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Profitability Analysis of Long Duration Grid-scale Battery Storage Assets in the Nordic Spot Market and Ancillary Markets

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Abstract

The growing proportion of green energy in the electricity grids brings with it a growing need of grid stabilizing resources to counteract the inherent intermittency of renewable energy resources. This is where the grid scale energy storages come in handy. They efficiently offset the intermittencies of solar, wind etc. resources by energy arbitrage and peak shifting.

This thesis looks into the economic performance of energy storage assets in the Nordic energy markets by analyzing their income potential from the day-ahead market, intraday market and ancillary services market. It tries to assess whether an investment in a battery storage project will be profitable considering various cost and earnings estimates over the lifetime of the battery. The thesis investigates the business cases for batteries of 1-hour, 2-hour, 4-hour and 6-hour duration and also of various technologies, e.g. lithium-ion battery, redox flow battery and sodium-ion battery. It strives to formulate a simple bidding strategy based on the price patterns in various market segments.

After the analysis the study finds out that a battery participating in any one of the mentioned energy markets cannot be profitable. Even a bidding strategy where a battery participates in various markets at various parts of a day is not profitable, given the battery cost and price forecasts available. However, the price forecasts might be inaccurate, therefore a number of sensitivity analyses are performed that gives the price levels that will make the investment profitable.

Among various battery technologies, sodium-ion batteries are found to be most attractive economically, followed by lithium-ion batteries. Moreover, the longer duration batteries are found to be relatively more attractive investment than 1-hour batteries.

Keywords: Energy arbitrage, BESS, Frequency containment reserves, Elspot, Elbas, Bidding strategy

Acronyms

TSO	Transmission System Operator
FFR	Fast Frequency Reserve
FCR	Frequency Containment Reserve
FCR-N	Frequency Containment Reserve - Normal
FCR-D	Frequency Containment Reserve – Disturbance Up and Down
aFRR	Automatic Frequency Restoration Reserve
mFRR	Manual Frequency Restoration Reserve
BESS	Battery Energy Storage Systems
SOC	State of Charge
IRR	Internal Rate of Return
NPV	Net Present Value
APs	Availability payments
kW	Kilowatts
kWh	Kilowatts-hours.
O&M	Operation and Maintenance
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
NREL	National Renewable Energy Lab
PNNL	Pacific Northwest national Laboratory
EBIT	Earnings Before Interests and Tax
EBITDA	Earnings Before Interests, Tax, Depreciation and Amortization
ENTSO-E	European Network of Transmission System Operators for Electricity
CAGR	Compound Annual Growth Rate

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Chapter-1

Introduction

1.1 Context

The impending threat of global warming is triggering a green transformation of the electricity grids worldwide. Presently renewable resources account for roughly one-third of global electricity production (1) but this figure is projected to increase rapidly in the next few decades. Although beneficial for the planet, this trend of power grids becoming more and more renewable-rich brings a set of unique technical challenges. Solar, wind etc. renewable resources have a common drawback: they are intermittent in nature. Hence, their rapid and unexpected fluctuations can cause sudden spikes in the grid frequency and destabilize its normal operation.

One of the most promising solutions to cater this issue is to install more and more grid-scale energy storages. Energy storages are capable of effective frequency regulation by energy arbitrage and peak-shaving. A Battery Energy Storage System (BESS) coupled with a renewable generation has the capability to supply the grid with constant electric power. This is a reason why commissioning of more and more energy storage assets is gaining momentum worldwide. The global grid-scale battery market size is projected to grow from $12.78 billion in 2024 to $48.71 billion by 2032, at an impressive CAGR (Compound Annual Growth Rate) of 18.20% (2). However, to continue such an ambitious growth in storage assets and carry on with attracting investment in this sector it is essential that batteries remain an attractive investment option. As of now, in the Nordic energy market there are mainly two avenues of income from a storage asset. They are: energy arbitrage and providing frequency reserve services.

The revenue from energy arbitrage depends on the price spread of the market, i.e. gap between highest and lowest prices. As more and more energy storages enter the market, potential of making such profit reduces. With more energy storages entering the system, the number of cycles it can operate at maximum load reduces too, which reduces its effective utilization. These phenomena will be discussed a little more elaborately in the later sections. However, this casts a long shadow on the profitability scenario of batteries in the long run.

On the other hand, in most countries, grid-scale energy storage is perceived as a comparatively new segment of the energy market. Therefore market design and optimization of the regulations aiming at the fulfillment of both profitability of the storage assets and the grid discipline are still under development. Whether the earnings from frequency regulation ancillary services can itself be sufficient to support a feasible business case for a battery storage asset is still debatable. Further, estimating the evolution of this income potential over the period of next 10-15 years and comparing it against the cost reduction projections of the batteries make this puzzle a little more complicated. Understandably, assessing the exact value of an energy-storage asset in an energy market over the period of its lifetime is an active field of research.

1.2 Purpose of the study and research questions

The purpose of this master's thesis project is to analyze the profitability of a grid-scale battery storage asset (especially 4-8 hours storage) which participates in energy arbitrage and frequency regulation services in the Nordic day-ahead spot market, intraday market and ancillary market. Which means, the project will attempt to study the price behavior in the mentioned market segments for the last few years and also study some price forecasts to estimate possible revenue flow by bidding in them. An attempt will also be made to prepare a simple bidding strategy. Then a business model will be developed involving these strategies and it will be applied on batteries of various storage durations and various technologies, viz. lithium-ion battery, redox flow battery, sodium-ion battery etc. to find out their feasibility. The final report is expected to help BayWa r.e. in making some strategic bidding/investment decisions.

The following are the research questions for the thesis:

- Which energy market segments have the best revenue potential while bidding with battery storage assets over the period of its lifetime?
- Can a simple bidding strategy be developed for each of these market segments? What should be the overall operational strategy?
- How much might be the Net Present Value (NPV) and internal rate of return (IRR) of BESS projects under most optimistic and most pessimistic scenarios?
- How much 'price spread' is required on average in day-ahead spot market and intraday market to make the investment in BESS projects profitable?
- How does the feasibility of this business model change for various technologies of the battery?
- Which one of the above mentioned battery types is the best fit for 4-8 hours of storage application?

1.3 Methodology

- The study first reviews all the latest information and market regulations available on the Nordic electricity markets.
- Then historical market data for the period of 2017-2023 are collected from various resources. The thesis also uses a set of confidential market price forecasts received from Baywa r.e.
- Next, detailed statistical data analysis of past and forecasted future market prices are performed to find out any useful pattern and assess the profitability of storage assets in the Nordic energy market for the coming years. For this data analysis Python-codes are used.
- Further an excel-based business case file is prepared to execute the financial feasibility analysis of the BESS system. The profit quantum as calculated from the Python codes are put as inputs into the business case file. Also, battery cost figures as found from literature survey are put into the business case as another set of inputs. The business case file mainly calculates the net-present-value (NPV) and internal rate of return (IRR) for various scenarios to do the economic analysis.
- At the end, the study performs a few more data analyses to calculate the sensitivity of the business model with respect to various parameters.

  Chapter 3 and 4 will discuss in more details the various stages of the method followed.

1.4 Scope and Limitations

The project assumes a battery storage system of 1 MW capacity commissioned in the SE4 bidding zone of Sweden in 2024 to participate in day-ahead spot market, intraday market and frequency reserve markets to earn profits over its lifetime. It assumes that the battery always fulfils all technical conditions of providing FCR-N, FCR-D and FFR.

The thesis studies the business cases for 1-hour, 2-hour, 4-hour and 6-hour batteries of the same 1 MW rating. Also, it compares profitability of lithium-ion battery, sodium-ion battery and redox flow battery of the mentioned ratings. The reason for choosing these three technologies is explained in section 2.3. In the business case modelling, discount rate of 7% is applied as per consultation with Baywa r.e. executives.

Following are the delimitations of the study:

- The study only looks into energy arbitrage between different hours of a single day. It does not take into account energy arbitrage in between two consecutive days, or between the weekdays and the weekend; or between two different market segments, e.g. day-ahead and intraday markets.
- Among various frequency reserve products, the study mainly looks into FCR-N and FCR-D as investment vehicles. It avoids the mFRR and aFRR due to bid size constraints (minimum bid size requirement of 5 MW and 1 MW respectively). It also abstains from detailed analysis of FFR as this product is rarely activated and a business model cannot be planned relying on it.
- The project does not model the battery degradation and goes deep into the life cycle implications of the battery participating in various markets. The thesis assumes battery degradation to be negligible.
- While calculating revenue from frequency reserve market, the study does not consider the energy payment of the FCR-N into account. The underlying reason is the finding from various literature reviews that the energy payments are only a very small fraction of the net income from the frequency reserve market (3) (4).
- This study does not employ multi-stage stochastic optimization technique to simulate the exact bidding behavior.
- The project does not consider the energy management strategies of the battery for optimum functioning.
- The study quantifies a simplistic bid acceptance probability in frequency reserve markets by analyzing the historical traded volumes and applies it on future forecasted prices. Although it is known from (5) that FCR-D has undergone a changeover from a pay-as-bid market product to a pay-as-clear product and the past traded volume behavior might not be exactly representative of the future cleared volume behavior; it has been done for the purpose of simplicity.
- The study does not take into consideration the variable cost of feeding in electricity into the grid.

Chapter-2

Theoretical Background

2.1 The Nordic Power System and Electricity Market

2.1.1 Synchronous Areas and Electricity Trading Zones

The Nordic power system is one of the five interconnected systems of Europe that fall under ENTSO-E. These interconnected power grids are also called synchronous areas (SA), as the grid frequency is same all over the area. These are: the Continental Europe Area, the Nordic Area, the Baltic Area, the United Kingdom Area, and the Ireland Area as shown in Fig. 1.

Figure 1 The five synchronous areas of Europe (5)

Within the Nordic area, there are four TSOs (Transmission System Operators), who look after their parts of the electricity grid. They are: Svenska Kraftnät of Sweden, Statnett of Norway, Fingrid of Finland and Energinet of Denmark. TSOs are the apex bodies for maintaining energy balance, energy scheduling, outage coordination and grid discipline within their control area.

Now, if we go within the country of Sweden, the power system is organized in three layers. The high voltage transmission grid is owned and operated by the TSO, Svenska Kraftnät. It mainly consists of 400kV and 220 kV lines of total length more than 15000 kms. Whereas, the distribution grid is owned and controlled by a number of DSOs (Distribution System Operators). The DSOs can again be divided into two groups: regional and local DSOs, operating on different voltage levels. There are mainly four DSOs who own and maintain the regional distribution grid consisting of 10-20 kV lines. They are: Vattenfall, E.ON Sverige, Fortum Power and Heat and Skellefteå Kraft. Other than them there are a number of local DSOs looking after the low-voltage network (6).

Next, if we look at the electricity market side, electricity is traded on the common marketplace of Nord Pool for all 16 countries of the whole Nordic and Baltic region. Presently, there are mainly four types of electricity markets: the day-ahead market (Elspot), the intra-day market (Elbas), the frequency regulation market and the balancing market. Nord Pool acts as the market operator for the day-ahead and intraday markets, whereas the TSOs are responsible for the latter two.

The whole Nordic region is divided into a number of electricity trading zones as shown in Fig. 2. The price of electricity can differ among these zones because of transmission constraints present in the power system. For example, Sweden is divided into four trading areas: SE1 and SE2 in the north; SE3 and SE4 in the south.

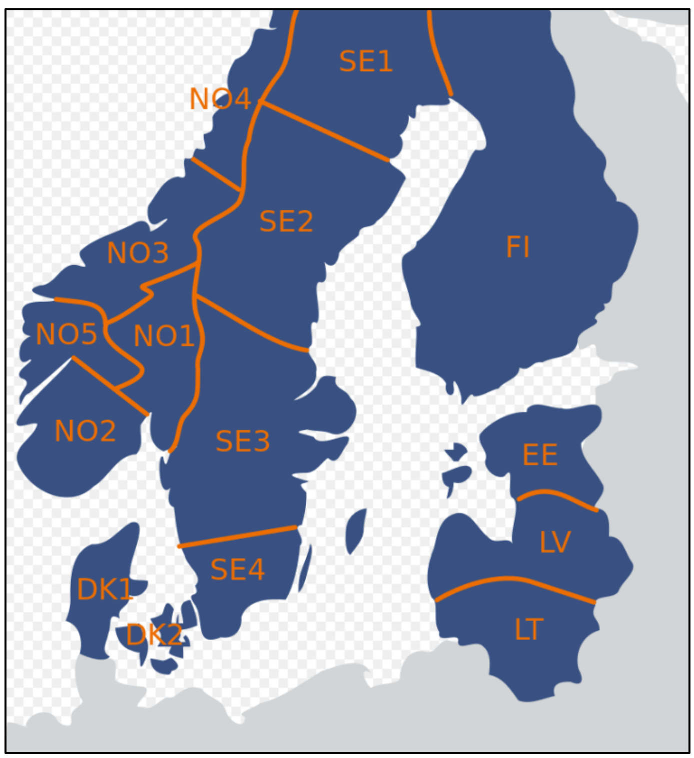


Figure 2 Electricity Trading Zones of the Nordic Area (7)

As more generation is concentrated in the Northern part of the country and main load centers are in the South, generally electricity prices are higher in SE3 and SE4 compared to the rest of two.
Here, Denmark is split into two synchronous areas, DK1 being a part of the Central European synchronous area and DK2 a part of the Nordic synchronous area.

Next, we will discuss about various electricity markets in brief.

2.1.2 Day ahead Market (Elspot)

The day ahead market contains the maximum bulk of electricity trading. It opens 36 hours before the start of the day of delivery and bids must be submitted no later than 12:00 hrs. on the day before delivery. There is a daily auction for all the hours of the following day, where bidders have to declare the amount of energy they wish to buy or sell and at what price. Then, aggregated demand and supply curves are created for each hour to calculate the system price for each hour. Now, all the participants whose bids were cleared must pay/accept the same system price irrespective of their bidding prices(7). This is called marginal price based bidding. Since 2014, Sweden has been part of a European collaboration with the goal of creating a common European day-ahead market. The project is called SDAC, short for Single Day-Ahead Coupling.

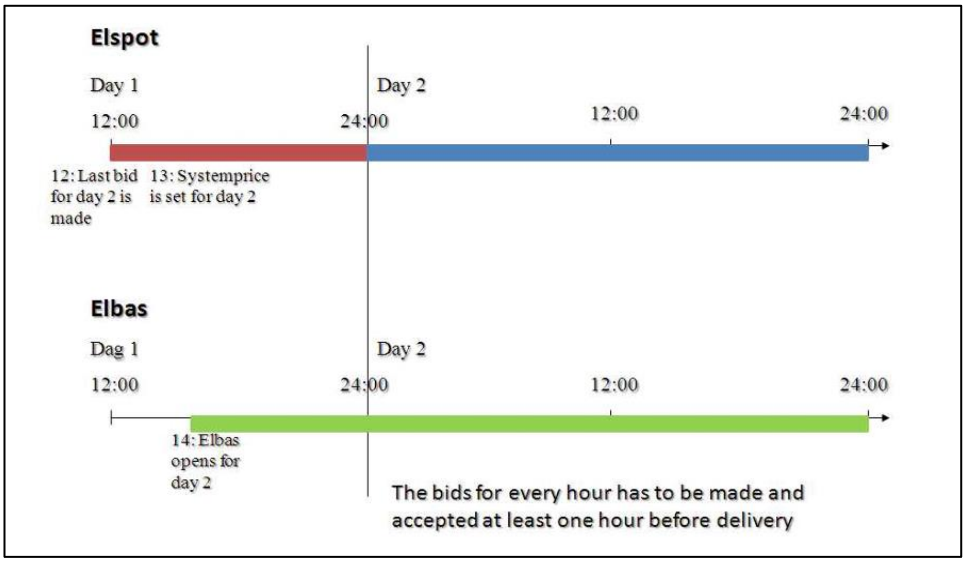


Figure 3 Timelines of Elspot and Elbas markets (9)

2.1.3 Intraday Market (Elbas)

After closing of the day-ahead market, another market starts within each electricity area, called the intraday market (Elbas). Here, a continuous trade takes place from 14:00 hrs. the day before until one hour before the delivery hour. The TSOs provide the capacities for the intraday market from the flow results of the day-ahead market. The prices for this market are set on the first-come first- served principle through a continuous matching between sell and buy offers, so-called ‘pay-as-bid’. The lowest sell price and highest buy price are used to calculate the best prices. The intraday market Elbas was introduced in 1999 to facilitate the adjustment of traded volumes during the time between the day ahead market and the delivery hour.

Although traditionally the purpose of the intraday market has been to enable the adjustment of imbalances between forecasted and actual production/consumption; with the growing share of renewable energy sources in the grid, the intraday market is gaining an expanded purpose of physical trading closer to the actual time of delivery. In 2018, the new cross-border European intraday market SIDC (Single Intraday Coupling) was introduced, which means better opportunities for cross-border trading between bid areas.

There is a plan of starting 'pay-as-clear' auctions in addition to continuous trading in the Elbas market from 13th June, 2024. Three intraday auctions will occur at 15:00 hrs. of (D-1), 22:00 hrs. of (D-1) and 10:00 hrs. of D. Here, 'D' signifies the delivery day and (D-1) means the day before the delivery. Fig. 4 shows the proposed process.

The intraday auctions are expected to facilitate fairer distribution of transmission capacity, better price signal and valuation of transmission capacity (8)

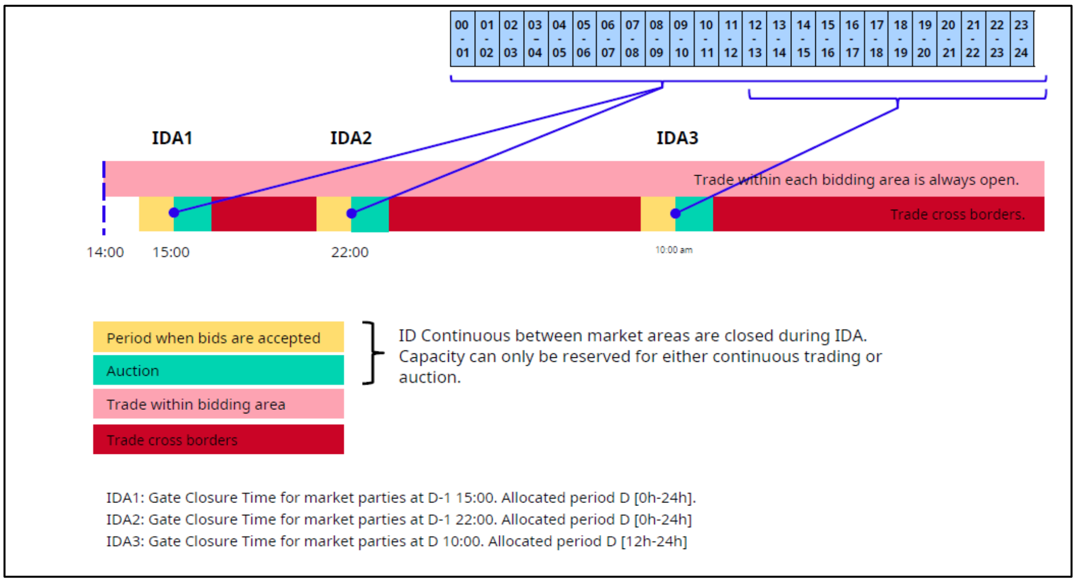


Figure 4 Proposed Methodology of Intraday Market Auction (10)

2.1.4 Frequency Reserve Market

To keep the power grid balanced, the TSOs need several reserve products for different purposes. Some products are responsible for stopping (containing) a frequency fall or rise in case of a disturbance, while others are to restore the frequency back to 50 Hz after a disturbance. Fig. 5 shows various reserve products in case of a disturbance.

2.1.4.1 FFR

In case of any frequency fall, the FFR acts as the primary reserve. It activates automatically within 1.3 seconds of the frequency drop and its magnitude for the Swedish system can go up to 100 MW. The purpose of FFR is generally to handle the initial rapid and transient frequency deviations that can occur in case of low levels of inertia in the Nordic power system. The FFR was initiated only 3 years ago by the TSOs (May, 2021).

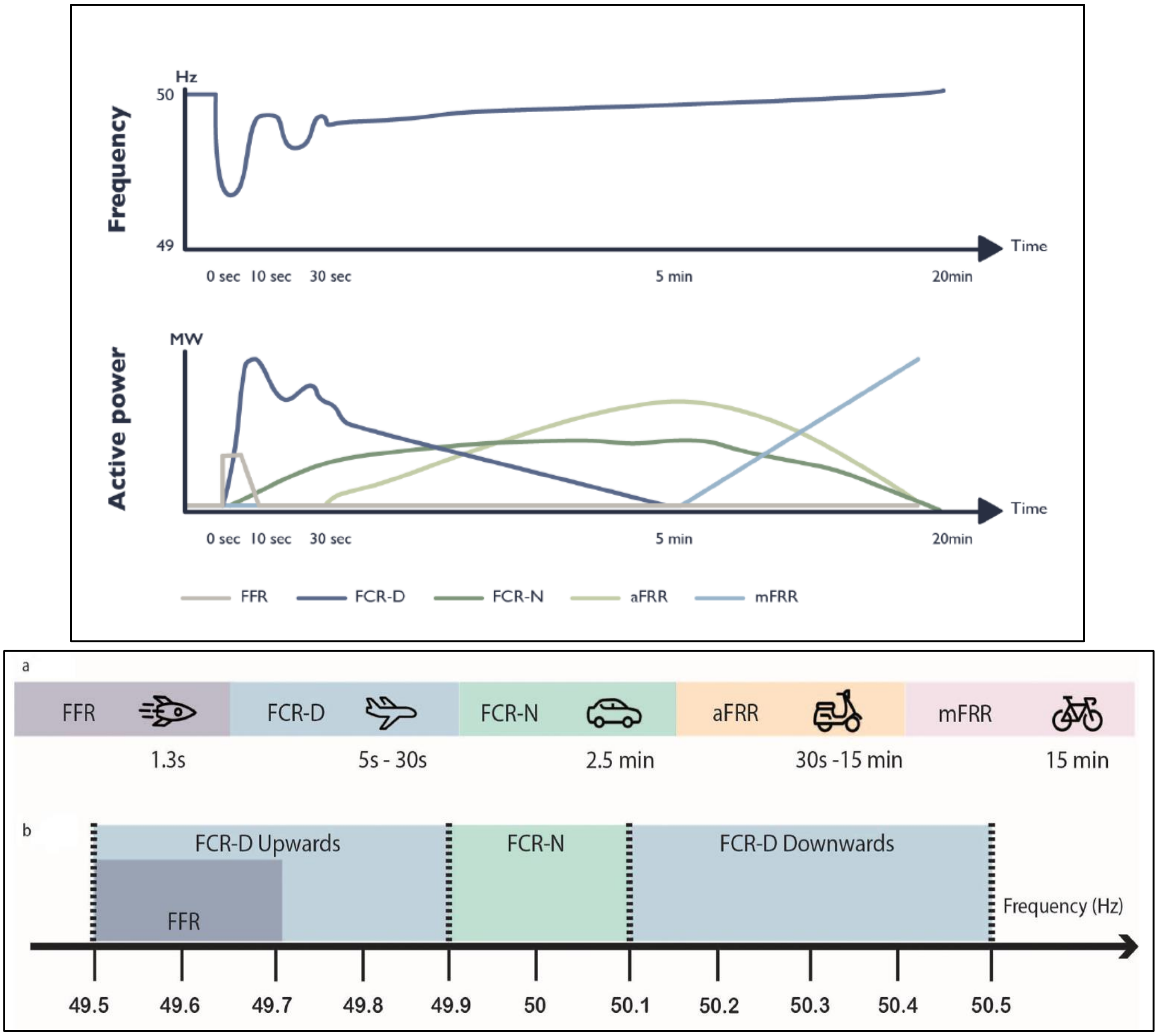


Figure 5 Various frequency Reserve Products according to time and frequency of activation (3,11)

FFR is procured on national capacity markets and the market setup varies between the Nordic countries. The energy volumes for FFR are low and there is no remuneration for activated FFR energy.

In Sweden procurement of FFR is done on yearly basis where providers state their capacity and bid price for each season. Then the actual procurement of needed capacity is done twice a week based on the inertia forecast. The Swedish FFR market is an hourly market with minimum bid size of 0.1 MW. The auctions have marginal pricing system (5). Endurance requirements for FFR providers are mentioned in Fig. 8.

2.1.4.2 FCR-N

The Frequency containment reserve for Normal Operation (FCR-N) is a symmetric product that is linearly activated when frequency varies between 49.9 Hz -50.1 Hz. Its main purpose is to counteract the continuous frequency deviations during normal operation. The same volume for up or down regulation should be offered during the bidding, so this service is called a symmetrical product.

The FCR-N is activated automatically. The Eastern part of Denmark (DK2) and Sweden have a common market for FCR-N capacity, which is an hourly market split into two auctions. One auction occurs before the day-ahead market and another one after it (Fig. 6). These auctions were pay-as-bid previously but now it is marginal price based.

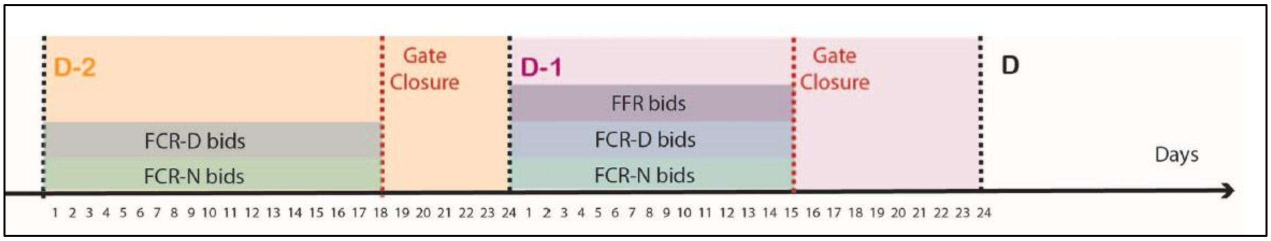


Figure 6 Timelines of FFR, FCR-N and FCR-D auctions. Here 'D' means the Delivery Day (3)

The m-FRR price is used as the energy price of FCR-N, i.e. activated energy for FCR-N up regulation is compensated with m FRR up regulation price and activated energy for down regulation is compensated with m FRR down regulation price. The activation energy of FCR-N is calculated with the droop control equation.

2.1.4.3 FCR-D Up and Down

FCR-D is used to contain the fall or rise of the frequency, if it goes outside the normal band (49.9-50.1 Hz). Contrary to FCR-N, FCR-D providers are only compensated for the capacity and there is no energy compensation for the activated energy. FCR-D Down was introduced quite recently in January, 2022. Here too, DK-2 and Sweden have a common hourly market split into two auctions as shown in Fig. 6. The logic and magnitude of FCR-D activation are shown in Fig. 7.

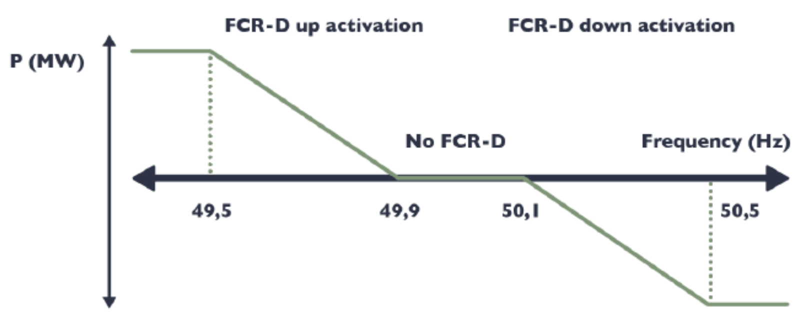
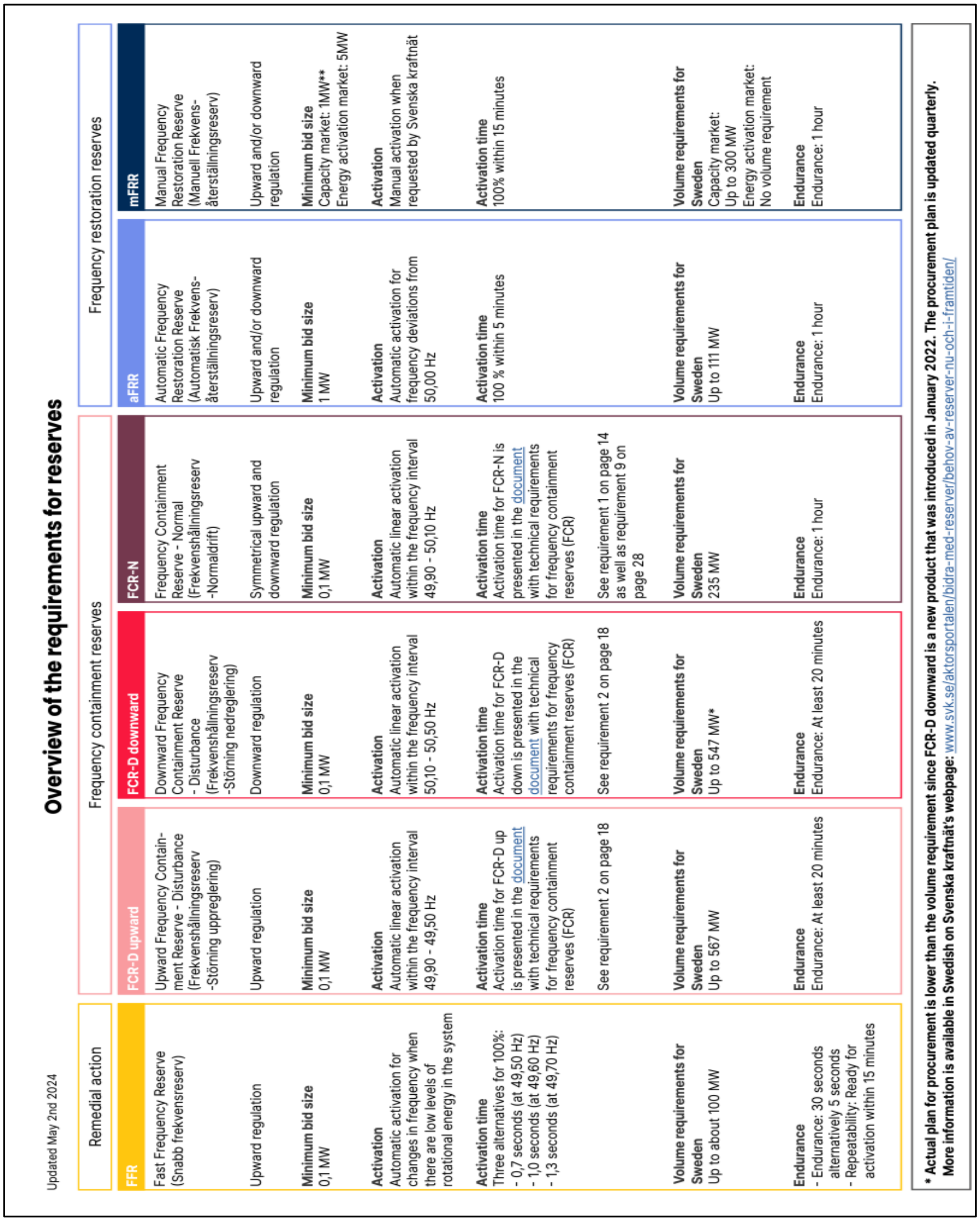


Figure 7 Activation logic of FCR-D (11)



Updated May 2nd 2024

Overview of the requirements for reserves

Remedial action	Frequency containment reserves			Frequency restoration reserves	
FFR	**FCR-D upward**	**FCR-D downward**	**FCR-N**	**aFRR**	**mFRR**
Fast Frequency Reserve (Snabb frekvensreserv)	Upward Frequency Containment Reserve - Disturbance (Frekvenshållningsreserv -Störning uppreglering)	Downward Frequency Containment Reserve - Disturbance (Frekvenshållningsreserv -Störning nedreglering)	Frequency Containment Reserve - Normal (Frekvenshållningsreserv -Normaldrift)	Automatic Frequency Restoration Reserve (Automatisk Frekvens-återställningsreserv)	Manual Frequency Restoration Reserve (Manuell Frekvens-återställningsreserv)
Upward regulation	Upward regulation	Downward regulation	Symmetrical upward and downward regulation	Upward and/or downward regulation	Upward and/or downward regulation
Minimum bid size 0,1 MW	**Minimum bid size** 0,1 MW	**Minimum bid size** 0,1 MW	**Minimum bid size** 0,1 MW	**Minimum bid size** 1 MW	**Minimum bid size** Capacity market: 1MW** Energy activation market: 5MW
Activation Automatic activation for changes in frequency when there are low levels of rotational energy in the system	**Activation** Automatic linear activation within the frequency interval 49,90 - 49,50 Hz	**Activation** Automatic linear activation within the frequency interval 50,10 - 50,50 Hz	**Activation** Automatic linear activation within the frequency interval 49,90 - 50,10 Hz	**Activation** Automatic activation for frequency deviations from 50,00 Hz	**Activation** Manual activation when requested by Svenska kraftnät
Activation time Three alternatives for 100%: - 0,7 seconds (at 49,50 Hz) - 1,0 seconds (at 49,60 Hz) - 1,3 seconds (at 49,70 Hz)	**Activation time** Activation time for FCR-D up is presented in the document with technical requirements for frequency containment reserves (FCR) See requirement 2 on page 18	**Activation time** Activation time for FCR-D down is presented in the document with technical requirements for frequency containment reserves (FCR) See requirement 2 on page 18	**Activation time** Activation time for FCR-N is presented in the document with technical requirements for frequency containment reserves (FCR) See requirement 1 on page 14 as well as requirement 9 on page 28	**Activation time** 100 % within 5 minutes	**Activation time** 100% within 15 minutes
Volume requirements for Sweden Up to about 100 MW	**Volume requirements for Sweden** Up to 567 MW	**Volume requirements for Sweden** Up to 547 MW*	**Volume requirements for Sweden** 235 MW	**Volume requirements for Sweden** Up to 111 MW	**Volume requirements for Sweden** Capacity market: Up to 300 MW Energy activation market: No volume requirement
Endurance - Endurance: 30 seconds alternatively 5 seconds - Repeatability: Ready for activation within 15 minutes	**Endurance** Endurance: At least 20 minutes	**Endurance** Endurance: At least 20 minutes	**Endurance** Endurance: 1 hour	**Endurance** Endurance: 1 hour	**Endurance** Endurance: 1 hour

*** Actual plan for procurement is lower than the volume requirement since FCR-D downward is a new product that was introduced in January 2022. The procurement plan is updated quarterly. More information is available in Swedish on Svenska kraftnät's webpage:** www.svk.se/aktorsportalen/bidra-med-reserver/behov-av-reserver-nu-och-i-framtiden/

Figure 8 Summary of various Ancillary Services as available in Svenska Kraftnät Website (12)

2.1.4.4 a-FRR and m-FRR

The automatic frequency restoration reserve or aFRR is automatically activated when the frequency deviates from 50 Hz. It is an asymmetrical product, therefore a-FRR up and down are used for up and down regulations respectively. Its activation is initiated by the control signal sent in every 10 seconds by the TSO, who purchases aFRR in advance. Minimum bid size in the aFRR market is 1 MW.

The mFRR service has the same purpose as the aFRR except that this service is activated manually upon the direction of TSOs and has longer activation time. It is a symmetric product. There are separate mFRR capacity markets in national level. Sweden has recently implemented its mFRR capacity market in October 2023. All these capacity markets have a marginal pricing method. On the other hand, the whole Nordic region has a common m FRR energy activation market where the pricing method is pay-as-clear. The gate closure time for submitting the offers is 45 minutes before the delivery hour. The TSOs choose offers in price order and send activation requests electronically to the market participants. mFRR energy activation market is the last open reserve market before the delivery hour starts.

2.1.5 Pay-as-bid and Pay-as-clear Mechanisms

In general, there can be two types of market clearing. Pay-as-bid or continuous trading and Pay-as-clear or marginal-price based trading. Both of them are explained below.

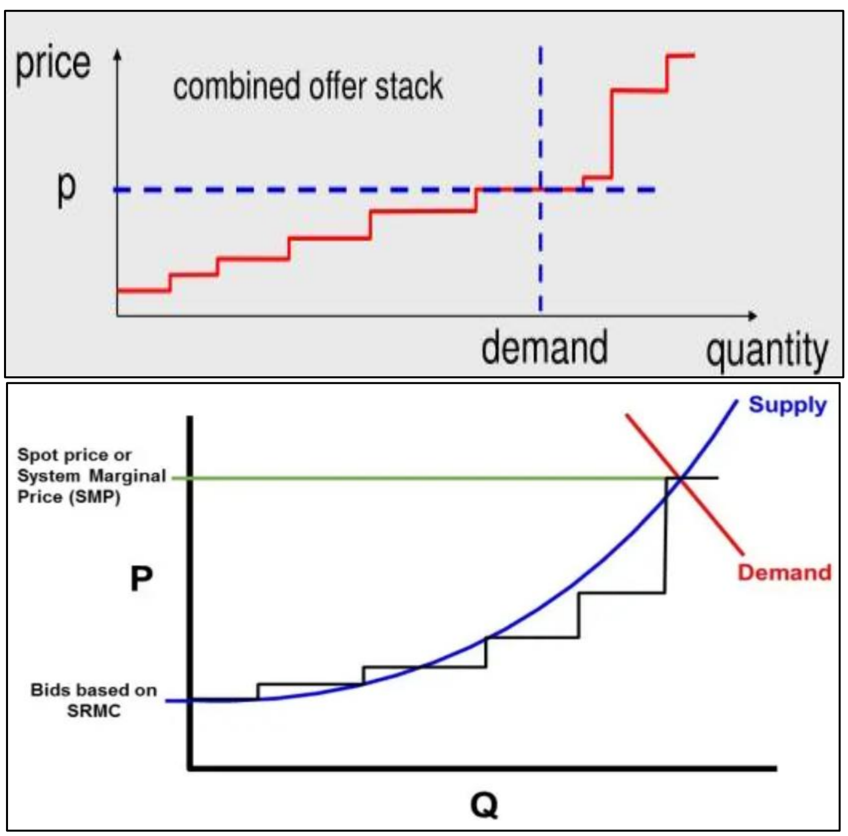


Figure 9 a. Pay-as bid mechanism (9) vs. **Figure 9 b.** Pay-as-clear mechanism (10)

As can be seen in Fig, 9.a, the red line gives supply curve with ‘merit order’, i.e. products of the least price are sold first, followed by more costly items. The demand curve here is assumed to be ideally inelastic, i.e. the demand remains same whatever be the price. In pay-as-bid mechanism, participants receive the corresponding bidding prices, i.e. sellers are paid with the price they asked for. However, if they ask too high a price that is out of the merit order, their bid does not get accepted.

On the other hand, in case of pay-as clear mechanism, all the participants are paid with the market clearing price (MCP), not their individual bidding prices. In Fig. 9.b this is referred to as spot price or system marginal price (SMP).

In a pay-as-bid mechanism participants have an incentive to bid at the price of the most expensive offer that is expected to be cleared. Therefore, in order to maximize their profit, they should bid at a price more than their short-run marginal cost (SRMC). Here, ‘marginal cost’ can be defined as the additional cost to be incurred for production of one more unit of electricity. However, they cannot bid too high, or there is a risk of their bid not getting accepted. So, in pay-as-bid mechanism, the strategy of the participants is a little bit complex.

In pay-as-clear mechanism however, the participants are automatically awarded the most expensive offer accepted, so there is an incentive to bid only at their short-run marginal cost. One needs to bid enough to cover his/her costs, and the market determines if there is a possibility of surplus profit depending on the market condition. Therefore, the strategy for participants becomes quite straight forward here (11).

2.2 Ways of revenue generation by the battery

2.2.1 Energy Arbitrage

In order to understand how a battery can generate income from energy arbitrage let us assume a random day with spot market energy prices as shown (Fig. 10). The vertical axis gives electricity price in Euro/ kW and the horizontal axis gives hours of a day. If we take a battery of 1 kW/ 1 kWh capacity that gets charged from the grid by buying electricity at point A and stores it for 5 hours. Then it sells the same amount of electricity at point B by discharging into the grid. Just by this activity, the battery earns Euro 2175, i.e. the difference of prices at these two points. This is called energy arbitrage and batteries can earn by this technique using price difference at different points of time.

The charging at point A and discharging at point B complete one cycle of the battery operation. The battery can operate more than one cycle per day in order to increase daily income. For example at point B the battery is fully discharged, therefore it can again get charged at point C and discharge that energy at D. Here, the battery is operating two cycles a day. In this way, depending on the price profile the battery can operate a number of cycles per day.

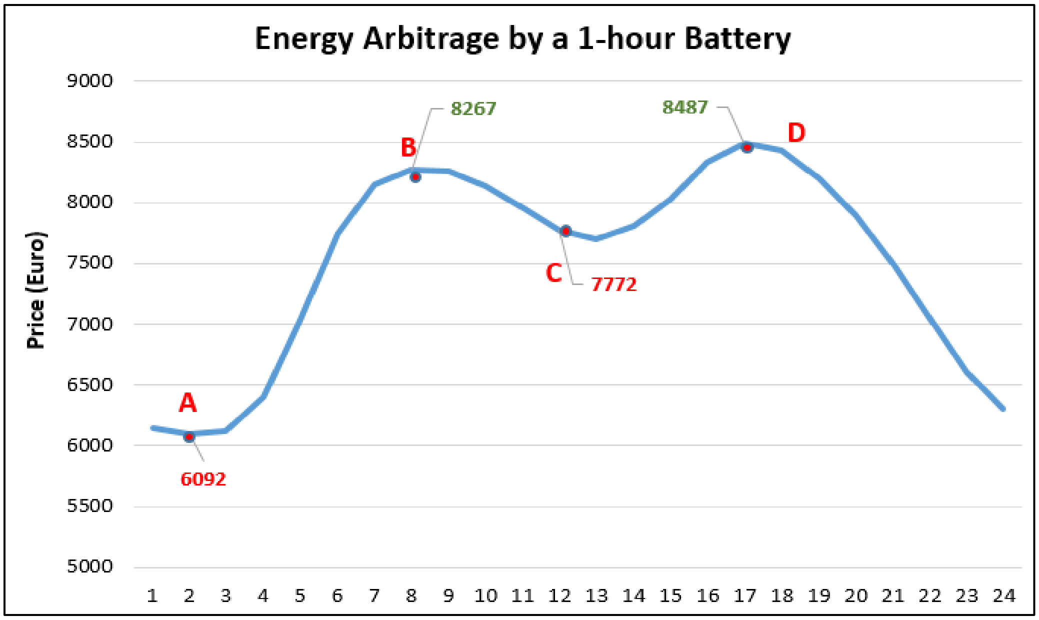


Figure 10 Energy Arbitrage by a 1-hour Battery (13)

Next, if we assume a 4-hour battery operating under the same price-conditions (Fig.11), it charges during the cheapest 4 hours, i.e. hours 1-4 and discharges during the costliest 4 hours, i.e. 7-10 hours. Here the average buying price becomes 6189 Euro (the average of hours 1-4) which is greater than the 1-hour battery buying price and average selling price becomes 8203 Euro, which is less than the 1-hour battery selling price. So it is easily understandable here that the average per kWh income reduces in a 4-hour battery compared to a 1-hour battery, although the total income is more in a 4-hour battery. This happens because

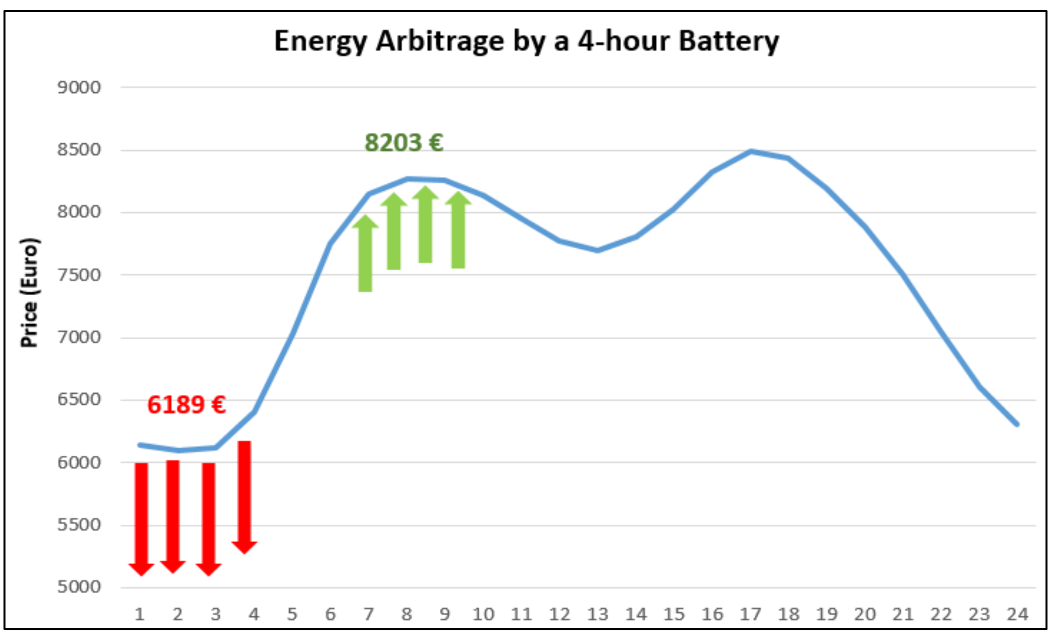


Figure 11 Energy Arbitrage by a 4-hour battery

a 1-hour battery picks the cheapest and the costliest hour for buying and selling respectively, whereas a longer duration battery averages out the buying and selling prices.

The battery state of charge (SOC) in case of Fig. 11 operation is as follows. It is assumed here that the battery is fully discharged at the start of a day. Therefore it is 25% charged at the end of 1st hour and by the end of 4th hour the battery is fully charged. Similarly it gets discharged during hours 7-10 and returns to the initial fully discharged condition.

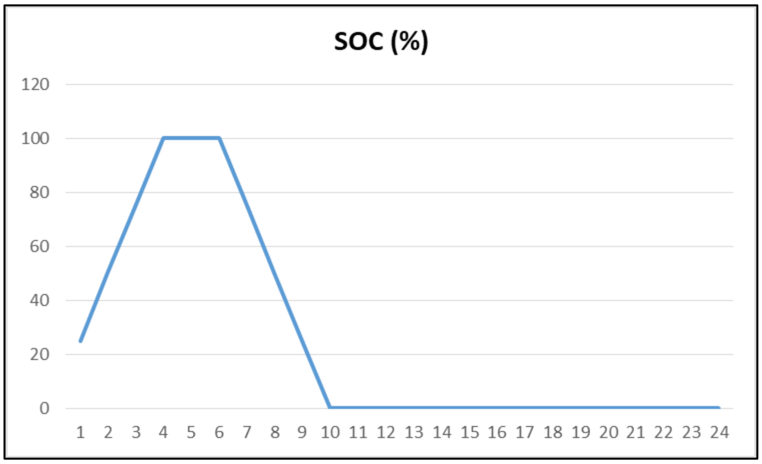


Figure 12 SOC of the 4-hour Battery operation as shown in Fig. 11

It is evident from Fig. 10 and 11 that income from price arbitrage will depend on the 'price-spread' or price-gap between the two points of buy and sell. Now, Fig. 13 shows what happens with the price-spread if new storage assets enter the market. The vertical axis represents price and horizontal axis represents quantity of

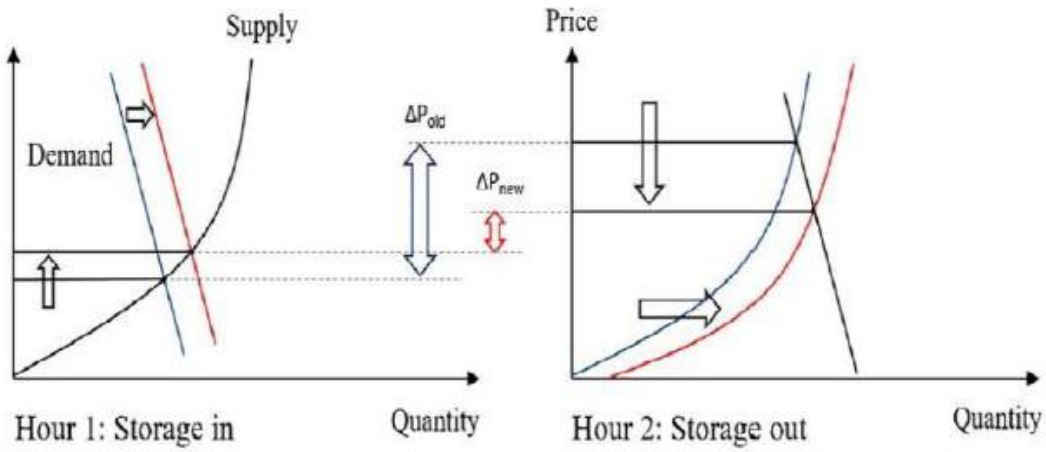


Figure 13 The effect of more storages on the 'price-spread' (13)

power. It is assumed that the supply curve is convex and where it cuts the demand curve, it gives the market clearing price. On the left graph, when a battery is getting charged, i.e. buying from the market, it is adding to the aggregate demand curve. That is why the aggregate demand increases and the demand curve is shifting to the right (the red line). As a result the new price is more than the old one. On the other hand, when the battery is discharging into the grid, it adds up to the aggregate supply curve. As a result the supply curve shifts to the right and resulting new price is lower than the previous price. By combined effect of these two phenomena the new price gap (in red) becomes less than the old one (in blue).

It explains the fact that in case of lots of storage assets entering into a particular market, the profitability from energy arbitrage reduces.

2.2.2 Ancillary Services

There are several types of ancillary services provided by energy storage assets. Fig. 14 shows various types of ancillary services, divided into the short-term and long-term services.

The focus of short-term ancillary services is to compensate for real-time demand and production imbalances. Apart from more commonly known frequency regulation, grid-scale energy storage projects can significantly help in the black start. Grid-scale batteries can significantly help in voltage support too, as they can act both as a generator and load. Energy storages connected at the overdrawing nodes can start discharging and those connected at the under-drawing nodes can start charging from the grid. By this they can help in voltage control.

Over a longer duration, energy storages have the capacity to peak-shave the load profile, therefore reducing the necessity of reserves. Also, it can help in transmission and distribution system upgradation deferrals.

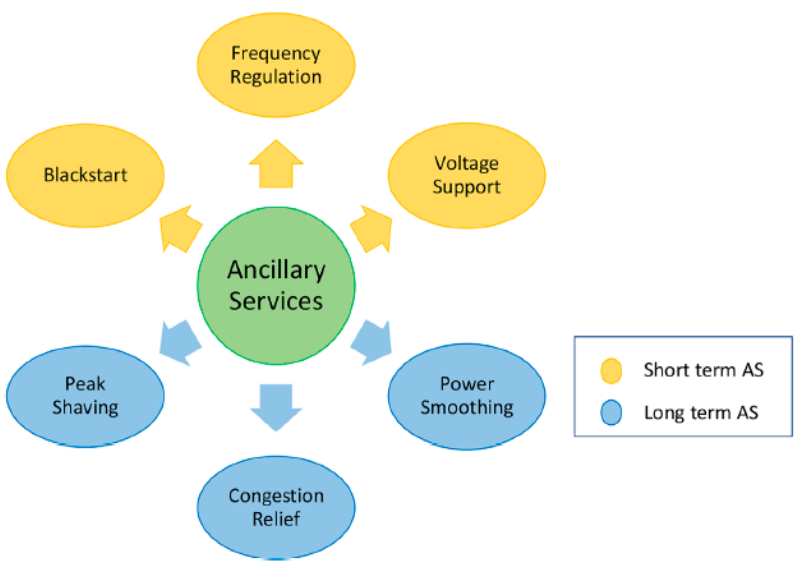


Figure 14 Types of Ancillary Services provided by a Storage Asset (14)

All these services are extremely necessary for optimum and reliable functioning of the grid. Therefore, all of them can be monetized, given there are adequate regulatory instruments present. In the Nordic system, batteries can earn mainly from frequency regulation ancillary services.

2.3 BESS System Components

A typical BESS system looks as the following (Fig. 15).

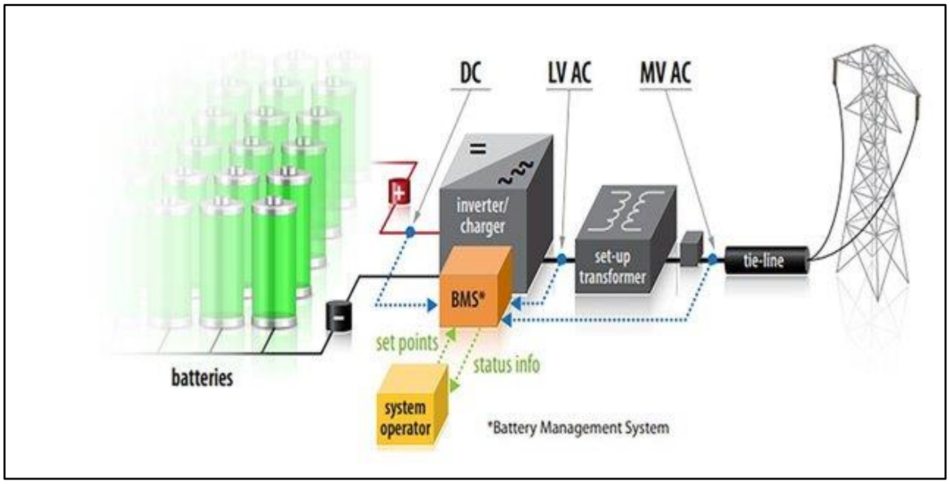


Figure 15 Key Components of a BESS system (12)

It is composed of the battery modules, a transformer, a battery management system (BMS), power conversion system (PCS), energy management systems (EMS) and protection systems. The transformer steps up the voltage for connection to the transmission grid. The BMS system monitors and manages the battery cells ensuring optimal performance, safety, and longevity. It balances the charge across cells, monitors the temperature and protects against deep discharge, overcharging or short circuits. The power conversion system (PCS) includes inverters and converters that convert direct current (DC) from the batteries to alternating current (AC) for grid use or the vice versa. The energy management system (EMS) manages the overall operation of the BESS, optimizing the charge and discharge cycles. It also integrates the BESS with other energy systems like renewable generation units, the grid, or other storage units. Apart from these, there are some relays and fault detection systems to prevent hazardous situations.

2.4 Comparison of Different Battery Technologies

At the moment, Li-ion batteries are by far the most popular and widespread technology of battery storage with global energy storage market share of more than 95% at 2022 (13). Considering the current price, supply chain, project scale and technological maturity, non-lithium-ion batteries are undoubtedly unable to compete with lithium-ion batteries. Additionally, the falling price of lithium has removed the investment incentives in alternative technologies.

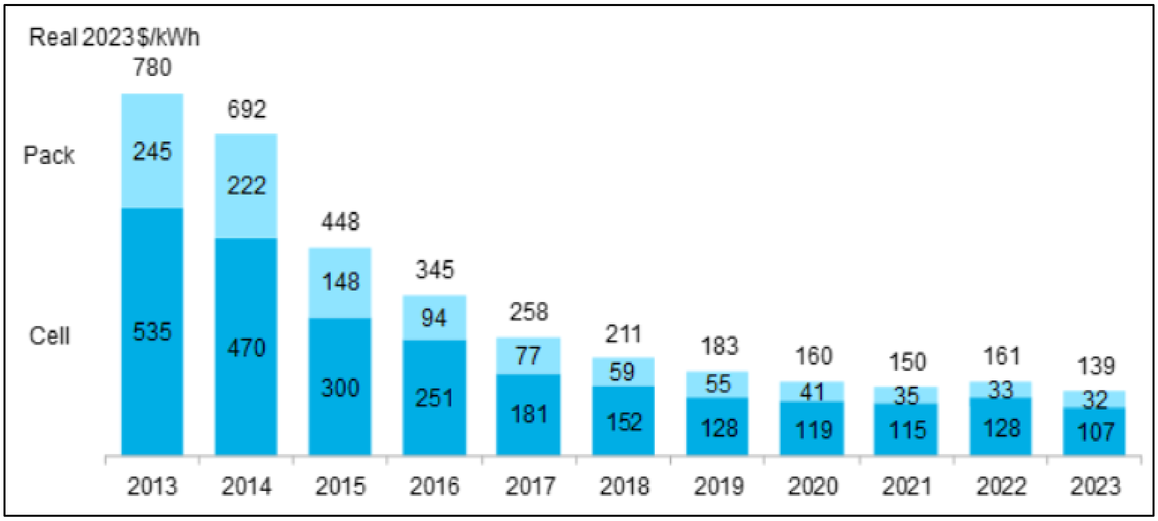


Figure 16 Falling Price of Li-ion Batteries (16)

Still, a number of technologies are emerging as alternatives to Lithium in the backdrop of extreme projected battery demand in near future and sustainability issues associated with lithium-mining. Some of them are: sodium-ion battery, zinc battery, iron-air battery, iron-flow battery, vanadium redox-flow battery, sodium Sulphur battery etc. Each of them has diverse set of advantages and disadvantages with respect to lithium batteries.

However, among them, the vanadium flow battery is the most commercialized and widely deployed worldwide. As of 2022, vanadium redox flow batteries constitute roughly 93% of all non-lithium batteries worldwide (13) and 60% of them are concentrated in China. Due to their long cycle life, they are especially suitable for long-duration storage applications. This is another reason why it is interesting for this thesis. As per (13), the annual production rate of vanadium redox batteries should touch the impressive mark of 123 GWh by 2032, which will be roughly 13% of global battery production at that time.

Another technology whose supply chain is developing impressively because of its cheap raw materials and diverse applications is sodium-ion battery. As of 2023, the installed capacity of sodium ion battery worldwide is 42 GWh, roughly 95% of which are concentrated in China. This capacity is projected to be 186 GWh by 2033 (14).

Because of their impressive potential in the coming years, only vanadium redox-flow battery and sodium-ion battery are picked among the non-lithium batteries for this thesis. Their chemistry and properties are discussed briefly in the next paragraphs.

- **Lithium-ion Battery**

By Li-ion battery we actually mean a diverse family of batteries with different chemistries. Generally, as the cathode a compound of Lithium is used and graphite is used as anode. Some common Li-ion batteries are Lithium Cobalt-Oxide battery (LCO), Lithium Manganese Oxide battery (LMO), Lithium Iron Phosphate (LFO) batteries, Lithium Nickel Manganese Cobalt Oxide (NMC) batteries, Lithium Titanate Battery (LTO) etc. The following figure summarizes chemical reactions for various types of Li-ion batteries.

Chemical name	Chemical Reaction at Cathode	Chemical Reaction at Anode	Overall Reaction
LCO($LiCoO_2$)	$CoO_2 + Li^+ + e^- \leftrightarrow LiCoO_2$	$LiC_6 \leftrightarrow C_6 + Li^+ + e^-$	$LiCoO_2 + C_6 \leftrightarrow LiC_6 + CoO_2$
LMO($LiMn_2O_2$)	$MnO_2 + Li^+ + e^- \leftrightarrow LiMnO_2$	$LiC_6 \leftrightarrow C_6 + Li^+ + e^-$	$LiCoO_2 + C_6 \leftrightarrow LiC_6 + CoO_2$
NCA($LiNiCoAlO_2$)	$NiCoAlO_2 + Li^+ + e^- \leftrightarrow LiNiCoAlO_2$	$LiC_6 \leftrightarrow C_6 + Li^+ + e^-$	$LiCoO_2 + C_6 \leftrightarrow LiC_6 + CoO_2$
NMC($LiNiMnCoO_2$)	$NiMnCoO_2 + Li^+ + e^- \leftrightarrow LiNiMnCoO_2$	$LiC_6 \leftrightarrow C_6 + Li^+ + e^-$	$LiCoO_2 + C_6 \leftrightarrow LiC_6 + CoO_2$
LFP($LiFePO_4$)	$FePO_4 + Li^+ + e^- \leftrightarrow LiFePO_4$	$LiC_6 \leftrightarrow C_6 + Li^+ + e^-$	$LiCoO_2 + C_6 \leftrightarrow LiC_6 + CoO_2$
LTO($LiTiO_3$)	$4Mn_2PO_4 + 4Li^+ + 4e^- \leftrightarrow 4LiMn_2O_4$	$Li_4Ti_5O_{12} + 4Li^+ + 4e^- \leftrightarrow 4LIMn_2O_4$	$4Mn_2O_4 + Li_4Ti_5O_{12} \leftrightarrow 4LiMn_2O_4 + Ti_4O_{12}$

Figure 17 Chemical Reactions at Various types of Lithium-ion Batteries *(15)*

The following figure gives comparison of performance of these technologies based on specific energy, C-rate, lifespan, safety and cost.

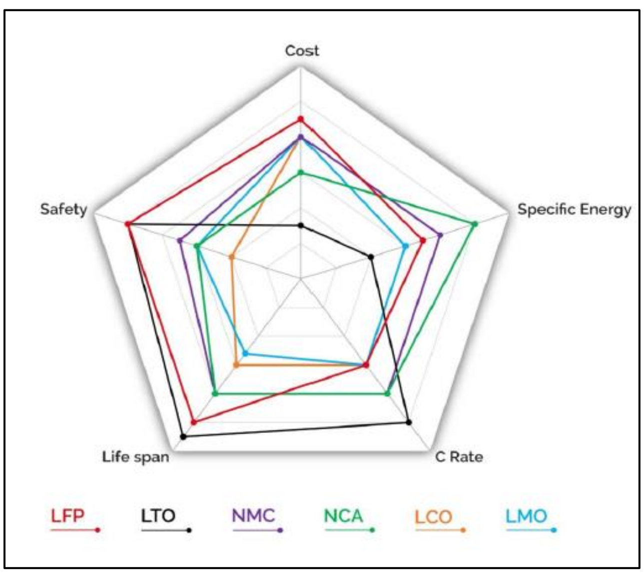


Figure 18 Summary of performance of various Li-ion batteries (12)

- **Redox-flow Battery**

Redox flow batteries (RFBs) are a type of electrochemical energy storage system that stores energy in two separate liquid electrolyte solutions, typically containing dissolved metal ions, which are circulated through a cell containing electrochemical reaction chambers. This design allows for decoupling of energy and power capacity, meaning the energy storage capacity can be increased simply by enlarging the storage tanks, independent of the power output capacity of the system. Also, it can be left fully discharged without any risk of damage. RFBs are particularly suitable for large-scale energy storage applications due to their scalability, long cycle life, and the ability to achieve high efficiencies. However, it has low energy density and constitutes a complex system (16,17).

Various types of RFBs exist, including all-vanadium systems, which are the most commercially advanced, as well as emerging technologies like zinc-bromine, zinc-iron, and organic aqueous flow batteries that use quinones and other organic compounds as active materials (18).

The reactions occurring at the Vanadium redox flow battery are:

Positive electrode: $V^{5+} + e^{-} \rightarrow V^{4+}$
Negative electrode: $V^{2+} \rightarrow V^{3+} + e^{-}$

It can be recharged by replacing the vanadium solutions or by supplying external power.

- **Sodium-ion Battery**

Sodium-ion batteries (Na-ion batteries) are emerging as a promising alternative to lithium-ion batteries due to their cheap and abundant raw materials. These batteries operate on similar principles to lithium-ion batteries, involving the movement of sodium ions between the anode and cathode during charging and discharging processes (19, 20).

The energy density of sodium-ion batteries has been improving, with current values ranging from 130 to 160 Wh/kg, and projections suggest they could reach 200 Wh/kg, making them competitive with some lower-end lithium-ion batteries. Additionally, sodium-ion batteries exhibit better thermal stability and safety characteristics, such as a lower risk of fire and the ability to discharge completely to zero volts, which simplifies storage and transportation (21, 22).

While sodium-ion batteries currently have a shorter cycle life compared to lithium-ion batteries, advances in cell chemistry are closing this gap. For instance, certain sodium-ion batteries have achieved up to 6,000 cycles with 80% capacity retention, which is comparable to lithium-ion counterparts (21). Compared to lithium ion batteries, sodium-ion batteries are larger in size and have more stringent requirements in terms of material structure stability and kinetic properties. This is also one of the reasons why sodium-ion batteries have been difficult to commercialize (23).

Although the technology of sodium-ion batteries are not as mature as Li-ion batteries, a wave of commercialization and mass-production have started with HiNa Battery (Anhui and Shanxi gigafactories) and CATL of China, Faradion in the United Kingdom, Tiamat in France, Northvolt in Sweden, and Natron Energy in the USA (24) (13).

2.5 Literature reviews

Significant research is going on to estimate the theoretical earning potential of a battery using various mathematical models. For example, in (3), Hameed et al. studies hourly frequency reserve price patterns in the Danish market (DK-2) for 2015-2020 and attempts to find out the profitable bidding hours. The paper analyses availability costs of FCR-N, FCR-D and FFR and energy cost of FCR-N only. The study calculates the number of hours when FCR-N, FCR-D etc. are activated from the frequency data and assumes that bids are placed for all such hours. The magnitude of FCR-N is calculated from droop-control equation. It further assumes that each bid is accepted. Therefore, this study gives the theoretical maximum possible revenue that can be earned by the BESS units and does not account for the uncertainty of bids not getting cleared into the analysis. It shows that FCR-N availability prices are generally higher from midnight to early morning compared to day-time hours, although no such clear pattern is visible with FCR-D availability prices. Further, the FCR-N availability prices are lower for the months of January–April and start to increase in May–August. It is also found that FCR-N energy payments are 5-8% and FCR-D energy payments merely 0.05% of the availability payments. Therefore, the main source of revenue for the BESS owners are the availability payments. When comparing FCR-N and FCR-D as probable options of income, the study recommends to go for FCR-N only when its availability cost is significantly higher than that of FCR-D. When both availability costs are close, it is better to bid in FCR-D as the actual activation of reserves is less probable in FCR-D market as compared to FCR-N. The BESS asset can benefit from reducing its charging-discharging cycles by remaining in the FCR-D market.

In another paper (25) Zakeri et al. proposes an interesting methodology for calculating potential revenue of an energy storage system from day-ahead spot market (Elspot), intraday market (Elbas) and balancing market combined. Then the methodology is applied on different Nordic countries and different battery technologies. This methodology has been used in this study too, therefore it will be discussed elaborately in section 3.4. The study analyses market prices of 2012-15 and concludes that Finland, followed by two Danish price-areas offer best profitability in the day-ahead market. Denmark having a significant share of wind power in its grid has the highest potential in intraday market. In balancing market, FI, DK1 and SE1 are the most profitable zones. In general, the study proposes that balancing market has the highest earning potential in €/MW, followed by Elspot. Elbas has the least theoretical potential.

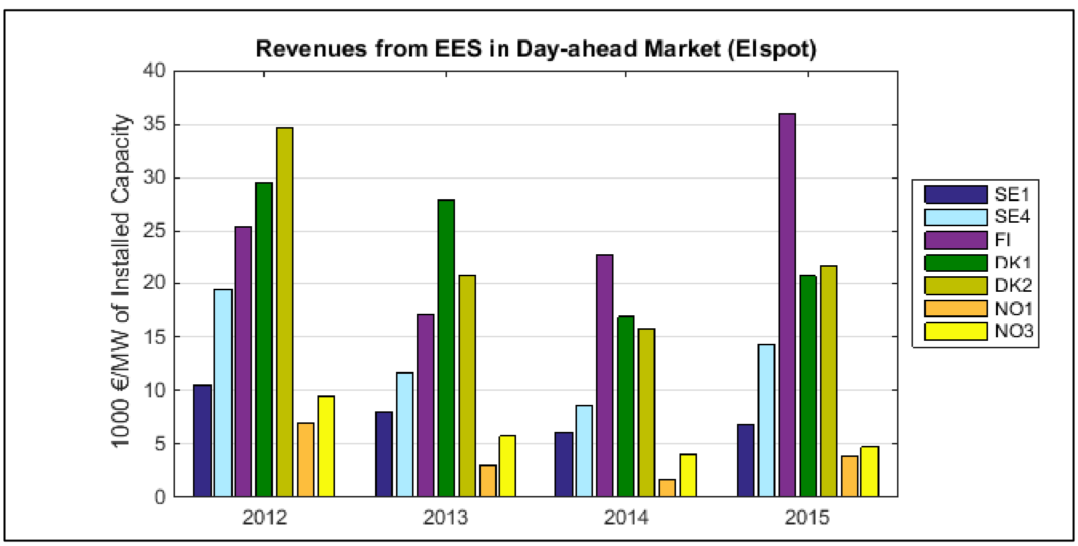


Figure 19 Maximum revenue potential of daily price arbitrage comparison among various Nordic bidding zones (2012-2015) while bidding in Day Ahead Market (Elspot) by Pump Hydro Storage plants (20)

Another research paper (4) develops a mathematical model that provides the optimal bidding strategy on a specific summer day and a specific winter day in the bidding zone SE-3 for a battery smaller than 5 MW capacity. It uses the state of the art two-stage stochastic mixed-integer and linear optimization technique in

GAMS and includes the battery price, degradation, control cost and risk cost in the bid price. Quantifying the risk cost is the most novel aspect of this paper. It is calculated as:

Risk cost of bidding in FCR-D = (Probability that FCR-D is required)* (Probability that this battery is called for the whole time)* (Probability that this unit fails to provide the called power)

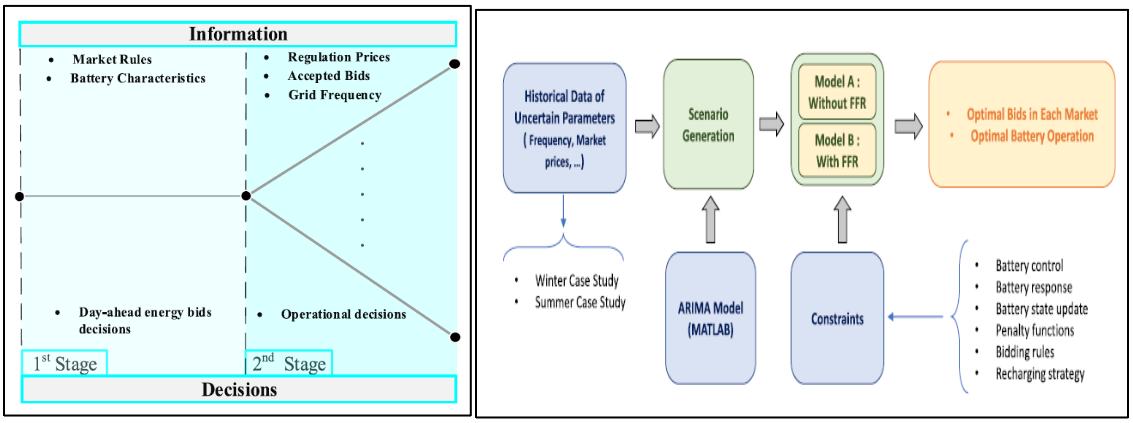


Figure 20 Flow chart of the method followed by (4) with formation of a two-stage stochastic optimization problem with recourse in the second stage.

The paper also runs a few sensitivity analysis and concludes that the profit is most sensitive to discharge power of the BESS (compared to price of the energy used for recharging, bid prices of the pay-as-bid market etc.).

There are other literatures that try to evaluate optimum operation strategies of a BESS system with the objective of increasing its revenue and feasibility. In (26) Berg et al. takes a Norwegian football stadium with 1.1 MWh installed battery energy storage system (BESS) and a 800 kWp photovoltaic (PV) power plant within it as the subject of the analysis. Then the paper analyses revenue potential from various operation strategies focusing either self-consumption maximization, feed-in limitation, peak shaving, or increasing earning from energy arbitrage in addition to the previous functions. The software tool SimSES is used to simulate BESS degradation. The study assumed the load to be constant throughout the analysis period (10 years), while the PV system is assumed to age by a factor of 0.5% per year. A perfect forecast of electricity assumed, i.e. spot market prices of 2018 are taken for next 10 years.

Although none of the cases was found to be profitable in Norway, 2018, but an operation strategy that has several objectives was found to be comparatively more profitable than single-purpose strategies, even though it might result in higher battery degradation.

In another study (27), the authors simulate various operation strategies of a Li-ion battery storage combined with a PV production (modeled after a 3.5 MW PV park located in Fyrislund, Uppsala). They generate five scenarios where the priority services are: lowering the cost of connecting the PV park to the power grid, lowering the cost of feeding in energy to the power grid, increasing the revenue of selling electricity on the Nord Pool spot market, increasing the revenue by performing energy arbitrage and increasing the revenue by participating in the primary frequency regulating markets. The scenarios are evaluated by calculating the net present value (NPV) of the system over 10 years with an annual discount rate of 5 %.

Here too, the main conclusion is that: more the number of services provided, more is the NPV of the system. This study also tries to find out some realistic bidding strategies by reserving certain hours of a day during summer and certain hours during winter for a hybrid set-up (battery and PV). It also conducts some interesting sensitivity analysis with respect to battery investment cost, typical meteorological year (solar generation), spot price and monthly resolution.

Although calculating theoretical earning potential in a certain energy market is quite common in literature, formulating a simple bidding strategy by fixing certain hours of the day for a certain market segment is comparatively scarce. Due to unpredictable dynamics and ever-increasing variability in the energy market, it is indeed a big challenge to formulate a bidding strategy simple enough to carry out by any small battery-owner without any automation. This is the first novelty of this study that it tries to chalk out a simple bidding strategy for a battery to participate in a number of energy market segments. Another novelty of this study is that it attempts to develop a business model for a battery asset in the Nordic energy market over the period of its lifetime and tests that on various technologies of batteries, viz. lithium-ion, sodium-ion, redox-flow battery etc.

Chapter-3

Data Collection and Programming

3.1 Details of all Price data collected

3.1.1. Downloaded Historical data

As the thesis is a data-intensive study and all desired insights have to be explored by in-depth data-analytics, especially of market data; quality and quantity of these electricity market data are of paramount importance. Mainly three sources were used for data collection.

First, the MIMER portal of Svenska kraftnät (28) was used to collect the following data:

- FCR-N hourly prices in EUR/MW for 2017-2023
- FCR-N hourly volumes in MW for 2021-2023
- FCR-D Up hourly prices in EUR/MW for 2017-2023
- FCR-D Up hourly volumes in MW for 2021-2023
- FCR-D Down hourly prices in EUR/MW for 2022-2023
- FCR-D Down hourly volumes in MW for 2022-2023
- FFR hourly price and volume for 2021-2023
- Sweden hourly Hydro generation in MW for 2017-2023
- Sweden hourly Wind generation in MW for 2017-2023
- Sweden hourly Net Demand in MW for 2017-2023

The next source of data download was NORDPOOL website. In the website, daily Day-ahead Spot market (Elspot) and Intraday Market (Elbas) price and volume data are available up to a certain time point in the past. Elspot prices and volumes could be collected for the years 2017-2023 with the help of NORDPOOL. However, collecting data for the Elbas market was a little bit more complicated. A web-scrapping code had to be employed to automatically download hourly intraday prices and volumes from NORDPOOL website. Therefore Elbas data could be collected only for 2022 and 2023 and were used for the analysis.

3.1.2. Confidential Forecasted Price data received from Baywa R.E.

Apart from the downloaded data, another set of forecasted data are used in the analysis that has been provided by Baywa r.e. These include forecasted prices in Elspot, Elbas, FCR-N, FCR-D Up and Down and FFR for the years 2024-2050 and all the prices are available in hourly resolution. It is understandable that price forecast over such a long horizon must have some limitations. Therefore, the forecast data have been used for calculations of the base case only and then sensitivity analysis has been performed on them to understand possible impact of the inaccuracy of the forecast on the business cases. This is explained in more details in section 4.2.

3.2 Details of Battery Data

Battery cost data for various technologies and storage durations as collected from various reports of Bloomberg NEF, Wood Mackenzie etc. and various academic literatures of NREL, PNNL etc. have been used for the business case modelling (29) (30) (31). For example (32) gives a very interesting projection of Li-ion battery cost evolution:

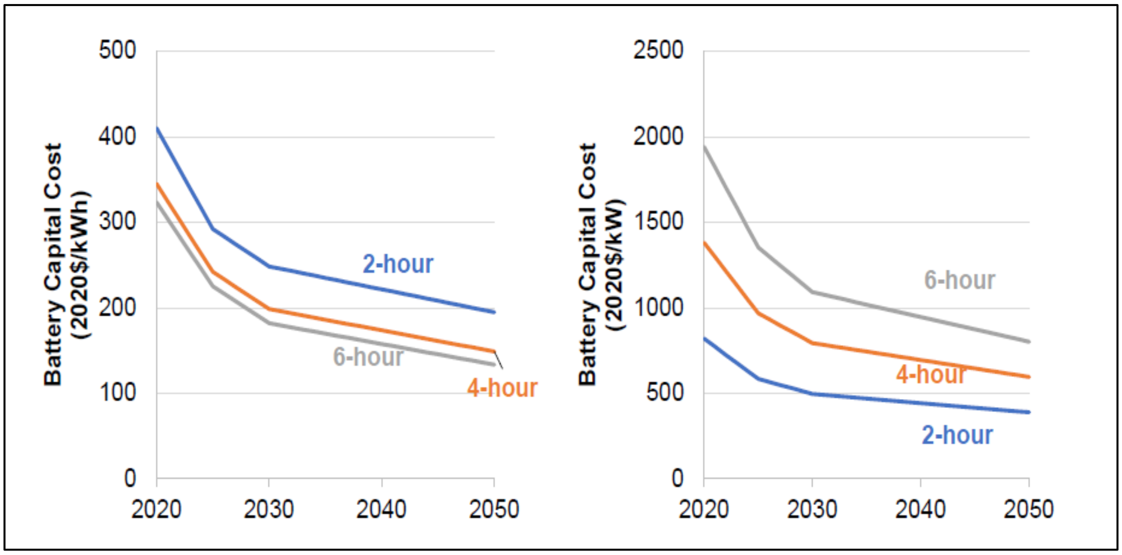


Figure 21 Lithium-ion batteries of various sizes capital cost projection in \$/kW and \$/kWh (27)

The following graph (Fig. 22) shows an approximate break-up of fixed and variable costs of Vanadium redox batteries. Here the fixed cost signifies that part of the BESS cost that remains more or less same with changing hour storage size. The variable CAPEX on the other hand is the component that changes with kWh size of the storage. Generally, per kWh battery cost goes down slightly with increasing hour-storage but the installation costs per kWh remains more or less same.

For this calculation, first the prices of vanadium redox batteries of various sizes were taken from (13). Then the prices were broken into two components so that the fixed cost as well as variable cost per kWh remains more or less constant.

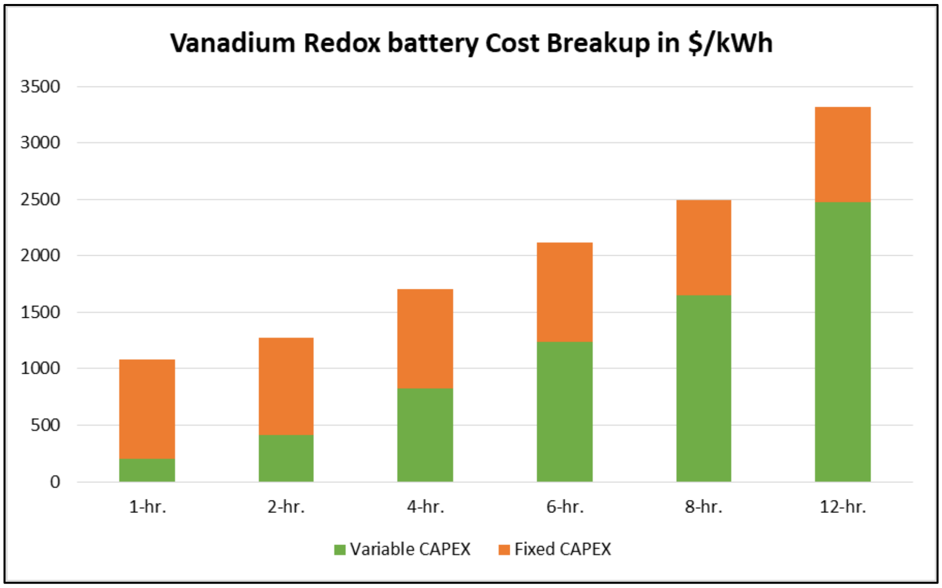


Figure 22 Fixed and Variable cost components breakup of Vanadium Redox batteries CAPEX in $/kWh (9)

The cost also depends on the location. For example, battery cost in China is roughly 30-60% of that at the USA. In Figure 23 the battery prices in China are plotted on the secondary axis (right hand side).

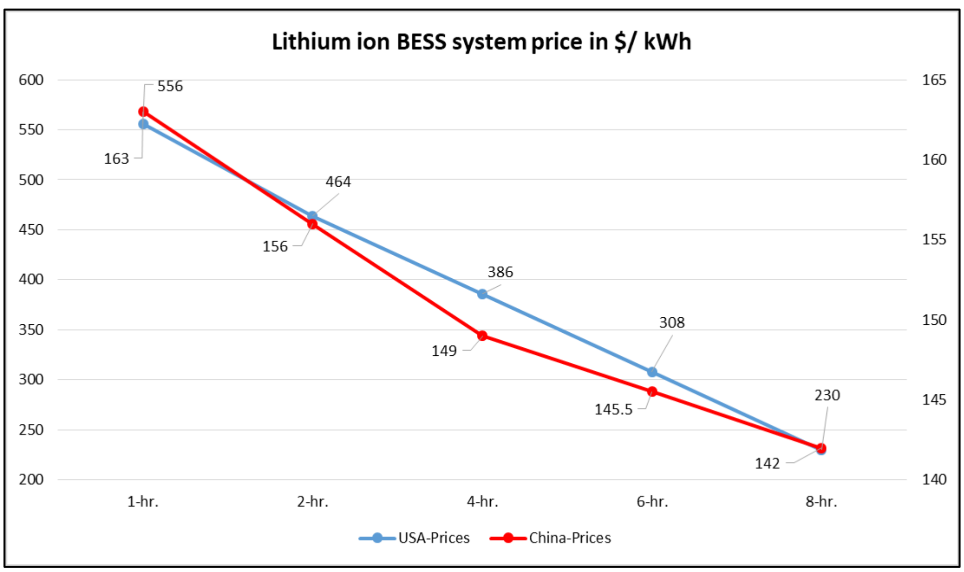


Figure 23 Lithium ion battery price comparison in China and the USA (2023)(13)

For this thesis, however, the battery prices in the USA have been considered which are much closer to the prices in the EU.

The following table summarizes all the important parameters of various types of batteries used for the thesis.

Table 1 Summary of important parameters for business case modelling of three types of Batteries (33)

	Li-ion Battery				Redox-flow Battery				Na-ion Battery			
	1-hr.	2-hr.	4-hr.	6-hr.	1-hr.	2-hr.	4-hr.	6-hr.	1-hr.	2-hr.	4-hr.	6-hr.
CAPEX (€/ kWh)	512	427	355	283	999	587	392	324	257.6	NA	NA	220.8
Fixed Annual OPEX (€/kW/year)	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
Variable Annual OPEX (€/ kWh/ Year)	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027
Lifetime (Years)	15	15	15	15	25	25	25	25	7	7	7	7
System Round Trip Efficiency	86%	86%	86%	86%	70%	70%	70%	70%	86%	86%	86%	86%

3.3 Algorithm for theoretical arbitrage potential calculation

By theoretical arbitrage potential we mean the scenario when the battery automatically picks up the cheapest hours of a day for buying electricity and costliest hours of a day to sell the electricity. For a 4-hour battery it automatically picks up the cheapest 4 hours of a day to buy electricity irrespective of any pattern. On the contrary, in a manual arbitrage strategy, the battery owner must know a price pattern to set the bidding strategy. Certain hours of the day will be reserved to buy from the grid and certain hours of the day to sell electricity.

In the next page the theoretical arbitrage potential calculation algorithm is discussed with a flow chart (Fig. 24). In Fig. 24 up and down percentile corresponds to the storage duration of the battery. If it is run for a 1 hour battery, it will try to pick up the cheapest 1 hour to buy electricity and costliest 1 hour to sell electricity. The cheapest 1 hour of a day corresponds to 4.16 percentile (100 divided by 24) and the costliest 1 hour corresponds to 95.84 percentile. Therefore, in case of a 1 hour battery, the up and down percentile inputs will be 95.84 and 4.16 respectively. In the similar way, for a 2 hour battery, the up and down percentiles will be 91.66 and 8.34 respectively.

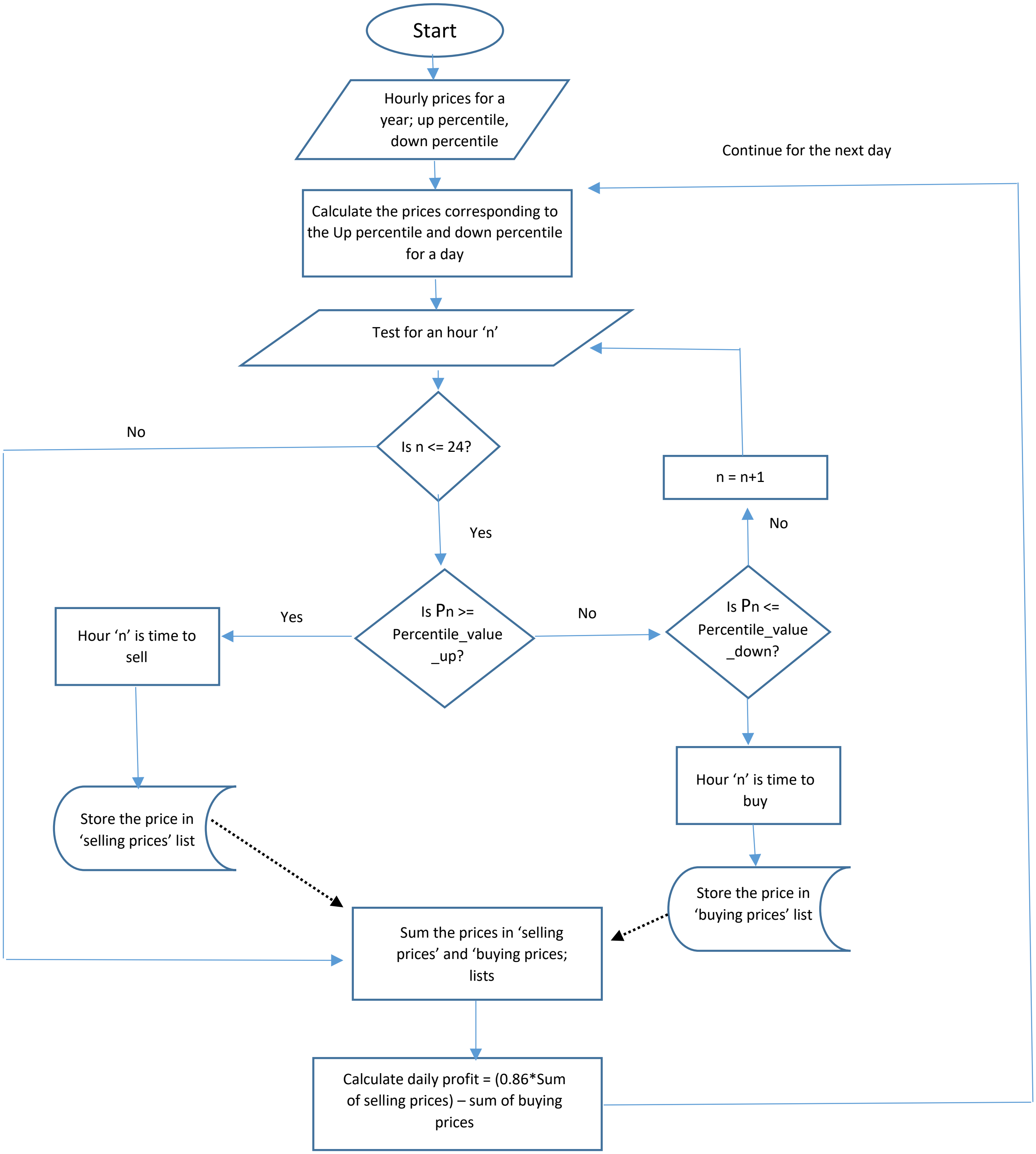


Figure 24 Flowchart of the theoretical arbitrage potential calculation

In the last step, while calculating profit, the factor 0.86 is introduced to represent the roundtrip efficiency of the BESS system, which has been assumed to be 86%, as mentioned in Table-1.
The manual bidding arbitrage potential calculation is comparatively straightforward, therefore not explained with flow chart.

3.4 Algorithm for calculating the theoretical frequency reserve revenue

Compared to day-ahead or intraday markets, it is much more complicated to quantify profitability from frequency reserve markets, as it depends on a lot of factors. First, there is a significant uncertainty regarding the grid frequency behavior and it is almost impossible to correctly forecast the frequency fluctuations over a certain period in future. Secondly, it is even more difficult to quantify the probability of a bid getting accepted, as the exact number of bidding agents at a certain hour as well as their bidding prices are difficult to know.

There are significant research works going on this topic. For this thesis, the method as used by (25) is taken as the primary procedure. The method was originally formulated by the author for the intraday market with a two-price model. Then in the later part of the literature, the method was slightly tweaked for frequency reserve markets. Therefore, while explaining the algorithm, terms like 'buy price', 'sell price' etc. will be used. Although it seems counterintuitive, here 'buy price' actually refers to regulation down price and 'sell price' refers to regulation up prices. Now, let us explain the method as described in the literature.

Initially it is assumed that the frequency reserve product is required for all the hours of a day. Therefore, it is assumed that bids are made at all the hours and all bids are accepted. Also, it is assumed that the battery can either charge or discharge at a certain hour. Then, the method intends to maximize the objective function [1] for a market with two prices:

$$max_{i,j} \sum_{t=1}^{h} [P_d . E_{s,j}(t). \eta_{tot} - P_c . E_{b,i}(t) - C_{mcd}] \qquad [1]$$

The expression [1] actually gives the daily profit from the market.

Where P_d and P_c are discharging and charging power of the battery respectively.

$E_{s,j}$ and $E_{b,i}$ are selling price and buying price of electricity.

C_{mcd} is the marginal cost of discharge of battery. More simply saying, this is the levelized variable O&M cost component of the battery.

η_{tot} is the round-trip efficiency of the battery system.

t represents the number of possible charge-discharge hour-sets per day. h is the maximum possible value of t in a day.

For example, $E_{b,14}(8)$ indicates buying electricity price at 13-14 o'clock, which is a part of the 8th buy-sell set of that day.

Given the following constraints:

i) $\forall\ t$: $P_d . E_{s,j}(t). \eta_{tot} - P_c . E_{b,i}(t) > C_{mcd}$

ii) The first hour of a day cannot be used for discharge, or the last hour of that day for charging: $i = \{1, 2, \dots, 23\}$; $j = \{2,3, \dots, 24\}$

iii) Charging always happens before discharging:

$\forall: \ i < j$

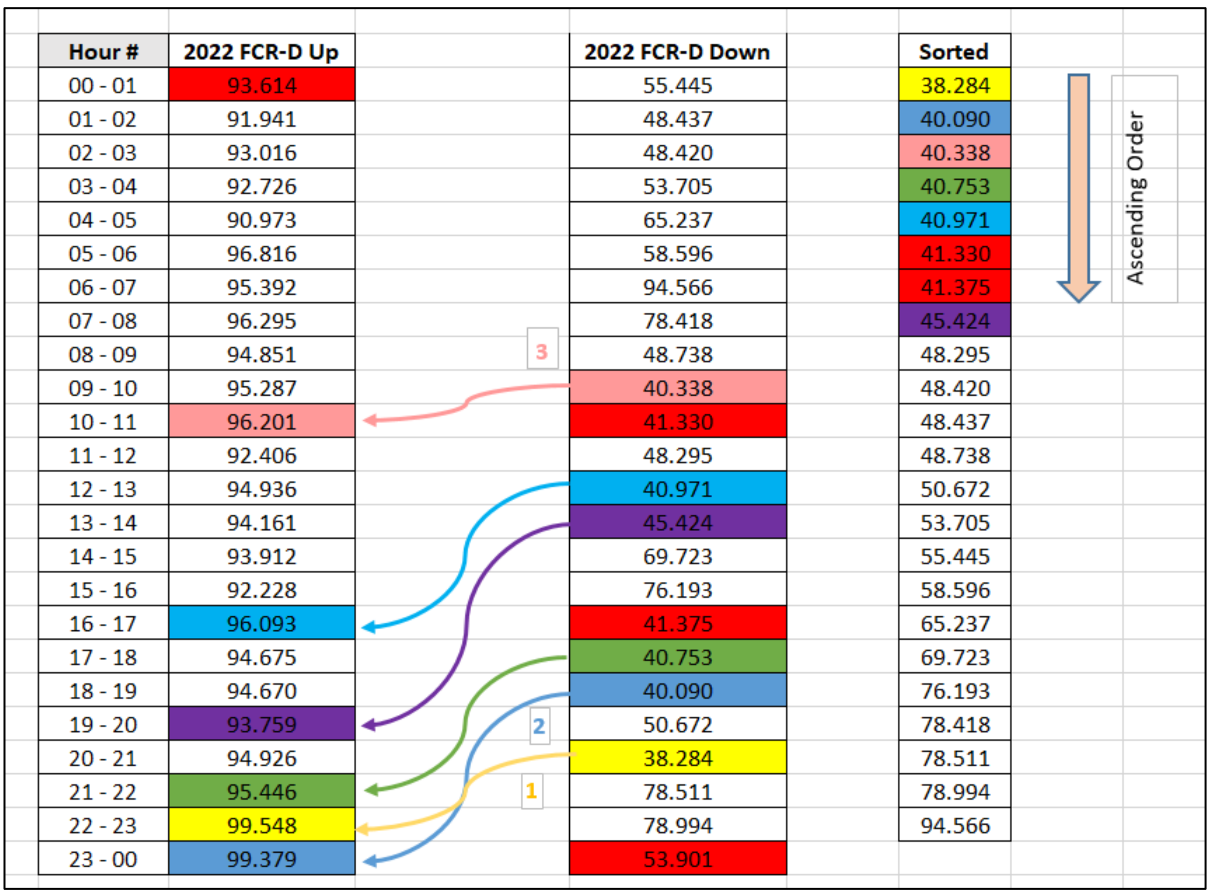
iv) There cannot be charging and discharging simultaneously at the same hour.

v) The selected charge-discharge set at each t must be unique (none of them selected before on the same day).

vi) The equation [1] is true for the intraday market with a two-price model (as it was before 2019). The (-) sign has to be replaced with (+) in equation [1] for frequency reserve markets, as the battery earns even while charging in case of frequency reserve markets.

Now, let us explain how this method is implemented in the algorithm of the code used for this thesis.

First, let us look at the FCR-D availability prices in EUR/ MW for 26th September, 2022 (28). Various colors have been used to easily denote the buying and selling price sets. Red color for a price denotes that it does not get picked up.



Hour #	2022 FCR-D Up	2022 FCR-D Down	Sorted
00 - 01	93.614	55.445	38.284
01 - 02	91.941	48.437	40.090
02 - 03	93.016	48.420	40.338
03 - 04	92.726	53.705	40.753
04 - 05	90.973	65.237	40.971
05 - 06	96.816	58.596	41.330
06 - 07	95.392	94.566	41.375
07 - 08	96.295	78.418	45.424
08 - 09	94.851	48.738	48.295
09 - 10	95.287	40.338	48.420
10 - 11	96.201	41.330	48.437
11 - 12	92.406	48.295	48.738
12 - 13	94.936	40.971	50.672
13 - 14	94.161	45.424	53.705
14 - 15	93.912	69.723	55.445
15 - 16	92.228	76.193	58.596
16 - 17	96.093	41.375	65.237
17 - 18	94.675	40.753	69.723
18 - 19	94.670	40.090	76.193
19 - 20	93.759	50.672	78.418
20 - 21	94.926	38.284	78.511
21 - 22	95.446	78.511	78.994
22 - 23	99.548	78.994	94.566
23 - 00	99.379	53.901	

Figure 25 Illustrated explanation of the algorithm used for calculating income from frequency reserve services with 6 sets of prices

On the right, the FCR-down prices have been sorted in ascending order for reference. This algorithm considers the FCR-down price as buying price and FCR-up price as selling price. It tries to buy at the least possible price and sell at the highest possible price to increase profit. The FCR-D Up price of the first hour and FCR-D Down price of the last hour of the day are marked red; which signifies the constraint (ii) of the method: the battery cannot discharge at the first hour and charge at the last hour.

So, the algorithm first picks up the lowest FCR-D down price '38.284' of '20-21' hours. The corresponding selling price must be one of the last three hourly prices of the day (as selling must be done after buying and buying-selling cannot be at the same hour). The algorithm picks up the highest of the three available prices '99.548'. Similarly, next the algorithm picks up '40.090' as the buying price (second lowest) and chooses the highest selling price available among the last 5 hourly prices of the day : '99.379'. As the price corresponding to '22-23' hour is already assigned, the best selling price that is available is of '23-00' hours. The algorithm goes on doing the same for three more such price-sets (denoted by different colors).

When the turn arrives for the sixth lowest buying price '41.330', the algorithm cannot pick it up as the selling price of the same hour ('10-11') has already been assigned. The battery cannot charge and discharge at the same time. The same logic holds for the buying price of '16-17' hour; which has also been marked red.

In this way, the process continues and sums up the FCR-D Up and Down prices selected. The number of buy-sell sets that gives the highest sum, is the optimum solution. For example, in Fig. 25 the daily profit is 826.28 Euro for a set of 6 buy-sell prices. This is not the optimum solution. The profit will further increase with increase in number of sets and it can go up to 12 sets for a certain day.

In the literature (25), no specification was made regarding the hour-storage of the battery while describing this method. For convenience of analysis, it is assumed that the revenue from frequency reserve markets remains same for batteries of all storage durations (1-hour system to 6-hour systems).

3.5 Method for quantifying Bid Acceptance Probability in Frequency Reserve Market

The method described in the previous section assumes that bids are placed for all the hours of a year and all bids into the reserve markets are accepted. However, in reality frequency reserves will not be required at all the hours throughout a year and there will be instances where bids of a certain battery operator will not be accepted. In (25) the author looked at the FCR cleared volume quantum for each hour and ruled out those hours where zero or next to zero volume was cleared. The hourly profits of the rest of the hours were summed to find out yearly income. This way only 2-25% of the projected revenue as calculated with the procedure as described in section 3.4 could actually be achieved. This thesis will refer to the revenue as calculated from section 3.4 as 'theoretical revenue' and the factor of 2-25% as mentioned before will be termed as the 'bid acceptance probability' for easy reference.

This thesis adopts a similar kind of method but goes a step forward. It picks up the greatest cleared volume within the available mass of data and scale the rest of the data with respect to it. Then theoretical revenue of all those hours are multiplied by that fraction to calculate the realistic revenue.

As no FCR volume data were available in the SVK website for 2017-2020, FCR data for 2021-2023 period are considered for this analysis.

In order to quantify the probability of bid acceptance, first we find out the highest hourly FCR-N cleared volume in the region SE4 for 2021-2023. That value is found to be 34.4 MW. This is assumed to be the theoretical maximum FCR-N volume at a certain hour in the bidding zone of SE4 subject to all variabilities. To be clearer, it is assumed: if the frequency deviations are maximum at an hour and there is no transmission constraint to provide FCR-N within or outside the bidding zone, the FCR-N volume becomes 34.4 MW. It is assumed that at that hour the theoretical revenue as calculated from section 3.4 is attainable. For any other hour, the realistic revenue from FCR-N bidding at the nth hour is calculated as:

$$(\text{Realistic Revenue})_n = \frac{(\text{Theoretical Revenue at nth hour}) * (\text{FCR}-\text{N cleared volume at nth hour})}{\text{FCR}-\text{N maximum cleared volume}} \quad [2]$$

Now, total realistic revenue for a year is calculated by summation of the above calculated values from equation [2] for all the hours in a year.

Next, probability of a bid getting accepted is arrived at by dividing this value with the total theoretical revenue as calculated from section 3.4.

$$\text{Bid Acceptance Probability} = \frac{\text{Realistic Revenue in a year as calculated from eqn.(2)}}{\text{Theoritical Annual Revenue as calculated from section 3.4}} \quad [3]$$

The bid acceptance probabilities as calculated for 2021, 2022 and 2023 are averaged to get at the average bid acceptance probability. This parameter is used for the forecasted FCR-N prices in the future years. For example, if average bid acceptance probability is calculated to be 5% for FCR-N and theoretical revenue from FCR-N bidding in 2030 is calculated to be EURO 10000, the realistic revenue will be 500 EURO.

The same procedure is followed with FCR-D.

3.6 Algorithm for Hourly Pattern Analysis

In this section, the code for analyzing the peak hours of the day is analyzed. So, we assume to have a 6-hour battery bidding in the day-ahead spot (Elspot) or intraday market (Elbas) market. We take the hourly prices for a certain day and identify the 6 costliest hours and 6 cheapest hours in that day. Now we continue this exercise for all the days of the year and try to understand which hours of the day are appearing more frequently in the costliest 25 percentile and cheapest 25 percentile respectively. The hours that appear more number of times in the costliest 25 percentile group, are generally the best time to sell electricity into the grid. On the other hand, the hours appearing most number of times in the cheapest 25 percentile group are best time to buy electricity from the grid.

The similar kind of analysis can be done with a 1-hr. battery if we calculate occurrences in the top and bottom 4.16 percentile of a day. The similar numbers for a 2-hr. and 4-hr. battery will be 8.33 and 16.66 percentiles.

The flow chart of the code is shown in Fig. 26.

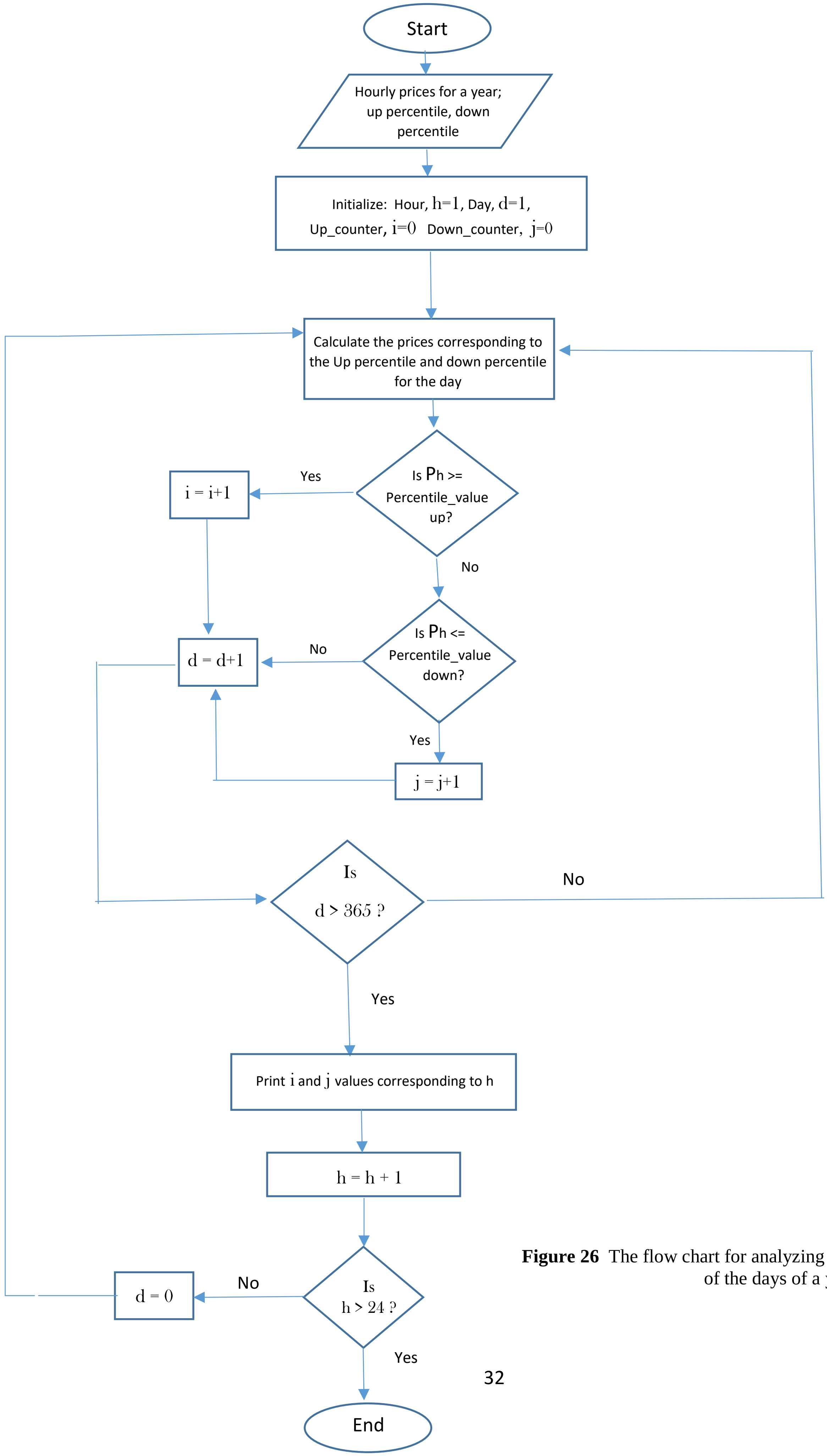


Figure 26 The flow chart for analyzing costliest and cheapest hours of the days of a year

Chapter-4

Business Case Modelling

4.1 Formulation and Assumptions

The business case of the battery is formulated by categorizing the cash flows into and out of the business. The capital expenditure (CAPEX), annual operational expenditure (OPEX), depreciation and income tax contribute to cash outflow. On the other hand, income from price arbitrage in day-ahead and intraday market and income from frequency reserve services constitute the cash inflow. The lifetime of the project depends on the type of battery used. For Li-ion battery the lifetime is taken as 15 years. For redox-flow battery it is taken as 25 years (34). The lifetime of sodium-ion battery is only 6-7 years if run one cycle/day (35). In order to make a realistic investment decision it was considered that the sodium ion battery is replaced at the 7th year and the project lifetime is assumed to be 14 years.

First, the CAPEX cost is taken at the start of the investment. Then income values calculated as per section 3.3 and 3.4 are put over the years of the battery lifetime. Also, annual OPEX costs are calculated as described in section 3.2. Now the following formulas are used to calculate net present value of the costs and revenues:

$NPV_C = C_t / (1+i)^t$ $\qquad$ $NPV_R = R_t / (1+i)^t$

Where, C_t and R_t are Costs incurred and Revenues earned at year t

i is the discount rate.

Now, the net profit is calculated as

$= \sum_{t=0}^{n} (C_t - R_t)$

Throughout the thesis, the discount rate is assumed to be 7%. No additional interest rate is employed in the calculations. Further, the following steps are followed:

- First, for each year of the battery lifetime, EBITDA (Earnings Before Interests, Tax, Depreciation and Amortization) is calculated as follows:

  EBITDA = (Yearly income – Yearly OPEX Costs) ; i.e. $(R_t - C_t)$
  This generally comes as a positive quantity.

- The depreciation is taken as 20% and for the first 5 years of the lifetime this is calculated (negative quantum) and added with the EBITDA. As a result, we get the EBIT (Earnings Before Interests and Tax)
  EBIT = EBITDA + depreciation

This quantum will generally be negative for the first 5 years.

- In Sweden the tax losses are carried forward (36). As the EBIT is effectively net operating income, when EBIT is negative, it can be termed as net operative loss. This net operating loss will be carried forward to the next year of the life time as a cumulative sum.

  From the 6th year of the lifetime, the EBIT will be positive and will be deducted from the cumulative sum of the carried forward net operative loss. If there remains any extra EBIT left after compensating this deduction that will go to taxable income. Tax is levied at 20.6%.

- The NPV will now be calculated on the net income after all deductions. The IRR (Internal Rate of Return) will be calculated with the yearly cash flow values as per the Excel formula.

4.2 Generation of Various Scenarios

- After formulating a base case for a Li-ion battery, the same model is applied on batteries of various size and technologies. In this thesis, Li-ion battery, Sodium-ion battery and Redox flow battery technologies are explored. Size wise 1-hour, 2-hour, 4-hour and 6-hour batteries are investigated.

- For each of these, business cases are formulated for scenarios when the battery is participating only in Day-ahead market (Elspot), only in Intraday Market (Elbas), only in frequency reserve market (mainly FCR-N) or combined bidding (participating in all). The reason for preferring FCR-N over FCR-D will be discussed in section 5.1.3.

- Moreover, performance of the business model is examined when the battery is either bidding automatically or bidding manually. By ‘automatic bidding’ we assume that the battery owner has impeccable price forecasts available from beforehand and he / she picks up the costliest and cheapest hours without following any pattern. On the other hand, in context of this thesis, ‘manual bidding’ means that the battery owner has identified a number of hours for buying and a number of hours for selling based on past price behavior in the market.

- In cases where the business model is not profitable, sensitivity analysis is carried out with respect to CAPEX of the project and price-gap available in the market in order to find out the desired level of CAPEX and price levels to make the investment profitable. In order to attain the breakeven point (where the NPV is zero) only the CAPEX can be varied, only the price gap can be varied or both can be varied. Heat maps are used to examine the scenarios where both are varied.

- CAPEX sensitivity is examined by varying the CAPEX as 15%, 25%, 50%, 75% and 100% of the actual CAPEX as described in section 3.2. In case of Li-ion battery, CAPEX sensitivity is also investigated for battery prices in the Chinese market in 2023 as those price levels are between 30-45% of the battery prices in Europe and provides a realistic case for investigation.

- For price gap sensitivity analysis, 4 cases are generated in addition to the forecasted price levels as received from Baywa r.e. (Fig. 27). The 'forecasted' curve here gives theoretical income potential from price arbitrage in the intraday market by a 6-hour Li-ion battery. It will be discussed in more details in the section 5.1.

  Case-1 refers to 50% of the forecasted price level. Case-2 and 3 signify 150% and 200% of the forecasted price levels respectively. For case-4 we assume a high price period around the years 2032-33, when the price levels are as high as 2022-23. Fig. 27 showcases the price levels for various scenarios in the intraday market (Elbas). Similar scenarios are analyzed for the day-ahead market too.

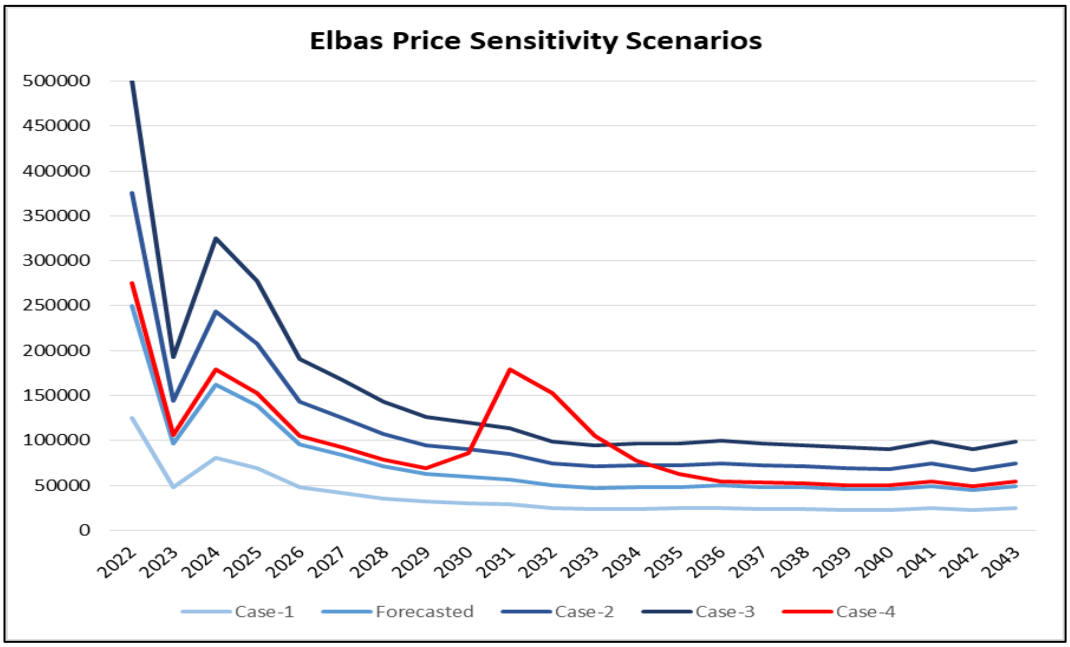


Figure 27 Generation of various scenarios for analyzing price sensitivity of the business case

- A few more sensitivity analyses are run by varying the bid acceptance probability in the frequency reserve market.

- At the end, two combined bidding strategies are tested: one of them 'automatic' and the other one 'manual'. By combined bidding we mean that the battery is participating in all three of day-ahead, intraday and frequency reserve markets.

  In the automatic one, it is assumed that the battery owner having perfect price forecasts can judge in advance which of the three markets will provide most income for the next day and accordingly employ the battery for the entire day in that market exclusively. This way, the battery can bid throughout the first day of a week in Elbas only, second day in FCR-N only and day-3 in Elspot only. This will be discussed in more details in section 5.2.5.

In the manual bidding strategy various hours of a day are reserved for participating in various market segments. For example, let us assume the battery participates in day-ahead market for hours 1-8, in intraday market for 9-16 and in FCR-N for hours 17-24. These hours will be decided by studying the price patterns in these market segments and picking up the most profitable hours for each market. In this strategy it is really important to monitor the state of charge of the battery. During the analysis, any probable change in the battery lifetime due to change in the number of cycles/day is neglected.

These two strategies and their economic performance will be discussed in details in the section 5.2.5.

Chapter-5

Results and Discussions

5.1 Price Patterns

5.1.1 Day Ahead Spot Market (Elspot)

First, we calculate the theoretical arbitrage potential in day-ahead spot market of 1 hour, 2 hour, 4 hour and 6 hour batteries each of 1 MW rating for the years 2017-2048. Out of these, actual historical price data are considered for 2017-2023 and forecasted price data received from Baywa r.e are considered for the period of 2024-2048. When the values are plotted, the graph looks as follows:

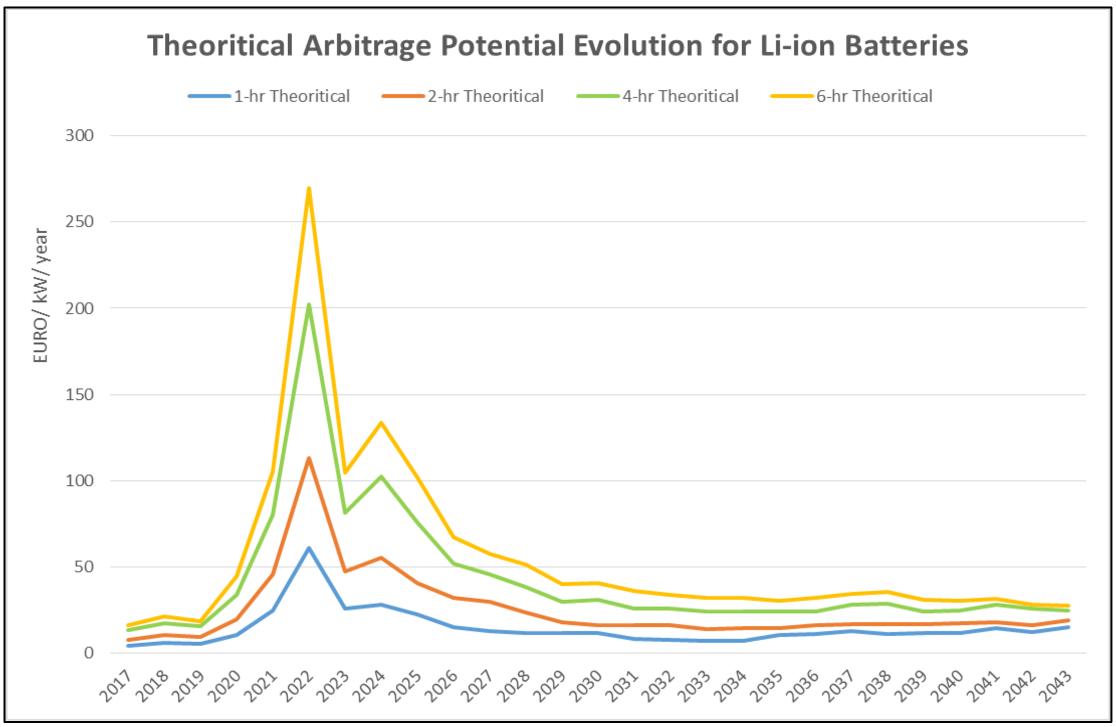


Figure 28 Theoretical Arbitrage Potential Evolution for Li-ion Batteries of Various Sizes bidding in Elspot market

So, the theoretical arbitrage potential has continuously risen from 2017 to 2022 and then reduced a little bit in 2023. However, as per the forecast, the profitability from arbitrage decreases gradually in the coming years and then flattens. The price forecasts might look quite pessimistic as they never reach the level of 2022-23. Therefore, these data have been used to formulate the base case and then sensitivity analysis has been performed by varying this price level.

In any future market scenario, the forecasted price-gap mainly depends on two opposing factors. With increasing renewables in the power-mix, variability should increase, causing an increase in the price-gaps. On the other hand, the saturation effect as explained elaborately in section 2.2 caused by entry of more and more energy storage assets into the market can reduce the price-gaps. The forecast being used in this thesis is perhaps projecting the second effect to outweigh the first. As can be seen in Fig. 28, for a 6-hour battery, the profit plunges from the maxima of EUR 270/ kW in 2022 to roughly EUR 25/ kW in 2048.

However, this theoretical arbitrage potential is impossible to attain in real world. Only if a 100% correct price forecast is known in advance, only then the battery can flawlessly pick the cheapest 6 hours to buy electricity and costliest 6 hours to sell electricity. A more realistic approach is to study the past years' price data and try to find out any pattern in them. Depending on the price pattern it is possible to devise a bidding strategy which should generate a profit close to the theoretical margin.

So, we assume to have a 6-hour battery bidding in the day-ahead spot (Elspot) market. Then the methodology as explained in section 3.6 is undergone. The resulting graph for the bidding area SE4 in the year 2017 looks as the Fig. 29. Here the horizontal axis gives the hours of a day and vertical axis gives number of occurrences in a year.

An alternative way of deciding this daily price pattern (identifying peak and off-peak hours) could be averaging the price data of an entire year over a single day (24 hours), so that each of the 24 price points is an average of 365 inputs. Although this is a simpler method, there is a risk of over-averaging of the seasonal patterns, where strong summer and winter price patterns of opposite polarity might compensate each other and might not appear in the final graph. By summing up number of occurrences in the top or bottom 25 percentile, this risk is averted.

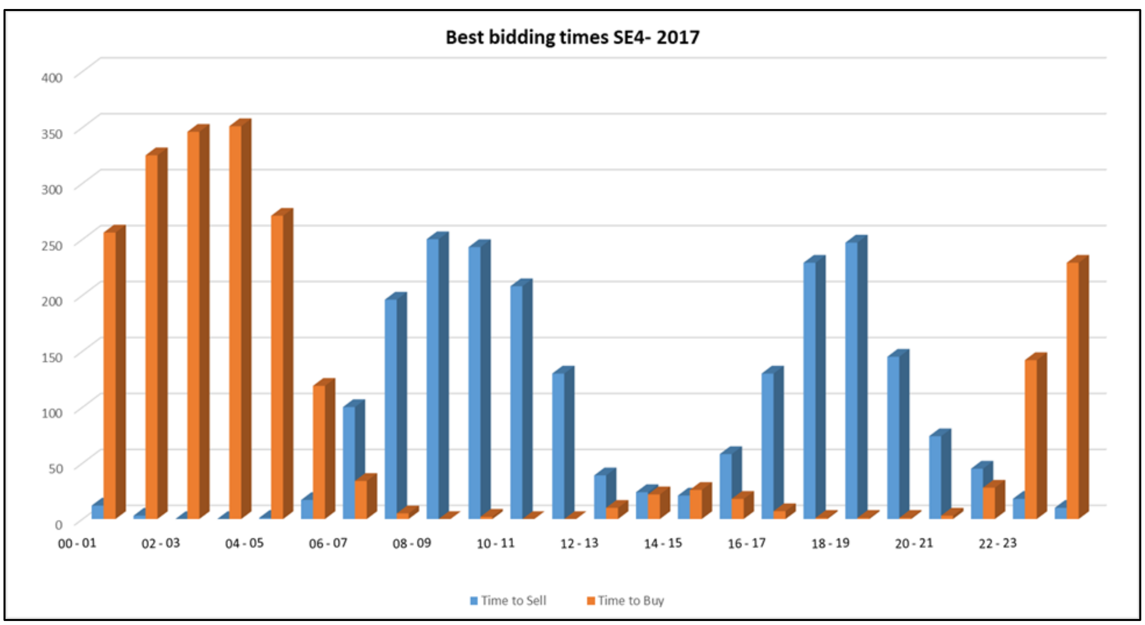


Figure 29 The costliest and cheapest hours of a day for bidding zone SE4 in 2017; where the horizontal axis gives the hours of a day and vertical axis gives number of occurrences in a year

In fig.29 the height of the orange bar represents the number of times a certain hour appears in the lowest 25 percentile of a day. For example, ‘03:00 hrs.-04:00 hrs.’ has appeared close to 340 number of times within the ‘cheapest 6 hours of a day’ set (out of 365 days). Therefore, it is the best hour to charge the battery (buy electricity from the market). Similarly, the lengths of the blue bars signify the hour’s suitability as discharging hour (selling electricity to the market).

From fig.29 it can be clearly observed that night hours are best for charging the battery as the prices are generally low then. Best hours for discharging into the grid are 07:00 to 11:00 hrs. (Morning peak) and 17:00 to 20:00 hrs. (Evening peak).

A similar kind of pattern can be observed in 2023 too (Fig. 30).

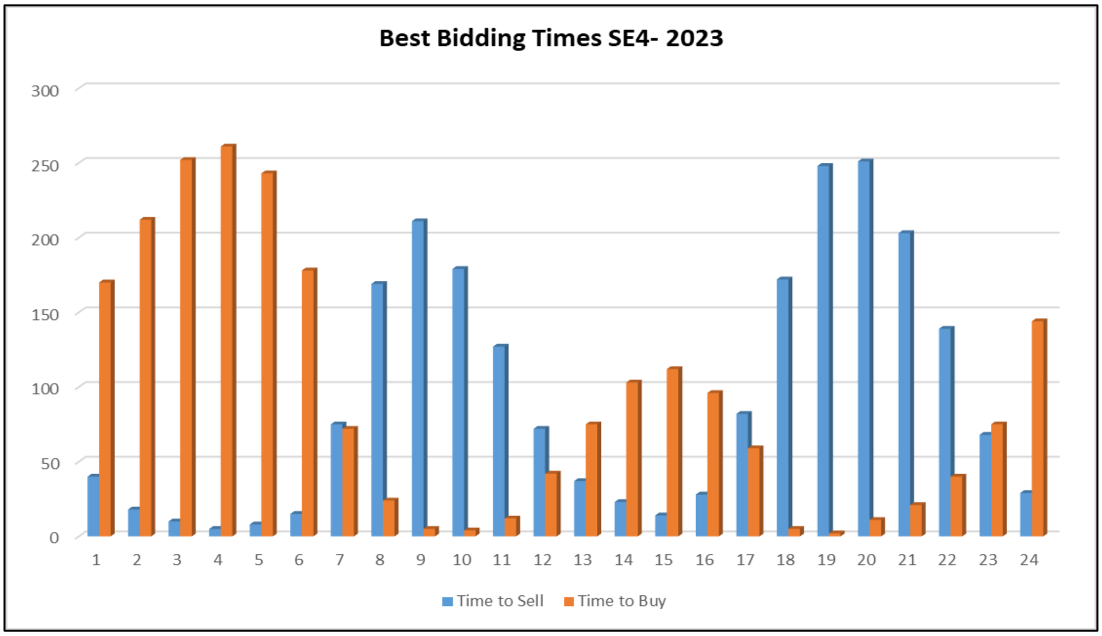


Figure 30 The costliest and cheapest hours of a day for bidding zone SE4 in 2023

A more or less identical trend continued between 2017 and 2023 both for SE4 and SE3.

So, based on this analysis, best bidding strategy for a 6-hr battery can be formulated as the following:

Best times to buy: 23:00 hrs. To 5:00 hrs.

Best time to sell: 07:00 to 10:00 hrs. & 17:00 to 20:00 hrs.

Also, it is evident from the above results that it is best to operate the battery for 1 cycle per day, i.e. charging once a day and discharging once a day. The battery could be charged again during 11:00 hrs. to 17:00 hrs. to attempt a second cycle, but the price gap accessible is not sufficient to make the second cycle profitable. More discussion on this will be done in subsequent sections.

This way of reserving a number of hours for buying and a few more for selling only will be referred to as 'manual bidding' throughout the rest of this thesis. If we assume to bid with the above mentioned strategy over the lifetime of the battery, the generated profit remains roughly in the range 20-50% of the theoretical potential. The same has been illustrated in Fig. 31. Here the secondary axis on the right hand side gives the previously mentioned percentage values.

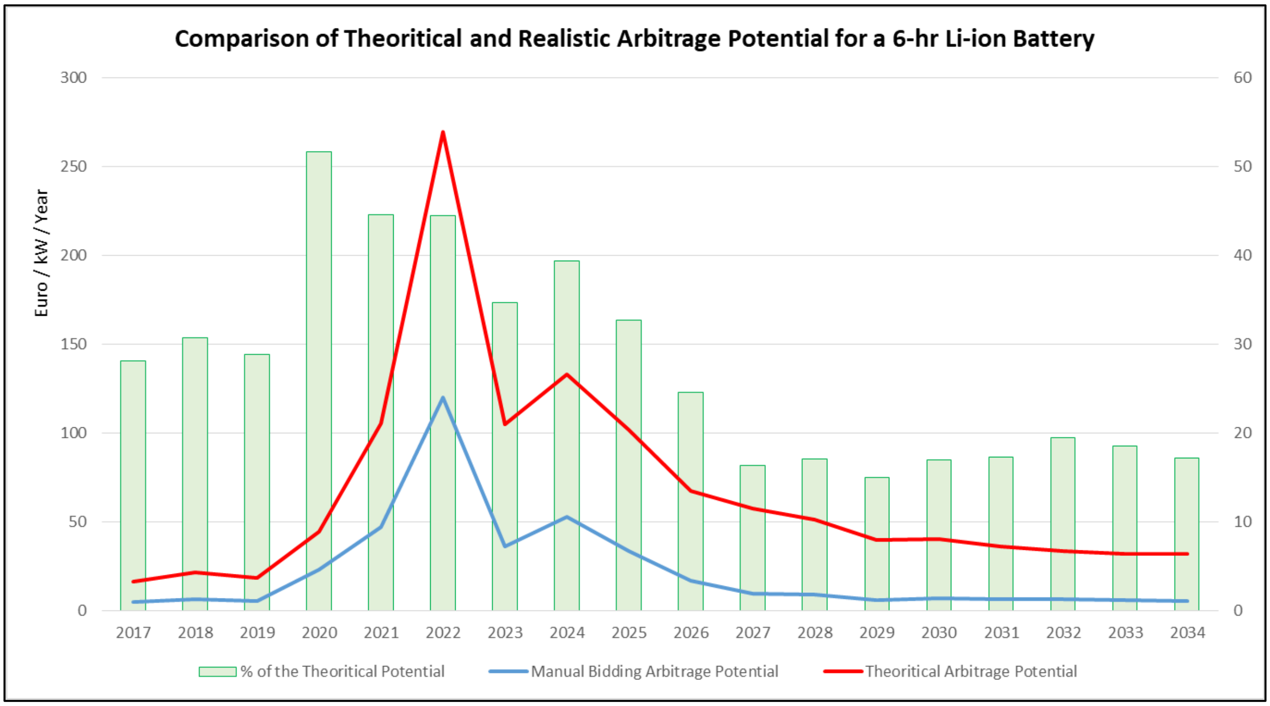


Figure 31 Theoretical vs. Realistic Arbitrage Potential of a 6-hr. Li-ion battery bidding in Day-Ahead Market

The manual bidding arbitrage potential curve has roughly the same pattern as the theoretical arbitrage potential graph. The 'percentage of theoretical potential attained' reached more than 50% mark in 2020 but are in the range 10-20% in the distant future as per forecast data.

Next, similar kind of analysis can be executed to devise the optimum bidding strategy for 1-hr, 2-hr and 4-hr batteries as follows:

Table 2 Optimum Bidding Strategy in Day-Ahead market for 1-hr., 2-hr, 4-hr. and 6-hr. batteries

	1-hr. battery	**2-hr. battery**	**4-hr. battery**	**6-hr. battery**
Best Buying Time	23:00 hrs. to 24:00 hrs.	02:00 hrs. to 04:00 hrs.	01:00 hrs. to 05:00 hrs.	(00:00 hrs. to 05:00 hrs.) & (23:00 to 24:00 hrs.)
Best Selling Time	19:00 hrs. to 20:00 hrs.	18:00 hrs. to 20:00 hrs.	(08:00 hrs. to 10:00 hrs.) & (18:00 hrs. to 20:00 hrs.)	(07:00 hrs. to 10:00 hrs.) & (17:00 hrs. to 20:00 hrs.)

If we plot a similar graph as Fig. 31 for the 1-hr. battery, it looks as the following:

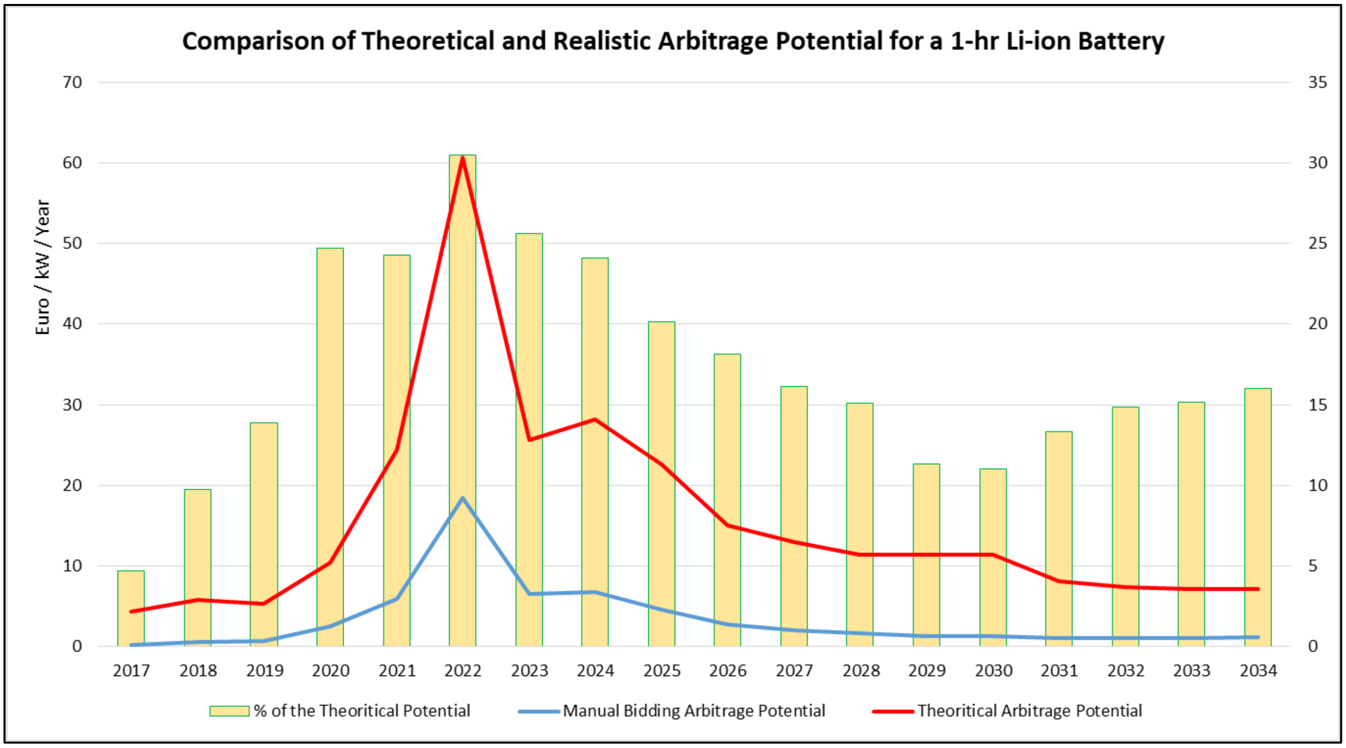


Figure 32 Theoretical vs. Realistic Arbitrage Potential of a 1-hr. Li-ion battery bidding in Day-Ahead Market

Here, the percentage value maxima has been reached in 2022 (roughly 30%), but that value reduces in the future.

Both in Fig. 31 and Fig. 32 the bidding strategy seems to get more and more inefficient in the future years. The reason might be: the price pattern is not behaving as per 2017-2023 years and peak hours are falling more and more out of the periods mentioned in Table 1. To better understand this, same analysis as Fig. 25 and 26 is repeated with the forecasted Elspot prices received from Baywa r.e. The price patterns for 2024, 2026, 2030 and 2034 look as follows:

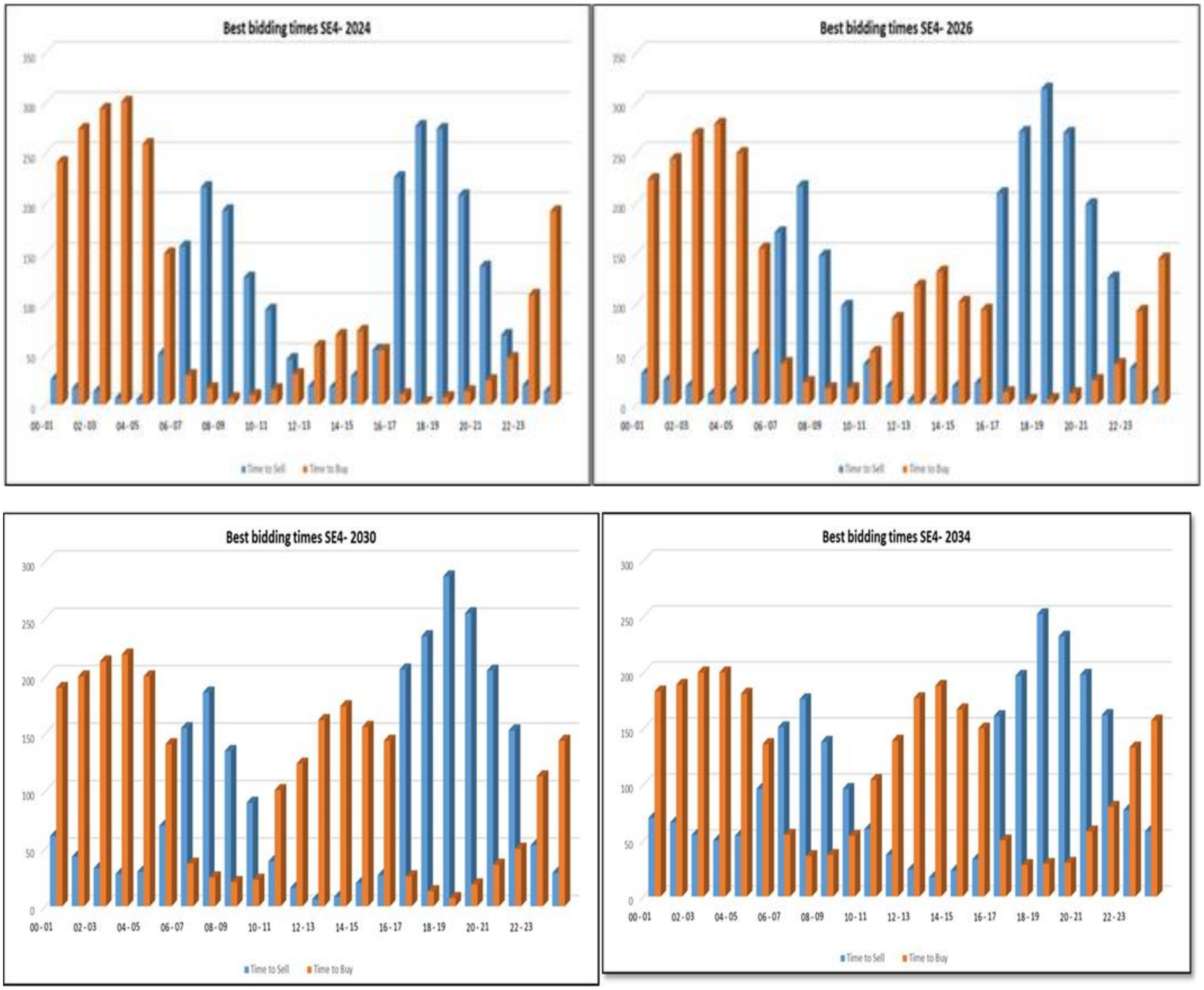


Figure 33 The costliest and cheapest hours of a day for bidding zone SE4 in 2024, 2026, 2030 and 2034

From these graphs it can be clearly observed that prices for 11-16 hours are getting gradually cheaper with passing time, especially after 2030. Also, the night hours are more and more appearing in the costliest 25 percentile segment. This phenomenon can be explained to a certain extent with the expected increase in solar generation during the mid-day hours. Sweden's present yearly solar generation is roughly 3 TWh which is projected to triple by 2027 (37). As more percentage of the electricity mix becomes solar, the night hours start suffering from generation capacity crunch, when the demand is actually greater than the present years. This might shoot up the spot market prices.

As a result, in future it might be beneficial to operate 2 cycles of the battery per day, i.e. charging during the night then discharging it during 6-11 hours; again charging it during 11-17 hours and discharging during 17-23 hours.

In section 3.3 the algorithm shown in Fig. 24 gives value of this profit from arbitrage. It can be observed that the daily profit from arbitrage can go negative only because the round-trip-efficiency is less than 1 (0.86 for Li-ion battery). Otherwise, at the extreme case, the profit would have been zero (when price is equal throughout the day).

Now, the number of days in a certain year when the daily net profit is positive can be an important parameter that represents the profitability of the bidding strategy. For a 6-hr. and 1 hr. battery bidding with the optimum strategy as mentioned in Table 1 the trend of positive profit days in a year looks as the following:

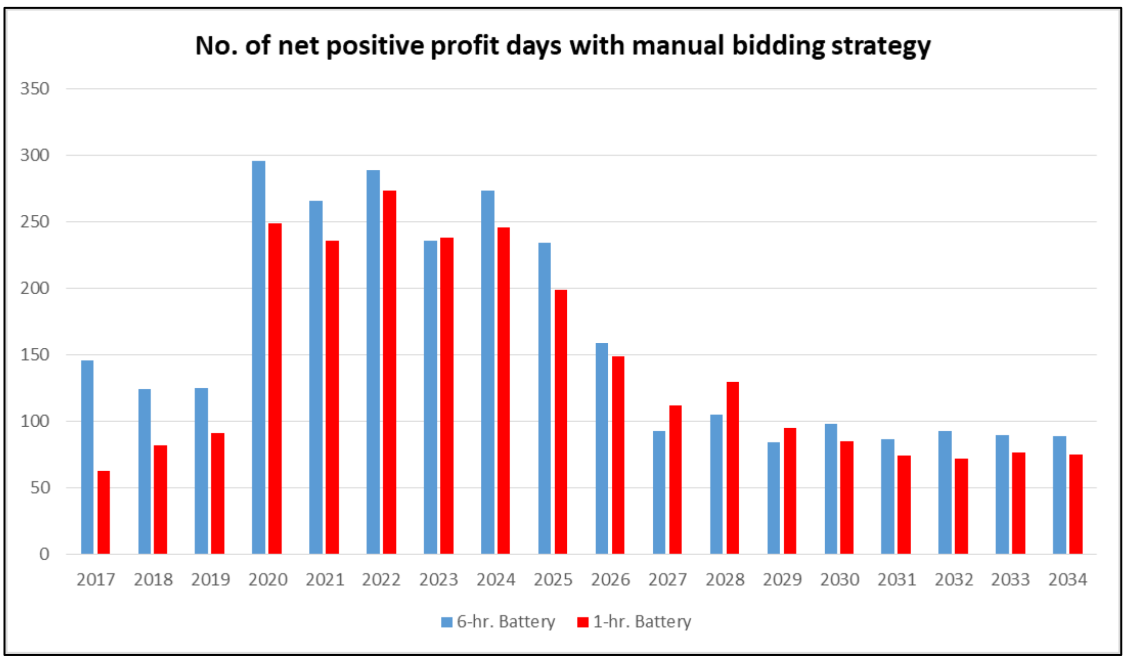


Figure 34 No. of days with net positive profit in a year while following the manual bidding strategy as per Table 2

As per the graph, the number of days when one can participate in Elspot profitably with the bidding strategy as discussed in table 2 decreases in future years.

5.1.2 Intraday Market (Elbas)

If the theoretical arbitrage potential is calculated in the same way as day-ahead market, the trend for 2022-2035 looks roughly same as that of day-ahead market.

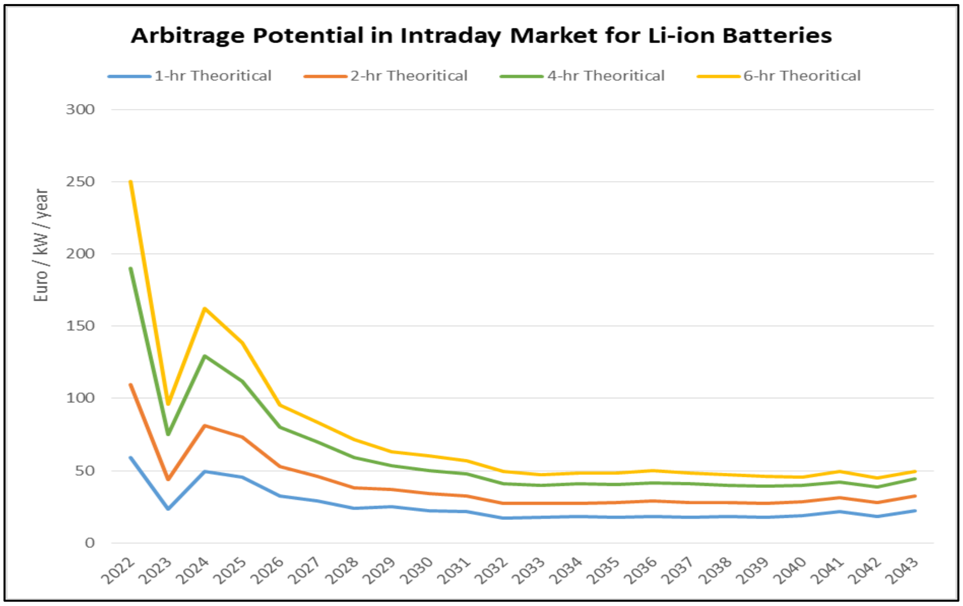


Figure 35 Theoretical Arbitrage Potential Evolution for Li-ion Batteries of Various Sizes bidding in Elbas market

The theoretical arbitrage potential from the intraday market can be 95% to 2.5 times the day-ahead market potential income. If the same analysis as Elspot is continued with Elbas market prices to understand daily price patterns, the following graph is obtained for SE4 in 2023.

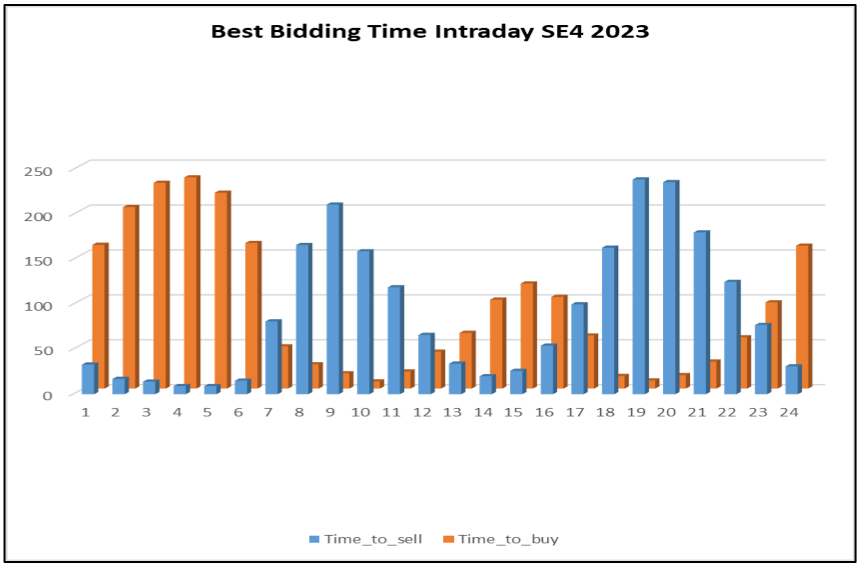


Figure 36 The costliest and cheapest Elbas hours of a day for bidding zone SE4 in 2023

So, the price pattern is more or less same as the day ahead market. If we plot the similar graphs with forecasted future prices, it looks as following:

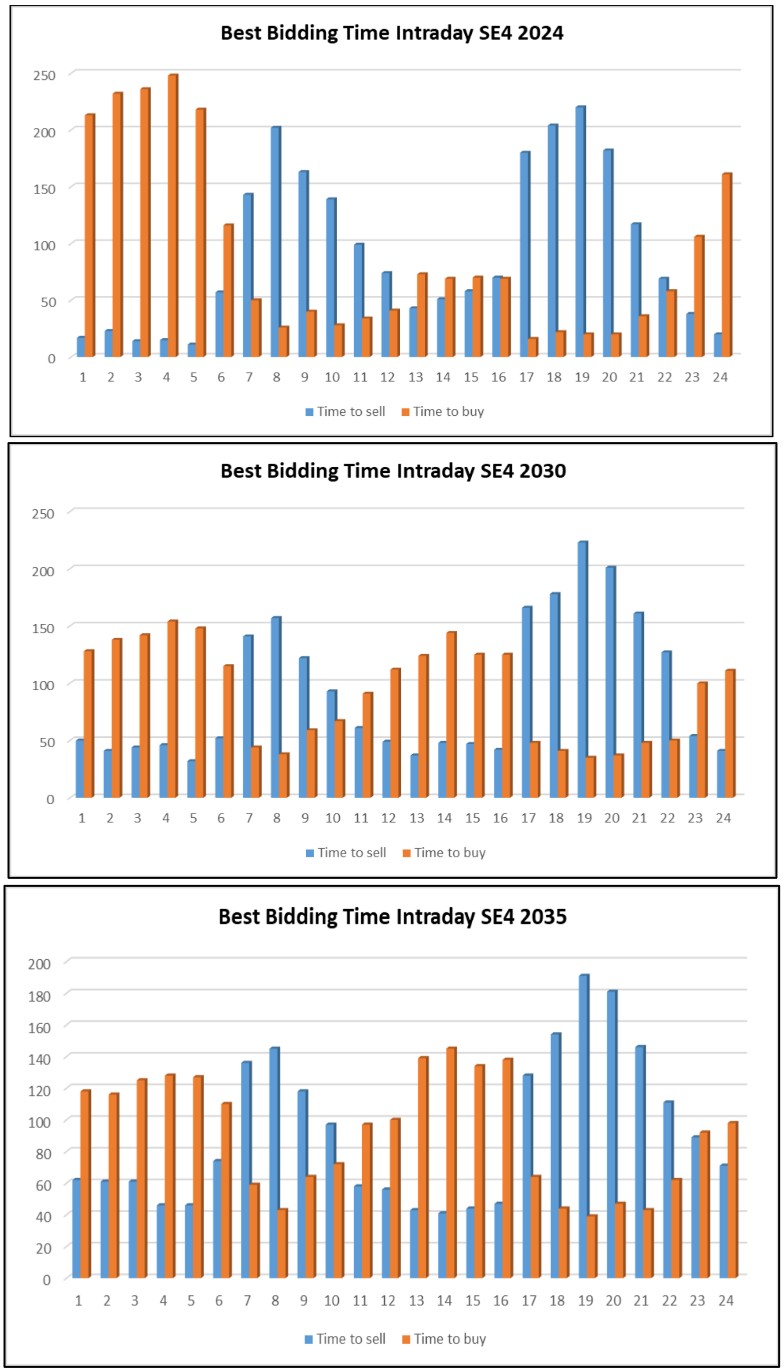


Figure 37 The costliest and cheapest Elbas hours of a day for bidding zone SE4 in 2024, 2030 and 2035

So, a bidding strategy similar to that of the day-ahead market has to be formulated here.

5.1.3 Frequency Reserve Market

As per the methodology discussed in section 3.4, first we get the maximum theoretical income potential from frequency reserve services. This value assumes that bids are placed for all the hours of the year and all the bids are accepted. Next, we employ the method as described in section 3.5 to calculate the bid acceptance probability.

Bid acceptance probability for FCR-N in the years 2021, 2022 and 2023 are calculated to be 3.92%, 7.09% and 7.91% respectively. If these three values are averaged, the average bid acceptance probability comes as 6.3 %. This percentage will be applied over the future forecasted theoretical FCR-N revenues to calculate the realistic income potential.

Similar calculations are done with FCR-D data of 2022-2023. The bid acceptance probability for 2022 and 2023 are calculated to be 7.74% and 11.51%. The average of these two values is 9.62 % and we are going to use this factor on the future forecasted FCR-D revenues.

When the income potential from FCR-N and FCR-D over the period of next 10 years are plotted, it can be observed that FCR-N income potential is generally greater than that of FCR-D income potential.

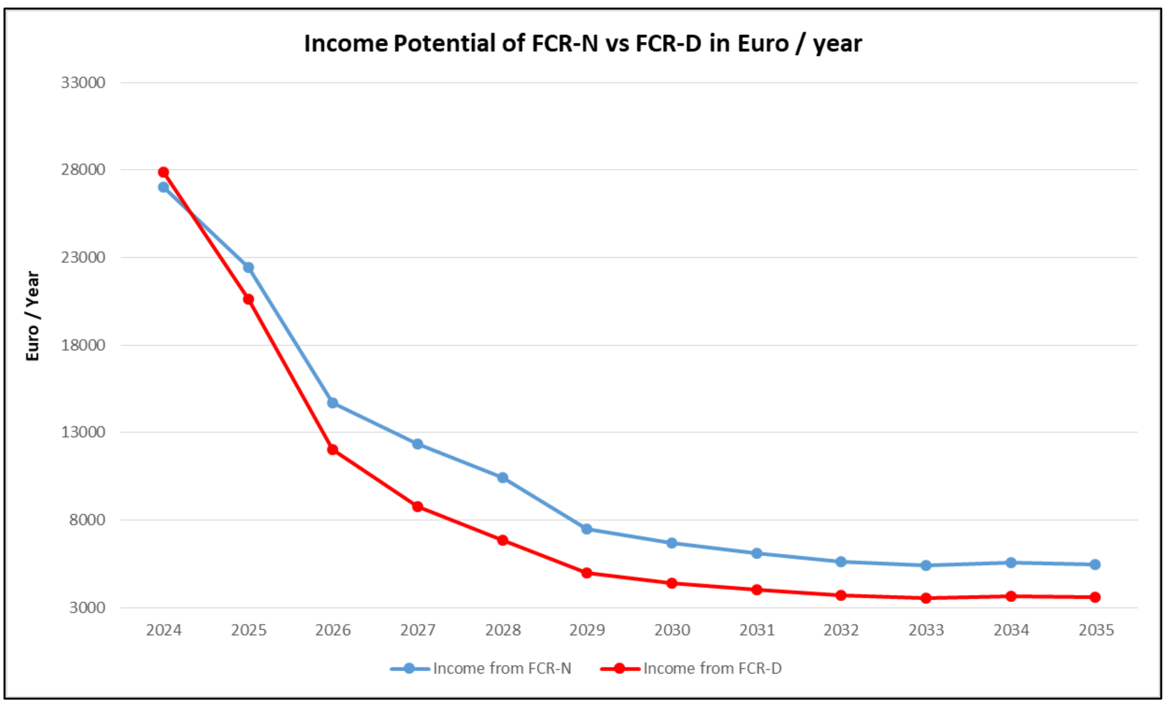


Figure 38 Comparison of Realistic Income Potential of FCR-N and FCR-D over the years

Later, availability prices of FCR-N and FCR-D for the years 2017-2022 are compared in Fig. 43 and the similar trend is confirmed.

In general also, the income potential of FCR-N is roughly 15-20% of day-ahead spot market and 10-15% of intraday market. If we plot the realistic income potential of FCR-N, Elspot and Elbas market for a 6-hr battery during the years 2021-2035, it looks as the following:

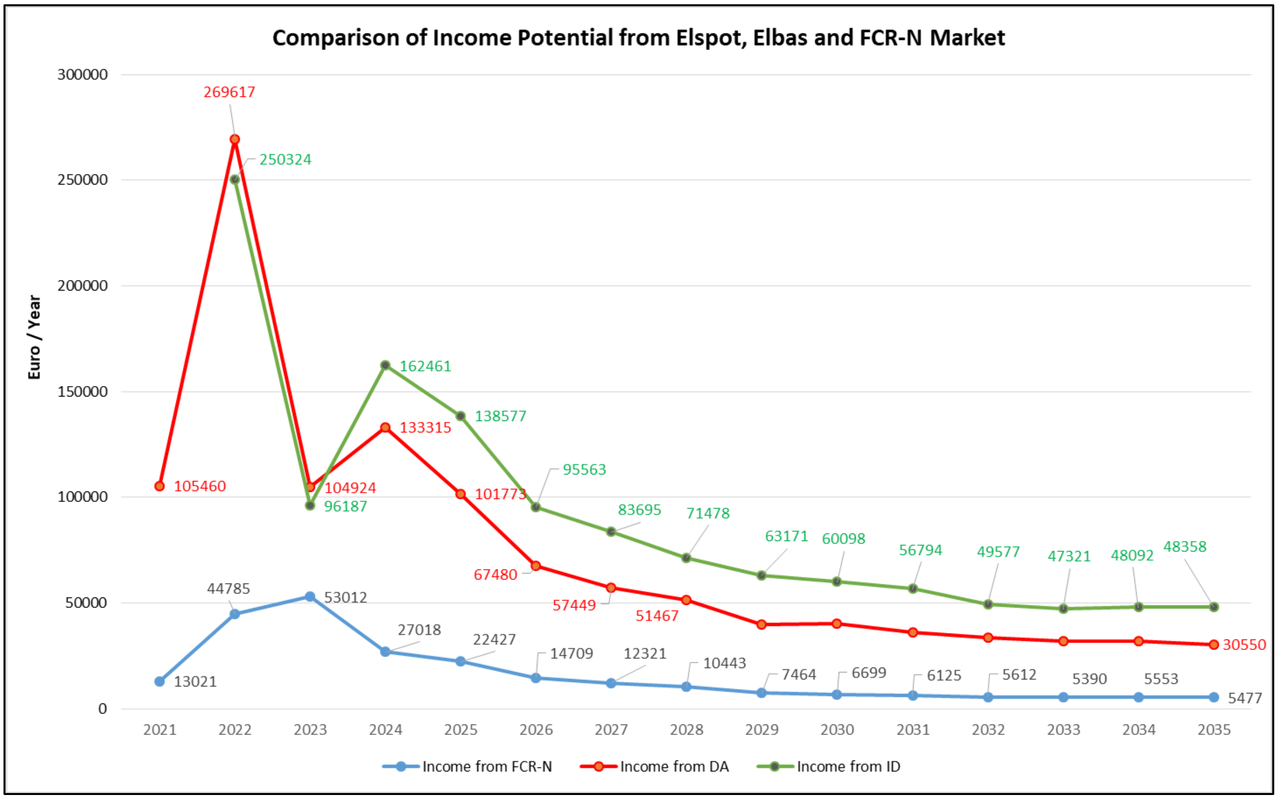


Figure 39 Comparison of Income Potential of Elspot, Elbas and FCR-N

As can be observed from the Fig. 39, the theoretical income potential of day-ahead market and intraday market are comparable. But the potential income from FCR-N is roughly 15-20% of day-ahead or intraday market.

In the next step, in order to make the calculation further realistic, we assume that a battery owner cannot bid in the frequency reserve market at all the hours of a day. Therefore, a more pragmatic approach is to reserve certain hours of the day for bidding in these segments. So, we would try to formulate a bidding strategy in FCR-N and FCR-D by understanding their price patterns (if there is any).

If we look at the number of occurrences of a particular hour of the day into the top 25 percentile of daily prices over a year, the following graphs are generated:

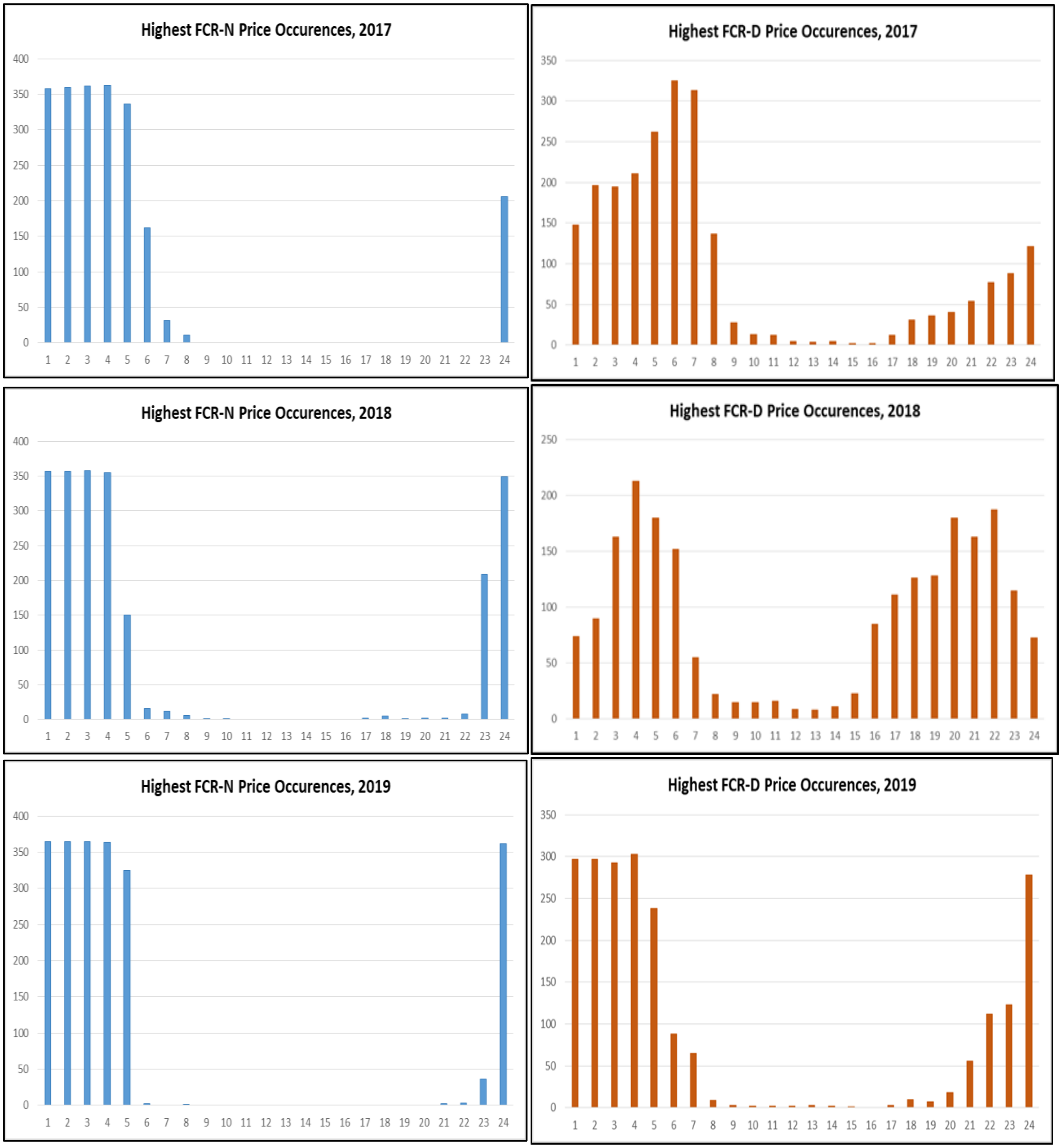


Figure 40 The costliest hours of a day in respect of FCR-N and FCR-D availability prices for bidding zone SE4 2017-2019

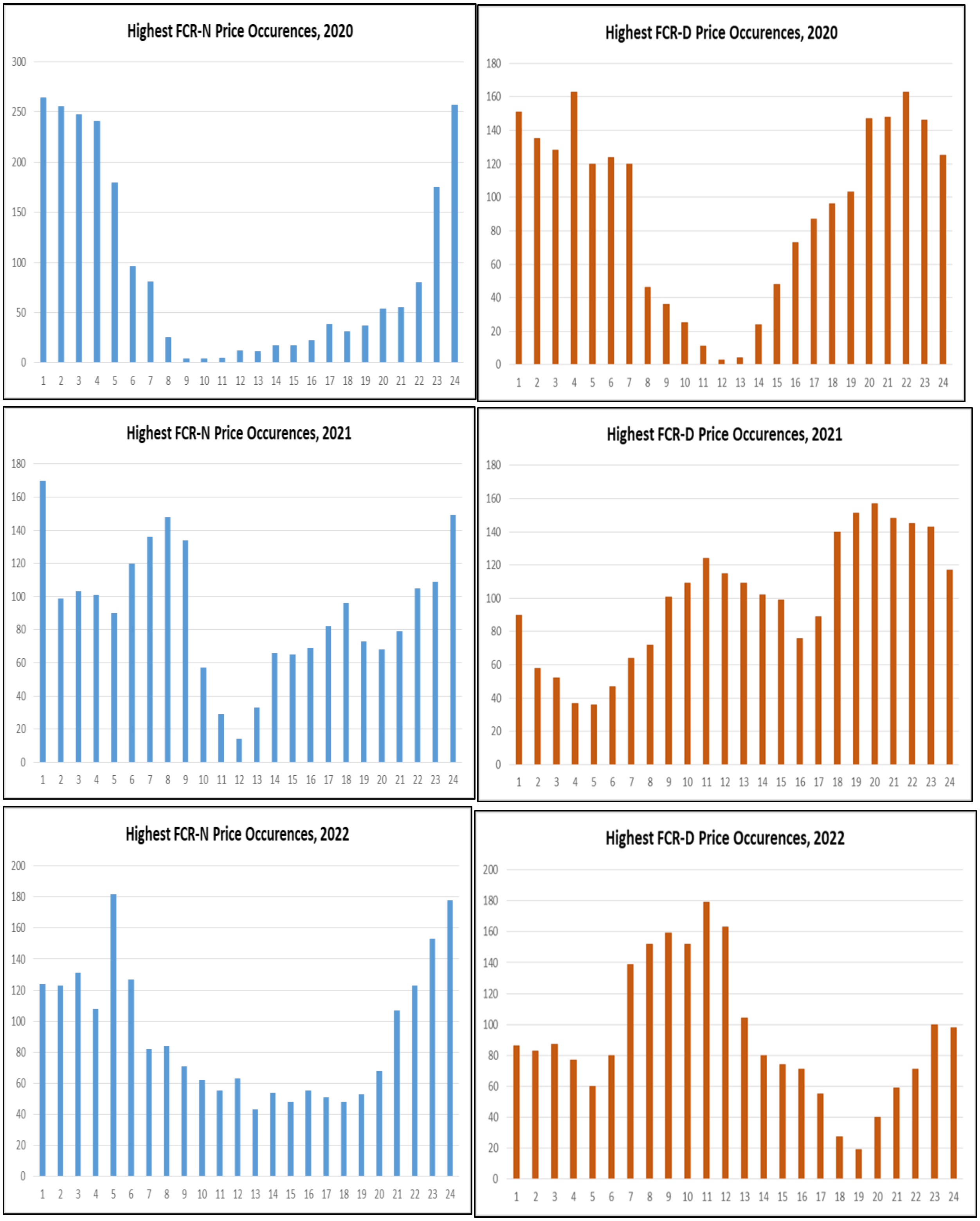


Figure 41 The costliest hours of a day in respect of FCR-N and FCR-D availability prices for bidding zone SE4 2020-2022

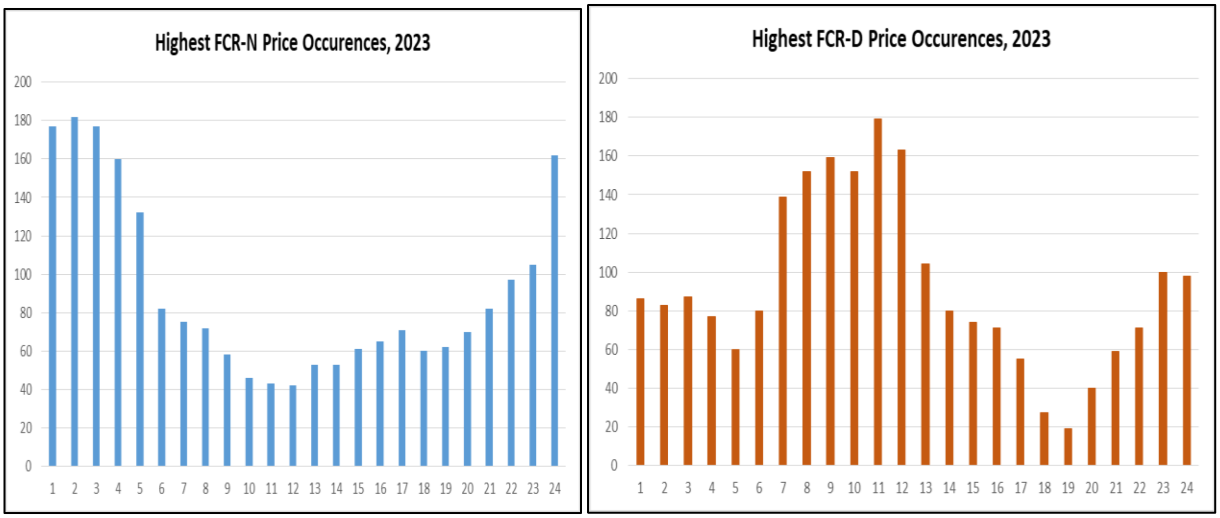


Figure 42 The costliest hours of a day in respect of FCR-N and FCR-D availability prices for bidding zone SE4 2023

From the above graphs, two observations can be made. Firstly, the FCR-N shows a clear price pattern of remaining high during the night hours and low during the day hours. This conclusion is supported by the paper (3), which finds a similar pattern with FCR prices of the Danish bidding zone DK-2. As a reason of this price behavior, the paper mentions that most big generation units remain disconnected during the off-peak hours. Therefore, the need of FCR-N services increase during those hours. This increased demand shoots up the price.

Secondly, the FCR-D shows a similar pattern for 2017-2020 but after that the pattern discontinues. The year 2021 is especially mentionable, as that year even the FCR-N pattern is comparatively less prominent. The paper (3) claims to have found no daily pattern in the FCR-D prices of DK-2.

Therefore, from this analysis it can be concluded that a bidding strategy can be formulated for FCR-N, but not for FCR-D. A part of or full night hours can be reserved for bidding in FCR-N.

Next, we investigate availability payment magnitude-wise which of FCR-N and FCR-D is more attractive. For this, we average the yearly FCR prices over a period of 24 hours, so that each hourly price represents the average of 365 price points. When we plot this for 2017, 2020 and 2022, the graphs look as the following:

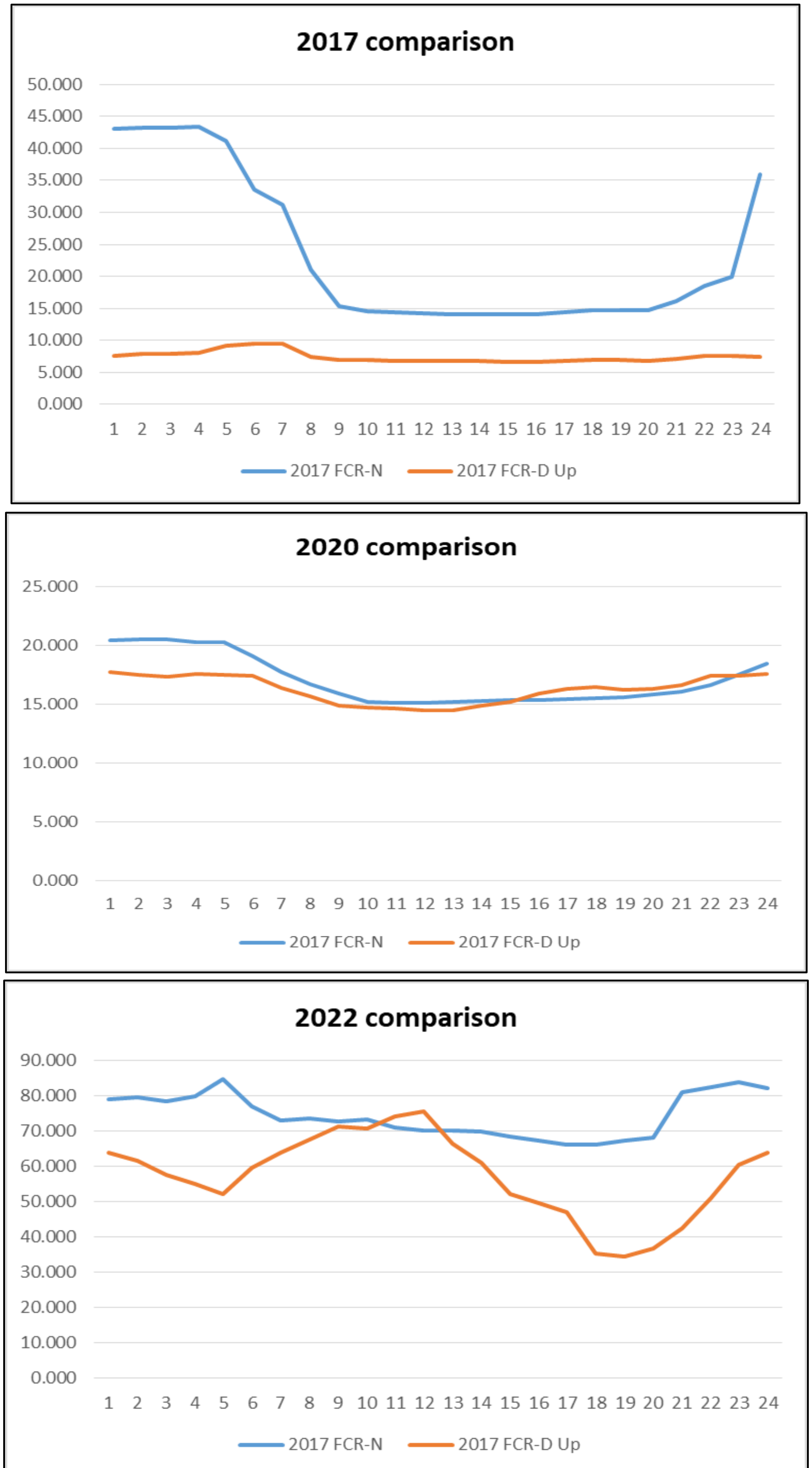


Figure 43 Comparison of Yearly Average FCR-N and FCR-D Availability Prices (Euro)

So, availability cost of FCR-N is generally more than that of FCR-D. This supports the conclusion from previous Fig. 38. So, FCR-N has both a clear daily price-pattern and its availability cost is higher on-average. From these two observations, FCR-N appears more attractive for this study and therefore certain hours of a day are fixed for bidding in FCR-N and rest of the times whenever the battery has some charge left, yet not participating in any market, it can be employed for FCR-D.

However, there is a counter-argument of preferring FCR-D over FCR-N. As discussed in (3) , a battery making its capacity available in FCR-D up or down segments has far less probability of being called to actually charge or discharge into the grid than in case of FCR-N. Therefore, a battery has an opportunity of earning just by making itself available in FCR-D market. In FCR-N on the other hand, it actually has to run a few cycles which causes battery degradation, wear and tear. As this thesis does not go into life-cycle implications of the battery providing various services, this kind of detailed analysis is beyond the scope of this study. The thesis takes FCR-N as the primary frequency reserve product.

If we reserve only 23:00 hrs. to 7:00 hrs. of each day for bidding in FCR-N, the Fig. 44 shows that almost 50% of the income potential from FCR-N can be achieved within those 8 hours only. This should be kept in mind while formulating a combined bidding strategy.

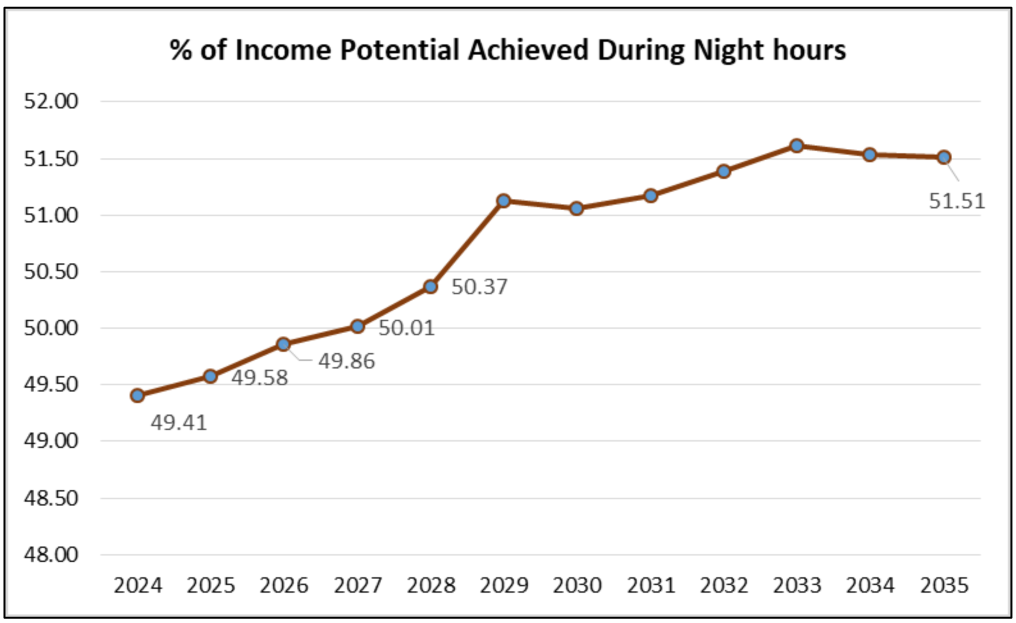


Figure 44 Percentage of Realistic Income Potential of FCR-N achieved during 23:00 hrs. to 07:00 hrs. of a day over the years

5.2 Business Case Analysis

5.2.1 Lithium-ion Batteries

5.2.1.1 Automatic Bidding

The business case for lithium-ion battery as explained in section 4.1 is filled with battery cost values as described in section 3.2 and automatic bidding revenues from various market segments as shown in 5.1.1. Any one of the day-ahead, intraday or frequency reserve market by itself cannot make the business case feasible, which is evident from the NPV and IRR values of the business case (Fig. 45). Here the NPV values have been shown as percentages of the corresponding CAPEX amounts for better understanding of the economic performance. It can be noticed that the IRR stays within the range -8 to -9 percent when the battery participates only in Elbas market. Whereas this value goes down to -21% in case of Elspot market. From Fig. 45 it can also be understood that FCR-N bidding produces least revenue of all and is the furthest from the break-even point.

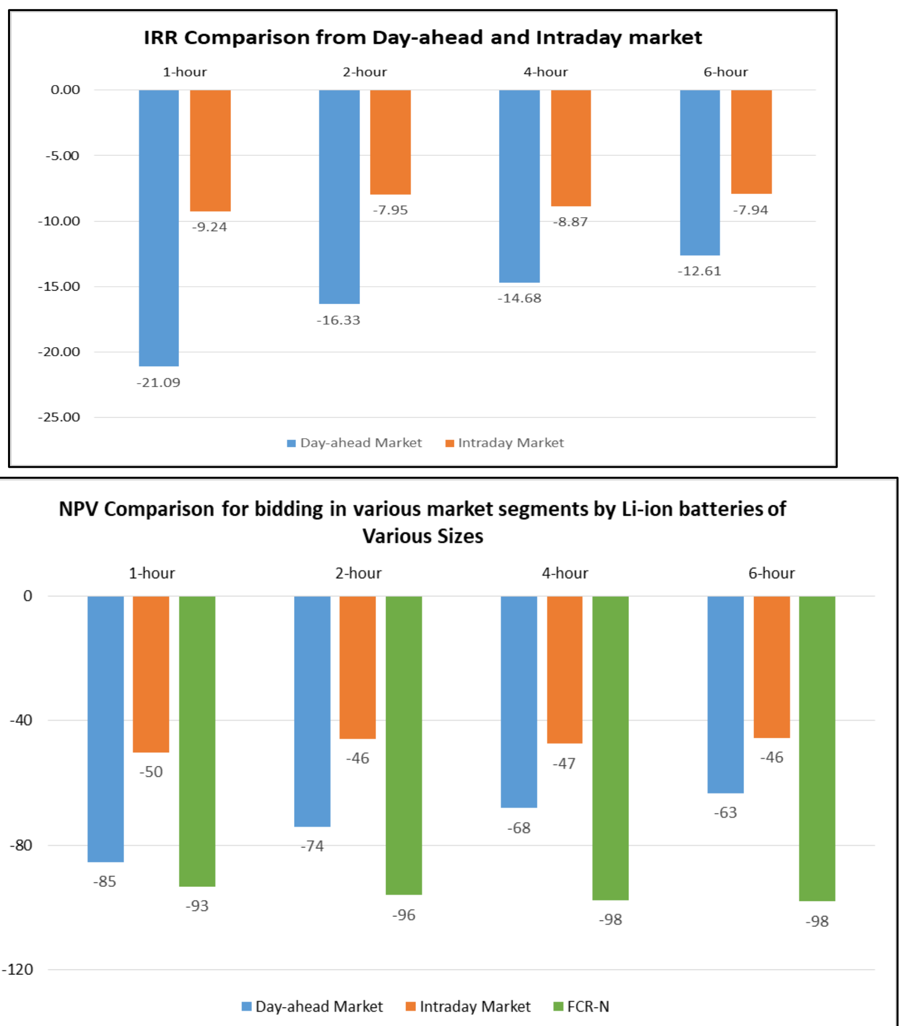


Figure 45 NPV and IRR Comparison for bidding in various market segments by Li-ion batteries of various Sizes

Now, it is important to judge under what conditions such investments might be feasible. So, we run sensitivity analysis with respect to two important parameters: CAPEX and price spread. In Fig. 46, NPVs of a Li-ion battery bidding in Elspot market is shown for CAPEX values 15%, 25%, 50%, 75% and 125% of the actual values as discussed in section 3.2 while keeping all other parameters unchanged. BESS project CAPEX prices in the Chinese market in 2023 as received from (13) is also used as a reference point here. It can be observed in that even at 15% CAPEX cost, the 1-hour battery investment is marginally profitable, whereas the 6-hour battery becomes break-even at 35% CAPEX.

The Chinese market CAPEX conditions in 2023 although do not make the investment profitable, but still are quite near to the break-even point compared the USA / Europe.

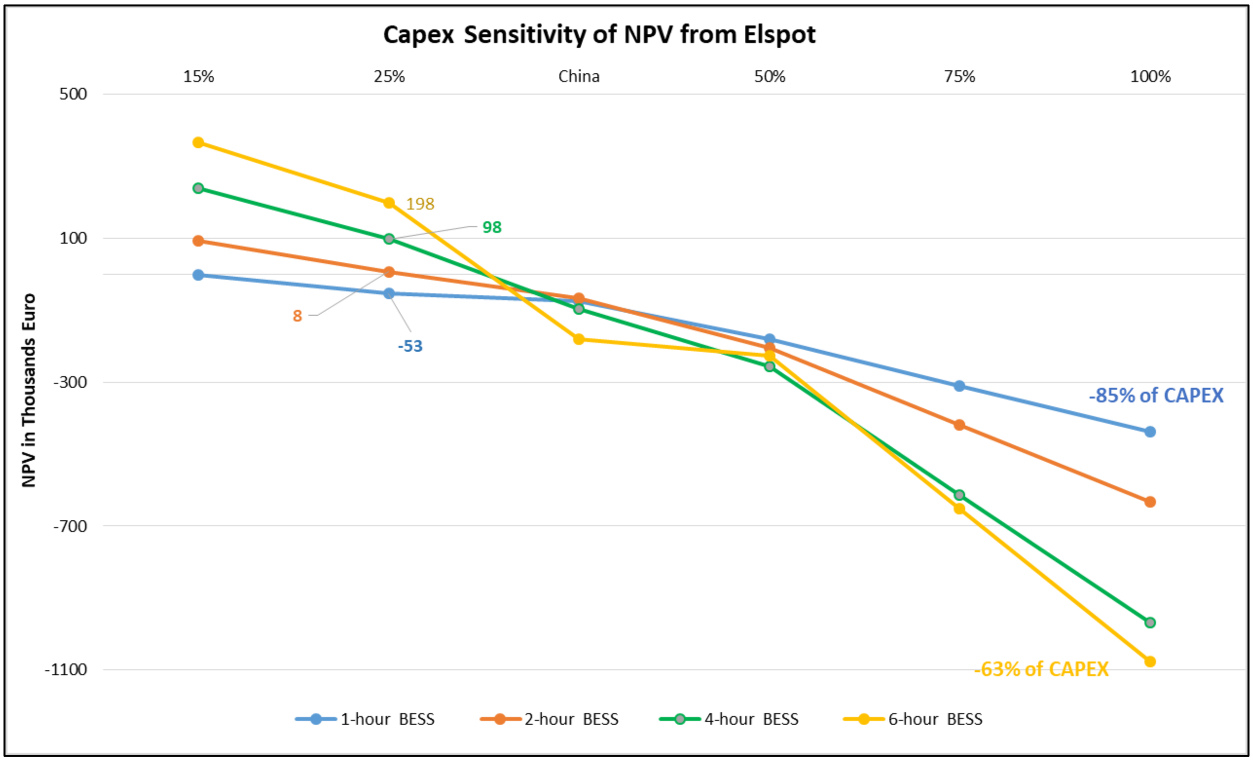


Figure 46 Sensitivity of the business case with respect to CAPEX for Li-ion Batteries of Various Sizes participating in Elspot Market only

For analyzing price sensitivity we formulate 5 scenarios as described in section 4.2. The case-1, case-2 and case-3 represent 50%, 150% and 200% of the forecasted price gap respectively. For case-4 we assume a high price period around the years 2032-33. When NPVs are calculated keeping all other parameters unchanged, it can be seen that a 6-hour Li-battery investment becomes break-even at 1.72 times the forecasted price gap, when bidding in Elbas only. When participating in Elspot only, the investment becomes break even at 2.4 times the forecasted price gap.

When the similar analysis is performed with a 1-hour Li-ion battery, the investment again becomes break-even at 1.72 times the price spread, when bidding in Elbas only. When participating in Elspot, the investment becomes break-even at 3.4 times the forecasted price gap.

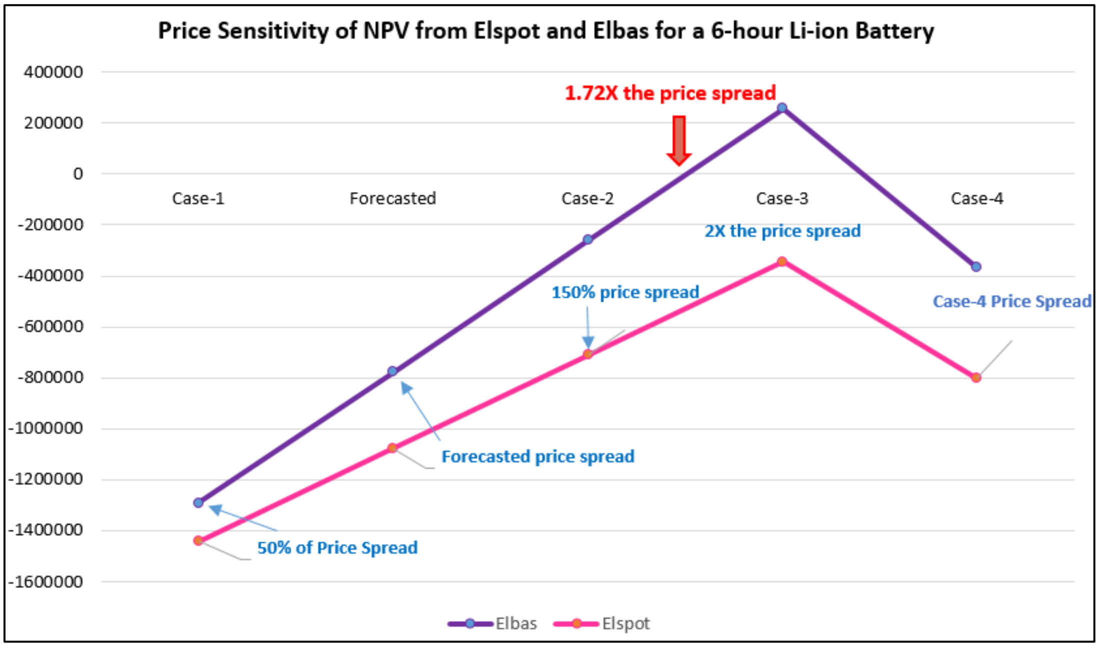


Figure 47 Sensitivity of the business case with respect to Price-gap in Elspot and Elbas markets for a 6-hour Li-ion Battery

Now, instead of varying only one parameter while keeping another constant, if we vary both CAPEX and the price spread, the resulting NPV for a 6-hour Li-ion battery participating in Elspot only are shown in the following heat map (Fig. 48 a).

Here the red cells have negative NPV and are therefore unprofitable. The green ones have positive NPV and are profitable. The color calibration has been done such that pure red represents the minimum NPV value, pure green represents maximum NPV value and pure yellow gives the NPV value of '0'. Naturally, the cells across the diagonal having yellowish color mostly represent the break-even scenarios. For example, 50% CAPEX and 1.5 times the price spread give IRR of 2.8% and NPV of EURO 138733. So, it is easy to guess that the exact break-even point will be very close to these values. Similarly, if we consider the forecasted battery price estimate in 2032 as per (30), the business case becomes break even at 1.6 times the forecasted price spread in Elspot market for a 6-hour battery.

Capex	Price-Spread				
	0.5	1	1.5	2	2.5
15%	2376	368083	733789	1099496	2146217
25%	-167640	198067	563773	929480	1976201
50%	-592680	-226973	138733	504440	1551161
75%	-1017720	-652013	-286307	79400	1126121
100%	-1442760	-1077053	-711347	-345640	701081
125%	-1867800	-1502093	-1136387	-770680	276041

Capex	Price-Spread				
	0.5	1	1.5	2	2.5
15%	-0.35	31.25	57.76	83.87	109.89
25%	-9.44	14.08	30.44	46.08	61.62
50%	-17.71	0.39	9.77	18.12	25.99
75%	-21.39	-5.60	2.27	8.39	14.01
100%	-23.69	-9.14	-1.96	3.17	7.71
125%	-25.34	-11.56	-5.07	-0.04	3.69

Figure 48 a. NPV (in Euro) Heat-map for a 6-hour battery participating in Elspot Market; **Figure 48 b**. IRR Heat map of a 1-hour battery participating in Elbas Market

If we look at Fig. 48 b, a 1-hour battery participating in Elbas market reaches break-even point when the CAPEX is halved (with price-gap unchanged). Or if the price-gap is 150% the forecasted values, it can reach break-even point at 75% of the CAPEX only.

5.2.1.2 Manual Bidding

As observed in Fig. 31 the revenue potential of manual bidding is only 15-25% of that of the automatic bidding, therefore it is easily guessable that business case with manual bidding will be even more unprofitable. For example, if we analyze the case of a 1-hour Li-ion battery participating in day-ahead market only, the NPV comes as -587677 EURO. The investment becomes break-even only if the CAPEX is made 5% and simultaneously the price-spread in day-ahead market is made 5 times the forecasted value.

Similarly the business case of a 6-hour Li-ion battery participating only in the intraday market (Elbas) was analyzed and the NPV was found to be -1590772 EURO. The investment will only be break-even if the CAPEX is made 50% and simultaneously the price-gap becomes 5 times.

Therefore, it can be safely concluded that with manual bidding it is impossible to attain a profitable business case.

5.2.2 Redox Flow Batteries

If the same calculations as section 5.2.1.1 are repeated for a redox flow battery, the IRR and NPV values generally improve a little bit (Fig. 49), but still the investment remains unprofitable. Here, although the net arbitrage profit is lesser than that of a Li-ion battery due to lesser round-trip efficiency, it can earn over a longer duration of life time (assumed 25 years here). That is contributing in better IRR and NPV values (except for 1-hour battery participating in Elbas).

Here also, the CAPEX and price-gap can be modified to make the investment profitable. For a 6-hour redox flow battery participating in Elspot market only, breakeven point can be reached if the CAPEX is halved and the price gap is doubled at the same time. For a 1-hour redox-flow battery, the CAPEX and price-spread need to be halved and tripled respectively to reach the same point.

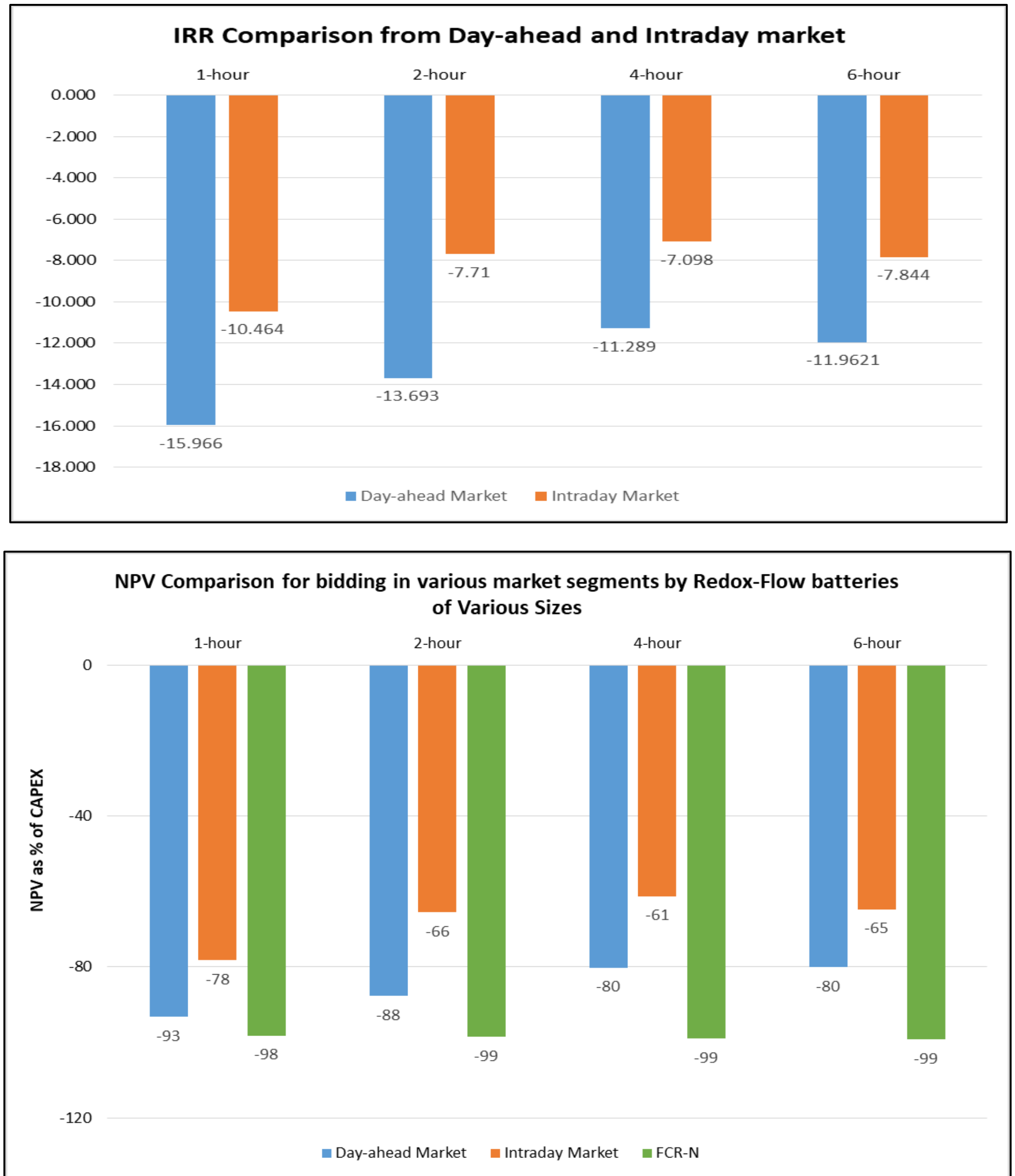


Figure 49 NPV and IRR Comparison for bidding in various market segments by Redox-Flow batteries of Various Sizes

Again, for a 1-hour battery participating in the Elbas market, the break-even point is reached when the CAPEX is made 25% (without changing the price-gaps). For a 6-hour battery the CAPEX and price-spread need to be halved and doubled respectively to reach the same point.

5.2.3 Sodium Ion Batteries

If NPV of sodium ion batteries participating in day-ahead and intraday markets are plotted, it looks as the following (Fig. 50).

Here, for a 6-hour battery bidding in the Elbas market alone, either making the CAPEX 50% or making the price-spread 1.5 times moves the investment past the breakeven point. On the other hand, for a 6-hour battery bidding in the Elspot market only, both the CAPEX has to be halved and the price-gap has to be doubled in order to reach the breakeven point.

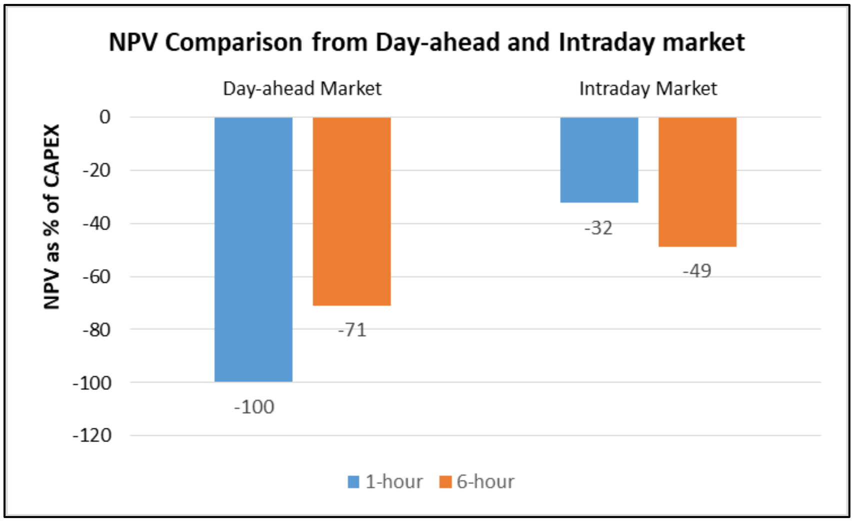


Figure 50 NPV Comparison for bidding in Day-ahead and Intraday market segments by Sodium-ion batteries

5.2.4 Comparison among three types of Batteries

The following table summarizes the whole sensitivity analysis with respect to CAPEX and price-gap. The ways of achieving the breakeven point by varying the CAPEX and the price-spread to various extents can be noticed here. For example, when a 1-hour lithium-ion battery is participating in Elspot only, breakeven point can be achieved by making the price-gap 3.4 times the forecasted value (keeping CAPEX unchanged). Whereas, if the CAPEX is halved, the breakeven can be achieved with 2 times the projected price-gap only.

The logic “AND” means both the CAPEX and price gap requirement have to be fulfilled in order to make the investment profitable. Whereas, the logic “OR” signifies that any one of the two requirements is enough to drive the business case beyond breakeven point.

Table 3: Summary of sensitivity analysis with respect to CAPEX and price-gap

		1-hour BESS			6-hour BESS		
		CAPEX Requirement	Logic	Price-gap Requirement	CAPEX Requirement	Logic	Price-gap Requirement
Li-ion battery	Elspot	---	---	340%	---	---	240%
		50%		200%	50%	AND	150%
	Elbas	---	---	172%	---	---	172%
		50%	-	-	50%	---	---
		75%	AND	150%	---	---	---
Redox	Elspot	50%	AND	300%	50%	AND	200%
	Elbas	25%	---	---	50%	AND	200%
Na-ion	Elspot	50%	AND	180%	50%	AND	200%
	Elbas	65%	---	---	50%	OR	150%

Now, if we want to see in absolute terms, how much price-spread is required to make the investment feasible for a certain value of CAPEX, the following Table 4 summarizes that.

The price-gap requirement for a 1-hour battery is calculated as the daily income requirement from price arbitrage. The underlying assumption is that the battery is working only 1 cycle/day. Similarly, for a 6-hour battery, the price gap is calculated as daily income requirement from price arbitrage divided by 6. Also, as observed from Fig. 28 the income from arbitrage can vary widely over the lifetime of a battery and its value at the time it is dismantled can easily reach 20% of its value at the start of its lifetime. Therefore it is really difficult to give a specific price-gap value as requirement of going profitable. So, the price-gap shown here is the average of yearly price-gaps over the lifetime of a battery.

Here, the colored rows represent the present CAPEX values as received from (30) and (13). Therefore, the corresponding price gaps give the present requirements. The other rows give the projected price-gap requirements in case of CAPEX reduction in future.

Table 4 CAPEX and Price-gap requirement to make a certain battery profitable

	1-hour BESS		6-hour BESS	
	CAPEX Requirement (€/kWh)	Price-gap Requirement (€ / hour)	CAPEX Requirement (€/kWh)	Price-gap Requirement (€ / hour)
Li-ion battery	511.52	115.07	283.36	57.08
	383.64	95.89	212.52	43.38
	255.76	68.49	141.68	29.68
Redox	999.12	136.99	162.23	128.77
	499.56	82.19	81.11	82.19
Na-ion	257.60	87.67	220.80	57.08
	128.80	60.27	110.40	33.33

From the above table, it can be concluded that Sodium-ion batteries seem to be the most economically attractive option based on present costs and price levels; followed by lithium-ion batteries. Both of them have similar project lifetime and round-trip efficiency.

However, the high price-gap requirement for redox flow batteries might have emerged because of the fixed arbitrage income assumption over the lifetime of the battery. More analysis by varying the discount rate is required to understand this phenomenon.

For a realistic reference, it can be mentioned that average price gap available in 2022 Elspot market for 1-hour and 6-hour batteries were 166.34 €/ hour and 123.1 €/ hour respectively. The same for 2023 were 70 €/ hour and 48 €/ hour respectively. Therefore a price level equivalent to 2022 can make a BESS project participating only in spot market profitable even with present CAPEX rates. This explains the prevalent optimism in the energy storage market at the moment.

5.2.5 Combined Bidding Strategies

- **Automatic Strategy:** As discussed in section 4.2 the 'automatic' combined bidding strategy picks up that market which gives the highest revenue at a particular day. This way it assigns the battery to a specific market for a whole day. The following graph explains how this strategy works for the days of January, 2024.

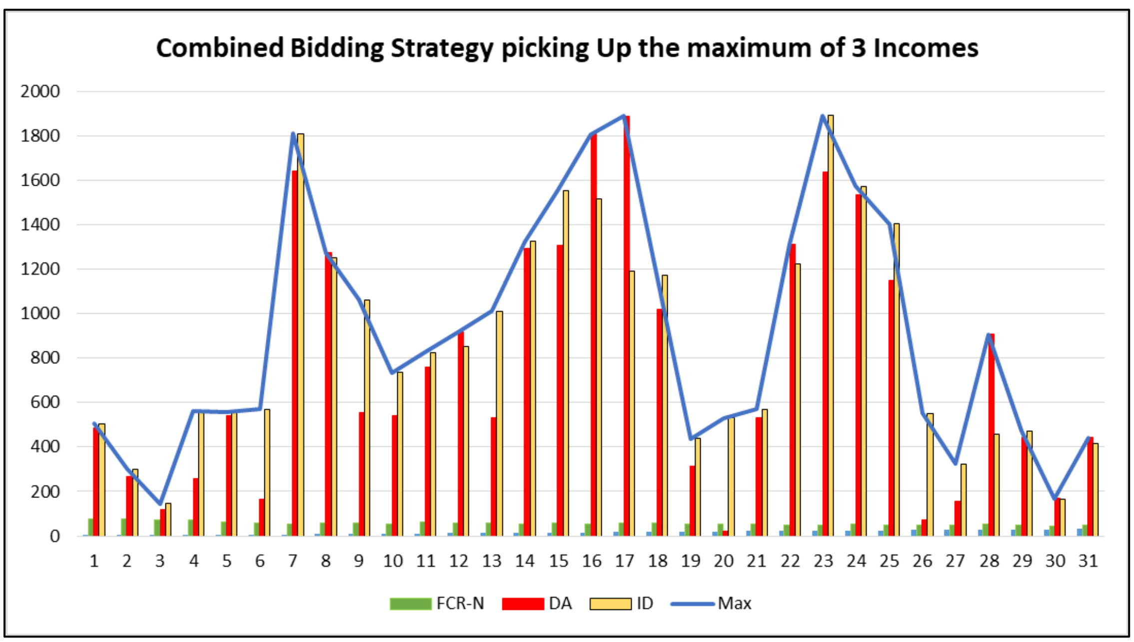


Figure 51 Combined Bidding Strategy picking up the market with the highest daily income

Here, the green bars represent earnings from FCR-N given the battery is reserved for bidding in FCR-N only the whole day. Similarly red and yellow bars signify daily earnings from day-ahead and intraday markets respectively. The blue line is the maximum of these three values. Therefore, by knowing the price forecasts exactly, the battery owner can maximize his / her return.

If economic performance of this strategy is investigated for a 6-hour Li-ion battery, the IRR is calculated as -7.17%, so even this strategy is not profitable. However, it can reach profitability if the price gaps are doubled or the CAPEX becomes half.

- **Manual Strategy:** In order to maximize gain from all three market segments it is essential to pick up the most profitable hours of those markets and set an hourly bidding strategy to facilitate that. From Fig. 30 and Fig. 36 it is clearly understandable that price patterns are almost similar in day-ahead and intraday markets. To maximize profit either the morning peak or the evening peak has to be capitalized and for both of them generally intraday market provides greater price-spread than day-ahead market. Fig. 52 shows comparison of average price spread values in morning and evening peak for these two market segments calculated over the forecasted prices in 2024-2027.

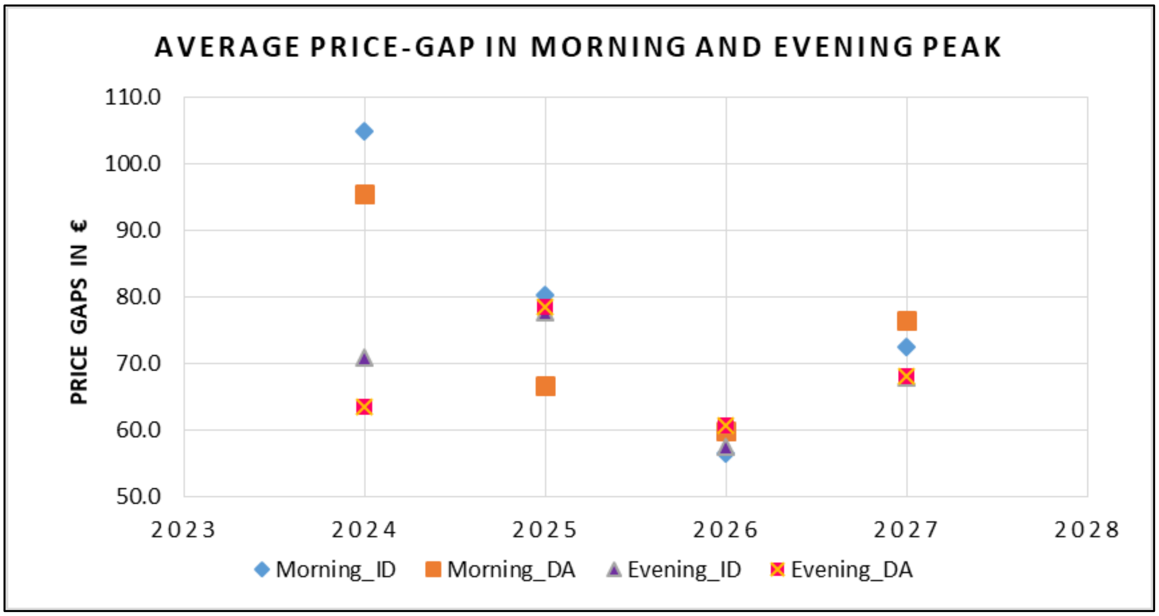


Figure 52 Average Price gap in Euro for Day-ahead and Intraday market in the Morning and Evening Peak

Another important observation from Fig. 30 and 36 is: price being quite low during 12-16 hours due to increase in solar penetration. This trend is found to increase in future years (Fig. 33). Therefore, this strategy employs two cycles/ day for arbitrage purpose.

Again, from Fig. 40-42 it is evident that night hours are profitable for frequency reserve services.

Therefore, the combined bidding strategy is as follows:

23:00 hrs. to 03:00 hrs. : Battery Bidding in FCR-N
03:00 hrs. to 07:00 hrs. : Battery Buying from Intraday market
07:00 hrs. to 11:00 hrs. : Battery Selling in Intraday market

12:00 hrs. to 16:00 hrs. : Battery Buying from Day-ahead market
17:00 hrs. to 21:00 hrs. : Battery Selling in Day-ahead market

Now this strategy is employed on a 4-hour Li-ion battery and the economic performance is judged.

The investment is found to be not at all profitable with NPV value -1372536 Euro, which is roughly 95% of the initial CAPEX. The investment reaches breakeven only when the CAPEX is made 25% and total income is made thrice the calculated value.

5.2.6 Sensitivity Study with respect to Bid Acceptance Probability

For the calculation of income from ancillary services a fixed bid acceptance probability is applied on the forecasted prices. For FCR-N this is taken as 6.3% and for FCR-D it is taken as 9.62%. However, as suggested in (25), this fraction can vary over a wide range (2-25% in that literature). So, a sensitivity analysis can be done with respect to this fraction to check the resulting business case performance.

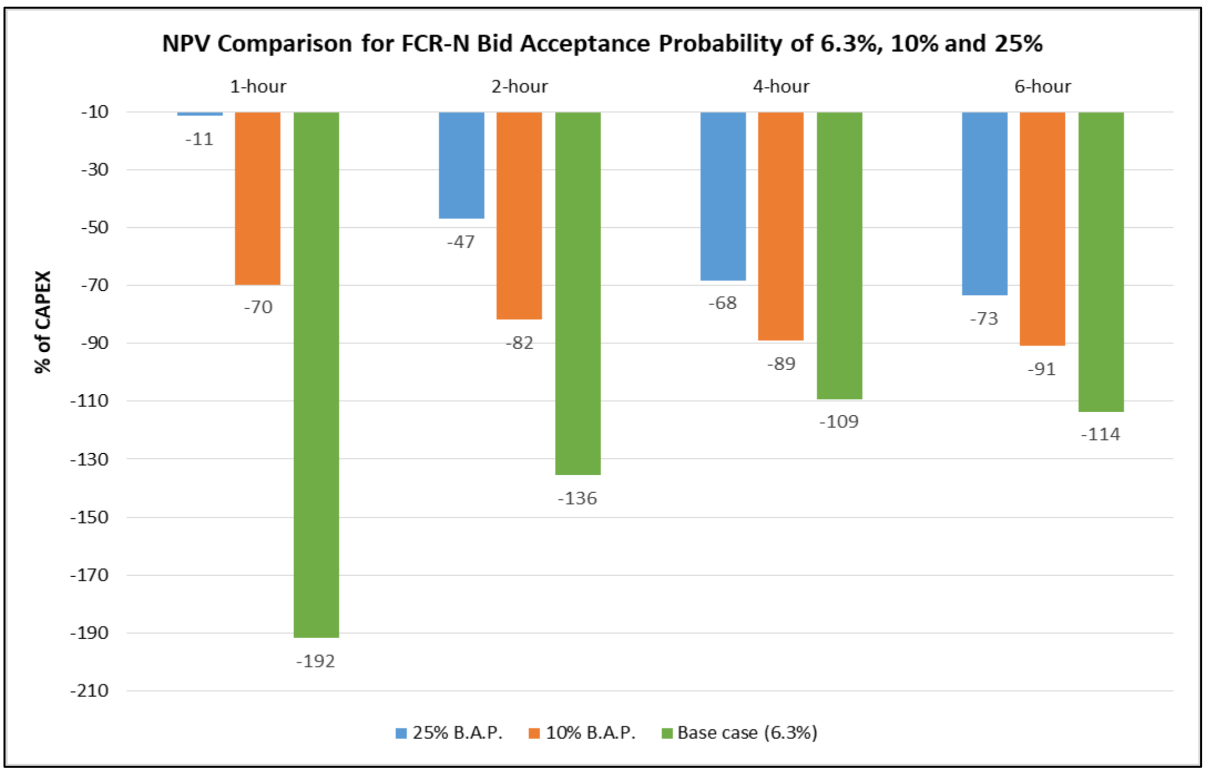


Figure 53 NPV Comparison for FCR-N Bid Acceptance Probability of 6.3%, 10% and 25% in a Li-ion battery

In Fig. 53 the vertical axis gives NPV as a percentage of the corresponding CAPEX values. So, it is clear that larger bid acceptance probability can bring the business case nearer to the breakeven point, especially in case of short-duration batteries.

5.2.7 Relative Profitability of Long-duration Batteries

If we want to compare relative profitability of 1-hour and 6-hour batteries based on forecasts available, the 6-hour battery is nearer to the break-even point than 1-hour battery. As can be observed from Table 4, the 6-hour batteries need smaller price-gap than 1-hour batteries to go profitable, independent of the battery technology.

When per MWh CAPEX versus per MWh revenue for batteries are compared for various sizes (Fig. 54), both the quantum reduces with increase in battery size. However, the reduction in CAPEX with increasing size is more than reduction in revenue. For example in Fig. 54.a, per MWh CAPEX of a Li-ion battery is compared with per MWh revenue in 2024 from Elspot. Per MWh Elspot revenue in 2024 for a 6-hour battery is roughly 21% lesser than that of a 1-hour battery whereas the per MWh CAPEX is roughly 44% lesser than 1-hour battery. In Fig 54.b, the same comparison is done with the revenue over the battery's lifetime (without considering any discount rate). Here also, per MWh revenue reduction is roughly 33% which is lesser than per MWh CAPEX reduction of 44%.

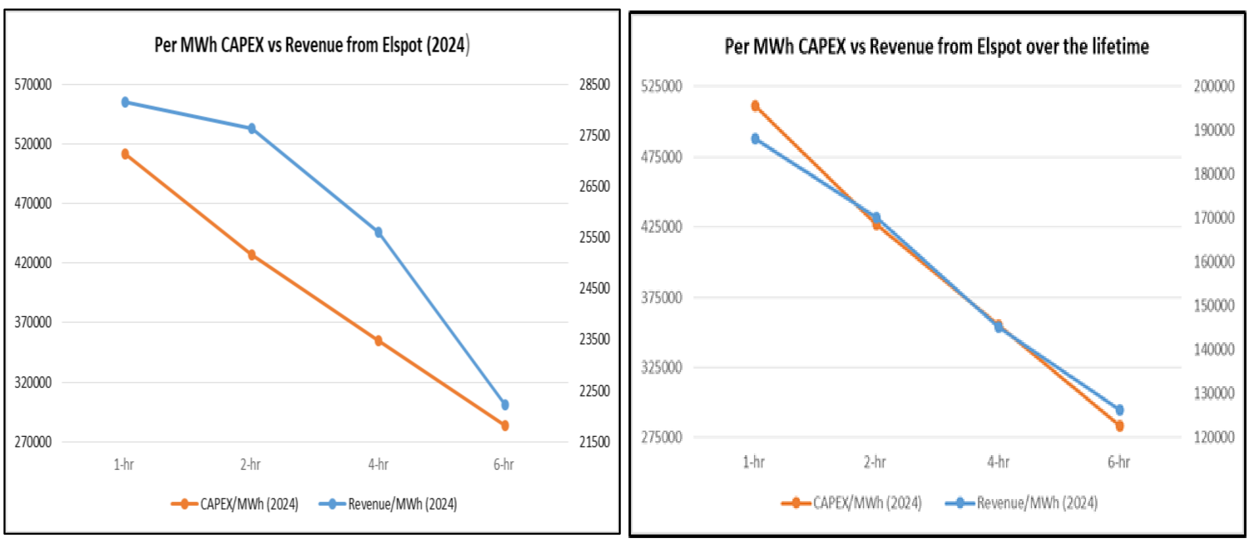


Figure 54.a Per MWh Revenue from Elspot for 2024 vs. per MWh CAPEX ; **Figure 54.b** Per MWh Revenue from Elspot over the lifetime vs. per MWh CAPEX

If the same comparison is done with 2032 price levels taking both battery cost and income predictions into account, the trend remains the same (Fig. 55). The 'per MWh revenue' reduces 25% from 1-hour to 6-hour systems; whereas the corresponding CAPEX reduces by 42%.

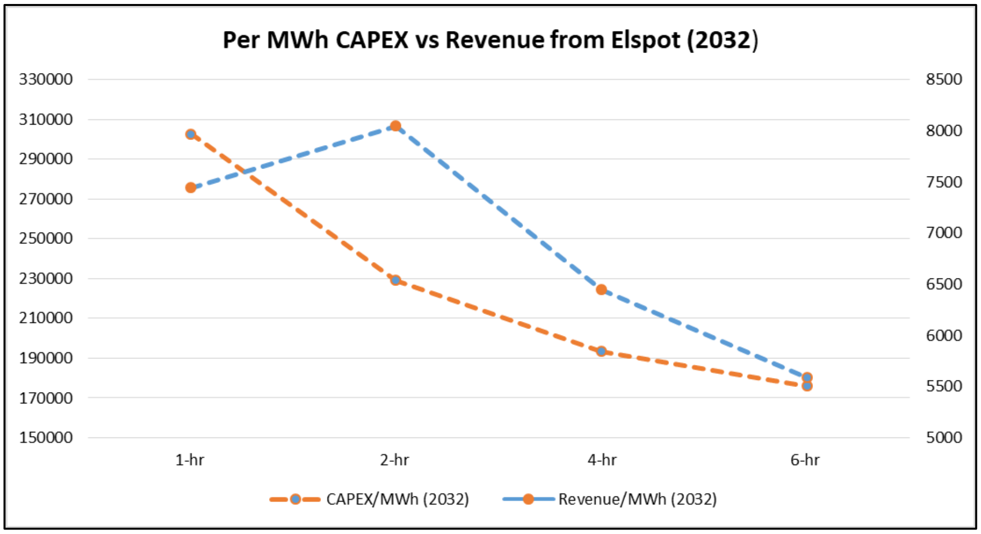


Figure 55 Per MWh Projected Revenue from Elspot for 2032 vs. per MWh Projected CAPEX

Now, if the analysis is extended to redox flow batteries and 8-hour batteries are included too, the trend remains the same (Fig. 56). Here, the per MWh CAPEX drop is 71% in contrast to per MWh revenue drop of 62%.

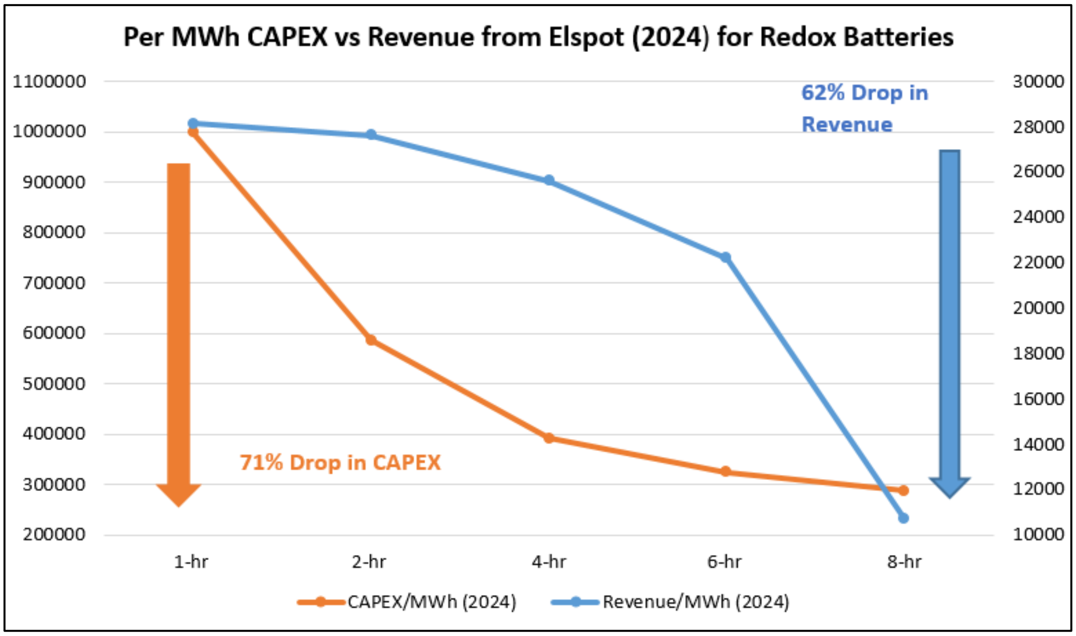


Figure 56 Per MWh CAPEX and Revenue drop in Euro for a Redox Flow battery

The similar trend continues with intraday market and sodium-ion batteries too. So, based on the above analysis, it can be concluded that although none of them are profitable at the moment, long duration batteries are relatively more profitable than their 1-hour counterparts, if they are participating in day-ahead or intraday markets.

However, if we assume a battery participating in ancillary markets only, the trend changes (Fig. 57). Here the revenue per MWh drops 83.33% from 1-hr. to 6-hr. battery in contrast to 44.6% for the corresponding CAPEX drop. This is mainly because of the assumption that income from ancillary services remains more or less same for all storage durations.

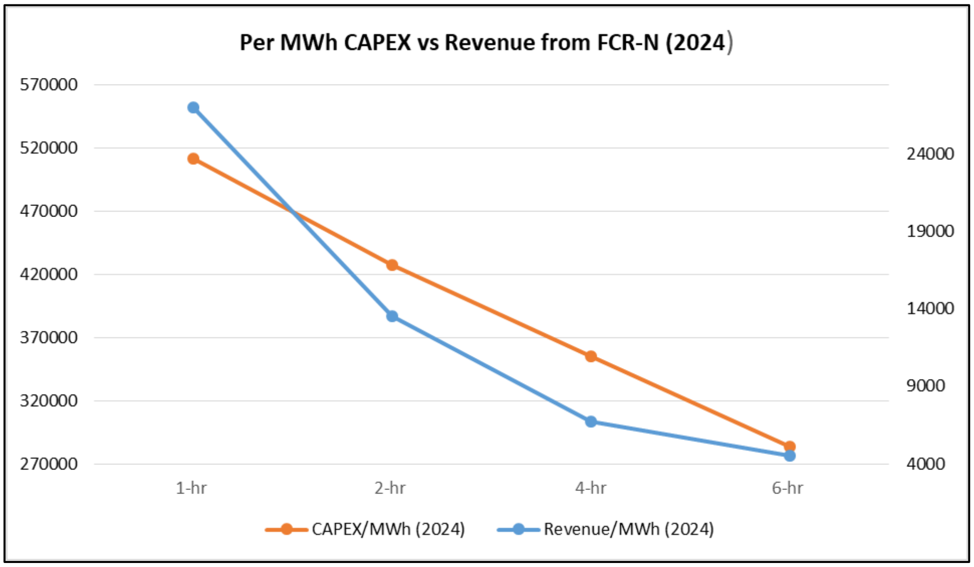


Figure 57 Per MWh CAPEX vs per MWh Revenue from FCR-N (2024)

For a battery participating in all three energy market segments, the relative profitability of long-duration battery is a topic of further research. It can be guessed that it will depend on the relative magnitude of incomes from various markets. If income from energy arbitrage dominates the net income, it will be profitable to invest in long duration batteries. Whereas, if income from ancillary services dominates the net income the reverse might be true.

Therefore, given the costs and price levels being faced by the batteries, it can be definitely recommended that the battery owners should explore investing in long-duration batteries, independent of the technology; if they can afford the greater initial investment.

Chapter-6

Conclusion and Future Work

After the detailed discussions of the results, it can be stated that a battery cannot perform well economically by participating in any one market segment. If it participates in more than one segment, the probability of profit increases. As per the present CAPEX values and price forecasts used for this thesis, none of the battery investments are found to be profitable. However, it is understandable that price forecasts over such a long horizon are meant to have some limitations. Therefore, price levels required to make the investment profitable for a certain value of CAPEX have been mentioned in table 4.

It was further observed that 'manual' bidding strategies, although quite simple and straightforward to follow, are less profitable compared to 'automatic' strategies using forecasts. Among various battery technologies, sodium-ion batteries are found to be most attractive economically, followed by lithium-ion batteries. However, their future cost evolution can change this order.

To quantify the income from frequency reserve services has been the toughest challenge of this study. It is understandable that a lot of uncertainty still remains with the 'bid acceptance probability' and profitability of the business cases can change considerably if income from ancillary services are much greater than calculated here.

The Table 4 values and discussions at section 5.2.7 indicates that for this set of CAPEX and price forecast data, 1MW/6MWh BESS systems are relatively more profitable than 1MW/1MWh BESS.

A number of interesting ideas emerge at the end of the study that can be pursued in future research works.

Firstly, this thesis employed the procedure as mentioned in (25) for calculating income from ancillary services. However, the method is not without its limitations. It treats the FCR-N and FCR-D markets in the same way as intraday market and proposes charging and discharging in a sequential way looking into the prices. However, as (3) and (4) confirm, a battery actually has to charge or discharge into the grid for a very small fraction of the period it declares its availability in the frequency reserve services. Combining this information with the fact that a battery can earn both by charging and discharging, it can be assumed that a battery can participate in a frequency reserve market throughout a day (irrespective of up or down regulation required) after just charging once at the start of the day. What happens with the profitability with this strategy can be explored in a future work.

Also, the discount rate can be varied to find out any changes in the profitability situation.

Moreover, the economic performance might be better if the battery is not stand-alone but in combination with a PV or wind generation unit. (27) looks into such a hybrid system in Sweden that tries to optimize the operation strategy as well as the profit. Such kind of study might be really interesting for this type of system.

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