selling power from/to the grid and benefits from the hourly price violation. Unlike the FCR-N market, there is no availability payment in Elspot, and as such storage is not obliged to maintain the capacity available. Therefore, it can optimize its Elspot market participation based on revenue maximization. The period of energy arbitrage service is one day. The SoC at the beginning and at the end of the day was forced to 50% of energy capacity to allow BESS flexibility (buying or selling) in grid exchange. Participation of 1 MW/ 1 MWh and 1MW/ 10 MWh BESS in Elspot is provided in Fig. 5.6. The red line of Fig. 5.6a and 5.6b shows the change in the SoC of the BESS. The blue lines demonstrated the volatility of the price in a Day-ahead Nord Pool market. The price change is between 210 EUR/MWh to 430 EUR/MWh with an average price of 295 ERU/MWh. The green line shows the cycles of the BESS as a response to market price change. Negative is for charging and positive is for discharging. We can notice that when the prices were peaking between the 5-th and the 11-th hours, the battery was selling power to the grid, while energy content was restored in the periods of the price drops (for example, between the 2-nd and the 5-th hours, and between 12-th and 16-th hours for the BESS of 1MW/10MWh size).

Elspot represents the energy market, and therefore higher energy content allows greater exchange with the grid during prolonged deep or peak price values as shown in Fig. 5.6 and Fig. 5.7. However, there is again a trade-off between the revenue generated by the higher energy storage capacities (MWh) and incurred costs. Therefore, NPV analysis is performed to propose the BESS size that can yield the highest profit.



(a) 1MW/1MWh BESS



(b) 1MW/10MWh BESS

Figure 5.6: Participation of the BESS in a day-ahead Elspot market.

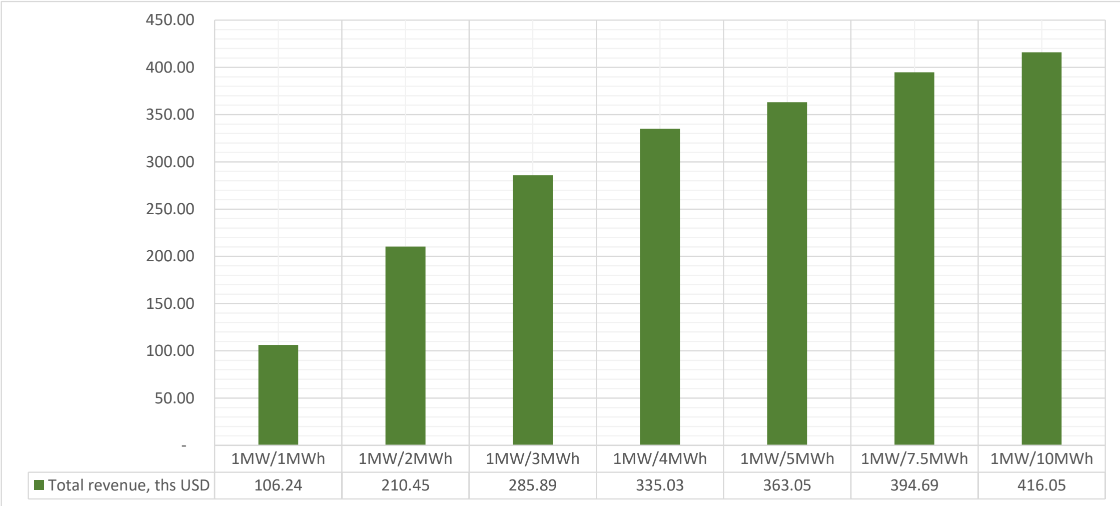


Figure 5.7: Comparison of annual revenues of BESS in Elspot market, ths USD.

Source: Self-made

The number of full cycles of the BESS when performing arbitrage varied between 2 to 3 per day depending on the energy capacity of the storage and were lower for the greater storage duration as can be seen from Fig. 5.6. NPV for the BESS is calculated for 12 years of operation given that the total cycles of available BESS technologies are between 10000-12000 cycles whereas DA cycles per year are between 730 and 1095. NPVs for studied sizes of the BESS in Elspot are provided in Fig. 5.8.

Figure 5.8: Comparison of NPV at the end of a lifetime of BESS in Elspot market, ths USD.

Source: Self-made

Despite a correlation coefficient between the E:P ratio of the BESS and yielded revenue being 0.88 in the Elspot market, which suggests a strong positive correlation between revenue and the E:P parameter, the combined analysis of revenue and NPV concluded that the E:P ratio of 4 is recommended for BESS that participates in energy arbitrage in a DA market. This is due to a trade-off between increasing project costs and the amount that can be offset by the generated revenue. Considering that arbitrage in Elspot is an energy market, obtained conclusion is aligned with general size recommendations for storage energy-based applications. Conclusions will be further validated in Section 5.6.

The value of the BESS in the Nordic Elspot market is calculated as a ratio between the total generated revenue $Profit_{DA}$ that corresponds to the highest NPV and installed capacity $p_{installed}$ and will be provided in section 5.5 for comparison of studied markets. Financial performance indicators for the recommended 1 MW/ 4 MWh BESS are summarized in Table 5.2.

Table 5.2: Financial indicators of the recommended 1 MW/ 4 MWh BESS participating in Elspots' energy arbitrage.

Recommended 1 MW/ 4 MWh BESS in Elspot	
Financial Indicator	**Value**
Total annual revenue, ths USD	335.47
Project CAPEX, ths USD	1,120.00
Total O&M costs at the end of a lifetime, ths USD	52,285.75
Income at discount rate at the end of a lifetime, ths USD	2,282.82
NPV, ths USD	**1,110.56**

5.2.3 BESS participation in the Nordic FFR Profile

FFR, which is employed to tackle large imbalances during the low inertia periods with frequencies equal to or below 49.7 Hz, requires balance providers to activate the 100% of committed resources automatically as a response to the frequency dips 49.7 Hz, 49.6 Hz, or 49.5 Hz depending on the selected frequency threshold. As detailed in Section 4.3, the total duration of under-frequency events 49.7 Hz in the studied months was set to 58 sec which corresponds to the Nordic frequency quality report. FFR is only procured in summer periods between May to October. The profile of frequency violations in mHz for the studied 8 months (from May to October) is given in Fig. 5.9 on a second basis.

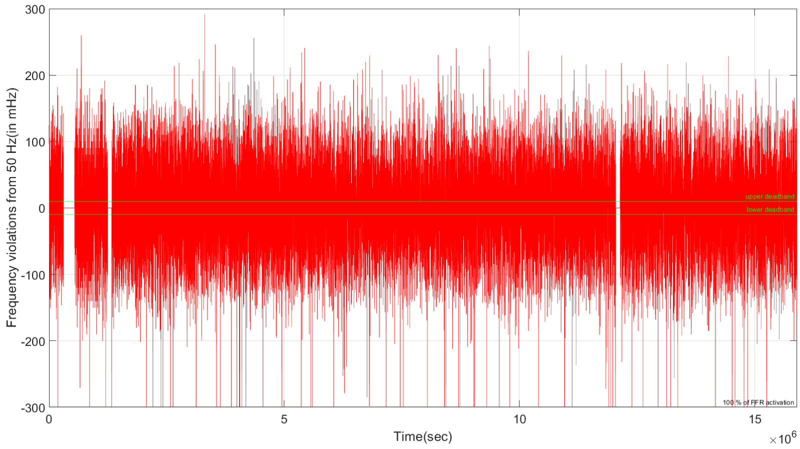
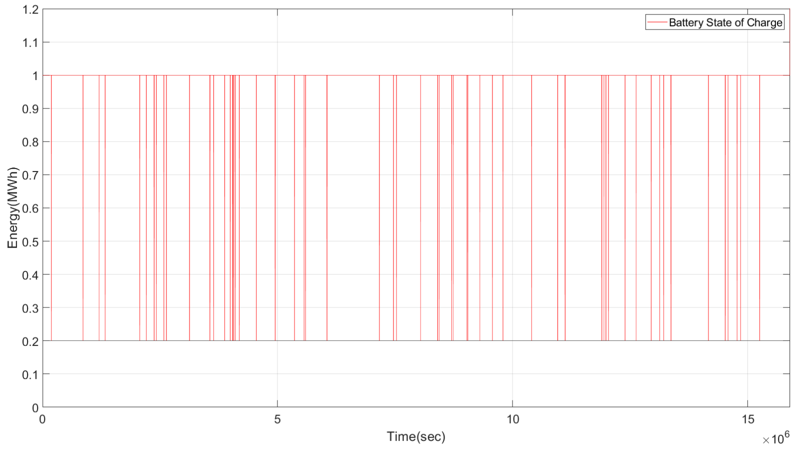


Figure 5.9: Instantaneous measured Nordic power system frequency violations in mHz from the reference frequency for the studied months (May - October).

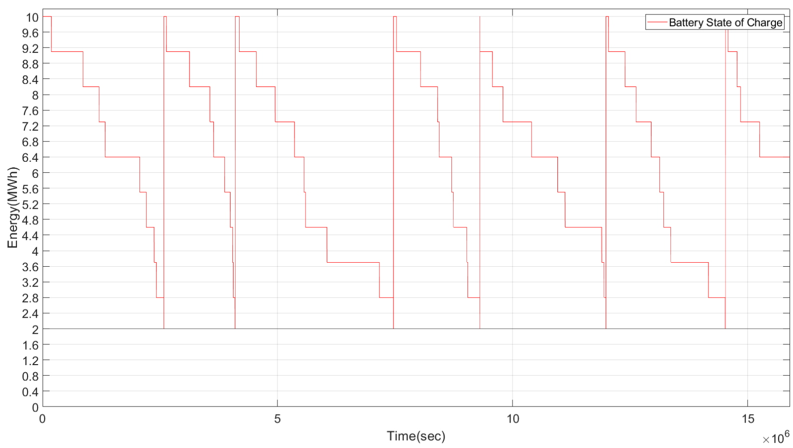
Source: Self-made based on data set from [120], Matlab

Green lines represent the dead-band frequency zone and white patches show the period when the grid frequency was 50 Hz. The frequency violations of 300 mHz (shown with a negative sign to represent the drop) in Fig. 5.9 require 100% FFR activation. Unlike FCRN, FFR is an asymmetrical service and is procured only for up-ward regulation. Because of that, a certain strategy is needed to restore the BESS SoC. As explained in Section 4.7, if the battery reaches its minimum SoC and the grid frequency is within its dead-band, it will be recharged to 100% of energy capacity from the grid, and compensate the energy payment to the grid accordingly.

The BESS SoC for 1MW/1MWh and for 1MW/10MWh is shown in Fig.5.10.



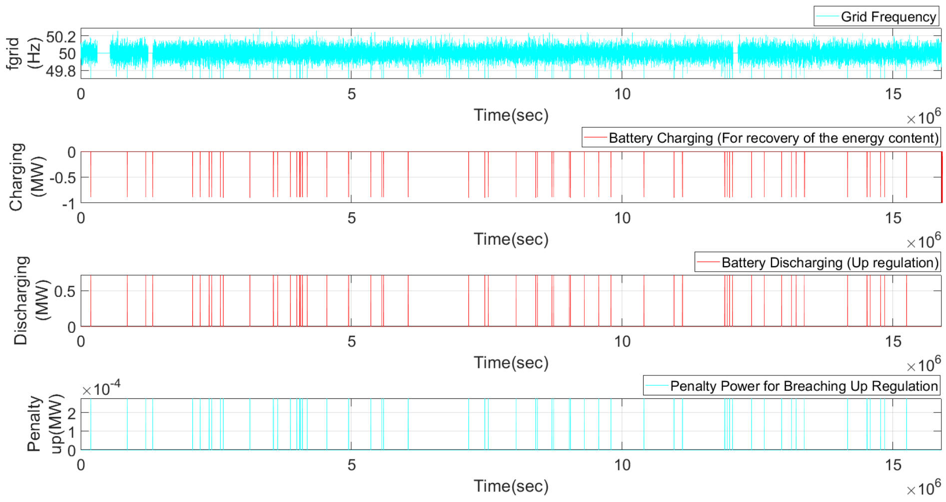
(a) 1MW/1MWh BESS



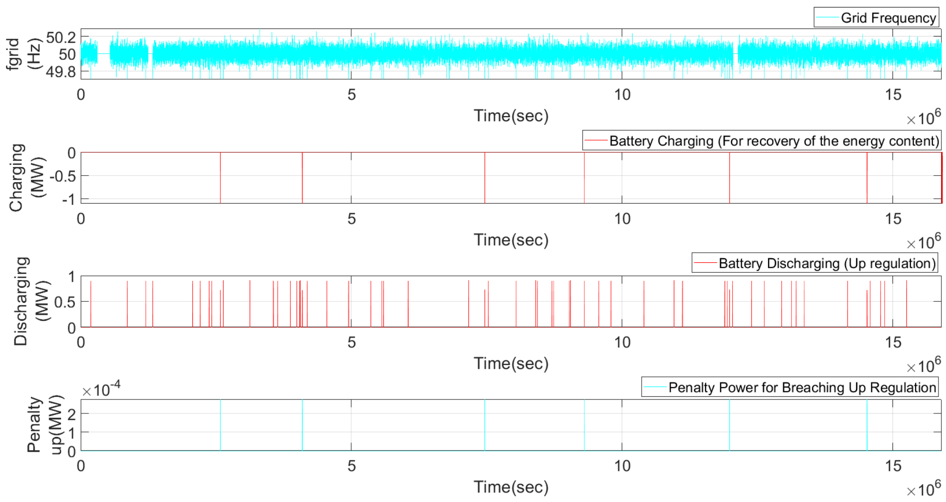
(b) 1MW/10MWh BESS

Figure 5.10: SoC of BESS operating in FFR market.

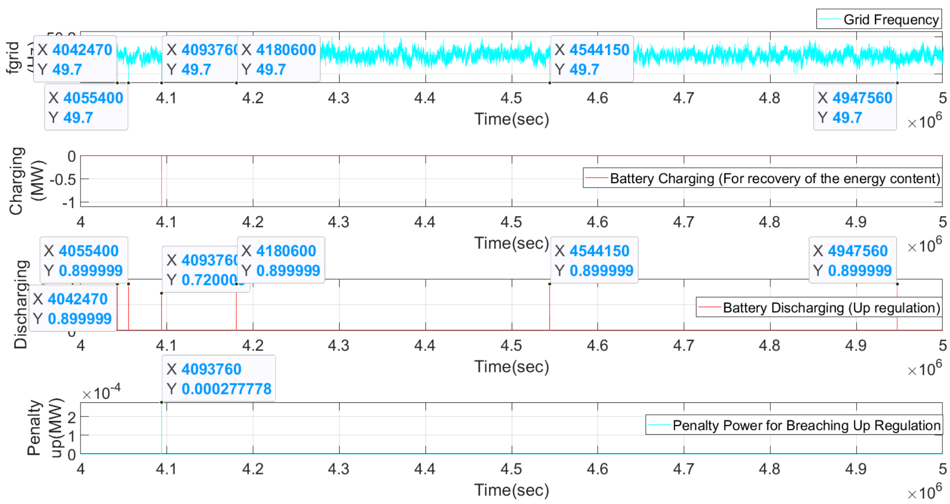
The BESS operation in the FFR market is cyclic. This is due to the requirement to provide 100% of capacity when the grid frequency drops to 49.7 Hz, and then restore energy content to 100% based on the strategies explained above. When E:P ratios are greater than 1, less energy is needed from the grid and the discharging is gradual as shown in Fig.5.10b. Given that under-frequency events of FFR activation magnitude are rare, even a 1:1 E:P ratio does not cause exhaustion of a lifetime BESS that is tied to a certain number of cycles. The BESS cycles as a response to under-frequency events and for restoring the energy content for 1MW/1MWh and for 1MW/10MWh are shown in Fig. 5.11. The impact of greater E:P ratios on the reduction of energy purchased from the grid along with lower penalties can be observed from Fig. 5.11a and Fig. 5.11b.



(a) 1MW/1MWh BESS



(b) 1MW/10MWh BESS

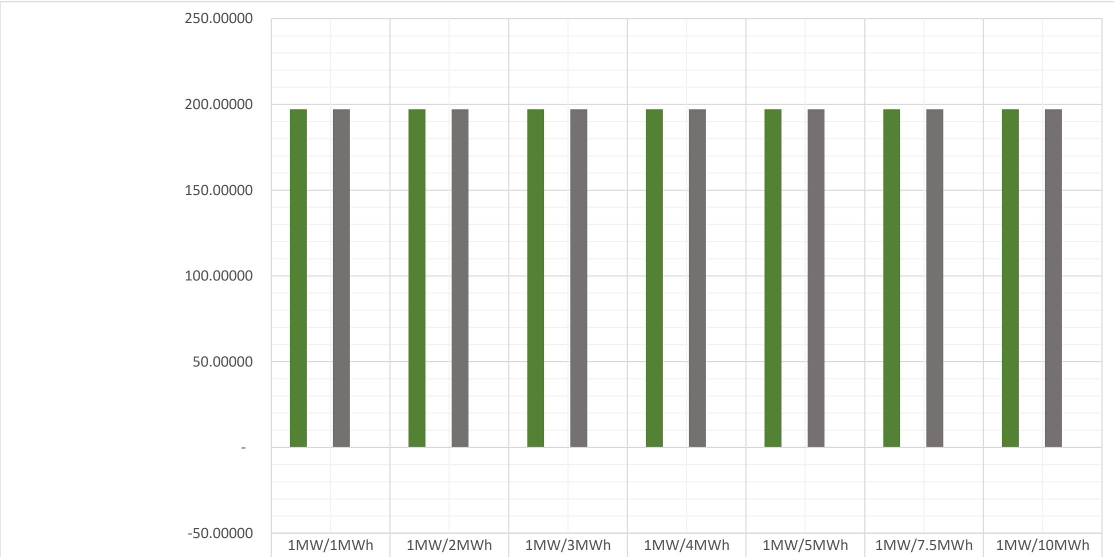


(c) 1MW/10MWh BESS-zoomed operation

Figure 5.11: Operation of BESS in FFR market.

Fig. 5.11c demonstrates BESS operation logic in the FFR market. The period between the 4000000-th and 5000000-th second is plotted. Within the selected period, the frequency goes down to 49.7 Hz (first blue diagram) six times (six seconds in total). The first two times, BESS provides its 100% (third red diagram) of power capacity adjusted by roundtrip efficiency and self-discharge losses (0.899 MW) as a response to the under-frequency event (49.7 Hz). However, the minimum limit of SoC is reached after that, and the third activation of the BESS provides only partial discharge at 4093760-the second (0.72 MW) when penalty power ($p_{installed}/3600$) is assigned to the battery (fourth blue diagram). After the grid frequency goes back into the dead-band zone (normal frequency operational range), BESS is recharged from the grid to its full energy capacity of 10 MWh (second red diagram) at 4094090-th second and ready to operate again. Because the selected zoomed example represents the energy capacity of the BESS equal to 10 MWh, during the three following subsequent grid frequency drop events, the battery is capable to provide the required power without being penalized.

The monetary value expressed in total revenue and NPV from participation in NPV market is shown in Fig. 5.12 and Fig. 5.13.



	1MW/1MWh	1MW/2MWh	1MW/3MWh	1MW/4MWh	1MW/5MWh	1MW/7.5MWh	1MW/10MWh
Total revenue, ths USD	197.19783	197.19932	197.20006	197.20042	197.20049	197.20118	197.20135
Total energy payment, ths USD	-0.00063900	0.00085200	0.00159750	0.00194895	0.00202350	0.00271575	0.00288615
Total availability payment, ths USD	197.20	197.20	197.20	197.20	197.20	197.20	197.20
Total penalty payment, ths USD	-0.0000010	-0.0000005	-0.0000003	-0.0000003	-0.0000002	-0.0000001	-0.0000001

Total revenue, ths USD · Total energy payment, ths USD · Total availability payment, ths USD · Total penalty payment, ths USD

Figure 5.12: Comparison of revenue streams of BESS in FFR market from May to October, ths USD.

Source: Self-made

Similarly to the FCR-N market, BESS earns revenue from bidding to the capacity market expressed as availability payment AP_{FFR}. Additional energy payment is received from the energy activation market as a response to under-frequency events EP_{FFR}. The revenue is however deducted by the energy payments to the grid due to recovery of the state of charge, and therefore, the net energy payment is negative for lower E:P ratios as BESS ends up paying more to the grid (power drawn from the grid to battery to restore 100% SoC is higher than power drawn from the battery to the grid due to adjusting power exchange values by roundtrip efficiency of conversion system). Another negative term that impacts the revenue is the penalty payment PP_{FCR} for breaching upward regulation due to SoC constraints. For a 1:1 E:P ratio, the energy payment is negative and contributes less than 1% to the total revenue for all other cases. Penalty payment declines with the increased E:P and accounts for less than 1% for all studied sizes. Availability payment contributes to 99.99854% of the total revenue for E:P of 10, and over 100% for E:P of 1 as it is reduced by negative energy payment values. As in all studied cases power capacity was fixed to 1

MW and AP_{FFR} is the main revenue contributor, the total revenue for studied sizes differs only in decimals. And therefore, NPV tends to decline with the increased E:P.

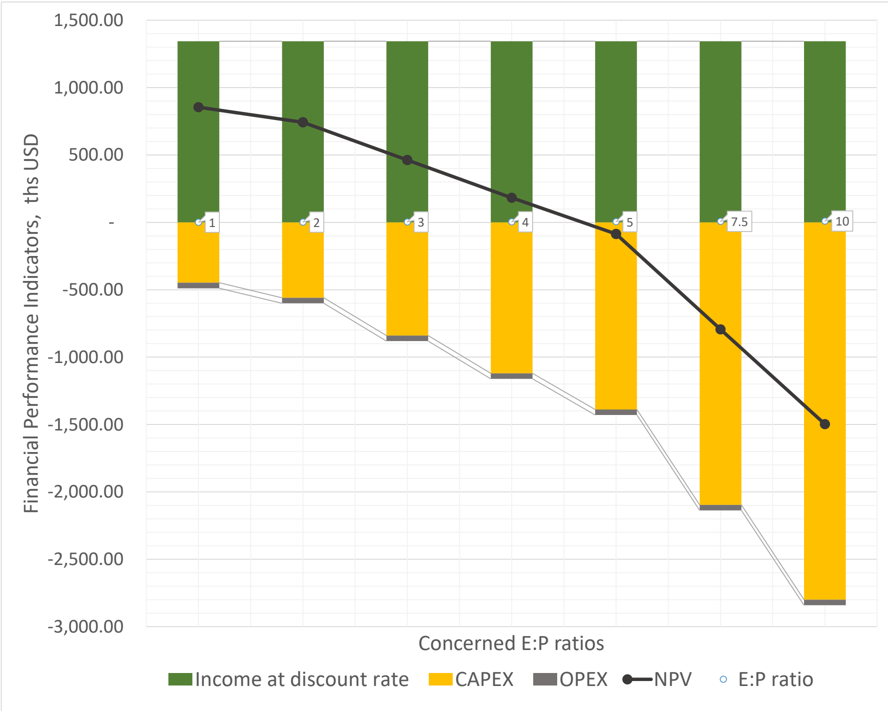


Figure 5.13: Comparison of NPV at the end of a lifetime of BESS in FFR market, ths USD.

Source: Self-made

The general rule is that higher E:P ratios ensure lower energy payment to the grid for the recovery of SoC and lower penalties for breaching up-ward regulation commitment. However, overall benefits from the higher energy capacities are negligible due to the specifics of the FFR market discussed in this section, and as demonstrated by NPV analysis E:P of 1 provides the highest profit at the end of a lifetime of the BESS participating in the FFR market.

The recommended E:P ratio was applied to the maximum allowable bid size (5 MW) in the FFR Profile market to calculate the value of BESS in FFR. The value of the BESS in FFR is calculated as a ratio between the total generated revenue $Profit_{FFR}$ and installed capacity $p_{installed}$ and will be provided in section 5.5 for comparison of studied markets. Financial performance indicators for the recommended 5 MW/ 5 MWh BESS are summarized in Table 5.3.

Table 5.3: Financial indicators of the recommended 5 MW/ 5 MWh BESS participating in FFR Profile.

Recommended 5 MW/ 5 MWh BESS in FFR Profile market	
Financial Indicator	**Value**
Total annual revenue, ths USD	985.989
Total annual energy payment, ths USD	-0.00318
Total annual availability payment, ths USD	985.99
Total annual penalty payment, ths USD	- 0.0000052
Project CAPEX, ths USD	2,240.00
Total O&M costs at the end of a lifetime, ths USD	205.365
Income at discount rate at the end of a lifetime, ths USD	11,831.869
NPV, ths USD	**4,272.86**

It should be noted that FFR Profile is only procured from May to October (including May and October), and therefore annual in Table 5.3 refers to the period between May to October.

5.2.4 Value stacking from BESS participation in multiple Nordic markets

The strategy for value stacking, which is the practice of leveraging multiple revenue streams or value sources from a single BESS simultaneously or sequentially, was explained in Section 3.2. Due to the requirements of Nordic frequency ancillary markets, participation of the BESS with the same bidding capacity in multiple markets is possible on a seasonal basis only (please refer to Table 4.5 for the bidding periods). Selection and justification of bidding periods are provided in Section 4.2. Value stacking of the BESS was analyzed for the combination of a DA and FCR-N, a DA and FFR, and an FFR and FCR-N markets. Revenues and NPVs were calculated for concluding the BESS values and comparing them against single-market participation results. Results are captured in Table 5.4 and Fig. 5.14.

Table 5.4: Financial indicators of the BESS participating in multiple Nordic markets, ths USD.

Financial Indicator	Combination of markets	Value, ths USD							
		1MW/1MWh	1MW/2MWh	1MW/3MWh	1MW/4MWh	1MW/5MWh	1MW/7.5MWh	1MW/10MWh	5MW/5MWh
Total annual revenue	FCR-N+DA	537.73	580.80	612.83	634.99	649.25	669.16	682.67	2,688.67
	FFR+DA	249.88	301.56	338.97	363.34	377.23	392.92	403.52	1,249.42
	FFR+FCR-N	399.13	402.30	404.89	407.05	408.86	412.30	414.68	1,995.64
Total availbility payment	FCR-N+DA	492.40	492.40	492.40	492.40	492.40	492.40	492.40	2,462.02
	FFR+DA	197.20	197.20	197.20	197.20	197.20	197.20	197.20	985.99
	FFR+FCR-N	395.44	395.44	395.44	395.44	395.44	395.44	395.44	1,977.22
Total energy payment	FCR-N+DA	10.71	19.50	26.72	32.72	37.76	47.27	53.75	53.53
	FFR+DA	- 0.00064	0.00085	0.00160	0.00195	0.00202	0.00272	0.00289	- 0.00318
	FFR+FCR-N	0.00384	0.00700	0.00959	0.01174	0.01356	0.01699	0.01937	0.01918
Total penalty payment	FCR-N+DA	0.31	0.30	0.29	0.28	0.28	0.27	0.27	1.53
	FFR+DA	0.0000010	0.0000005	0.0000003	0.0000003	0.0000002	0.0000001	0.0000001	0.0000052
	FFR+FCR-N	0.150	0.147	0.144	0.142	0.140	0.137	0.135	0.752
NPV at the end of a lifetime	FCR-N+DA	2,867.16	2,795.38	2,525.02	2,222.05	1,903.93	1,056.90	257.69	14,335.78
	FFR+DA	1,212.06	1,450.71	1,424.24	1,309.04	1,133.76	532.24	- 99.47	6,060.30
	FFR+FCR-N	2,067.48	1,842.93	1,470.82	1,114.05	780.81	- 49.24	- 838.24	10,337.38

The combination of FCR-N and DA markets demonstrated the highest revenue and NPV with the E:P of 1 (5MW/ 5 MWh) representing the most profitable scenario. It is followed by the FFR+FCR-N and FFR+DA. For services where FFR was involved, E:P of 10 (1MW/10MWh) generated a negative NPV. The results can be explained by the specifics of each market. In the case of FCR-N frequency change is continuous and service itself is procured throughout the year in both directions (up-ward and down-ward). However, the magnitude of frequency change is small, and therefore it does not exhaust the battery energy content as often as the FFR service. FFR is only activated a limited amount of times as the frequency quality in Nordics is strictly controlled, and also it is only procured in summer periods. As the frequency threshold for FFR requires activation of 100% of FFR capacity the service is more cyclic. Also, due to the fact that FFR is asymmetrical, service strategies are required for the balance providers to restore the energy content of the storage, and as such, if the storage plant is not coupled with the generating unit, extra energy is procured from the grid that creates negative term in energy payment for lower E:P ratios.

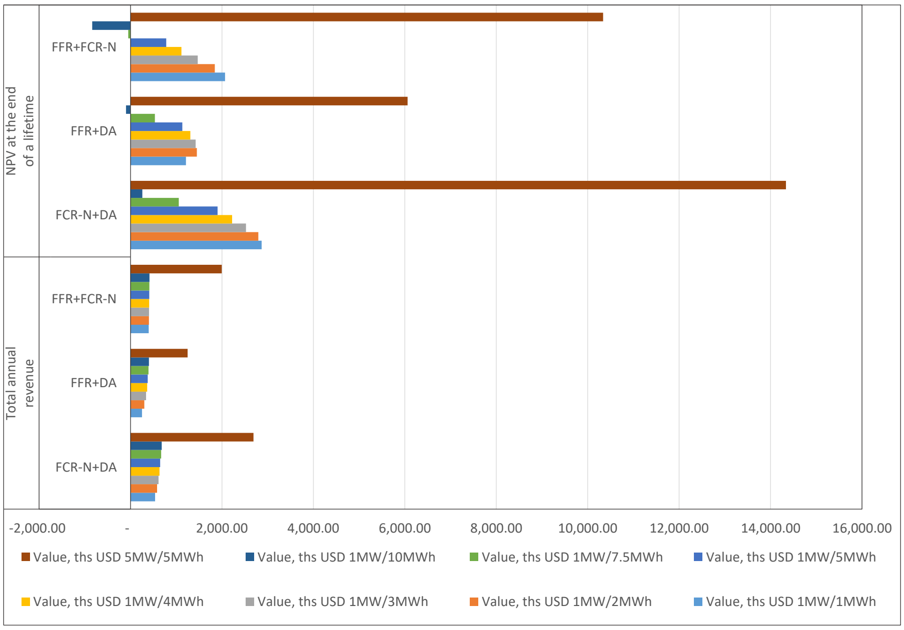


Figure 5.14: Comparison of NPV and revenues of BESS participating in multiple Nordic markets, ths USD.

Source: Self-made

Values stacking will be further compared with single market participation and overall conclusions on the BESS participation in the selected Nordic markets will be made in section 5.2.5.

5.2.5 Value of BESS in the Nordic markets

The value of BESS in the Nordic markets was evaluated for

A. Frequency ancillary markets:

- FCR-N;
- FFR

B. Energy markets:

- Energy arbitrage in a Day-Ahead Elspot market;

C. And their seasonal combination for value stacking:

- FCR-N (May - December) + Day-Ahead (remaining period);

- FCR-N (remaining period) +FFR (May-October);
- FFR (May - October) + Day-Ahead (remaining period)

The detailed discussions on each case are available through Sections 5.2.1 to 5.2.4.

The value of BESS (USD/kW/year) is calculated as a ratio between the total generated revenue $Profit$ that corresponds to the highest NPV (ths USD) and installed capacity $p_{installed}$ (MW). Based on the obtained size recommendations, for the cases that cover frequency services (only frequency markets or their combination) the E:P ratio of the BESS used in the value analysis, is 1. For energy arbitrage, the value of BESS is calculated for an E:P ratio of 4. The same approach was applied for NPV (USD/KW) calculations. Value (USD) and NPV (USD) of 1kW BESS are provided in Fig. 5.15 and in Fig. 5.16 accordingly.

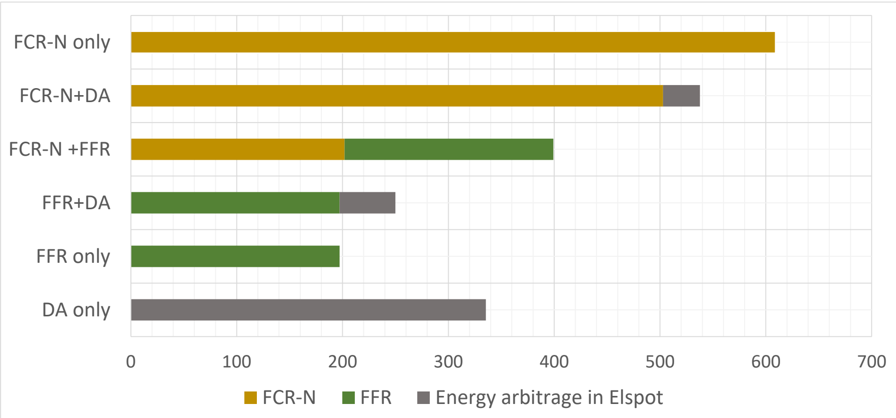


Figure 5.15: Value of BESS (USD/kW/year) in the Nordic markets.

Source: Self-made

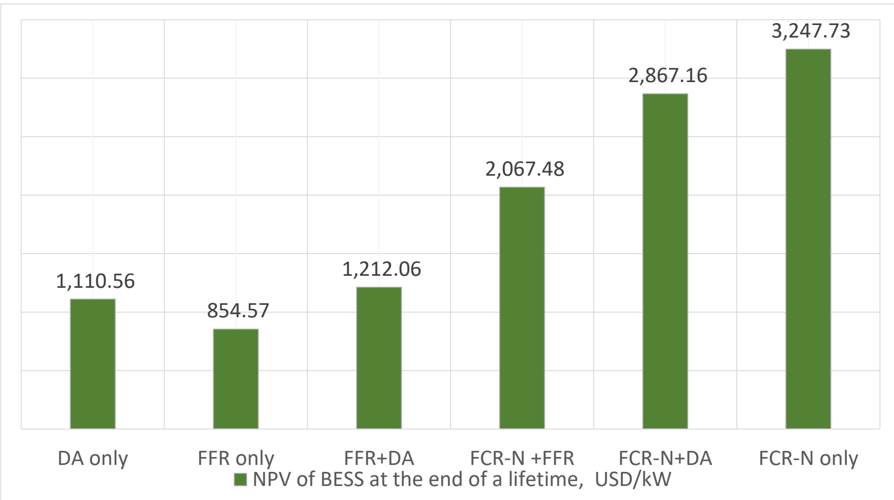


Figure 5.16: NPV of BESS (USD/kW) in the Nordic market at the end of its lifetime.

Source: Self-made

5.2.6 Case 1: BESS Technology - Conclusions

The following conclusions were drawn from the BESS in Nordic markets analysis:

1. All selected markets have the potential of providing a positive business case for BESS technology;

2. Nordic requirements for automatic frequency ancillary services (FCR-N, FFR) prohibit the participation of the same balancing capacity in multiple markets, and as such only seasonal/ sequential value stacking is possible;

3. The recommended E:P ratio for automatic frequency markets (FCR-N, FFR) is 1. Given the maximum allowed single bid capacity of 5MW in FFR Profile and FCR-N markets, the BESS size of 5MW/ 5 MWh is recommended;

4. The recommended E:P ratio for energy markets is 4. There are no capacity limitations specified for exercising energy arbitrage. The analysis demonstrates that it is possible to yield a revenue of above 300 USD per kW per year of installed BESS capacity in the Elspot market. The revenue is a result of benefiting from the daily price volatility in a Day-Ahead market (EUR/MWh). Daily there are on average 4 price zones, and depending on the storage energy capacity the number of full cycles per day varies between 2 to 3;

5. The highest revenue contributor in frequency markets is availability payment AP which BESS receives for the accepted committed capacity in Nordic currency/MW;

6. FCR-N is a symmetrical service procured throughout the year for up- and down-ward regulation within the normal frequency range (excluding dead-band zone) and requires continuous availability of storage. However, the frequency change magnitude is small and therefore, the BESS rarely goes from the minimum to maximum energy capacity in one cycle. As such the dependency of BESS lifetime from the full cycles resource does not hinder its operation in the FCR-N market;

7. FFR is procured only in summer periods (from May to October for FFR Profile) and used for up-ward regulation (asymmetrical service) of frequencies 49.7 Hz and below. Because the frequency threshold requires 100% FFR committed capacity activation, FFR service is cyclic. However, given the quality of frequency in the Nordic Power System, the occurrence of under-frequency events of that magnitude is rare and was totaling at 58 seconds for the studied period. As such, the BESS lifetime cycles constraint does not represent any drawback in participating in FFR either. FFR has no down-regulation component, and therefore BESS operator should adopt a certain strategy for restoring the battery's energy content. In the thesis, this was done by recharging the battery from the grid when the grid frequency was within its normal operation range and compensating at up-ward energy regulation prices. Therefore, for smaller E:P ratios, the energy payment term of the total revenue was negative for FFR service;

8. The highest value of BESS can be obtained from the FCR-N market and evaluated to be 609.99 USD/kW per year based on the revenue from 5MW/5MWh BESS with NPV totaling at 3,247.73 at the end of a BESS lifetime (12 years);

9. If storage is already participating in the FFR market, then its value can be increased by combining it with FCR-N (estimated value is 399.13 USD/kW/year) or Elspot DA market (249.88 USD/kW/year). This is mostly because FFR is procured only seasonally and therefore would otherwise sit idle if not sequentially stacked with other services;

10. Combination of FCR-N + DA generated higher revenue compared to FCR-N + FFR because in the former case, FCR-N was deployed during the most profitable period and supplemented by DA, whereas in the latter case the period for FCR-N procurement was adjusted around the fixed time window for FFR period;

11. Participation of BESS in a DA only has a limited value and is almost three times less of FCR-N generated NPV.

5.3 Case 2: FESS Technology - results interpretation

Case 2 is concerned with FESS technology. Participation of the FESS is evaluated in the same frequency ancillary markets as for BESS such as FCR-N and FFR. The energy arbitrage is discarded for FESS as non of the tested cases provide positive NPV. This is due to the E:P constraints of FESS discussed below. For the same reason, with the current FFR market rules in Nordics, FESS cannot provide a positive business case while providing FFR, and will be discarded from the value stacking analysis (please see details in Section 5.3.2. Therefore, no service combination is possible for FESS, and FESS value will be only quantified for the FCR-N market. Technical and financial metrics of the FESS performance adopted for the analysis, are explained in Section 5.1. The analytical formulation and requirements of the above markets are detailed in Sections 4.4, 4.6, and 4.7. Input data utilized in simulations is provided in Section 4.3.

The main constraint of FESS apart from the high (up to 100% per day) self-discharge losses, is the available E:P ratios. This is due to the fact that the flywheel stores energy which is proportional to its spinning speed as explained in Section 2.1.1. And therefore, to achieve higher energy storage (MWh), the flywheel would need to spin faster, but there are practical limitations to how fast the speed can be associated with material strength, losses, and safety considerations.

Currently, the highest achieved E:P of FESS in commercial projects is 0.25. Given the maximum capacity limit of 5MW in the FCR-N and FFR Profile market, the FESS sizes and positive revenue cases are very limited in their number. The energy-to-power ratios (E:P) of 0.25, 0.2, 0.15, and 0.1 will be tested in the selected markets with a baseline capacity of 5 MW. The advantages of FESS expressed in high efficiency (95%), a significant number of cycles per operational lifetime (175,000), no constraints on the DoD (o% of energy capacity), and quick response time (in seconds) make FESS still forth for consideration in frequency markets despite mentioned limitations.

5.3.1 FESS participation in the Nordic FCR-N

Simulations of FESS participation in FCR-N are performed for a year on a second basis. The profile of frequency violations in mHz for the studied year is given in Fig. 5.1. Readers are referred to section 5.2.1 where the discussion of properties of the FCR-N market was presented. Demonstration of FESS operation during over and under-frequency events within the FCR-N frequency activation range is done by plotting the period between 887691-st and 887841-st seconds. The SoC, grid frequency, FESS cycles, and bi-direction penalty power are plotted in Fig.5.17 and in Fig.5.18. The performance of 5 MW/ 1.25 MWh FESS is used for plotting.

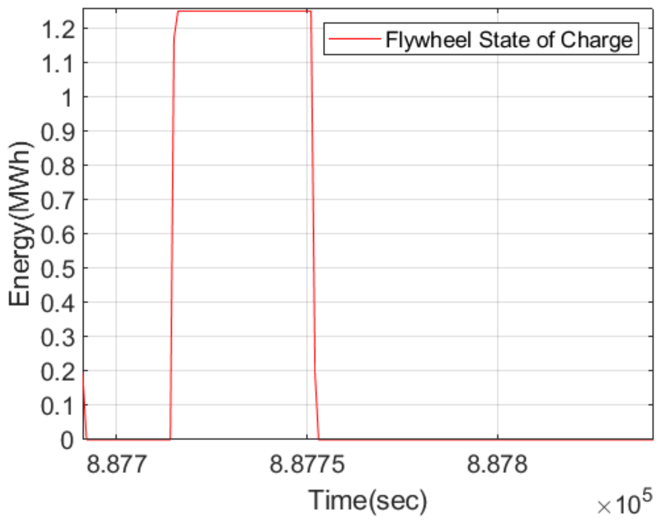


Figure 5.17: SoC of 5MW/1.25MWh FESS operating in FCR-N market, MWh.

Source: Self-made, Matlab

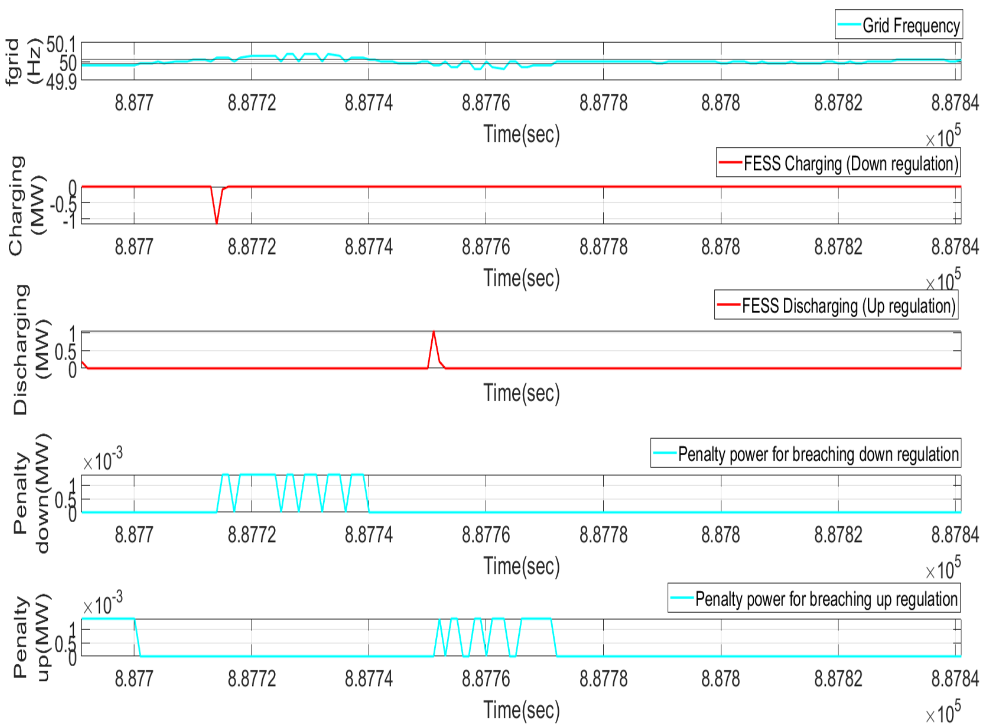
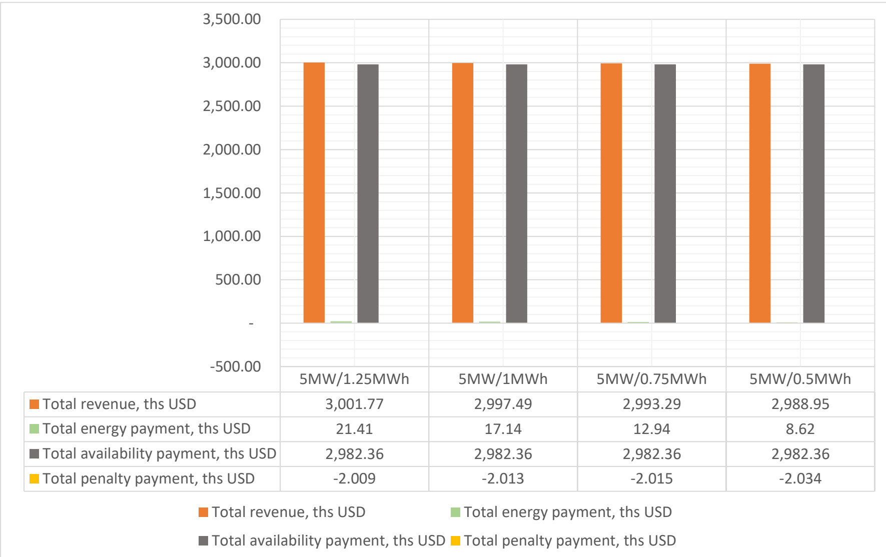


Figure 5.18: Operation of 5MW/1.25MWh FESS in FCR-N market.

Source: Self-made, Matlab

SoC in Fig.5.17 is limited by the maximum energy capacity of the FESS e_{max}=1.25 MWh. There is no limitation for the minimum State of Charge and therefore SoC_{min}=0% which releases more energy content of FESS. Fig.5.18 captures measured grid frequency in Hz(top blue line), flywheel charging and discharging cycles for up- and down-regulation accordingly in MW (second and third red lines), and down - and up penalty powers due to the FESS breaching its committed grid exchange power obligations in MW (two last blue lines). FESS charging is plotted with a reverse sign to show that the flywheel is acting as a load as seen from the grid. It can be noted from the first sub-plot in Fig.5.18 that under-frequency in the grid below the dead band 49.99 and above 49.9 Hz (FCR-N upward activation zone) is occurring until the 8877000-th second. However, the flywheel reaches its 0 SoC due to previous under-frequency cycles, and cannot discharge committed power for which its penalized until the grid frequency normalizes and enters a dead-band zone. Similarly, when over-frequency occurs above 50.01 Hz and below 50.1 Hz (FCR-N downward activation zone), FESS starts charging (second red line in the graph) and already reaches its maximum energy limit of 1.25 MWh in two seconds. The mismatch between the required flywheel charging and SoC constraints due to inherently low E:P ratio triggers downward penalty power (third blue line on Fig. 5.3) that is used for penalty payment calculation. The calculation formulas of charging p_t^{charge}, discharging p_t^{disch} and penalty power $P_{FCR}^{penalty}$ are given in Eqn. 4.14 and Eqn.4.22.



	5MW/1.25MWh	5MW/1MWh	5MW/0.75MWh	5MW/0.5MWh
Total revenue, ths USD	3,001.77	2,997.49	2,993.29	2,988.95
Total energy payment, ths USD	21.41	17.14	12.94	8.62
Total availability payment, ths USD	2,982.36	2,982.36	2,982.36	2,982.36
Total penalty payment, ths USD	-2.009	-2.013	-2.015	-2.034

Figure 5.19: Comparison of annual revenue streams of FESS in FCR-N market, ths USD.

Source: Self-made

From Fig.5.19 it is evident that the main contributor of revenue for the FCR-N market is availability payment AP (up to 99% of total revenue). Energy payment of BESS for the same power capacity was 3 times of FESS (please refer to Table 5.1). This is due to constraints of the maximum energy content of FESS explained above. Another noticeable difference is the number of full cycles per year. According to simulation results, for energy capacities of 0.75 MWh and 0.5 MWh were 35,000 and 87,500 respectively which despite the significant cycling resource of FESS have reduced their lifetime to 5 and 2 years accordingly. For higher energy capacities the cycles per year stayed below the annual cycling resource of FESS, and therefore the lifetime of 20 years for 1.25MWh and 1.2 MWh was accepted in NPV analysis (Fig.5.20).

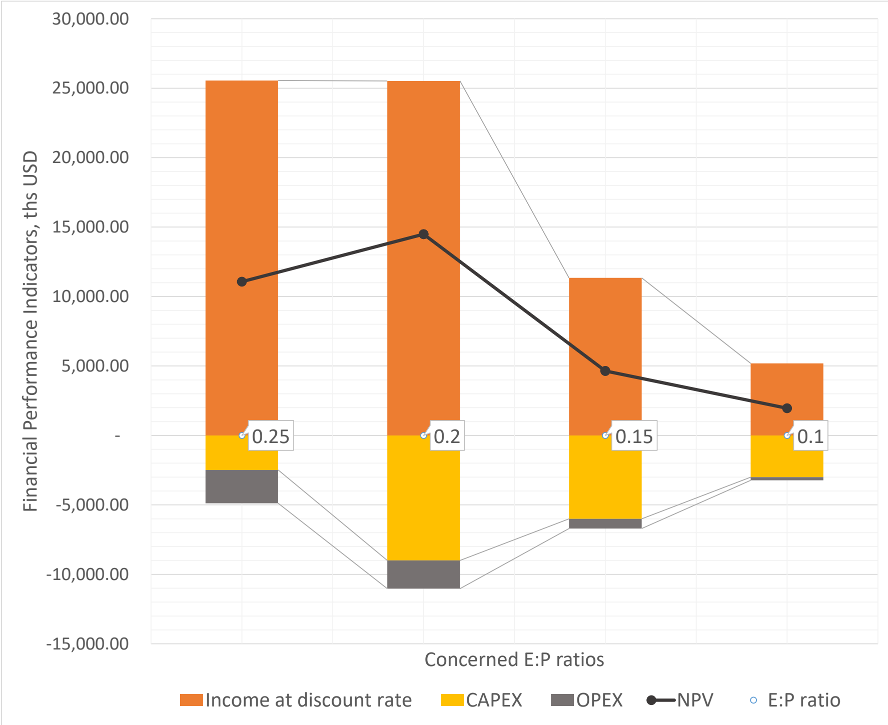


Figure 5.20: Comparison of NPV at the end of a lifetime of FESS in FCR-N market, ths USD.

Source: Self-made

CAPEX and OPEX costs are shown in Fig.5.20 with a negative sign as an indication of cash flowing out of the project. NPV is shown as black dots for studied sizes. The E:P of 0.2 which is equal to 5MW/1MWh of FESS storage provided the highest NPV.

The value of FESS in the FCR-N Nordic market will be calculated based on this size. Financial performance indicators for the recommended 5MW/ 1MWh FESS are summarized in Table 5.5.

Table 5.5: Financial indicators of the recommended 5 MW/ 1 MWh FESS participating in FCR-N.

Recommended 5 MW/ 1 MWh FESS in FCR-N market	
Financial Indicator	**Value**
Total annual revenue, ths USD	2,997.49
Total annual energy payment, ths USD	17.14
Total annual availability payment, ths USD	2,982.36
Total annual penalty payment, ths USD	-2.013
Project CAPEX, ths USD	9,000.00
Total O&M costs at the end of a lifetime, ths USD	2,030.63
Income at discount rate at the end of a lifetime, ths USD	25,519.33
NPV, ths USD	**14,488.7**

5.3.2 FESS participation in the Nordic FFR Profile

Simulations of FESS participation in the FFR Profile are performed for 8 months from May to October during the period when FFR Profile is procured by the Nordic TSOs. The profile of frequency violations in mHz for the studied months is given in Fig.5.9 and is on a second basis. Readers are referred to section 5.2.3 where the detailed discussion of the behaviour of the FFR market was presented.

Demonstration of FESS operation in FFR market is provided in the example of 5MW/1.25 MWh FESS in Fig.5.21.

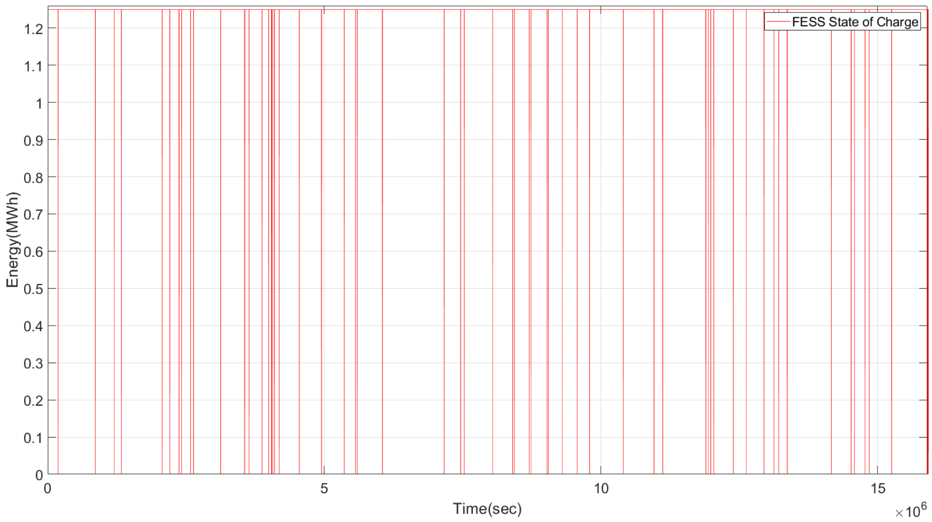


Figure 5.21: SoC of 5MW/1.25 MWh FESS operating in FFR market, MWh.

Source: Self-made

The FESS operation with the highest possible energy capacity of 1.25 MWh which corresponds to the 5MW limit of FCR Profile bid size, is cyclic. It goes from 100% to 0% of its energy content at every under-frequency event (six times in total in plotted period). And even though the number of cycles themselves is not an issue for FESS, it is prone to be penalized if there are sequential under-frequency events in the grid or if the frequency of the grid takes longer periods to go back into the dead-band zone, and therefore FESS has no possibility to restore its energy content. Also, FESS is inherently discharging power to the grid (maximum of 1.187 MW for 5MW/ 1.25 MWh) which is less than 100% of its installed capacity due to energy capacity being less than power capacity adjusted by efficiency and self-discharge losses. Therefore, at every under-frequency event, FESS was penalized. This could be observed in Fig.5.22 where zoomed operation of FESS between the 4000000-th and 5000000-th second is plotted. The first blue sub-plot represents grid frequency change, the second and third red sub-plots show FESS charging for SoC recovery and FESS discharging for performing its FFR duties, and finally fourth blue sub-plots corresponds to the penalty power incurred by FESS due to breaching its up-regulation power obligations.

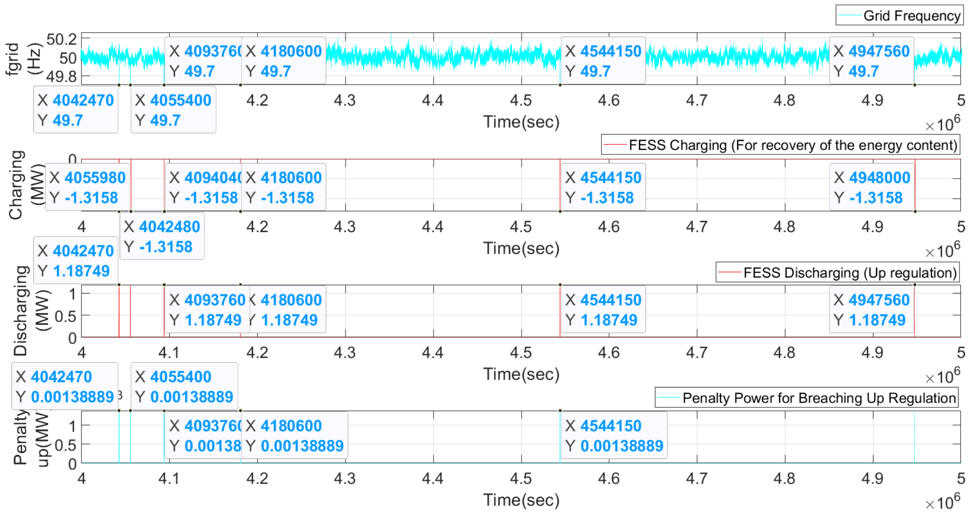


Figure 5.22: Operation of 5MW/1.25 MWh FESS in FFR market.

Source: Self-made

Despite the above limitations, FESS was still able to generate two positive NPV cases because of the availability of payment it receives from the FFR market. Revenue streams and NPV are presented in Fig.5.23 and Fig.5.24 accordingly. Negative energy payment is due to compensation paid to the grid for recharging FESS.

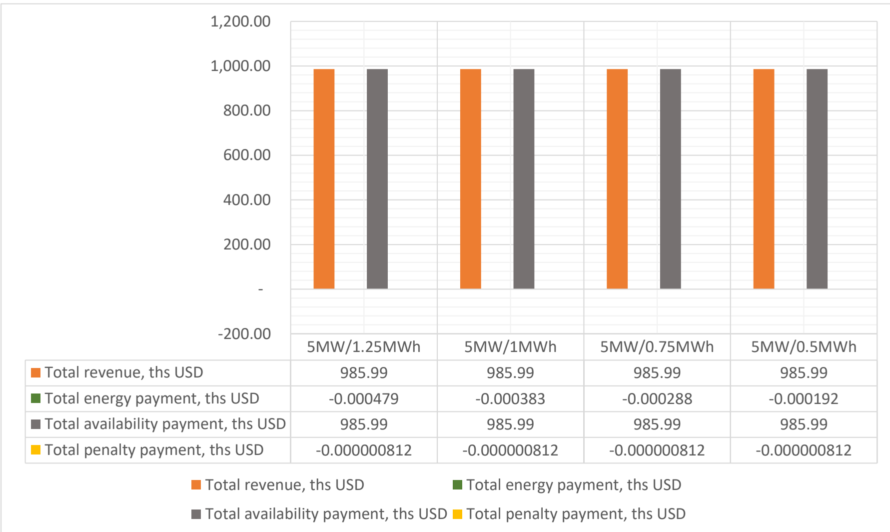


Figure 5.23: Revenue streams of FESS in FFR market, ths USD.

Source: Self-made

FESS had positive NPV only for two E:P ratios (0.15 and 0.1) with o.15 (1MW/0.75MWh) representing the highest positive NPV. However, this NPV is rather hypothetical and artificially inflated by availability payment.

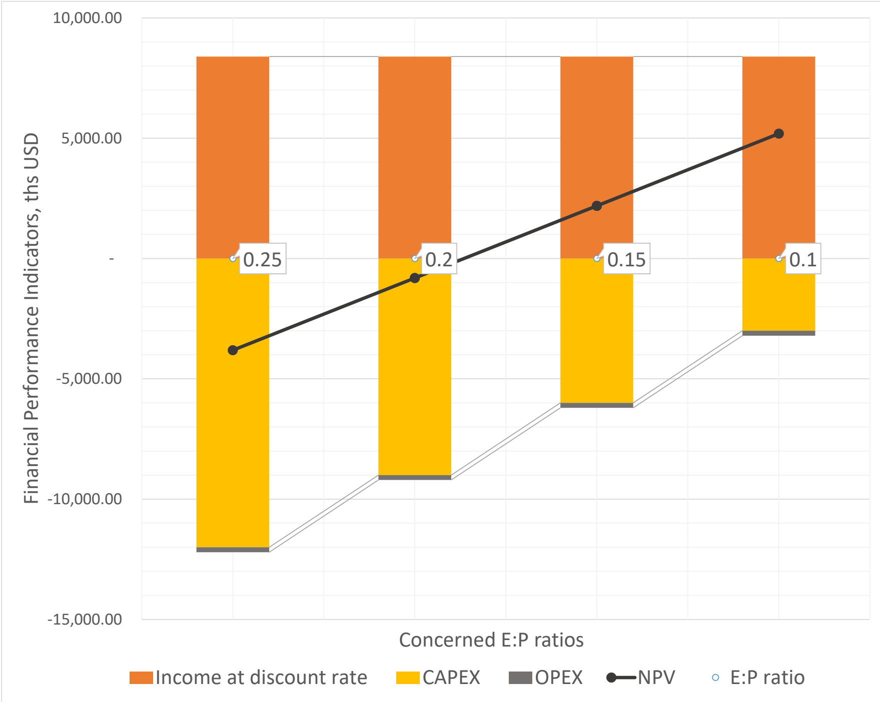


Figure 5.24: NPV of FESS in FFR market, ths USD.

Source: Self-made

In reality, bidding to FFR with a full power capacity of 5MW will inherently mislead the market as FESS grid exchange will be limited to its maximum energy capacity which in the best case is 4 times lower than FESS' power capacity. This can be overcome potentially by installing larger power capacities of FESS and only bidding a fourth of them to match the energy content. The simulations were repeated for the proposed strategy, i.e. 5 MW out of installed 20 MW were nominated in the market with an energy capacity of 5MWh which corresponds to E:P of 4. CAPEX was calculated for 20 MW/5 MWh whereas revenue and grid exchange figures were obtained from simulating 5MW/5MWh FESS meaning that committed power matches its maximum energy content. Results are summarized in Table 5.6 and provide negative NPV due to revenue from FFR not being able to offset capital costs of 20 MW FESS. Therefore, with the current FFR market rules in the Nordic market, FESS cannot provide a positive business case and will be discarded from the value-stacking analysis.

Table 5.6: Financial indicators of the proposed strategy to bid 5 MW/ 5 MWh FESS out of installed 20 MW/ 5 MWh for participating in FFR Profile.

Bidding 5 MW/ 5 MWh FESS out of installed 20 MW/ 5 MWh in FFR market	
Financial Indicator	**Value**
Total annual revenue, ths USD	985.99
Total annual energy payment, ths USD	-0.000096
Total annual availability payment, ths USD	985.99
Total annual penalty payment, ths USD	-2.5592E-06
Project CAPEX, ths USD	48,000.00
Total O&M costs at the end of a lifetime, ths USD	817.3
Income at discount rate at the end of a lifetime, ths USD	8,394.31
NPV, ths USD	**-40,422.99**

5.3.3 Value of FESS in the Nordic markets

The value of FESS in the Nordic markets was evaluated for

A. Frequency ancillary markets:

- FCR-N;
- FFR

The detailed discussions on each case are available in sections 5.3.1 to 5.3.2. The energy arbitrage in a DA market was discarded from the analysis due to inherent substantial energy capacity constraints as explained in the introductory part of Chapter 5.3.

Analysis of FESS participation in FFR has demonstrated that with the current Nordic market rules and price patterns given the low E:P ratio of FESS, it is not possible to obtain positive NPV under any scenario.

Therefore the value of FESS will be only quantified for the FCR-N market. The value of FESS (USD/kW/year) is calculated as a ratio between the total generated revenue $Profit$ that corresponds to the highest NPV (ths USD) and installed capacity $p_{installed}$ (MW). Based on the obtained size recommendations the FESS size of 5MW/ 1 MWh will be used for value analysis. Value (USD) and NPV (USD) of 1kW BESS are provided in Fig.5.25. The value of FESS is estimated to be 599.5 USD/kW per year with an NPV of 2,897.74 USD/KW at the end of a lifetime in the FCR-N market.

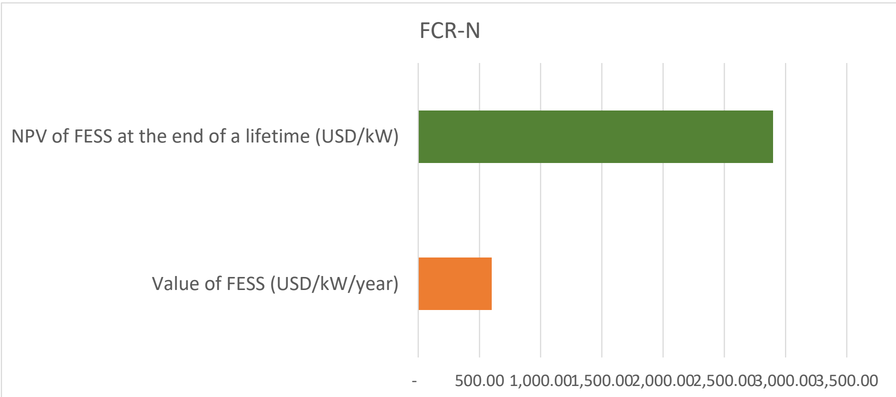


Figure 5.25: The value (USD/kW/year) and NPV (USD/kW at the end of its lifetime) of FESS in FCR-N market.

Source: Self-made

5.3.4 Case 2: FESS Technology - Conclusions

The following conclusions were drawn from the FESS in Nordic markets analysis:

1. Only the FCR-N market has the potential of providing a positive business case for FESS technology and as such it was not possible to perform value stacking of multiple services;
2. The recommended FESS E:P ratio for FCR-N is 0.2 out of the maximum possible ratio of 0.25. Given the maximum allowed single bid size of 5MW in the FCR-N market, the FESS of 5MW/ 1 MWh is recommended for participation in FCR-N;
3. The highest revenue contributor in the FCR-N market is availability payment AP which FESS receives for the accepted committed capacity in Nordic currency/MW;

4. FFR requires 100% FFR committed capacity activation when the frequency is at its threshold, and therefore FESS is inherently bound to be penalized as maximum power output will be less than installed power capacity due to energy constraints associated with low E:P. An alternative strategy can be adapted when only a fourth of the installed capacity is nominated at the FFR market to match energy and power capacity limits but as an analysis in section 5.3.1 demonstrates with the current rules and prices in the Nordic FFR market, revenue failed to offset high FESS' CAPEX costs, and negative NPV is yielded for the alternative strategy;

5. The value of FESS that can be potentially obtained from the FCR-N market, is evaluated to be 599.5 USD/kW per year based on the revenue from 5MW/1MWh FESS with NPV totaling at 2,897.74 at the end of a FESS lifetime (20 years);

5.4 Case 3: D-CAES Technology - results interpretation

Case 3 is concerned with CAES technology. The minimum mFRR market size of 5 MW was used for the power capacity with E:P ratios of 4, 5, 7, 10, 15, 18, and 20. Participation of the CAES is evaluated in Nordic manual frequency ancillary markets such as mFRR, energy market such as Elspot, and their combinations. Technical and financial metrics of the CAES performance adopted for the analysis are explained in section 5.1. The analytical formulation and requirements of the above markets are detailed in sections 4.4 and 4.8. Input data utilized in simulations is provided in section 4.3.

5.4.1 CAES participation in the Nordic mFRR

The mFRR reserve that is used to maintain the balance in the Nordic power system until the new equilibrium point is reached, releases FCR-N and aFRR. Similar two FCR-N and FFR, mFRR market has two components: capacity market and energy activation market. Availability payment is paid in the capacity market regardless of mFRR activation. Energy exchange is based on the orders from the Nordic TSO. Due to the specification related to a response time (in minutes) and requirements for substantial bidding volumes (between 5 to 50 MW), CAES is a good fit for the mFRR market.

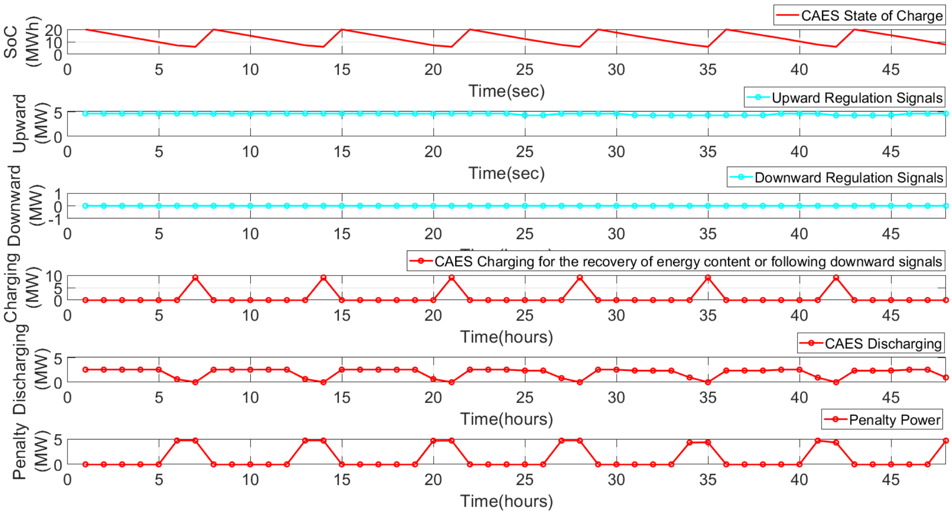
mFRR is a symmetrical service implying that TSOs can procure up- and down-ward regulation. However, the analysis of the historical data from the past years revealed that most Nordic TSOs (including Energinet from the study case) procured only up-ward regulation (grid discharge) forcing the need for mFRR balance providers to come up with a strategy to replenish energy content of the storage. The strategy of CAES charging from the grid and compensating at up-ward regulation prices was adopted to avoid or minimize breaching of CAES obligations in the provision of committed mFRR capacities.

Simulation of mFRR was conducted for the complete year on an hourly basis.

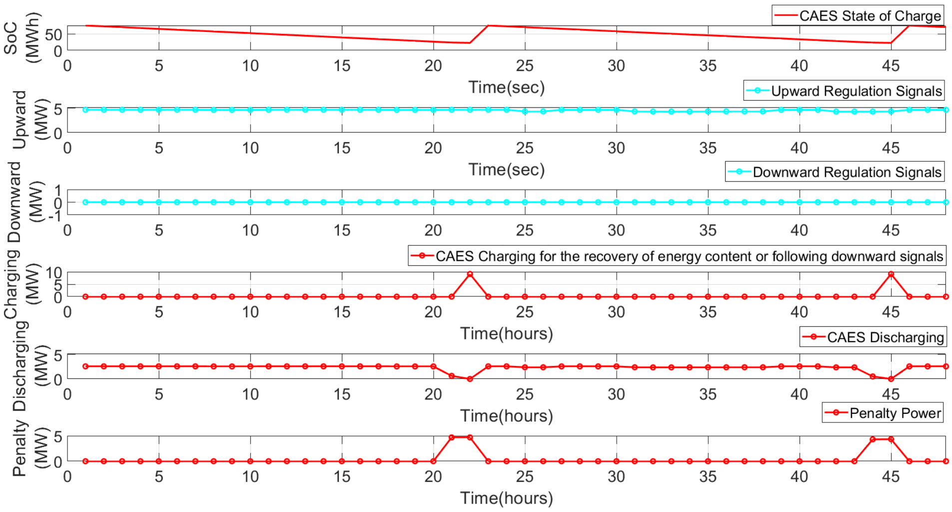
CAES operation in mFRR market is demonstrated through plotting its SoC, signals from TSO, cycles, and penalty power for the first 48 hours of the year for two sizes: 5MW/20MWh and 5MW/75 MWh. CAES starts operation at 100% of its energy capacity due to signals from the TSO having only up-ward nature (please refer to Fig.5.26).

Up-ward and down-ward signals from the TSO are shown on the 2-nd and 3-rd sub-plots of Fig.5.26 respectively (blue dotted lines). It is evident that there is a continuous request for discharge power while no (0) signals for downward (charge) regulation are observed. CAES discharge power is adjusted by its maximum discharge capacity and efficiency. 30% of DoD is kept based on the thermodynamic requirements in the system that were discussed in section 2.1.2. Depending on the energy capacity CAES is penalized after several discharge cycles when its SoC reaches minimum DoD (the 6-th red dotted line in Fig.5.26). From Fig.5.26a and Fig.5.26b it can be noticed that within plotted 50 hours, 75MWh capacity allows to reduce the penalty power by 3.5 times along with reduction of grid charging (the 3-rd red dotted line) and as such increase the total revenue. However, given the significant CAES project cost that is inter alia affected by the energy capacity component, the decision on the optimal E:P ratio should be made based on joint revenue and NPV analysis. NPV for CAES is calculated for 30 years and is cycles independent.

All equations used in the mFRR simulations are detailed in section 4.8. In mFRR market (please refer to Fig.5.27), the energy payment EP_{mFRR} is the main source of revenue, making up from 65% to 85% of the total revenue. Energy payment also considers costs incurred due to the CAES grid charging. It is possible to achieve a penalty payment reduction from 12% to 1.3% of the total revenue by increasing energy capacity from 20 MWh to 100 MWh. However, the cash outflow due to CAES increased CAPEX and OPEX costs impacts NPV growth trend, and E:P greater than 15 (5MW/ 75MWh) are exhibiting a declining trend (for example E:P 18 is smaller than E:P 15, and E:P 20 is smaller than E:P 18). Details can be seen in Fig.5.28.

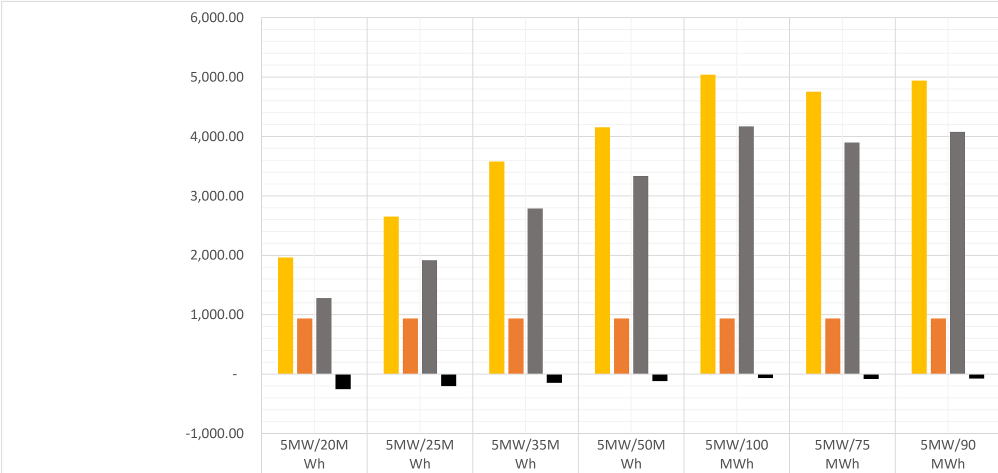


(a) 5MW/20MWh CAES



(b) 5MW/75MWh CAES

Figure 5.26: CAES operation in mFRR market.



	5MW/20MWh	5MW/25MWh	5MW/35MWh	5MW/50MWh	5MW/100MWh	5MW/75MWh	5MW/90MWh
Total revenue, ths USD	1,961.80	2,650.45	3,578.94	4,153.45	5,040.80	4,753.63	4,939.10
Total availability payment, ths USD	937.37	937.37	937.37	937.37	937.37	937.37	937.37
Total energy payment, ths USD	1,279.33	1,916.09	2,788.22	3,333.89	4,170.73	3,897.85	4,076.78
Total penalty payment, ths USD	-254.90	-203.00	-146.65	-117.80	-67.30	-81.59	-75.05

Figure 5.27: Comparison of annual revenue streams of CAES in mFRR market, ths USD.

Source: Self-made

Based on the analysis above the E:P of 15 is recommended as the optimal size of 5MW/75MWh capacity is used for the value assessment of CAES in the mFRR market that will be detailed in section 5.4.4.

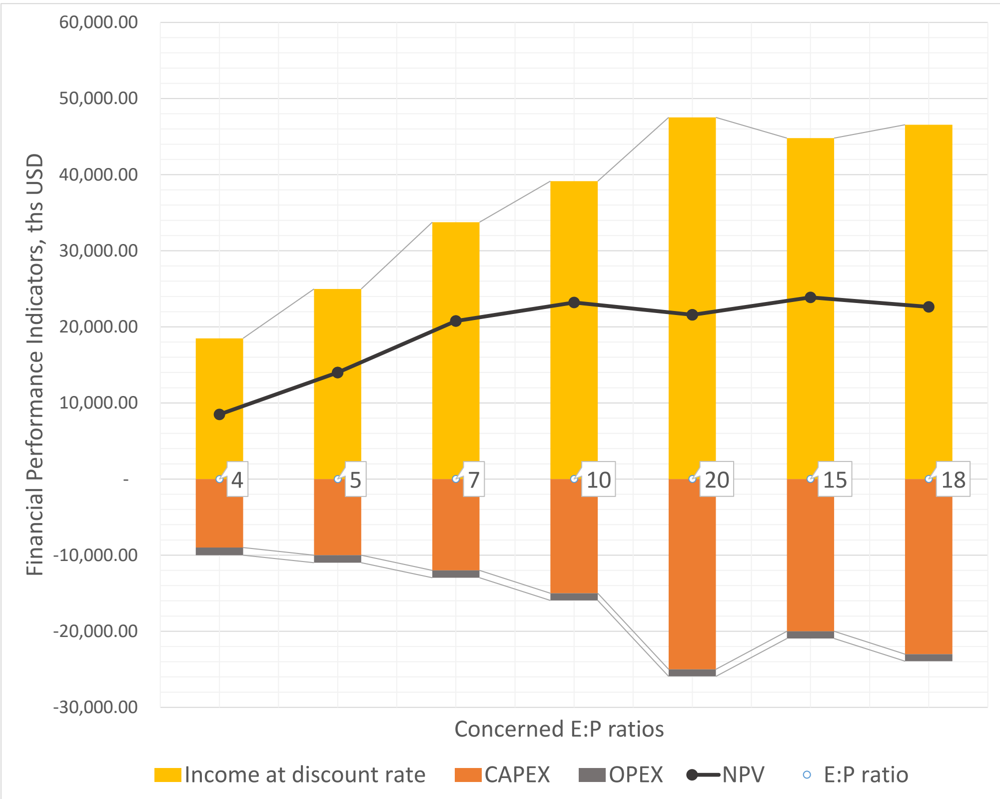


Figure 5.28: Comparison of NPV at the end of a lifetime of CAES in mFRR market, ths USD.

Source: Self-made

5.4.2 CAES participation in the Nordic Elspot

The behaviour of Elspot energy arbitrage market was discussed in great detail in sections 4.4 and 5.2.2. CAES sizes from the previous section 5.2.1 were tested in the Elspot market.

Cycles of 5MW/25MWh CAES participating in a DA Elspot are provided in Fig.5.29. Negative values represent charging (buying from the grid) and positive - discharging (selling to the grid) accordingly.

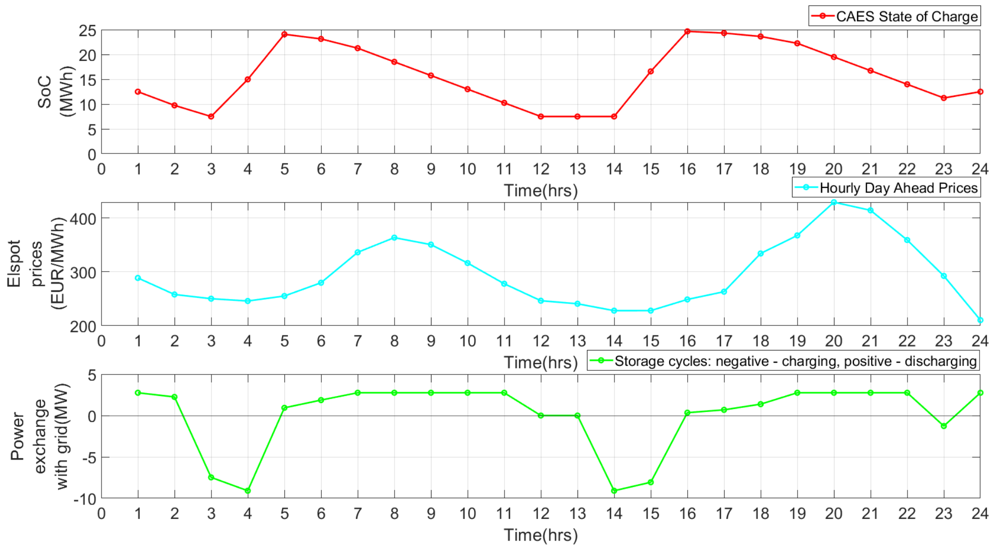


Figure 5.29: CAES participation in Elspot market by exercising energy arbitrage.

Source: Self-made

The revenue from participating in a DA market is lower compared to mFRR, and therefore E:P greater than 7 demonstrated negative NPV despite the positive correlation between the revenue and E:P increase as it is seen in Fig.5.30 and Fig.5.31.

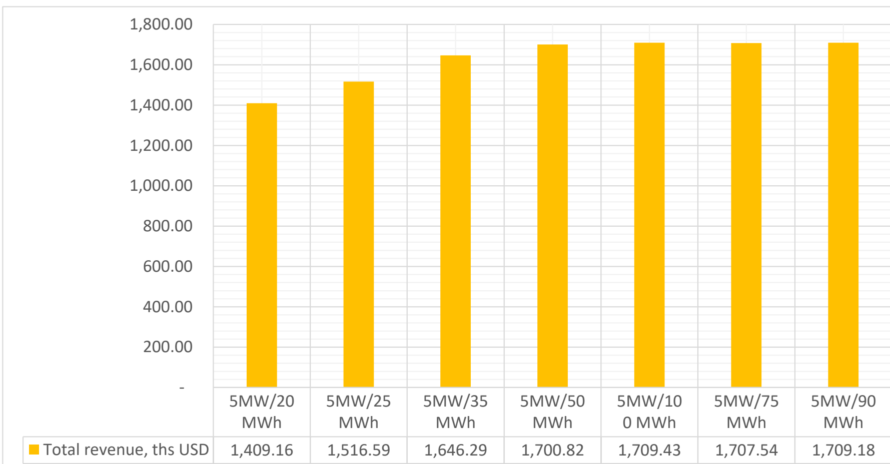


Figure 5.30: Comparison of annual revenues of CAES in Elspot market, ths USD.

Source: Self-made

Based on the analysis summarized in Fig.5.30 and Fig.5.31, the E:P ratio of 5 is recommended for CAES participating in Elspot's energy arbitrage and the optimal size of 5MW/25MWh capacity is used for the value assessment of CAES in a DA market that will be detailed in section 5.4.4.

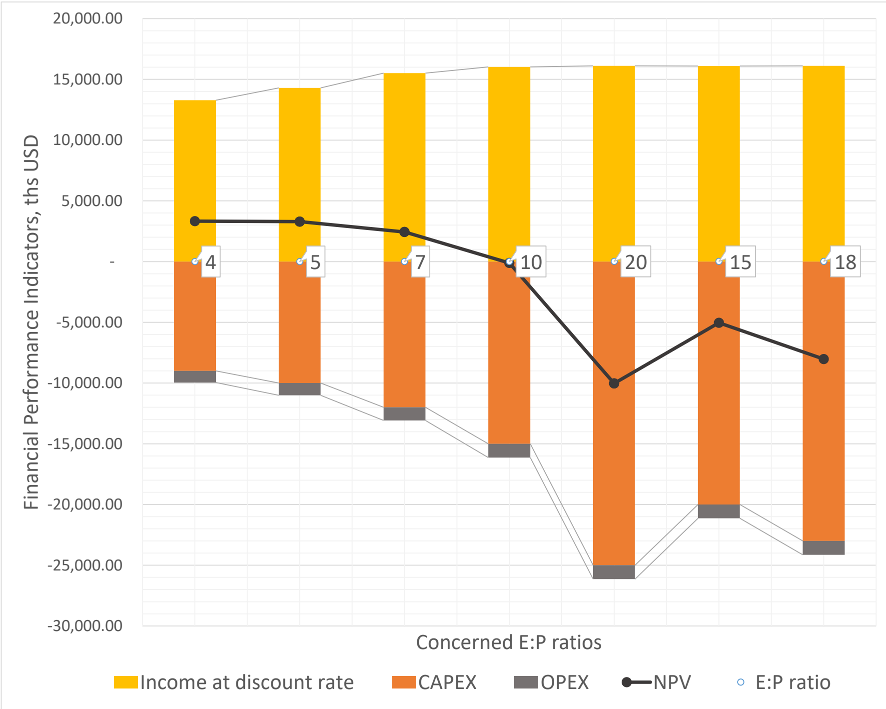


Figure 5.31: Comparison of NPV at the end of a lifetime of CAES in Elspot market, ths USD.

Source: Self-made

5.4.3 Value stacking from CAES' participation in multiple Nordic markets

Value stacking of CAES will be analyzed in the context of combining mFRR and DA energy arbitrage service.

Unlike, FCR-N and FFR, participation of a balance provider in mFRR's energy activation market does not require a presence in the capacity market. It only requires the ability to receive online orders through electronic messages from the TSO and activate available capacities. That implies that CAES participating in mFRR EAM does not receive any availability payment but also will not be penalized for non-availability, and therefore can plan its operation in multiple markets with the purpose of maximizing profit. The revenue will be generated from buying and selling in both Elspot and mFRR markets. The concurrent operation of CAES in multiple markets is shown in Fig. 5.32.

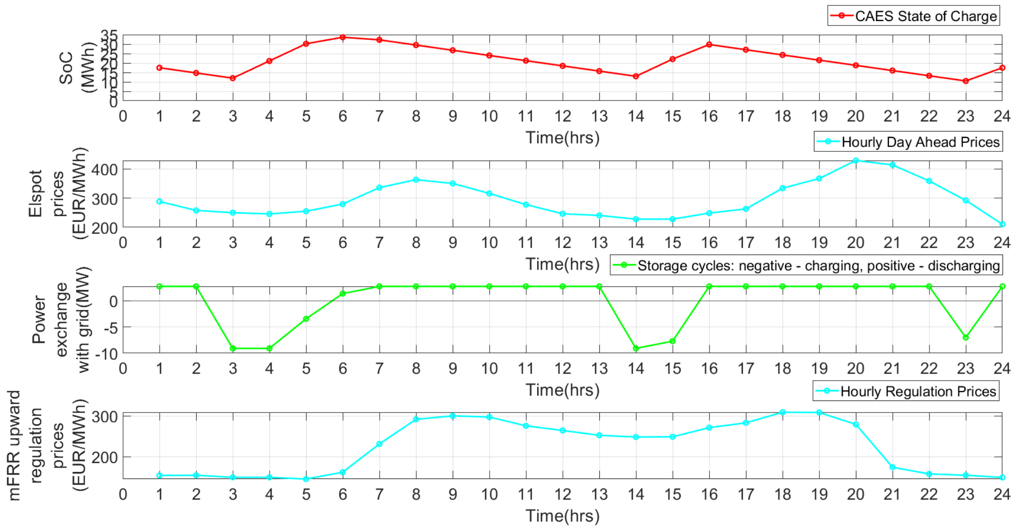


Figure 5.32: CAES participation in Elspot market by exercising energy arbitrage and mFRR market concurrently.

Source: Self-made

SoC is maintained between 30% and 100% (1-st sub-plot). CAES starts and finishes the day with forced 50% SoC which is the strategy adopted for all DA simulations to allow grid energy exchange flexibility in both directions. 2-nd and 4-th sub-plots in Fig. 5.32 represent hourly price violations in Elspot and up-ward regulation markets. By switching energy exchange (3-rd sub-plot) between these two markets CAES generates higher revenue and NPV compared to participation in a DA only.

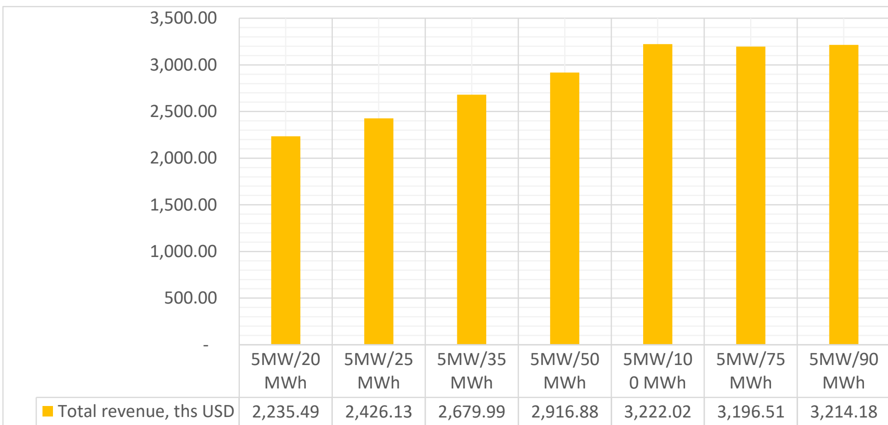


Figure 5.33: Comparison of annual revenues of CAES in combined Elspot and mFRR EA market, ths USD.

Source: Self-made

After combining the DA energy arbitrage with mFRR, the optimal E:P ratio was shifted from 5 to 7 with 5MW/35 MWh representing the most profitable case based on the NPV values. Even though both energy arbitrage and mFRR are energy content-intensive services, mFRR has the higher E:P ratio requirements. This will be further discussed in section 5.4.4. Values from revenue and NPV analysis for combined market participation of CAES can be seen in Fig.5.33 and Fig.5.34 respectively.

Figure 5.34: Comparison of NPV at the end of a lifetime of CAES in combined Elspot and mFRR EA markets, ths USD.

Source: Self-made

5.4.4 Value of CAES participation in the Nordic markets

The value of CAES in the Nordic markets was evaluated for

A. Manual frequency ancillary market:

- mFRR;

B. Energy markets:

- Energy arbitrage in a Day-Ahead Elspot market;

C. And their combination for value stacking:

- mFRR EAM + Day-Ahead (concurrently)

The detailed discussions on each case are available through sections 5.4.1 to 5.4.3.

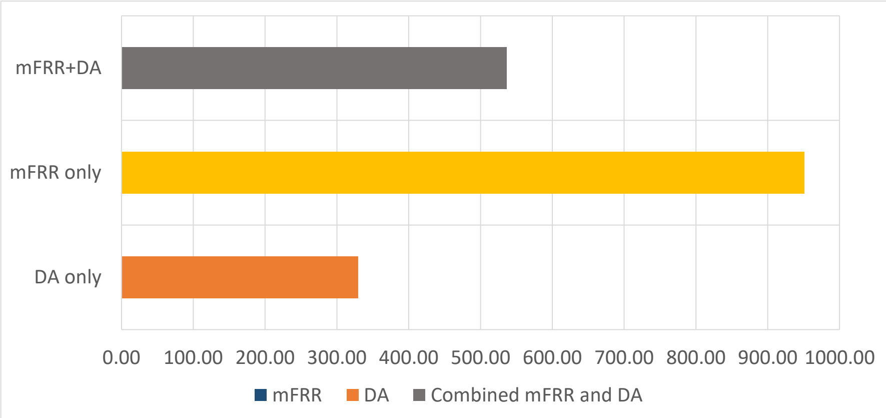


Figure 5.35: Value of CAES (USD/kW/year) in the Nordic markets.

Source: Self-made

The value of CAES (USD/kW/year) is calculated as a ratio between the total generated revenue $Profit$ that corresponds to the highest NPV (ths USD) and installed capacity $p_{installed}$ (MW). Based on the obtained size recommendations, for the cases that cover mFRR only the E:P ratio of the CAES used in the value analysis, is 15. For energy arbitrage, the value of CAES is calculated for an E:P ratio of 5. For the case of value stacking between mFRR EAM and Elspot, the recommended E:P of 7 is used. The same approach was applied for NPV (USD/KW) calculations. Value (USD) and NPV (USD) of 1kW CAES is provided in Fig.5.35 and in Fig.5.36 accordingly.

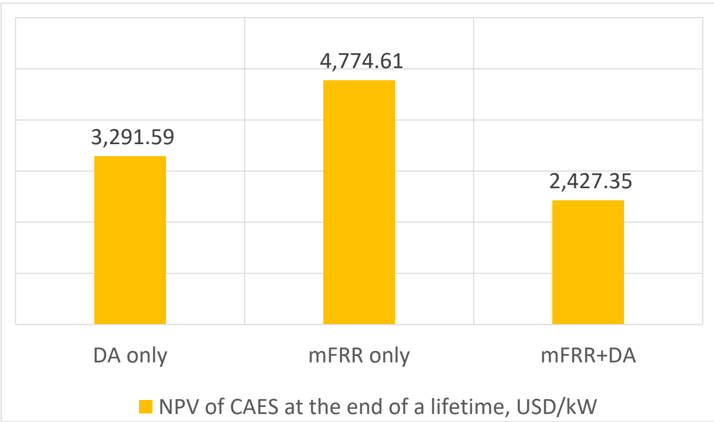


Figure 5.36: NPV of CAES (USD/kW) in the Nordic market at the end of its lifetime.

Source: Self-made

5.4.5 Case 3: D-CAES Technology - Conclusions

The following conclusions were drawn from the CAES in Nordic markets analysis:

1. All selected markets have the potential of providing a positive business case for CAES technology.
2. Nordic requirements for manual frequency ancillary market make it possible for balance providers to participate only in the energy activation market and as such value stacking can be realized during the same bidding time windows.
3. The recommended E:P ratio for the manual frequency market is 15. Given the minimum allowed single bid capacity of 5MW in mFRR, the CAES size of 5MW/ 75 MWh is recom-

mended for participation in mFRR services. The larger CAES power capacities were not tested within this thesis. It is because the grid was assumed to be non-congested in the analysis, and increasing the power capacities of CAES further could potentially cause a highly hypothetical estimation of CAES value without analyzing the grid transfer capacity.

4. The recommended E:P ratio for the energy market (energy arbitrage) is 5. There are no capacity limitations specified for that in the market rules. The analysis demonstrates that it is possible to yield a revenue of above 300 USD per kW per year of installed CAES capacity in the Elspot market. The revenue is a result of benefiting from the daily price volatility in a Day-Ahead market (EUR/MWh). Daily there are on average 4 price zones, however, this is not a concern for a CAES as its lifetime has no dependency on cycling.

5. The highest revenue contributor in mFRR market is energy payment EP which CAES receives for the activated capacity in EUR/MWh;

6. mFRR is procured throughout the year. It is stated to be a symmetrical service. However, historical data indicates that Nordic TSOs mostly procure up-ward regulation. Therefore CAES operator should adopt a certain strategy for recharging CAES. In the thesis, this was done by recharging the CAES from the grid and compensating at up-ward energy regulation prices.

7. The highest value of CAES can be obtained from mFRR service when CAES is bidding into both capacity and energy markets, and evaluated to be 950.73 USD/kW per year based on the revenue from 5MW/75MWh CAES with NPV totaling at 4,774.61 USD/ kW at the end of a CAES lifetime (30 years).

8. If the CAES operator for some reason wants to bid in a DA market for engaging in energy arbitrage, then combining it with mFRR EAM (estimated value is 536 USD/kW/year) can allow for increasing the total revenue. This is because CAES would have a wider selection of prices to choose from and can optimize its operation accordingly.

9. Participation of CAES in a DA only provides almost four times less of mFRR generated NPV.

10. Even though both energy arbitrage and mFRR are energy-demanding services, mFRR requires higher energy content availability (as demonstrated up to 15 hours) due to the continuous requirement for unidirectional regulation.

5.5 Cross-comparison of cases

The conclusions and values provided in sections 5.2.5, 5.3.3 and 5.4.4 are further summarized in this section for the purpose of comparing studied technologies and studied markets in order to answer the main research question of this thesis which is whether or not there is a value and niche for storage technologies in Nordic PS.

A self-explanatory matrix of financial indicators of BESS, FESS, and CAES in the analyzed markets is provided in Table 5.7. Positive revenues and NPVs are highlighted in dark green, and negative in red accordingly. Discarded cases of value stacking correspond to the scenarios when a negative performance of a storage technology was obtained in an individual market which removed the necessity to further combine markets/ services such as in FESS sub-cases. CAES was not tested in FFR due to its slow response time (in minutes vs required seconds) as explained in Chapter 4.1. Because CAES represents the long-duration storage possibility, it was evaluated for services that require higher energy capacities such as energy arbitrage and manual frequency restoration (mFRR). Battery's properties of fast response and medium storage duration allowed its valuation for multiple markets.

Table 5.7: Matrix of financial indicators of studied markets and technologies.

Indicator	Value (USD/kW/year)			NPV at the end of a lifetime (USD/kW)		
Technology / Market	BESS	FESS	CAES	BESS	FESS	CAES
FCR-N	608.98	599.50	not tested	3,247.73	2,897.74	not tested
FFR	197.20	negative, non feasible	not tested	854.57	negative, non feasible	not tested
DA	335.47	negative, non feasible	329.26	1,110.56	negative, non feasible	658.32
DA+ FCR-N	537.73	discarded	not tested	2,867.16	discarded	not tested
DA+FFR	249.88	discarded	not tested	1,212.06	discarded	not tested
FCR-N+FFR	399.13	discarded	not tested	2,067.48	discarded	not tested
mFRR	not tested	not tested	950.73	not tested	not tested	4,774.61
mFRR+DA	not tested	not tested	536.00	not tested	not tested	2,427.35

The valuation results of storage technologies and markets are given in Fig.5.37 and Fig.5.38.

Batteries can fit into the widest range of Nordic markets, and all obtained revenue/NPV of the BESS were positive. The dependency of their lifetime on the number of full cycles does not represent a barrier in the studied markets. Cyclic services such as FFR do not exhaust the cycle resource of the battery as the frequency drops to 49.7 Hz or below occur rarely (58 seconds in total for the studied year). Increasing the energy capacity of the battery also allows it to participate in energy arbitrage with 2-3 cycles per day. FCR-N requires continuous energy activation but the magnitude of frequency change is low and therefore storage operation is more smooth in terms of the SoC change over an operational period. FESS can only provide a positive business case in the FCR-N market. This is due to its low energy capacity which is 4 times less than its power capacity. FESS and BESS have shown almost equal revenue in the FCR-N market with 608.98 USD/kW/year and 599.5 USD/kW/year for BESS and FESS respectively. BESS NPV is 11% higher than FESS NPV in FCR-N. This is primarily because of higher CAPEX costs of FESS technology (please refer to Table 4.7 for per kW/kWh cost data used in simulations).

The value of energy arbitrage in a DA market is 335.47 USD/kW/year for BESS and 329.26 USD/kW/year. NPV, however, is greater for BESS which is due to substantially higher CAPEX and OPEX costs and lower efficiency of CAES technology despite its long operational lifetime (30 years for CAES vs 12 years for BESS).

CAES participating in mFRR services and bidding in both capacity and energy markets provide the highest revenue and NPV due to accessing both availability and energy payments.

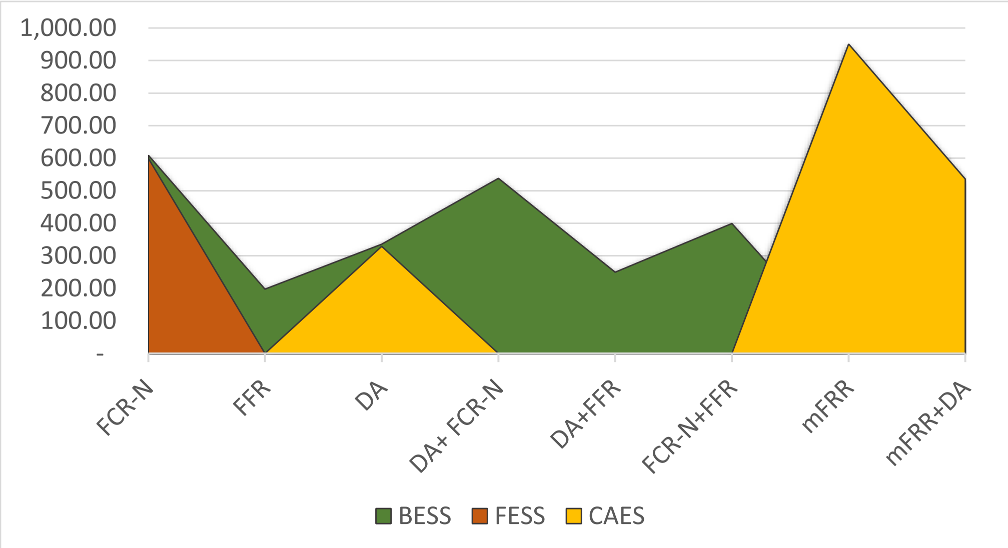


Figure 5.37: Value of evaluated storage technologies in Nordic markets, USD/kW/year.

Source: Self-made

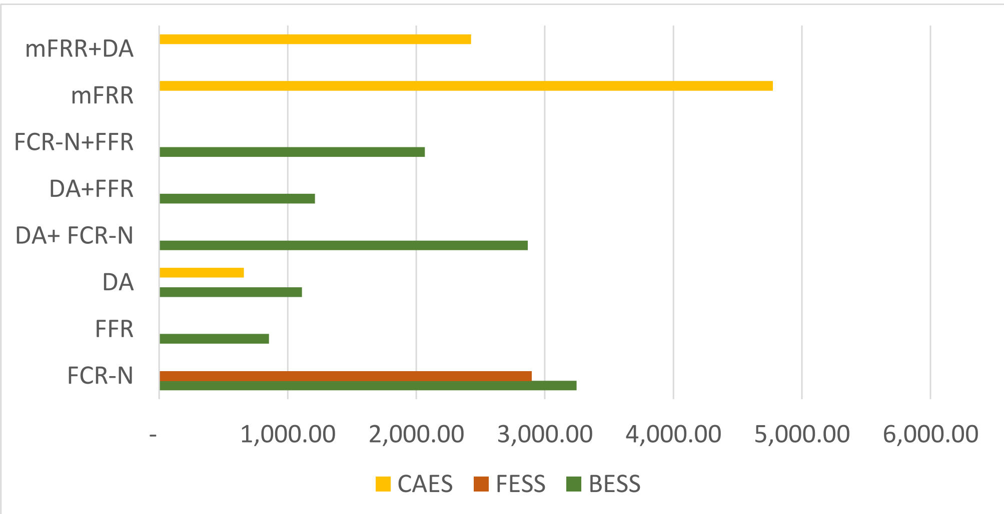


Figure 5.38: NPV at the end of a lifetime of evaluated storage technologies in Nordic markets, USD/kW.

Source: Self-made

Provision of FFR service only requires up-ward regulation, therefore strategies should be adopted to restore the energy content of storage. In the thesis, this was realized by recharging from the grid and compensating at up-ward regulation prices. That has caused negative energy payment in most studied scenarios. mFRR is a hypothetically symmetrical market and Nordic TSO retains the right to procure and active both up-and down-regulation. However, in practice the past years had only upward bids for the studied bidding zone (DK2), and therefore similarly to FFR service, recharging from the grid was done. However, the energy payment component of total revenue for mFRR was still positive and is the highest contributor to mFRR revenue. This is due to the large amounts of procured energy for tertiary manual regulation.

Table 5.8: Recommended storage sizes for the studied markets.

Category	**Recommended size**		
Technology / Service	BESS	FESS	CAES
FCR-N	5 MW/5 MWh	5MW/ 1MWh	not tested
FFR	5MW/5MWh	negative NPV, not feasible	not tested
Energy arbitrage in Elspot (DA)	1MW/ 4 MWh	negative NPV, not feasible	5MW/ 25 MWh
mFRR	not tested	not tested	5MW/ 75 MWh

Recommended sizes are provided in the Table 5.8.

Obtained conclusions will be further validated in section 5.6.

5.6 Results validation

This section has the goal to validate the developed models and to assess whether they accurately represent the real-world storage systems and Nordic market rules as they are intended to represent. It also aims to ensure that obtained conclusions are relevant and reasonable. Validation of the conclusions will involve comparing the findings of the thesis with existing knowledge and established results to determine if the presented conclusions are aligned or supported by the available body of literature.

As such, validation of the results consists of two parts:

- Validation of the developed Matlab models;
- Validation of thesis conclusions and findings

Part 1. Validation of the developed Matlab models

Developed mathematical models were explained in Chapter 4.

It was important to simulate the real behaviour of the selected storage systems by introducing such operational constraints as SoC, DoD, RT efficiency, self-discharge losses, and maximum and minimum charging/ discharging capacity limits.

Another critical aspect was to ensure that market rules analyzed in the thesis are properly reflected and storage is responding in a way it should while the models are providing the results on total power/energy exchange, storage energy content, incurred penalties, and quantifying revenues.

The operations of selected storage systems in the studied markets are given in:

- Fig. 5.2, Fig. 5.3, Fig. 5.6, Fig. 5.10, Fig. 5.11 for the BESS in FCR-N, Elspot and FFR markets respectively;
- Fig. 5.17, Fig. 5.18, Fig. 5.21, Fig. 5.22 for the FESS in FCR-N and FFR markets respectively;
- Fig. 5.26, Fig. 5.29, Fig. 5.32 for the CAES in mFRR, Elspot markets, and their combination respectively.

Readers are referred to sections 5.2.1, 5.2.2, 5.2.3, 5.3.1, 5.3.2, 5.4.1, 5.4.2, 5.4.3 where detailed explanations of simulation figures are provided in the same place where the plots themselves appear.

It is evident that:

- Soc of the BESS, CAES, and FESS is maintained between 20% -100%, 30% - 100%, 0%-100% accordingly;
- The power charge and discharge follow the maximum and minimum power thresholds and are adjusted by the technology's roundtrip and self-discharge losses;
- Response to the frequency fluctuations as specified in the FCR-N, FFR specifications is achieved;
- Response to the dispatcher's signals for mFRR is achieved;
- Response to the price fluctuations in Elspot market is achieved;
- Penalty assigning for breaching committed powers is achieved;
- SoC restoration services for FFR and mFRR and compensation to the grid for the same is achieved;
- Revenue streams calculation is achieved

Above proves that the target behaviour was achieved from all storage systems and markets, and formulated algorithms with specified constraints were implemented as desired.

Part 2. Validation of thesis conclusions

The thesis' major conclusions and findings consist of:

1. Recommendations on the sizes;
2. Results from the evaluation of markets relevance for storage deployment;
3. Results on the revenue streams and yielded NPV values

Conclusions on studied markets and storage technologies are provided in sections 5.2.5, 5.3.3, 5.4.4, and 5.5. A summary of the recommended storage sizes across studied markets is provided in Table 5.8.

The analysis conducted by the authors in [19], which is based on real-life battery projects, provides support for the thesis conclusions regarding the appropriate storage size for the respective markets. For automatic frequency regulation, the paper highlights that the observed E:P ratio of 1:1 for projects with capacities 1 MW and above are used. For energy arbitrage, the higher E:P ratio of up to 4:1 is pointed out which is explained by the daily load profile variations and the specific time windows when the system demands this service. These findings validate the alignment between the thesis conclusions and the E:P ratio considerations for storage size in the relevant markets. According to [130] recommended power size of energy storage for electric energy time shift/ energy arbitrage application is in the range of 1-500 MW with the storage duration between 1-5 hours. Power capacity and storage duration are in the same range as those proposed in the thesis. Flywheel sizing was studied in [131] where authors searched the optimal sizing scheme for the capacities of FESS and conventional generators. The paper concluded that with the optimal objective of combined technical and economical benefits, the FESS of 10 MW/ 2.505 MWh provides the highest benefit when deployed for frequency control. The proposed size combination corresponds to 0.2505 hours of FESS storage. In the case analyzed within the Master's thesis, automatic frequency markets have a bid size limit of 5 MW. The thesis suggests the FESS optimal size for FCR-N of 5MW/1 MWh or E:P equal to 0.2 which is close to the paper's conclusions. There is no specific paper found on the recommended sizes for mFRR market. European Association for Storage of

Energy recommends the storage duration for mFFR to be as long as required [132]. Report on CAES costs from Electric Power Research Institute(EPRI) [115] suggests that underground air CAES plant has attractive costs if uses a storage duration of about 10 hours and above. The duration of CAES proposed as a result of the thesis findings is 15 hours for mFRR which is aligned with EPRI general recommendations.

From the available literature review, it was found that analysis of the operation of storage in Nordic markets was mostly limited to FCR and FFR services, and BESS technology. According to [133], delivering the different FCRs was concluded as the most profitable application of a BESS in the Nordic market. This matches the thesis conclusion for the BESS' frequency market performance where FCR-N has demonstrated to generate the highest NPV and revenue (Fig. 5.38). Authors in [63] compare participation of battery storage in FCR and FFR. The study demonstrates that the FCR-N energy payments of 1MW/ 1 MWh BESS for the years 2015-2020 comprise only up to 8.8% of the availability payment. The master's thesis conclusion suggests the same and availability payment in automatic frequency markets is the main revenue contributor. The paper also concludes that bidding only in the FFR market generates three times less revenue in comparison to the FCR-N market, and value stacking with FCR-N or FCR-N + FCR-D should be considered. This is in line with the thesis findings on the revenue streams on different markets (Table 5.7 when FCR-N yielded 608.98 USD/kW/year for the BESS in contrast to 197.2 USD/kW/year provided by FFR). The constraints of frequency markets related to restoring the energy content of storage are highlighted in [134]. The authors acknowledge the necessity for storage to restore its state of charge from the grid on the example of BESS in the Finish market. Thesis simulations demonstrate that FFR and mFRR market requires power from the grid, and the SoC recovery from the grid when grid frequency is within its dead band while paying energy compensation to the grid, was adopted in the thesis.

The value of electricity storage in Denmark's frequency and energy markets was assessed in [99] per request of Energinet's subsidiary (Elsystemansvar). Revenue estimates are provided for a 1 MW/7.5 MWh battery. Availability payment according to the report equals 2.0 mln DKK per year with energy payment making up 0.14 mln DKK for FCR-N (up and down combined in DK2). If converted to USD this is equal to around 290 ths USD/year and 20 ths USD/year for the availability and energy components accordingly. According to the thesis results, a BESS of 1 MW/7.5 MWh can generate 596.47 ths USD for availability payment and 56.81 ths USD/year for energy payment. It can be noted that figures from the thesis are on the higher side. The reason for thesis estimations being greater than those of Energinet might lie in the difference in simulated data year. While [99] uses data from 2019, thesis analysis is based on 2022 data which as discussed in section 4.3 is reflective of upcoming years' market price levels. Nevertheless, revenue figures are of the same order of magnitude. As mentioned earlier no relevant recent literature was found on the potential of mFRR for deploying energy storage. Additionally, the discussions of the value of FESS and CAES in the reviewed literature body are disproportionately small compared to BESS technology. In [135] authors investigate the impacts of various control strategies of FESS response to the frequency drops below 49.9 Hz in the Great Britain system. Depending on the studied control strategy, the FESS NPVs were concentrated in the region of a £1,000-£2,500/kW. Masters thesis concludes that FESS can provide NPV of 2,897.74 USD/kW in the Nordic FFR market which is ca. 2,309.04£/KW and as such falls exactly into the range of [135] findings. The economic value of CAES is mostly studied in the US or Canadian context. The conclusions from the US Canada markets do not necessarily relevant for the Nordic conditions, however, the financial gains of CAES will be highlighted in this section for the sake of comparison of the relevance obtained from CAES profit magnitudes to literature estimates. In [136] Alberta market is chosen as an electricity market and CAES of 135 MW is studied. The CAES annual profit is in the range of 15 mln to 30 mln USD per year depending on the fuel price. The thesis concluded that in the Elspot market, 5 MW/ 100 MWh exercising energy arbitrage is evaluated to generate 3.2 mln USD annually.

The analysis above suggests that the findings of the Master's thesis are relevant and valid. Discussions on the mutual market and storage suitability in the thesis are aligned with those highlighted in the reviewed literature. Proposed sizes, obtained revenues and NPV are in the same range or magnitude order given the same or similar investigated market conditions.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The main research question of this Master's thesis was to determine the value and niche for storage technologies at the utility-scale in supporting the Nordic PS amidst the increasing penetration of Wind Farms. The thesis focus was on BESS, FESS, and CAES storage technologies. Frequency ancillary services in Nordic markets such as FCR-N, FFR, and mFRR along with energy arbitrage in Elspot were assessed. Simulation results are presented for 3 study cases, 11 scenarios, and 82 sub-scenarios. The major contribution of this thesis work lies in a comprehensive examination of the value and niche of storage technologies within the context of the Nordic systems.

Some conclusions on studied markets and storage technologies are provided in sections 5.2.5, 5.3.3, 5.4.4, and 5.5. Here are a summary and final remarks based on the literature review, investigation, modelling, and analysis of various research sub-questions:

1. *About Challenges and Strategies of Nordic Transmission System Operators (TSOs):* The Nordic TSOs have recognized the role of flexibility and the need for balancing in light of the growing VRE and wind farm penetration. The tripling of wind capacity after 2025 was identified as a significant risk exacerbating the already existing challenges in the Nordic system. However, according to the requirements imposed by the existing Nordic grid codes, wind farm operators are not particularly motivated or forced to equip volatile wind production with storage facilities in the majority of Nordic countries.
2. *About Challenges, Constraints, and Opportunities in Nordic Markets:* The signs of inflexibility in the Nordic markets, which could be further escalated due to the integration of VRE and WF, were revealed through a literature review. These challenges include increasing demand for power ramping capacities, risk of frequency excursions, volatility of market prices, and cases of negative market prices. Additionally, the uneven distribution of flexible resources across bidding zones in the Nordic region makes Sweden and Denmark more prone to price volatility and grid issues with the increasing injection of intermittent sources. The Nordic TSOs procure different frequency products to ensure the equilibrium of generation and production in the grid such as automatic (FCR-N and FCR-D, FFR, aFRR) and manual (mFRR) frequency services. FFR is an asymmetric service and is procured only seasonally (May - October for FFR Profile) and upward. All ancillary frequency markets except for FCR-D have the availability and activated energy payment components. FCR-D providers only receive the availability payment. Accepted bids automatically get paid for their availability. However, a failure to provide procured service when the grid instantaneous frequency reaches specified settings or balance providers receives the TSO order for purchased regulation power, entails penalties. Also, services that have access to the Availability payment cannot bid the same capacity in multiple markets according to Nordic market rules and as such, the value stacking is partially hindered and could be realized only on a seasonal basis. For mFRR however, the balance providers are not obliged to participate in the capacity

market and are allowed to bid only to the energy activation market given they are capable to react to the electronic messages from the TSO. Seasonal value stacking can be performed by combining different frequency services or frequency services and energy arbitrage in Elspot. If charging from the grid is not available as a part of service (downward regulation), such as in the case of for example FFR, the strategies should be adopted for restoring a state of charge of storage to avoid penalties and idle operation.

3. *About Evaluation and Sizing of Storage Technologies:* The evaluation of commercially available and emerging storage technologies, such as Battery Energy Storage Systems (BESS), Flywheel Energy Storage Systems (FESS), and Compressed Air Energy Storage (CAES), revealed that each studied type has its technical limitations and possibilities. These factors play a decisive role in selecting the relevant technology for specific applications and project conditions. BESS limitations related to the lifetime dependency on the number of cycles over a lifetime do not represent a drawback according to the thesis findings and positive profits are achievable in all analyzed markets given the size of BESS is tailored for the market. FESS technology, despite its substantial lifetime cycling resource, high conversion efficiency, and deep depth of discharge, has the drawback of a low E:P ratio (maximum 0.25), which discards it from the most of analyzed markets. The thesis concluded that FESS can participate in FCR-N only, where continuous, fast responsive, low magnitude charge/discharge capacities are required. The main short-stopper for CAES is its high CAPEX costs, low efficiency, and special requirements for the geographical location. However, as CAES has a very long lifetime (30 years), with the optimized duration CAES can be valuable for energy arbitrage and mFRR services. The recommended sizes and ratios for each technology were determined based on revenue potential and economic viability. Evaluation results of critical technical and non-technical parameters of storage can be found in Fig.4.1 and Fig. 4.2. A summary of the recommended storage sizes across studied markets is provided in Table 5.8.

4. *About the Value and the Niche of Storage in Nordic Power Systems and Markets:* **BESS** demonstrated potential for positive business cases in all selected markets. FCR-N was concluded as the most profitable market for BESS with the availability payment being the highest revenue contributor. The value of BESS in FCR-N is evaluated to be about 610 USD/kW/year based on the revenue from recommended 5MW/5MWh BESS with NPV totaling at 3,247.73 at the end of a BESS lifetime (12 years). The thesis showed that it is possible to yield a revenue of above 300 USD/kW/year of installed BESS capacity in the Elspot market. If storage is already participating in FFR market, then its value can be increased by combining it with FCR-N (estimated value is 399.13 USD/kW/year) or the Elspot DA market (249.88 USD/kW/year). This is mostly because FFR is procured only seasonally and therefore would otherwise sit idle if not sequentially stacked with other services. In the case of **FESS** technology, only the FCR-N market has the potential of providing a positive business case according to the thesis conclusions. FFR requires 100% FFR committed capacity activation when the frequency is at its threshold, and therefore FESS is inherently bound to be penalized as maximum power output is less than installed power capacity due to energy constraints associated with low E:P. An alternative strategy was tested for FESS in FFR when only a fourth of the installed capacity is nominated at the FFR market to match energy and power capacity limits, but an analysis demonstrated that with the current rules and prices in the Nordic FFR market, obtained revenue failed to offset high FESS' CAPEX costs, and negative NPV is yielded for the alternative strategy. The value of FESS that can be potentially obtained from the FCR-N market, is evaluated to be 599.5 USD/kW/year based on the revenue values from 5MW/1MWh FESS with NPV totaling at 2,897.74 USD/kW at the end of a FESS lifetime (20 years). For **CAES,** all studied markets also allowed yielding positive cases. The analysis has shown that it is possible to yield a revenue of above 300 USD/kW/year of installed CAES capacity in the Elspot market. The highest revenue contributor in the mFRR market is energy payment EP which CAES receives for the activated capacity in EUR/MWh. mFRR is procured throughout the year. It is stated to be a symmetrical service. However, historical data indicates that Nordic TSOs mostly procure up-ward regulation. Therefore, CAES operators should adopt a certain strategy for recharging CAES. In the thesis, this was done by recharging the CAES from the grid and compensating at up-ward energy regulation prices. The highest value of CAES can be obtained from mFRR service when CAES is bidding into both capacity and energy markets,

and evaluated to be 950.73 USD/kW per year based on the revenue from 5MW/75MWh CAES with NPV totaling at 4,774.61 USD/ kW at the end of a CAES lifetime (30 years). If the CAES operator for some reason wants to bid in a DA market then combining it with mFRR EAM (estimated value is 536 USD/kW/year) can allow increasing the total revenue. This is because CAES would have a wider selection of prices to choose from and can optimize its operation accordingly. Participation of CAES in a DA only provides almost four times less revenue than mFRR generated.

Finally, this thesis aimed to highlight assumptions and limitations of the models in a critical manner, and attempted to discuss the advantages/ disadvantages and applicability of the used methods, and compare results with the available literature body in order to ensure the adequacy and relevancy of the work.

6.2 Future work

The non-exhaustive list of suggestions for future works, which could improve or extend the scope of Masters thesis results and findings, is provided below:

- Considering degradation of storage systems over their lifetime. With degradation taken into account, albeit limited to a certain threshold per year as specified by manufacturers for the specific site conditions, the revenue may be potentially affected as less capacity is available to participate in services. Among studied technologies, BESS is more prone to degradation while FESS and CAES have high mechanical durability and normally do not experience capacity loss over time.
- Extending markets scope by adding two markets that were excluded from the thesis analysis such as FCR-D (dynamic) and aFRR. Given the procurement volumes of FCR-D will follow the historical patterns, FCR-D is expected to provide less revenue if compared to FCR-N. It is difficult to predict aFRR market behavior due to future plans of the Nordic balancing models for aFRR as discussed below.
- Investigating options for restoring a state of charge of storage and comparing them with the grid charging strategy employed in this thesis. A possible alternative could be a collocation with and charging of storage from a VRE plant. From a power system perspective, it is important to note that collocating storage with VRE does not necessarily represent the best option, and separate studies on storage siting should be conducted. However, it can be argued that storage could assist in deferring transmission construction or mitigating wind farm ramps. In addition to revenue considerations, the decision to opt for a hybrid plan, rather than maintaining standalone storage, would also depend on factors such as space availability, government incentives, and experience in operating hybrid plants. Therefore, this problem is complex, and it is challenging to speculate on whether the proposed option would be preferred.
- Conducting sensitivities of the impact of low, medium, high fuel, consumption, and VRE generation scenarios that can impact the profitability of storage projects. Low fuel scenario can improve the profitability of D-CAES as it uses fuel for pre-heating air before discharging cycles, and vice versa. Higher VRE generation could mean more opportunities for the storage systems through enhancing revenue streams by performing energy arbitrage, ancillary services, and grid balancing, thereby increasing profitability. The impact of consumption scenarios will depend on whether the load pattern will follow the current trends (with plateaus during the daytime, peaks in the evening, and drops in the night) or more demand-side management practices will be put in place for evening out the consumption curve. While in the former case, storage could benefit from peak shaving and FCR-N services, in the latter case ESS could compete with prosumers for providing flexible grid services.
- Incorporating grid congestion data and transfer capacities to ensure that proposed sizes could be evacuated to the grid. It is not expected that extending the thesis' analysis by applying

grid limits will affect the conclusions on BESS and FESS values due to the relatively small capacity limits of FCR-N and FFR markets behind a single point of grid interconnection (5 MW). However, for CAES, given the grid can absorb more power, the project capacity can be increased up to 50 MW according to mFRR capacity limits, and as such CAES could yield higher NPVs. However, consideration should be given to both revenues and project costs in a similar manner as it was approached in the thesis.

- Studying the impact of planned enhancements in the Nordic balancing market (plans to join European MARI and PICASSO) on the procured/ required volumes of storage. PICASSO platform is used within EU PS for joint coordination of the automatic frequency restoration process and stable system operation. MARI represents EU PS's platform for the operation of manually activated reserves. From one side, accessing PICASSO and MARI could positively impact aFRR and mFRR providers respectively by potentially increasing required bidding volumes. On the other side, it could also imply that Nordic TSOs will have access to EU PS's balance providers. The analysis might require a joint evaluation of flexibility requirements in both Nordic and EU PSs along with interconnectors' capacity considerations.

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Appendix

Appendices A and B are reproduced from my Specialization Project [11].

A Information on Nordic Power Systems

Nordic Power System also referred to as Nordic synchronous area (NSA) consists of power systems of Norway, East Denmark, Sweden and Finland [137]. West Denmark works synchronously with Continental Europe SA through its operation with Germany.

Electricity imports/ exports are the key to enabling the reliable and efficient operation of Nordic Power System. HVDC links totaling at a capacity of almost 10 GW[138] are provide in Fig. 1:

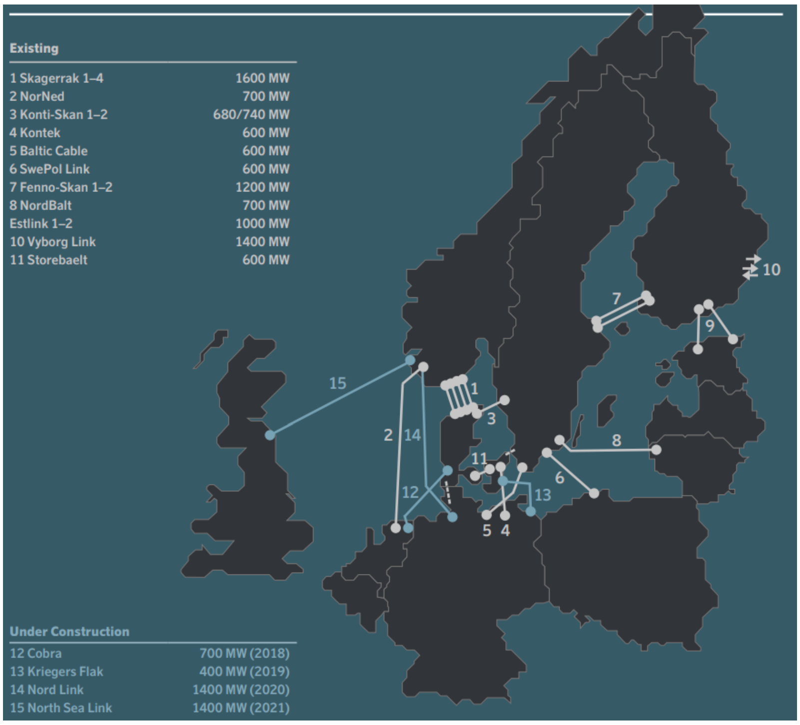

Figure 1: Overview of existing and planned HVDC interconnectors in the Nordic power system.

Source: Figure taken from [138]

NSA is also connected to the Continental Europe through HVDC links [139]: NorNed (Norway-Netherlands, 700 MW), Skagerrak (Norway-West Denmark, 1632 MW), KontiSkan (Sweden-West Denmark, 720 MW), Storebælt (West Denmark-East Denmark, 600 MW), Kontek (East Denmark-Germany,600 MW), Baltic cable (Sweden-Germany, 600 MW), SwePol(Sweden-Poland, 600 MW), Kriegers Flak (East Denmark and Germany, 400 MW), Nordlink (Norway - Germany, 1400 MW). Three other HVDC links connect NSA to Baltic SA: NordBalt (Sweden-Lithuania), Estlink (Finland-Estonia) and Vyborg HVDC (Finland-Russia).

Nordic region is among the least carbon intensive in the world. [140] platform provides the overview of real-time carbon intensity of electricity production and consumption. Data on generation mix can be accessed through [141]. Norway has a homogeneous generation fleet with over 90% coming from hydro plants. Hydro plants contribute to around 50% of production in Sweden. Nuclear power plants contribute to Swedish and Finland generation. Half of the generation in Eastern Denmark comes from wind power and other half is fossil fuel based (gas, oil and coal). Installed capacity back in 2020 was 97.2 GW with 15% being RE generation particularly onshore and offshore WF.

From Fig.2 we can see that VRE generation fleet quadruplet with WF being the main contributor.

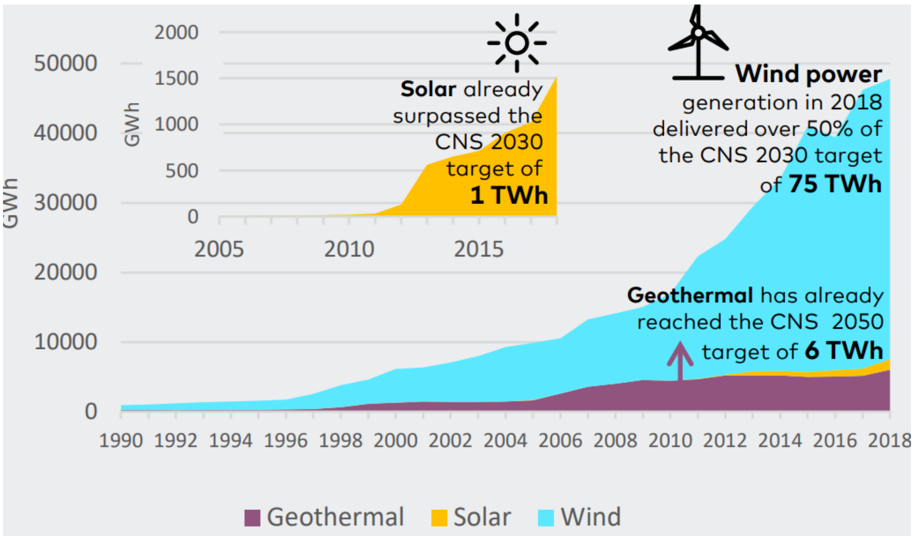

Figure 2: Nordic VRE generation between 1990 and 2018 (including Iceland).

Source: Figure taken from [142]

According to Nordic and Baltic Sea Winter Power Balance 2022-2023 Report [143], Norway can cover its peak demand locally for both cold and typical winters but other countries need to rely on imports from neighboring countries to meet the peak demand [143] (Fig.3):

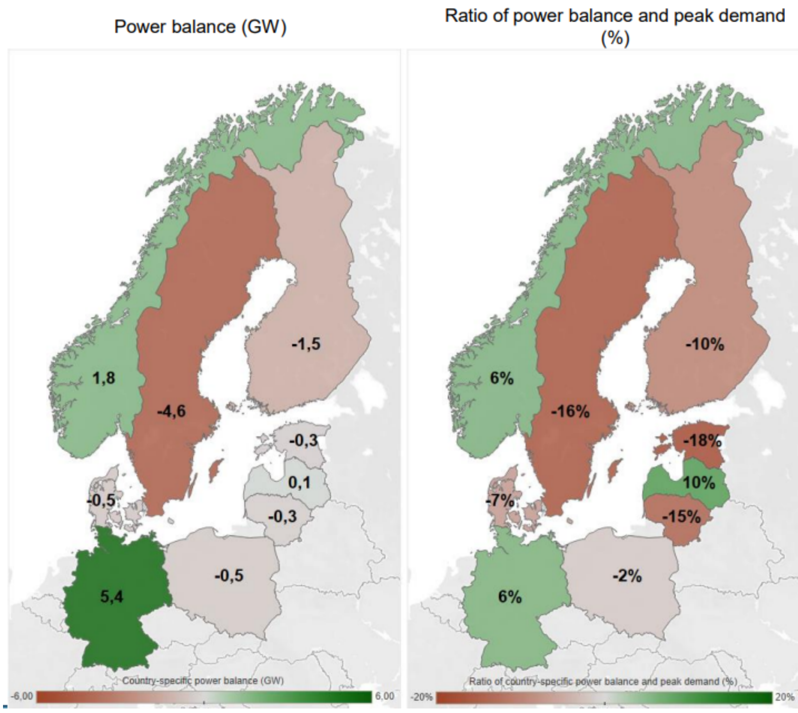

Figure 3: Peak demand coverage during cold winter: Nordic, Baltic and EU regions.

Source: Figure taken from [143]

B Examples of how wind generation emergency was handled in the Nordic region

Appendix 2 provides example of how real case emergency associated with wind farm storm was handled in the Nordic region on the case of Western Denmark.

On January 8 2005 hurricane known as ”Gurdun” crossed over parts of Scandinavia initially triggering high wind production in Western Denmark. However, wind turbines started to cutting out as speed exceeded their maximum threshold and as such wind production during afternoon hours dropped from 2200 MW to 100 MW in Western Denmark.

Fig.4 demonstrates how the system was handled during ”Gurdun”[137].

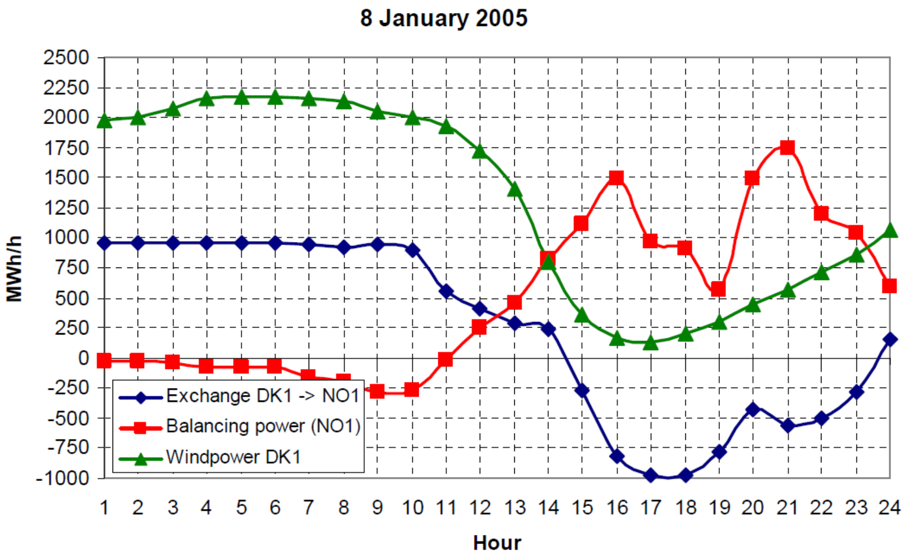

Figure 4: Western Denmark power system operation during hurricane ”Gudrun”, January 8, 2005

Source: Figure taken from [137]

There are several interesting observations from Fig.4:

- Due to the geographical distribution of wind farms in Western Denmark it took around 10 hours for wind production to drop from 2200 MW to 200 MW;
- The HVDC link between Southern Norway and Western Denmark was switched completely from exporting to importing;
- Balancing hydro power in Southern Norway allowed to handle wind emergency of such a magnitude.

C Matlab script for BESS and FESS participation in FCR-N market

```
%Script for the BESS or FESS participating in the Frequency Containment
%Reserve Normal (FCR-N) in a balancing market in DK2 zone.
%Frequency Containment Reserve N service has two part payment structure:
%availability payment and energy payment deducted by the penalty for failing
%FCR-N activation.

% Battery parameters or %Flywheel parameters (example below is for 5 MW capacity)
power_capacity = 5; % MW
energy_capacity = 5; % MWh 1.25 MWh for FESS
min_energy_capacity=0.2*energy_capacity; %MWh 20% recommended DoD for the BESS;
%0% for the FESS

round_trip_efficiency = 0.9; %90% RT efficiency for BESS;
%95% for the FESS
self_discharge = 0.000000578;
%self-dischare per second considering self-discharge losses
%of 5% per day for the BESS; 100% per day for the FESS

% FCR-N Frequency parameters
droop = power_capacity/0.09;
% 100% of power capacity shall be activated at 50.1 Hz or 49.9 Hz
%with a deadband between 49.99 and 50.01 Hz
charging_threshold = 50.1; % Hz FCR-N specification for down-regulation
discharging_threshold = 49.9; % Hz FCR-N specification for up-regulation
reffreq = 50; %Hz

% Payment structure - Load payment data from Excel files
avail_cost=xlsread('Fcrpayment.xlsx');
%read the content of the excel FCR capacity payment
%that contains 8760 rows %EUR/MW/h source:Energinet
availability_payment = avail_cost(:,2); % assign the capacity
%payment values from the second column; EUR/MW/h
energy_cost=xlsread('upward_downward_prices_DK2_2022_FCR_N.xlsx');
%read the content of the excel FCR energy payment file
%that contains 8760 rows %EUR/MWh source: NordPool
energy_payment_up = energy_cost(:,1);
% extract the energy payment values for up-regulation
%from the first column;  EUR/MWh
energy_payment_down = energy_cost(:,2); % extract the energy payment values
%for down-regulation from the second column; % EUR/MWh

% Measured frequency - Load grid frequency data from CSV file
%- frequency measured for the year 2018
freq_data = csvread('frequencyoutput.csv'); %read the content of the CSV
%frequency file that contains 31536000 rows
grid_frequency = freq_data(:,2); % extract the frequency values from the
%second column
grid_frequency(isnan(grid_frequency)) = reffreq; %replacing NaN
%(not measured) values with reference frequency

% Initialize hourly vectors
hourly_charging_power = zeros(8760, 1); %MW*s
hourly_discharging_power = zeros(8760, 1);  %MW*s
hourly_profit = zeros(8760, 1); %EUR
hourly_penalty_power_up=zeros(8760, 1); %EUR
```

```
hourly_penalty_power_down=zeros(8760, 1); %EUR
energy_profit=zeros(8760, 1); %EUR
penalty_payment=zeros(8760, 1); %EUR
availability_profit=zeros(8760, 1); %EUR
state_of_charge_yearly=zeros(31536000,1);
charging_power=zeros(31536000,1);
discharging_power=zeros(31536000,1);
penalty_power_up=zeros(31536000,1);
penalty_power_down=zeros(31536000,1);

% Compute the frequency violations of the instantenous measured frequency
% and reference frequency value
frequency_violations = abs(reffreq - grid_frequency);
frequency_violationssign = reffreq - grid_frequency; %for plotting
frequency_violations_mhz=-(1000* frequency_violationssign); % for plotting

% Initialize the battery state of charge, full cycle count and profit
state_of_charge(1) = energy_capacity/3;
% Assuming the bess starts at 30% capacity because FCR-N is a
%symmetrical service and therefore both charging
%and dischargig might be required
profit = 0;
full_cycle_count=0;

%Initialize values for counting occurence of underfrequency and
%overfrequncy events and bess ore fess triggering, failing duty
under=0; %occurence of underfrequency events
undertrig=0; % count of the BESS/FESS triggering during the underfrequency events
over=0; %occurence of overfrequency events
overtrig=0; % count of the BESS/FESS triggering during the overfrequency events
fail=0; %occurence of the BESS/ FESS failing its duty

for t = 1:length(grid_frequency)% Calculate occurence of
%frequency deviations based on FCR-N specification

if grid_frequency(t) > 50.01 && grid_frequency(t) <= charging_threshold
    over=over+1;
    under=under+0;
elseif grid_frequency(t) < 49.99 && grid_frequency(t)>= discharging_threshold
    over=over+0;
    under=under+1;
else
    over=over+0;
    under=under+0;
end

end

% Loop through each time step for calculation charging and discharging
% power
for t = 1:length(grid_frequency)% Calculate charging and
%discharging power (49.99 - 50.01 is a deadband frequency range)

if grid_frequency(t) > 50.01 && grid_frequency(t) <= charging_threshold &&
state_of_charge(t) < energy_capacity
    discharging_power(t) = 0;
    charging_power(t) = droop * frequency_violations(t);
    overtrig=overtrig+1;
```

```
    undertrig=undertrig+0;
elseif grid_frequency(t) < 49.99 && grid_frequency(t)>= discharging_threshold
&& state_of_charge(t) > min_energy_capacity
    charging_power(t) = 0;
    discharging_power(t) = droop * frequency_violations(t);
    overtrig=overtrig+0;
    undertrig=undertrig+1;
else
    charging_power(t) = 0;
    discharging_power(t) = 0;
    overtrig=overtrig+0;
    undertrig=undertrig+0;
end

% Adjust charging and discharging power for efficiency and self discharge
charging_power(t) = charging_power(t) / (round_trip_efficiency * (1 - self_discharge));
discharging_power(t) = discharging_power(t) * round_trip_efficiency * (1 - self_discharge);

% Compute the energy change and update the state of charge
energy_change(t) = charging_power(t) - discharging_power(t);
state_of_charge(t+1) = state_of_charge(t) + energy_change(t);

% Check if state of charge and energy capacity are within the limits
if state_of_charge(t+1) > energy_capacity
    % Limit charging to energy capacity
    charging_power(t) = (energy_capacity - state_of_charge(t))
    / (round_trip_efficiency * (1 - self_discharge));
    state_of_charge(t+1) = energy_capacity;
elseif state_of_charge(t+1) < min_energy_capacity
    % Limit discharging to min energy capacity
    discharging_power(t) = (state_of_charge(t) - min_energy_capacity)
    * (round_trip_efficiency * (1 - self_discharge));
    state_of_charge(t+1) = min_energy_capacity;
else
     charging_power(t) =  charging_power(t);
     discharging_power(t)=discharging_power(t);
end

% Check if charging & discharging power is within capacity limits
if charging_power(t) > power_capacity
    % Limit charging power to max power capacity
    charging_power(t) = power_capacity / (round_trip_efficiency * (1 - self_discharge));

elseif discharging_power(t) > power_capacity
    % Limit discharging power to max power capacity
    discharging_power(t) = power_capacity * (round_trip_efficiency * (1 - self_discharge));

else
     charging_power(t) =  charging_power(t);
     discharging_power(t)=discharging_power(t);
end

if state_of_charge(t) >= energy_capacity && state_of_charge(t-1) <=
min_energy_capacity %counting full cylcles
            full_cycle_count = full_cycle_count + 1;
end
```

```
    charging_power_neg(t)=-charging_power(t); %for plotting
    power_penalty=power_capacity/3600;
% Calculate penalty amount
if (grid_frequency(t) > 50.01 && grid_frequency(t) <= charging_threshold &&
charging_power(t) < (droop * frequency_violations(t))
/(round_trip_efficiency * (1 - self_discharge)))
    penalty_power_down(t) = min((droop * frequency_violations(t))/(round_trip_efficiency
    * (1 - self_discharge)), power_penalty);
    penalty_power_up(t)=0;
    fail=fail+1;
elseif(grid_frequency(t) < 49.99 && grid_frequency(t)>= discharging_threshold
&& discharging_power(t) < (droop * frequency_violations(t))
*(round_trip_efficiency * (1 - self_discharge)))
    penalty_power_up(t)= min((droop * frequency_violations(t))
    *(round_trip_efficiency * (1 - self_discharge)), power_penalty);
    penalty_power_down(t)=0;
    fail=fail+1;
else
    penalty_power_down(t)=0;
    penalty_power_up(t)=0;
    fail=fail+0;

end
state_of_charge_yearly(t)=state_of_charge(t);
end
% Loop through each hourly interval for accummulation of hourly charging and
% discharging power
for hour = 1:length(hourly_charging_power)
    % Calculate the starting and ending indices for the current hour
    start_index = (hour-1)*3600+1;
    end_index = min(hour*3600, length(charging_power));
    end_index = min(end_index, length(penalty_power_up));
    end_index = min(end_index, length(penalty_power_down));

    % Calculate the total charging, discharging and penalty power during the hour
    hourly_charging_power(hour) = sum(charging_power(start_index:end_index));
    hourly_discharging_power(hour) = sum(discharging_power(start_index:end_index));
    hourly_penalty_power_up(hour) = sum(penalty_power_up(start_index:end_index));
    hourly_penalty_power_down(hour) = sum(penalty_power_down(start_index:end_index));

    % Calculate the energy payment for the hour using the hourly energy payment
    % value from the Excel file
    %energy_payment_hourly = energy_payment(hour);
    energy_profit(hour) = energy_payment_down(hour)
    * hourly_charging_power(hour)/3600 + energy_payment_up(hour)
    * hourly_discharging_power(hour)/3600;
    penalty_payment(hour)= energy_payment_down(hour)
    * hourly_penalty_power_down(hour)/3600 +
    energy_payment_up(hour) * hourly_penalty_power_up(hour)/3600;


    % Calculate the profit for the hour by adding the availability payment,
    % energy payment, and penalty (if applicable)
    availability_profit(hour)=availability_payment(hour) * power_capacity;
    hourly_profit(hour) = availability_profit(hour) + energy_profit(hour)
    -penalty_payment(hour);
```

```
    % Add the hourly profit to the total profit
    profit = profit + hourly_profit(hour);
end

%saving soc throughout the complete operation into a CSV file
% filename = 'accumulated_socdata_55.csv';
% writematrix(state_of_charge_yearly, filename);

% Display the output values
p_chargetotal=sum(charging_power, 'all');
p_dischargetotal=sum(discharging_power, 'all');
p_penaltyuptotal=sum(penalty_power_up, 'all');
p_penaltydowntotal=sum(penalty_power_down, 'all');
c_energytotal=sum(energy_profit, 'all');
c_availtotal=sum(availability_profit, 'all');
c_penaltytotal=sum(penalty_payment, 'all');
display(under);
display(over);
%display(undertrig);
%display(overtrig);
display(fail);
fprintf('Number of full cycles: %d\n', full_cycle_count);
fprintf('Total profit: EUR%.2f\n', profit);
fprintf('Total energy payment: EUR%.2f\n', c_energytotal);
fprintf('Total availability payment: EUR%.2f\n', c_availtotal);
fprintf('Total penalty amount: EUR%.2f\n', c_penaltytotal);
fprintf('Total charge: MW%.2f\n', p_chargetotal);
fprintf('Total discharge: MW%.2f\n', p_dischargetotal);
fprintf('Total penalty power up: MW%.2f\n', p_penaltyuptotal);
fprintf('Total penalty power down: MW%.2f\n', p_penaltydowntotal);
%Plot the results
%----------------------------
figure;
subplot(1,1,1);
p1=plot(state_of_charge, 'g', 'LineWidth', 2);
set(gca,'fontsize', 26)
%legend({'Battery State of Charge'})
ylabel ( 'Energy(MWh)' )
xlabel ( 'Time(sec)' )
grid on
%xlim([0 31536000]);
xlim([887691 887841]);
%xlim([0 300]);
ylim([0 5.2]);
%set(gca,'XTick',[0:1:300])
set(gca,'YTick',[0:0.2:5.2])
hold on
yline(min_energy_capacity, 'LineWidth', 2);
legend('Battery State of Charge');

figure; %NEW GIGURE
subplot(5,1,1);
p2=plot(grid_frequency, 'c','LineWidth', 2);
%legend({'Grid Frequency'})
ylabel ( {'fgrid'; '(Hz)'})
xlabel ( 'Time(sec)' )
hold on
yline(49.9,'LineWidth', 2);
```

```
%legend('Discharging threshold');
hold on
yline(50.1,'LineWidth', 2);
%legend('Charging threshold');
yline(49.99);
%legend('Lower frequency deadband');
hold on
yline(50.01)
legend('Grid Frequency');
grid on
%xlim([0 31536000]);
xlim([887691 887841]);
set(gca,'fontsize', 20)
subplot(5,1,2);
p3=plot(charging_power_neg, 'r','LineWidth', 2);
legend({'Battery Charging (Down regulation)'})
ylabel ( {'Charging';'(MW)'})
xlabel ( 'Time(sec)' )
grid on
%xlim([0 31536000]);
xlim([887691 887841]);
set(gca,'fontsize', 20)
subplot(5,1,3);
p4=plot(discharging_power, 'r','LineWidth', 2);
%xlim([0 31536000]); plot for the annual operation
xlim([887691 887841]);
legend({'Battery Discharging (Up regulation)'})
ylabel ( {'Discharging'; '(MW)'} )
xlabel ( 'Time(sec)' )
set(gca,'fontsize', 20)
grid on
subplot(5,1,4);
p5=plot(penalty_power_down, 'c','LineWidth', 2);
%xlim([0 31536000]);
xlim([887691 887841]);
legend({'Penalty power for breaching down regulation'})
ylabel ( {'Penalty';'down(MW)'} )
xlabel ( 'Time(sec)' )
grid on
set(gca,'fontsize', 20)
subplot(5,1,5);
p5=plot(penalty_power_up, 'c','LineWidth', 2);
xlim([887691 887841]);
%xlim([0 31536000]);
legend({'Penalty power for breaching up regulation'})
ylabel ( {'Penalty';'up(MW)'} )
xlabel ( 'Time(sec)' )
grid on
set(gca,'fontsize', 20)

% figure; enable below for plotting frequency violations
% subplot(1,1,1);
% p8=plot(frequency_violations_mhz, 'r');
% %legend({'Frequency violations'})
% hold on
% yline(10, 'g', 'upper deadband', 'LineWidth', 2, 'FontSize', 20);
% hold on
% yline(-10, 'g', 'lower deadband','LineWidth', 2, 'FontSize', 20);
```

```
% hold on
% yline(100, 'k', '100 % of downward FCR-N activation','LineWidth', 2, 'FontSize', 18);
% hold on
% yline(-100, 'k', '100 % of upward FCR-N activation','LineWidth', 2, 'FontSize', 20);
% xlabel ( 'Time(sec)' )
% ylabel ( 'Frequency violations from 50 Hz(mHz)' )
% grid on
% xlim([0 31536000]);
% set(gca,'fontsize', 20)
```

D Matlab script for BESS and CAES optimization exercising energy arbitrage in Elspot market

```
%Script for the BESS or CAES participating in Energy Arbitrage
%in Nord Pool's Elspot market.
dataPrices = readtable('NordpoolPrices_DA.xlsx');
mcost=dataPrices{:,'Price'}; %test data from 2022 a deay ahead market in DK2 June 23
%BESS or CAES parameters
pmax = 5; %cap for power capacity charging MW
pmax_disch=0.00117*pmax+pmax; %this line should be enabled
%for CAES only
emax = 25; %cap for energy capacity MWh
delt=1; %absolute time between periods - 1 hour
n=24; %period over consideration - 24 hours
SOC_min=0.3; % Depth of discharge to maintain storage health
% 30% for CAES; and 20% for BESS
SOC_max=1; %Max state of charge
effic=0.55; % 55% efficiency for CAES, 90% efficienct for BESS
self_discharge=0.0000001; % self-dischare of CAES negligeable
%self-dischare of BESS 5% per day


%objective function - maximize cashflow
%from energy arbitrage through planning horizon - 1 day
cvx_begin
  variables p_stor(n) e_stor(n+1);

f=mcost'*p_stor
 maximize(f)
 subject to
    % constraints formulation

   p_stor<= pmax_disch*effic* (1 - self_discharge);
   %max power capacity constraint for discharging
   %adjusted to accommodate efficiency and self-discharge
   %losses + extra power from heating the air for CAES
   %for BESS pmax_disch should be replaced by pmax
   p_stor>=-(pmax/(effic* (1 - self_discharge)));
   %max power capacity constraint for charging
   %adjusted to accommodate efficiency and self-discharge losses
   e_stor>=0;
   e_stor<=emax*SOC_max;
   e_stor(1)==0.5*emax; %Starting at 50% of the energy capacity

   for t = 1:24
       e_stor(t+1) == e_stor(t) - p_stor(t);
       e_stor(t+1)>=emax*SOC_min; %discharge energy limit
       p_stor(t)*delt <= (emax-e_stor(t)); %max charge energy limit
       %p_stor(t)*delt <= (e_stor(t)-emax*SOC_min)*effic* (1 - self_discharge);
       %discharge energy limit
       e_stor(24)==0.5*emax % finish at 50% capacity


   end;
cvx_end
p_stortotal=sum(p_stor, 'all')
display (p_stor)
```

```
%display (e_stor);
%saving soc throughout the complete operation into a CSV file
% filename = 'accumulated_socdatada_55.csv';
% writematrix(e_stor, filename);

subplot(3,1,1);
p2=plot(e_stor, 'r','LineWidth', 2);
legend({'CAES State of Charge'})
ylabel ( {'SoC';'(MWh)'} )
xlabel ( 'Time(hrs)' )
set(gca,'fontsize', 20)
grid on
xlim([0 24]);
ylim([0 25]);
set(gca,'XTick',[0:1:24])
set(gca,'YTick',[0:5:25])
p2.Marker = 'o';
subplot(3,1,2);
p3=plot(mcost, 'c', 'LineWidth', 2);
legend({'Hourly Day Ahead Prices'})
ylabel ( {'Elspot'; 'prices'; '(EUR/MWh)'} )
xlabel ( 'Time(hrs)' )
set(gca,'fontsize', 20)
grid on
xlim([0 24]);
set(gca,'XTick',[0:1:24])
p3.Marker = 'o';
subplot(3,1,3);
p1=plot(p_stor, 'g','LineWidth', 2);
set(gca,'fontsize', 20)
hold on
yline(0);
ylabel ({'Power'; 'exchange'; 'with grid(MW)'} )
legend({'Storage cycles: negative - charging, positive - discharging'})
xlabel ( 'Time(hrs)' )
grid on
xlim([0 24]);
%ylim([-1.5 1.2]);
set(gca,'XTick',[0:1:24])
p1.Marker = 'o';
```

E Matlab script for BESS and FESS participation in FFR Profile market

```
%Script for the BESS or FESS participating in the Fast Frequency
%Reserve in a balancing market in NO5 zone from May-to-October.
%Fast Frequency Reserve Reserve N service has two part payment structure:
%availability payment and energy payment for FFR activation
%deducted by the compensation to the grid for
%recharging and penalty for failing servcie



% Battery or flywheel parameters
power_capacity = 1; % MW
energy_capacity = 1; % MWh
min_energy_capacity=0.2*energy_capacity; %MWh
%DoD is 20% for BESS and 30% for FESS
round_trip_efficiency = 0.9;
%RT efficiency is 90% for BESS and 95% for FESS
self_discharge = 0.000000578; %self-dischare per second
%considering self-discharge losses of 5% per day for BESS
%or 100% per fay for FESS

% Frequency parameters
discharging_threshold = 49.7; % Hz FFR service activates when frequency drops below 49.7 Hz
reffreq = 50; %Hz

% Payment structure
availability_payment = 41.93; % Uniform price in Norway
per hour for FFR flex from Statnett ; EUR/MW/h equal to 150 NOK
ffr_energycost=csvread('new_priceffr.csv'); %read
%the content of the excel FFR energy payment file that contains 4416 rows %EUR/MWh
energy_payment_up = ffr_energycost(:,1); % extract the energy payment values
%for up-regulation from the first column; % EUR/MWh
%energy_payment_down = ffr_energycost(:,2); % extract the energy payment
%values  for down-regulation from the second column -
%rate paid by the BESS to the grid; % EUR/MWh

% Load grid frequency data from CSV file - frequency measured for the year 2018
freq_data = csvread('new_freq.csv'); %read the content of the CSV frequency
%file that contains 15897600 rows
grid_frequency = freq_data(:,1); % extract the frequency values from the
%second column
grid_frequency(isnan(grid_frequency)) = reffreq; %replacing NaN values (not
%measured) with reference frequency

% Initialize hourly vectors - from May - October FFR Profile
hourly_charging_power = zeros(4416, 1); %MW*s
hourly_discharging_power = zeros(4416, 1);  %MW*s
hourly_profit = zeros(4416, 1); %EUR
hourly_penalty_power_up=zeros(4416, 1); %EUR
hourly_penalty_power_down=zeros(4416, 1); %EUR
energy_profit=zeros(4416, 1); %EUR
penalty_payment=zeros(4416, 1); %EUR
availability_profit=zeros(4416, 1); %EUR
state_of_charge_yearly=zeros(15897600, 1);
charging_power=zeros(15897600, 1);
discharging_power=zeros(15897600, 1);
```

```
penalty_power_up=zeros(15897600, 1);

% Compute the frequency violations
frequency_violations = abs(reffreq - grid_frequency);
frequency_violationssign = -(reffreq - grid_frequency); %for plotting
frequency_violations_mhz=1000* frequency_violationssign; % for plotting



% Initialize the battery state of charge, full cycle count and profit
state_of_charge(1) = energy_capacity;
% Assuming bess starts at 100% capacity because FFR
%is assymmetrical service and therefore only dischargig might be required
profit = 0;
full_cycle_count=0;

%Initialize values for counting occurence of frequency events and bess triggering, failing duty
under=0;
undertrig=0;
fail=0;

for t = 1:length(grid_frequency)% Calculate occurence of underfrequency events
%based on FFR specification

if grid_frequency(t) <= discharging_threshold
    under=under+1;
else
    under=under+0;
end

end

% Loop through each time step
for t = 1:length(grid_frequency)% Calculate
%charging (maintenace) and discharging (ffr support)power

if  grid_frequency(t) <= discharging_threshold &&
state_of_charge(t) > min_energy_capacity
    discharging_power(t) = power_capacity;
    charging_power(t) = 0;
    undertrig=undertrig+1;
elseif grid_frequency(t) >= 49.99 && state_of_charge(t)
<= min_energy_capacity % Check if energy content needs
%to be restored
    charging_power(t) = energy_capacity - state_of_charge(t);
    % Charge the battery from the grid to 100% of
    %its maximum energy capacity
    discharging_power(t) =0;
    undertrig=0;
else
    charging_power(t) = 0;
    discharging_power(t) = 0;
    undertrig=0;
end

% Adjust charging and discharging power for efficiency and self discharge
charging_power(t) = charging_power(t) / (round_trip_efficiency * (1 - self_discharge));
discharging_power(t) = discharging_power(t) * round_trip_efficiency * (1 - self_discharge);
```

```
% Compute the energy change and update the state of charge
energy_change(t) = charging_power(t) - discharging_power(t);
state_of_charge(t+1) = state_of_charge(t) + energy_change(t);

% Check if state of charge and energy capacity are within the limits
if state_of_charge(t+1) > energy_capacity
    % Limit charging to energy capacity
    charging_power(t) = (energy_capacity - state_of_charge(t))
    / (round_trip_efficiency * (1 - self_discharge));
    state_of_charge(t+1) = energy_capacity;
elseif state_of_charge(t+1) < min_energy_capacity
    % Limit discharging to min energy capacity
    discharging_power(t) = (state_of_charge(t) - min_energy_capacity)
    * (round_trip_efficiency * (1 - self_discharge));
    state_of_charge(t+1) = min_energy_capacity;
else
     charging_power(t) =  charging_power(t);
     discharging_power(t)=discharging_power(t);
end

% Check if charging & discharging power is within capacity limits
if charging_power(t) > power_capacity
    % Limit charging power to max power capacity
    charging_power(t) = power_capacity / (round_trip_efficiency * (1 - self_discharge));

elseif discharging_power(t) > power_capacity
    % Limit discharging power to max power capacity
    discharging_power(t) = power_capacity * (round_trip_efficiency * (1 - self_discharge));

else
     charging_power(t) =  charging_power(t);
     discharging_power(t)=discharging_power(t);
end

if state_of_charge(t+1) >= energy_capacity && state_of_charge(t) <= min_energy_capacity
            full_cycle_count = full_cycle_count + 1;
end

charging_power_neg(t)=-charging_power(t); %for plotting
power_penalty=power_capacity/3600;

% Calculate penalty amount
if grid_frequency(t) <= discharging_threshold && discharging_power(t)
< (power_capacity*(round_trip_efficiency * (1 - self_discharge)))
    penalty_power_up(t) =  min((power_capacity*(round_trip_efficiency
    * (1 - self_discharge))), power_penalty);
    fail=fail+1;
else
    penalty_power_up(t)=0;
    fail=fail+0;

end
state_of_charge_yearly(t)=state_of_charge(t);
end
% Loop through each hourly interval for accummulation of hourly charging and
% discharging power
for hour = 1:length(hourly_charging_power)
```

```
    % Calculate the starting and ending indices for the current hour
    start_index = (hour-1)*3600+1;
    end_index = min(hour*3600, length(charging_power));
    end_index = min(end_index, length(penalty_power_up));

    % Calculate the total charging, discharging and penalty power during the hour
    hourly_charging_power(hour) = sum(charging_power(start_index:end_index));
    hourly_discharging_power(hour) = sum(discharging_power(start_index:end_index));
    hourly_penalty_power_up(hour) = sum(penalty_power_up(start_index:end_index));

    % Calculate the energy payment for the hour using the hourly energy
    % payment and payment to the grid
    energy_profit(hour) = energy_payment_up(hour) * hourly_discharging_power(hour)/3600
    - energy_payment_up(hour) * hourly_charging_power(hour)/3600;
    %Total energy profit is deducted by the compensation
    %to the grid for maintaining SoC integrity
    penalty_payment(hour)=energy_payment_up(hour) * hourly_penalty_power_up(hour)/3600;


    % Calculate the profit for the hour by adding the availability payment,
    % energy payment, and penalty (if applicable)
    availability_profit(hour)=availability_payment * power_capacity;
    hourly_profit(hour) = availability_profit(hour) + energy_profit(hour)-penalty_payment(hour);


    % Add the hourly profit to the total profit
    profit = profit + hourly_profit(hour);
end


%saving soc throughout the complete operation into a CSV file for box
%plotting
% filename = 'accumulated_ffrsocdatabess_55.csv';
% writematrix(state_of_charge_yearly, filename);

% Display the output values
p_chargetotal=sum(charging_power, 'all');
p_dischargetotal=sum(discharging_power, 'all');
p_penaltyuptotal=sum(penalty_power_up, 'all');
c_energytotal=sum(energy_profit, 'all');
c_availtotal=sum(availability_profit, 'all');
c_penaltytotal=sum(penalty_payment, 'all');
display(under);
%display(over);
%display(undertrig);
%display(overtrig);
display(fail)
fprintf('Number of full cycles: %d\n', full_cycle_count);
fprintf('Total profit: EUR%.2f\n', profit);
fprintf('Total energy payment: EUR%.2f\n', c_energytotal);
fprintf('Total availability payment: EUR%.2f\n', c_availtotal);
fprintf('Total penalty amount: EUR%.6f\n', c_penaltytotal);
%fprintf('Total penalty: $%.2f\n', penalty_payment);
fprintf('Total charge: MW%.2f\n', p_chargetotal);
fprintf('Total discharge: MW%.2f\n', p_dischargetotal);
fprintf('Total penalty power up: MW%.4f\n', p_penaltyuptotal);
%Plot the results
figure;
```

```
subplot(1,1,1);
p1=plot(state_of_charge, 'r');
%legend({'Battery State of Charge'})
ylabel ( 'Energy(MWh)' )
xlabel ( 'Time(sec)' )
grid on
xlim([4990000 5000000]);
%xlim([0 15897600]);
ylim([0 5.1]);
%set(gca,'XTick',[0:1:420])
set(gca,'YTick',[0:0.1:5.1])
set(gca,'fontsize', 18)
hold on
yline(min_energy_capacity);
legend('Battery State of Charge');
%--------------------------------------------
figure; %NEW FIGURE
subplot(4,1,1);
p2=plot(grid_frequency, 'c');
%legend({'Grid Frequency'})
ylabel ({'fgrid'; '(Hz)'})
xlabel ( 'Time(sec)' )
hold on
yline(49.7);
%legend('Discharging activation threshold');
legend('Grid Frequency');
grid on
%xlim([4000000 5000000]);
set(gca,'fontsize', 20)
xlim([0 15897600]);
subplot(4,1,2);
p3=plot(charging_power_neg, 'r');
legend({'Battery Charging (For recovery of the energy content)'})
ylabel ( {'Charging';'(MW)'})
xlabel ( 'Time(sec)' )
grid on
%xlim([4000000 5000000]);
xlim([0 15897600]);
%xlim([0 420]);
%set(gca,'XTick',[0:1:420])
set(gca,'fontsize', 20)
subplot(4,1,3);
p4=plot(discharging_power, 'r');
%xlim([4000000 5000000]);
xlim([0 15897600]);
legend({'Battery Discharging (Up regulation)'})
ylabel ( {'Discharging';'(MW)'})
xlabel ( 'Time(sec)' )
grid on
set(gca,'fontsize', 20)
subplot(4,1,4);
p5=plot(penalty_power_up, 'c');
%xlim([4000000 5000000]);
xlim([0 15897600]);
legend({'Penalty Power for Breaching Up Regulation'})
ylabel ( {'Penalty';'up(MW)'})
xlabel ( 'Time(sec)' )
set(gca,'fontsize', 20)
```

```
grid on


% figure; enable below for plotting frequency violations
% subplot(1,1,1);
% p8=plot(frequency_violations_mhz, 'r');
% %legend({'Frequency violations'})
% hold on
% yline(10, 'g', 'upper deadband');
% hold on
% yline(-10, 'g', 'lower deadband');
% hold on
% yline(-300, 'k', '100 % of FFR activation');
% xlabel ( 'Time(sec)' )
% ylabel ( 'Frequency violations from 50 Hz(in mHz)' )
% grid on
% xlim([0 15897600]);
% %set(gca,'XTick',[0:10000:15897600])
% set(gca,'fontsize', 18)
```

F Matlab script for CAES optimization exercising energy arbitrage in Elspot market and mFRR Energy Activation Market

```
%Script for the CAES participating in Energy Arbitrage
%in Nord Pool's Elspot market and mFRR EAM.
dataPrices = readtable('NordpoolPrices_DA.xlsx');
mcost=dataPrices{:,'Price'};
%test data from 2022 a deay ahead market in DK2 June 23
mfrr_cost=xlsread('upward_downward_prices_DK2_2022_FCR_N_day.xlsx');
%read the content of the excel FCR energy payment file that contains 8760 rows %EUR/MWh
energy_payment_up = mfrr_cost(:,1);
%extract the energy payment values for up-regulation from the first column; % EUR/MWh
%caes parameters
pmax = 5; %cap for power capacity charging MW
pmax_disch=0.00117*pmax+pmax;
emax = 35; %cap for energy capacity MWh
delt=1; %absolute time between periods - 1 hour
n=24; %period over consideration - 24 hours
SOC_min=0.3; % Depth of discharge to maintain CAES thermodynamics
SOC_max=1; %Max state of charge
effic=0.55; % 55% efficiency of CAES
self_discharge=0.0000001; % self-dischare of CAES negligeable


%objective function - maximize cashflow from energy
%arbitrage through planning horizon - 1 day
cvx_begin
  variables p_stor(n) e_stor(n+1);

f=mcost'*p_stor+energy_payment_up'*p_stor
 maximize(f)
 subject to
    % constraints formulation

   p_stor<= pmax_disch*effic* (1 - self_discharge);
   %max power capacity constraint for discharging
   %adjusted to accommodate efficiency and self-discharge
   %losses + extra power from heating the air
   p_stor>=-(pmax/(effic* (1 - self_discharge))); %max power capacity constraint for charging
   %adjusted to accommodate efficiency and self-discharge losses
   e_stor>=0;
   e_stor<=emax*SOC_max;
   e_stor(1)==0.5*emax; %Starting at 50% of the energy capacity

   for t = 1:24
       e_stor(t+1) == e_stor(t) - p_stor(t);
       e_stor(t+1)>=emax*SOC_min; %discharge energy limit
       p_stor(t)*delt <= (emax-e_stor(t)); %max charge energy limit
       e_stor(24)==0.5*emax %finish at 50% capacity


   end;
cvx_end
p_stortotal=sum(p_stor, 'all')
display (p_stor)
%display (e_stor);
%saving soc throughout the complete operation into a CSV file
```

```
% filename = 'accumulated_socdatada_55.csv';
% writematrix(e_stor, filename);

subplot(4,1,1);
p2=plot(e_stor, 'r', 'LineWidth', 2);
legend({'CAES State of Charge'})
ylabel ( {'SoC';'(MWh)'} )
xlabel ( 'Time(hrs)' )
grid on
xlim([0 24]);
ylim([0 35]);
set(gca,'XTick',[0:1:24])
set(gca,'YTick',[0:5:35])
set(gca,'fontsize', 20)
p2.Marker = 'o';
subplot(4,1,2);
p3=plot(mcost, 'c', 'LineWidth', 2);
legend({'Hourly Day Ahead Prices'})
ylabel ( {'Elspot'; 'prices'; '(EUR/MWh)'} )
xlabel ( 'Time(hrs)' )
grid on
xlim([0 24]);
set(gca,'XTick',[0:1:24])
set(gca,'fontsize', 20)
p3.Marker = 'o';
subplot(4,1,3);
p1=plot(p_stor, 'g', 'LineWidth', 2);
hold on
yline(0);
ylabel ( {'Power'; 'exchange'; 'with grid(MW)'} )
xlabel ( 'Time(hrs)' )
legend({'Storage cycles: negative - charging, positive - discharging'})
grid on
xlim([0 24]);
set(gca,'fontsize', 20)
%ylim([-1.5 1.2]);
set(gca,'XTick',[0:1:24])
p1.Marker = 'o';
subplot(4,1,4);
p4=plot(energy_payment_up, 'c', 'LineWidth', 2);
legend({'Hourly Regulation Prices'})
ylabel ( {'mFRR upward'; 'regulation'; 'prices'; '(EUR/MWh)'} )
xlabel ( 'Time(hrs)' )
grid on
xlim([0 24]);
set(gca,'XTick',[0:1:24])
p4.Marker = 'o';
set(gca,'fontsize', 20)
```

G Matlab script for CAES participation in mFRR capacity and energy markets

```
    %profit for the CAES participating in mFRR in DK2.
%mFRR service has two part payment structure:
%availability payment and energy payment
%deducted by compensation to the grid for recharging
%when SoC approaching min DoD
%minus penalty for failing mFRR activation.

% CAES parameters
power_capacity = 5; % MW
power_capacity_discharge=0.00117*power_capacity+power_capacity;
energy_capacity = 20; % MWh
min_energy_capacity=0.3*energy_capacity; %MWh
round_trip_efficiency = 0.55;
self_discharge = 0.0000001; %per hour

% Payment structure
avail_cost=xlsread('MfrrReservesDK2test.xlsx'); %read the content of the
%excel availability (capacity) payment file that contains 8760 rows %EUR/MW/h
availability_payment = avail_cost(:,4); % extract the capacity payment
%values from the second column; %% EUR/MW/h
mfrr_cost=xlsread('upward_downward_prices_DK2_2022_FCR_N.xlsx'); %read the content of
%the excel FCR energy payment file that contains 8760 rows %EUR/MWh
energy_payment_up = mfrr_cost(:,1); % extract the energy payment values for
%up-regulation from the first column; % EUR/MWh

% Load regulation signals data from Excel file
regulation_signals_data = xlsread('MfrrReservesDK2test.xlsx');
upward_regulation = regulation_signals_data(:,3); % extract the upward
%regulation signal values
upward_regulation=0.0167*upward_regulation; %contribution of CAES to upward regulation
%- the percentage from the total procured amound by DK2 is chosen
%based on CAES nominated capacity
downward_regulation = regulation_signals_data(:,1); % extract
%the downward regulation signal values
downward_regulation=0.0167*downward_regulation; %contribution of CAES to downward regulation
%- the percentage from the total procured amound by DK2 is chosen based on CAES capacity


% Initialize the penalty, enery and availability payments
penalty_payment=zeros(8760, 1);
hourly_profit=zeros(8760, 1);
availability_profit=zeros(8760, 1);
energy_profit=zeros(8760, 1);
charging_power=zeros(8760, 1);
discharging_power=zeros(8760, 1);
state_of_charge=zeros(8760, 1);
penalty_power=zeros(8760, 1);
profit=0;

% Initialize the battery state of charge and profit
state_of_charge(1) = energy_capacity; % Assuming CAES starts at 100%
%capacity due to service mostly required for upward regulation
```

```
% Loop through each time step
for t = 1:length(upward_regulation)
    % Calculate charging and discharging power
    if upward_regulation(t) > 0 && state_of_charge(t) > min_energy_capacity
        discharging_power(t) = upward_regulation(t);
        charging_power(t) = 0;
    elseif downward_regulation(t) > 0 && state_of_charge(t) <= energy_capacity
        charging_power(t) = downward_regulation(t);
        discharging_power(t) =0;

    elseif downward_regulation(t)==0 && state_of_charge(t) <= min_energy_capacity
        % Check if energy content needs to be restored
        charging_power(t) = energy_capacity - state_of_charge(t);
        % Charge the CAES from the grid to 100% of its maximum energy capacity
        discharging_power(t) =0;
        undertrig=0;

    else
        charging_power(t) = 0;
        discharging_power(t) = 0;
    end

    % Adjust charging and discharging power for efficiency and self discharge
    charging_power(t) = charging_power(t) / (round_trip_efficiency * (1 - self_discharge));
    discharging_power(t) = discharging_power(t) * round_trip_efficiency * (1 - self_discharge);

    % Compute the energy change and update the state of charge
    energy_change(t) = charging_power(t) - discharging_power(t);
    state_of_charge(t+1) = state_of_charge(t) + energy_change(t);

    % Check if state of charge and energy capacity are within the limits
    if state_of_charge(t+1) > energy_capacity
        % Limit charging to energy capacity
        charging_power(t) = (energy_capacity - state_of_charge(t))
        /(round_trip_efficiency * (1 - self_discharge));
        state_of_charge(t+1) = energy_capacity;
    elseif state_of_charge(t+1) < min_energy_capacity
        % Limit discharging to min energy capacity
        discharging_power(t) = (state_of_charge(t) - min_energy_capacity)
        * (round_trip_efficiency * (1 - self_discharge));
        state_of_charge(t+1) = min_energy_capacity;
    else
    end
% Check if charging & discharging power is within capacity limits
    if charging_power(t) > power_capacity
    % Limit charging power to max power capacity
    charging_power(t) = power_capacity / (round_trip_efficiency
    * (1 - self_discharge));

    elseif discharging_power(t) > power_capacity_discharge
    % Limit discharging power to max power capacity
    discharging_power(t) = power_capacity_discharge
    * (round_trip_efficiency * (1 - self_discharge));

    else
     charging_power(t) =  charging_power(t);
     discharging_power(t)=discharging_power(t);
    end
```

```
% Calculate penalty amount
    if ((upward_regulation(t) > 0 && discharging_power(t) <min(power_capacity_discharge *
    (round_trip_efficiency * (1 - self_discharge)),
    upward_regulation(t)*(round_trip_efficiency * (1 - self_discharge))))
    || (downward_regulation(t) > 0 && charging_power(t) ==0))
    penalty_power(t) = min(power_capacity, upward_regulation(t));


    else
    penalty_power(t)=0;


    end

% Compute the profit for the time step
penalty_payment(t) = availability_payment(t) * penalty_power(t);
availability_profit(t)=availability_payment(t) * power_capacity;
energy_profit(t)=energy_payment_up(t) * discharging_power(t)
- energy_payment_up(t) * charging_power(t);
hourly_profit(t)=availability_profit(t) + energy_profit(t)
- penalty_payment(t);
profit = profit + hourly_profit(t);


end

% Display the total profit and charge
%profit_total=sum(profit, 'all');
avail_total=sum(availability_profit, 'all');
energypaym_total=sum(energy_profit, 'all');
penalty_total=sum(penalty_payment, 'all');
p_chargetotal=sum(charging_power, 'all');
p_dischargetotal=sum(discharging_power, 'all');
p_penaltytotal=sum(penalty_power, 'all');
fprintf('Total profit: $%.2f\n', profit);
fprintf('Total availability payment: $%.2f\n', avail_total);
fprintf('Total energy payment: $%.2f\n', energypaym_total);
fprintf('Total penalty payment: $%.2f\n', penalty_total);
fprintf('Total charge: MW%.2f\n', p_chargetotal);
fprintf('Total discharge: MW%.2f\n', p_dischargetotal);
fprintf('Total penalty power: MW%.2f\n', p_penaltytotal);
%Plot the results
subplot(6,1,1);
p1=plot(state_of_charge, 'r', 'LineWidth', 2);
legend({'CAES State of Charge'})
ylabel ( {'SoC';'(MWh)'} )
xlabel ( 'Time(sec)' )
grid on
xlim([0 48]);
ylim([0 20]);
set(gca,'fontsize', 20)
subplot(6,1,2);
p2=plot(upward_regulation, 'c', 'LineWidth', 2);
p2.Marker = 'o';
legend({'Upward Regulation Signals'})
ylabel ( {'Upward'; '(MW)'} )
xlabel ( 'Time(sec)' )
```

```
grid on
xlim([0 48]);
ylim([0 5.2]);
set(gca,'fontsize', 20)
subplot(6,1,3);
p3=plot(downward_regulation, 'c', 'LineWidth', 2);
p3.Marker = 'o';
legend({'Downward Regulation Signals'})
ylabel ( {'Downward'; '(MW)'} )
xlabel ( 'Time(hours)' )
grid on
xlim([0 48]);
set(gca,'fontsize', 20)
subplot(6,1,4);
p4=plot(charging_power, 'r', 'LineWidth', 2);
p4.Marker = 'o';
legend({'CAES Charging for the recovery of energy content or following downward signals'})
ylabel ( {'Charging';'(MW)'} )
xlabel ( 'Time(hours)' )
grid on
xlim([0 48]);
set(gca,'fontsize', 20)
subplot(6,1,5);
p5=plot(discharging_power, 'r', 'LineWidth', 2);
p5.Marker = 'o';
legend({'CAES Discharging'})
ylabel ( {'Discharging';'(MW)'} )
xlabel ( 'Time(hours)' )
grid on
xlim([0 48]);
ylim([0 5.2]);
set(gca,'fontsize', 20)
subplot(6,1,6);
p6=plot(penalty_power, 'r', 'LineWidth', 2);
p6.Marker = 'o';
legend({'Penalty Power'})
ylabel ( {'Penalty';'(MW)'} )
xlabel ( 'Time(hours)' )
grid on
xlim([0 48]);
set(gca,'fontsize', 20)
```

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