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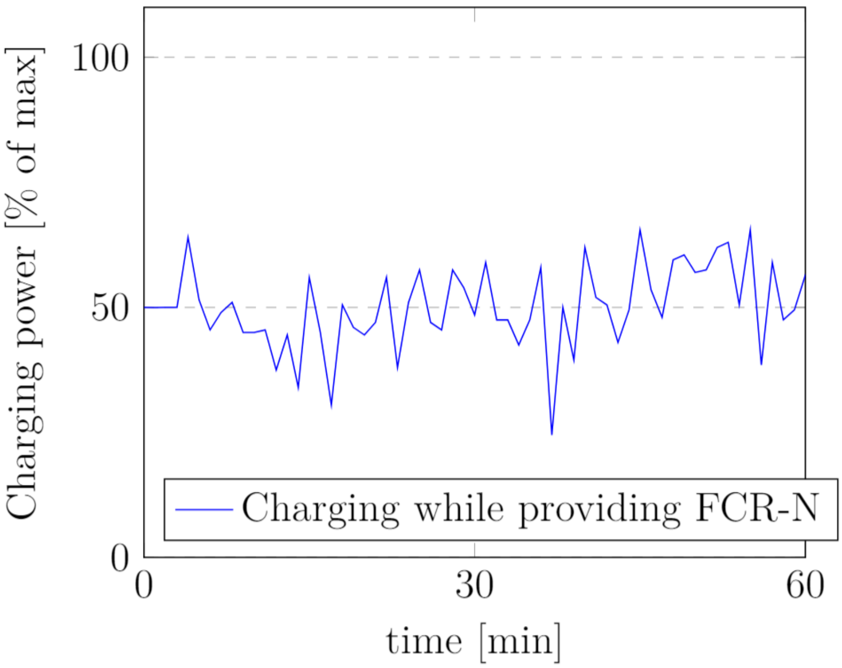

Forklift Batteries as Frequency Containment Reserve

Master's thesis in Sustainable energy systems

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Gothenburg, Sweden 2019

MASTER'S THESIS 2019

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Cover: Illustrative figure showing fluctuations in charging power for a battery that is charging while supplying FCR. (Calculated using frequency data provided by Svenska Kraftnät.)

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Abstract

Batteries are frequently discussed as one of the technologies which could be used to handle unbalances in the electricity system. To avoid the investment cost, batteries with another main purpose could be used to supply these services. Forklift batteries are not used for material handling all hours of the year and could potentially be used to supply frequency control power when they are parked and connected to a charger. However, batteries are not one of the traditional types of suppliers of frequency control power, and the frequency control power market in Sweden is not well adjusted to energy storage units. In this study, it was investigated what challenges there are in today's frequency control power market which might hold back energy storage units from participating on the market. In addition to this, a simulation model was developed to investigate to what extent the ordinary operation of forklift batteries would be affected by letting the batteries serve as frequency containment reserves when the forklifts are parked.

The result shows that the FCR market requirements in Sweden are not well adjusted to energy storage units regarding energy requirements and supplier type categorisation. The result also indicates that the activation of FCR power do not affect the ordinary operation considerably, provided that the parked forklifts are able to provide all requested power. However, the result clearly demonstrates that bid calculation strategy and charging algorithms in the studied case needs careful consideration and further development to make sure that all offered power is available and that no energy quantity problems occur.

Keywords: FCR, FCR-N, FCR-D, frequency, reserve, forklift, batteries, electricity, market.

Acknowledgements

First I would like to thank the people at Alelion for giving me the opportunity of doing my master's thesis there, and for their time and resources. I especially want to thank Felix Haberl for valued input, good discussions and support.

I would also like to thank my supervisor David Steen for great guidance and valued feedback during the project, and Tuan Le for being my examiner. Furthermore, thank you Simon Malmberg for your helpful comments and feedback.

Thank you Emil for supporting me.

Malin Jacobsson, Gothenburg, June 2019

Contents

1 Introduction

Facing climate challenge, the transition into a more sustainable energy system has started. Development of new technologies as well as policy instruments like subsidies and electricity certificates has led to increased shares of renewable, intermittent and decentralized electricity generation [1]. Renewable electricity generation is expected to keep conquer larger shares of the electricity generation market in the coming decades [2]. During this development, roles at the market might change. For example, an electricity consumer can start produce electricity by solar PV or use some kind of electricity storage to trade electricity [2]. This development is affected by electricity price and electricity price variations, market structures and types, regulations, policy instruments and grid installations [1]. Larger shares of renewable electricity generation come with new challenges for the electricity system. The intermittent nature of some of these resources, for example wind and solar, are expected to lead to more fluctuating electricity prices in the long-term future [3]. Electricity cannot be stored in the grid but have to continuously be consumed and produced in the same amount [4]. To handle large volumes of intermittent electricity generation, other types of generation as well as flexible consumption can be used for maintaining the balance between production and consumption [1]. To enable a large share of intermittent renewable generation, demand flexibility will be important [5]. Energy storage can switch between consuming and supplying electricity and can contribute to keeping the grid in balance. However, energy storage in the grid has historically not been economically competitive [4].

Another challenge when facing intermittent generation technologies and letting them replace traditional fossil (and nuclear) fueled thermal power plants, are challenges to maintain system stability due to a lower amount of rotating mass in the system, which entails increased sensitivity and increased risks of severe frequency deviations [5]. When electricity production and consumption in the system is equal, the system frequency is kept constant. In Sweden the nominal frequency is 50 Hz and is only allowed to differ between 49.9 and 50.1 Hz in normal operation [6]. Regulation power is used to maintain the instantaneous balance and hence keep the frequency near the nominal value [6].

Although energy storage is not one of the traditional types of regulation power suppliers, energy storage could also support with regulating power [7]. In a report from The Royal Swedish Academy of Engineering Sciences [8], it is stated that lithium-ion batteries are becoming less expensive, and that lithium-ion batteries might be used to provide services as short time storage (day-basis), frequency support and peak shaving in the future. They further state that the electricity market is not yet able to fully handle energy storage units, and that the future of battery storage for grid applications will be heavily affected by regulation and the development of the market. The possibility to use electric vehicles for energy storage and grid services are sometimes discussed [4]. Battery vehicles include for example trucks and cars, but also forklifts in material handling. In material handling, forklifts can be parked for example during parts of the day, over the night and over the weekend. Since the forklift's batteries are already in place, they could potentially be used for supplying grid services with low incremental cost. When a vehicle is parked and connected to a charger, it could be used for supplying frequency regulation power if the market structure and the technology allows it. Batteries can charge as well as discharge and can supply down-regulating power as well as up-regulating power, depending on their current state of charge and charging power.

Alelion Energy Systems (hereafter referred to as Alelion) is developing lithium-ion battery systems for forklifts. They are working on implementing smart systems and optimizing the charging, enabling purchase of electricity at the lowest cost and on-site peak load shavings to avoid breaking fuses or having to expand the grid connection capacity. They are also investigating what possibilities there are to trade energy and for example offer frequency regulation power. However, market structures for frequency regulation power varies between countries, as does the possibility for small private actors to participate in the market as frequency control power suppliers. Since Alelion is located in Sweden, the Swedish market structure and upcoming changes there, are of special interest. Alelion has developed algorithms which suggest what frequency regulation capacity to offer as grid supporting power. They want to make sure that making the forklift batteries available for frequency control would not have more than a minor effect on the ordinary operation of the forklifts.

1.1 Aim

The aim of this study is to investigate what possibilities there are to participate on the ancillary service market with forklift batteries for frequency regulation in Sweden. In addition to this, it is evaluated how frequency regulation use of Alelions forklift batteries would affect the ordinary operation of the forklifts. To reach the aim, the following questions need to be answered:

- What does the market structure for frequency control power looks like in Sweden?
- What challenges are there in today's frequency control power market requirements which might hold back energy storage units from participating?
- To what extent will the ordinary operation of Alelions forklift be affected by letting the battery storage serve as frequency containment reserve?

1.2 Scope and limitations

The investigation will be limited to the electricity markets of Sweden. Other countries are excluded. The literature study will focus on the market for frequency regulation power, although a general overview over the Swedish electricity market is needed to understand the frequency regulation market. Regarding the frequency regulation market, the four frequency regulating markets FCR-N, FCR-D, aFRR and mFRR are included. An add-on functionally to an existing simulation model is developed, to simulate the activation of FCR power. Simulations are only made for FCR-N and FCR-D, and not for FRR. This is because FRR is activated more rarely, and FCR is assumed to be a more suitable market for forklift battery reserve power since it is activated faster and have smaller requirements on capacity per bid [9]. Impact of FCR-N and FCR-D are simulated separately, to make it possible to compare the result. It is possible to participate on both markets at the same time but not with the same capacity, i.e. decisions must be made about how to allocate the frequency reserve offer between FCR-N and FCR-D. Technical details of the batteries are also excluded, as well as limitations of the grid. No locational dependency is considered since the frequency variations can be assumed to be the same everywhere in the synchronous electricity system [5]. The focus of this study is on the market requirements, limitations and the possibility for batteries to participate on the FCR market at all. Prices and revenues are excluded since that is considered to be a question more suitable at a later stage.

1.3 Methods

The investigation of the Swedish market structure was performed as a literature study. Simulations were made to answer the question of what impact it would have on the ordinary operation of the forklift to let the forklift batteries supply frequency control power. An add-on functionality for simulation of FCR activation was developed and used together with already existing forklift site simulation model. The developed model calculates the FCR activation and integrates the delivered FCR power into an existing model, to see how it affects the state of charge and hence the charging behavior of the forklifts. The simulation model calculates predicted impact of frequency regulation use of the batteries on the ordinary operation of the batteries, by calculating the number of extra charging minutes. Ability to deliver requested FCR is also simulated. Simulations were performed for some different bid sizes, size of bidding window and spare battery capacity. In addition to this, the impact of having to charge at a lower charging power to be able to deliver FCR for down-regulation were investigated. A more comprehensive description of simulation model is given in a later chapter. Real frequency data for one week per season the last two years were used, giving a simulated period of 56 days in total. Simulations of FCR activation were made using python, and frequency data were analyzed in Matlab.

2

The electricity market in Sweden

The electricity consumption in Sweden is about 135 TWh per year [5]. Electricity generation is mainly from hydro power and nuclear power, see figure 2.1 [10]. Level of precipitation and availability of nuclear plants are important factors that causes yearly variations in available electricity production [11]. Available wind power production, of which many installations have been made last years, varies from year to year but also varies considerably on shorter time basis [11]. According to the Swedish energy agency, closedown of old power plants and the decentralization of parts of the electricity production will lead to future changes in the electricity system as well as in the electricity market [2].

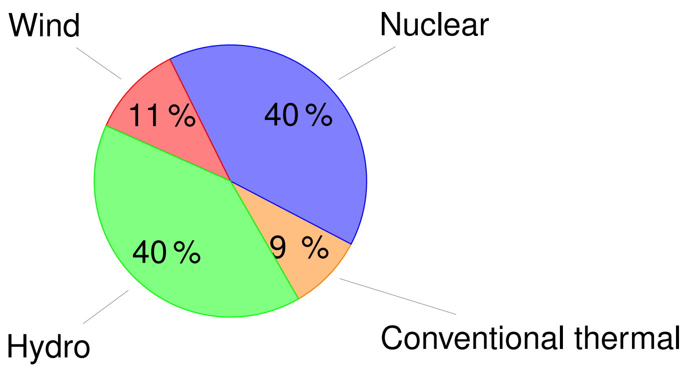


Figure 2.1: Electricity generation in Sweden during 2017. Conventional thermal power includes generation from from CHP plants, condensed power plants, gas turbines etc.

2.1 General market structure in Sweden

There are several ways to trade electricity in Sweden. An overview of the markets described in this section is given in table 2.1. Most electricity trading is made at the day-ahead spot market [12]. In the day-ahead spot market, producers and consumers place their bids per hour according to their planned operation, and the price is settled at a level near the market equilibrium [12]. The price is set according to the marginal price setting model [13], meaning that all participating actors will get the same price. Transmission grid capacity is also considered [12]. The electricity market in Sweden is divided into 4 electricity price areas, numbered from north (SE1) to south (SE4) [14]. During hours when the connecting transmission lines between areas are congested, the electricity price can be different in connected areas [14].

If electricity price variations are large at the day-ahead spot market, financial forward contracts covering a long time period such as weeks, months or years, can help mitigate the risk caused by large price fluctuations [15]. Forward contracts are negotiated and agreed between two parties, specifying the time period for the contract, amount of power and price. [16].

Conditions might change between settlement of the day-ahead market and the time near the operation hour. In these cases, actors can purchase and sell electricity at the intraday market, which is open until one hour before the operation hour [17].

Table 2.1: Overview of electricity markets and trading time.

Market		**Trading time**
Day-ahead spot market		Day before delivery
Intraday market		Until one hour before delivery
Forward contracts		Often for longer time periods such as weeks, moths or years
Balance market	FCR	One and two days before delivery
	aFRR	Thursday before the delivery week
	mFRR	Handed in continuously and changeable until 45 minutes before delivery

The major electricity trading platform in Sweden is Nord pool, where about 95% of the total production is traded, and both day-ahead and intra-day trading can be made [18][11]. About 380 electricity producers, retailers, large consumers and other actors sell and purchase electricity at Nord pool [11]. Of these, about 160 are electricity producers, of which five companies named Vattenfall, Uniper, Fortum, Statkraft Sverige and Skellefteå kraft in 2016 together accounted for a market share of about 80%. The market for electricity trading in Sweden has been deregulated since 1996 [11]. Today, both public and private companies take part in the ownership [11]. Sweden is part of the Nordic electricity market, in which areas in nearby countries cooperate with operation and regulation of the system [5].

Svenska kraftnät, the Swedish TSO, is responsible for the overall operation of the high-voltage grid, the security of the grid, and has the responsibility of ensuring balance between supply and demand on a instantaneous time basis [19]. Another important role in the Swedish electricity system is Balance responsible parties, of which there are 31 in Sweden [20]. Balance responsible parties (BRP:s) have the economic responsibility to make sure that the electricity production is equal to electricity consumption for the electricity which the balance responsible party produces, consumes or trades in the electricity area [19]. That is, to keep the average electricity production equal to the average electricity consumption each hour. Since the production and consumption of electricity cannot be predicted exactly, the electricity balance needs to be maintained continuously during operation in real time. To regulate the electricity balance on a minute basis, Svenska kraftnät purchases balance power, which the balance responsible parties later pays for [19]. The balance power is purchased from balance responsible parties which participate on the balance market. Only balance responsible parties can participate on these markets [19] [21]. The Swedish electricity market has several different kinds of reserves [9]. Fastest are the frequency containment reserves (FCR), while frequency restoration reserves (FRR) have a longer activation time. The FCR market is divided into two different kinds of FCR called FCR-N, for normal mode, and FCR-D, which is activated during disturbances. The FRR market is divided into an automatic and a manual one, called aFRR and mFRR [9]. The basic characteristics and differences between the four reserve types FCR-N, FCR-D, aFRR and mFRR are shown in table 2.2 [22].

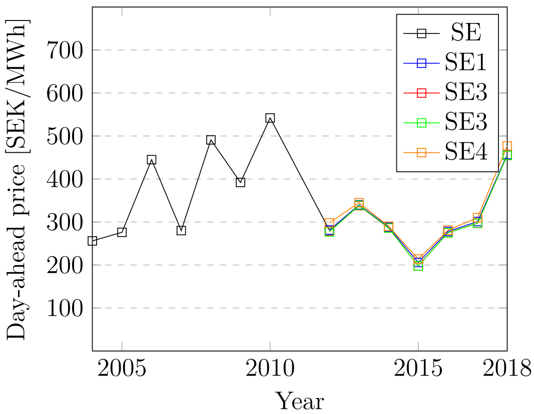
Table 2.2: Overview of the reserve types FCR and FRR.

Reserve type	**Purpose**	**Reserve**	**Explanation**
FCR	Stabilize frequency	FCR-N	Frequency Containment Reserve for normal operation
		FCR-D	Frequency Containment Reserve for disturbances
FRR	Restore frequency	aFRR	Frequency Restoration Reserve with automatic activation via control signal
		mFRR	Frequency Restoration Reserve with manual activation

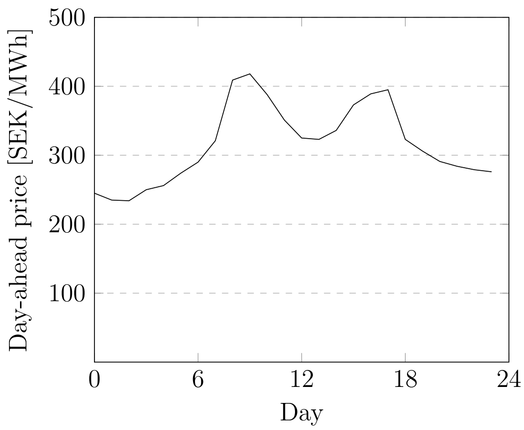
Bids of both FCR-N and FCR-D can be handed in separately to Svenska kraftnät two (D-2) or one (D-1) day before the day of delivery, specifying bids for all hours of the delivery day [19]. It should be specified in which electricity area the reserve is located. D-2 bids are handed in before 3 pm two days before the delivery, and information about acceptance is got 4 pm the same day, at the latest. Bids in the D-1 market is handed in before 6 pm the day before the delivery, and information about acceptance is provided before 8 p.m. that day. Bids of aFRR power are handed in for one week at a time, and bids for Saturday to Friday should be handed in before 10 a.m. on Thursday the week before [19]. Bids of mFRR are handed in continuously to Svenska kraftnät, and it is possible to change the bid until 45 minutes before the hour of operation [19]. More about the technical characteristics, requirements and market settlement of these different regulation power types are given in section 2.4.

2.2 Electricity price and its volatility

Electricity day-ahead spot prices vary over the year. Average prices are lower during the spring and early summer, and higher during the cold winter months [23]. Variations in average price over the years are large [23] as shown in figure 2.2a. The variations is caused mainly of the variation i availability of hydro power. Yearly average prices are approximately the same for the four regions in Sweden, and has been so since the split into several areas about ten years ago [23]. Prices can vary greatly both on yearly basis and between hours [23]. Figure 2.2b shows price variations during a Monday in Sweden. The reader can find additional figures showing electricity spot price variations in Appendix B, figure B.1 and B.2. According to a scenario analysis made by Svenska kraftnät, a small increase in average electricity price might be expected to year 2030 [3]. However, investments in transmission capacity can lead to less variations in yearly average prices in the same period. They further state that the opposite, i.e. somewhat lower average prices and larger electricity price variations between different years, are likely to appear in 2040 due to an increased share of electricity generation from intermittent resources. Svenska kraftnät are currently working on what changes are needed in the balance power markets to handle the volatility [3].



(a) Yearly average price in price area SE and SE1-SE4 in year 2004-2018 (data from 2011 were missing).



(b) Hourly prices in SE3 during a Monday in January 2018.

Figure 2.2: Price variations in Sweden [23].

2.3 Energy storage and power for regulation

Energy storage can be used to handle fluctuations, by storing energy when the electricity supply is greater than the demand, and later provide energy when the demand is greater than the supply. This can be done as frequency support or on a longer time scale. Energy storage can also be used to help avoid congestion of the grid and to ensure energy availability [8]. Surplus energy can either be stored in some storage type for which the energy is converted back to electricity at a later moment, or the extra energy can be used to warm district heating water or used in a power-to-gas unit [4]. These technologies do not necessarily compete, since they are suited for different needs of activation time, capacity, energy quantities and durability, and since several different storage types might be used in large-scale to meet different needs in the future energy system.

Pumped hydro power is, when geographically available, considered the most economically feasible storage technology [7]. It is also the world's most common electricity storage type. Global electricity storage capacity for hydro power and some other storage types can be found in Appendix B3. Sweden do not have considerable amounts of pumped hydro storage but many hydro power facilities with hydro reservoirs which supplies flexibility due to their built-in ability to store the water and use it when needed [4]. Compared to batteries, hydro power storage can typically provide greater power during longer time and hence larger energy quantities, according to the global multi-stakeholder network REN21 [7]. They further state that battery storage is best suited for a maximum 1-2 hours storage, and that batteries can be activated very fast. The Royal Swedish Academy of Sciences argues that lithium-ion batteries seem to be the most cost efficient (compared to other storage technologies) for about 2-4 hours storage [8].

2.4 The reserve market

Figure 2.3 shows an example of how the frequency fluctuated during two hours in January 2017. To keep the frequency near its nominal value, the energy balance between production and consumption of electricity needs to be maintained instantaneously. This means that there must be units available and ready to supply balance energy at request. As mentioned earlier, Svenska Kraftnät is responsible for maintaining this balance, and does so by purchasing balancing power from other electricity market actors (BRPs).

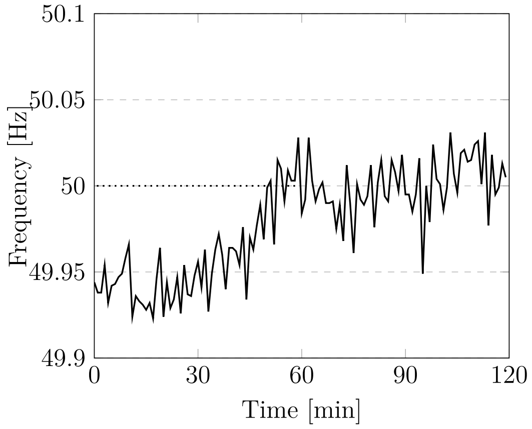


Figure 2.3: Example of frequency fluctuations during two hours in January 2017. (Data from 170101 00:01-02:00, provided by Svenska Kraftnät on request.)

The reserves have different requirements regarding activation time, frequency activation value, total capacity volume in Sweden, lowest allowed bid size etc. [9]. Common to all these four markets is the general requirements on real time measurement, electronic communication, endurance and an approved prequalification process to be able to participate on the market [9]. The compensation for the different types is either in the form pay-as-bid for having the capacity available, paid up- or down regulating price for supplied energy, or both [9]. Pay-as-bid means that the actors is payed the price of its own bid, which entails that actors will most likely get different payments for supplying the same power. FCR-N and FCR-D have considerably less requirements on the size of each bid compared to FRR, which makes those markets more suitable for small actors to participate in [9] [24]. Therefore, the major part of this section will be focused on the FCR markets.

2.4.1 Frequency restoration reserve

An overview of characteristics and requirements on aFRR and mFRR are presented in table 2.3 [9] [24] [22]. Bids of aFRR are given in SEK/MW separately for up-regulation and down-regulation and are called off in a size of 5 MW at a time, which is equal to the smallest allowed bid volume [19]. Bids for providing aFRR power from Saturday to Friday should be handed in together, specifying bids per hour [19]. For mFRR, the bids are given in SEK/MWh and should specify available up-regulating and/ or down-regulating capacity, together with information about how long time it will take to activate the bid [19]. Additional requirements can be found in the Balance Responsible Agreement by Svenska Kraftnät [19].

Table 2.3: Some of the requirements and characteristics of FRR.

	aFRR	**mFRR**
Minimal bid size	5 MW	10 MW (5 MW in SE4)
Activation	deviation from 50.00 Hz	deviation from 50 Hz
Maximum activation at	-	-
Activation type	automatic by central control signal	manually by request
Activation start-up time	2 min	15 min (exceptions allowed)
Minimal total capacity in Sweden	150 MW	-
Symmetric	No	No
Capacity payment	Yes (pay-as-bid)	No
Energy compensation	Yes (up/down regulating price)	Yes (up/down regulating price)

2.4.2 Frequency containment reserve

The activation of FCR can be either step wise or continuous. For the continuous case, activation of FCR power is linear to the frequency deviation, and the activation will be as shown in figure 2.4 and 2.5 for FCR-N and FCR-D respectively [25]. According to the requirements, if the activation is of the type Step wise, 0-10 % of the FCR capacity should be activated when the frequency is 50.00 Hz for FCR-N and 49.90 Hz for FCR-D [19]. The FCR power thereafter needs to respond to all frequency changes larger than +-0.01Hz for FCR-N and -0.1Hz for FCR-D [19]. For delivering FCR, minimal precision of frequency measurement is 10mHz [19]. Further, the activation of FCR must follow the requirements in table 2.4 [9] [24]. Note that FCR-D only does up-regulation. Also note that FCR-N bids must be *symmetric*, meaning that the bid has to be of the same size for up regulation as for down regulation. The average activated power for FCR-N is zero [21]. For both FCR-N and FCR-D, payments are pay-as-bid for providing the capacity. Historical average capacity payments are presented in table 2.5.

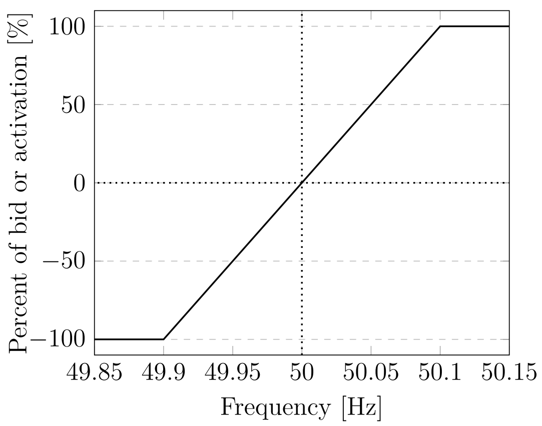


Figure 2.4: Linear activation of FCR-N [25].

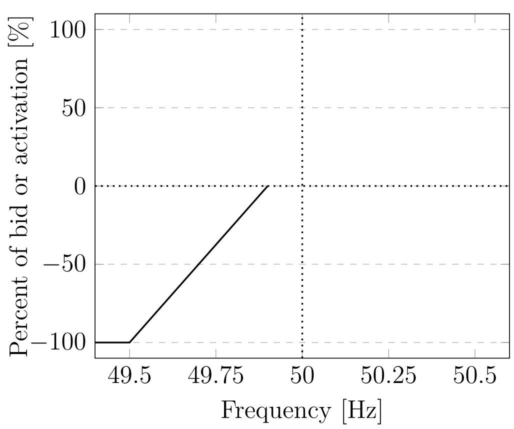


Figure 2.5: Linear activation of FCR-D [25].

Table 2.4: Some of the requirements and characteristics of FCR.

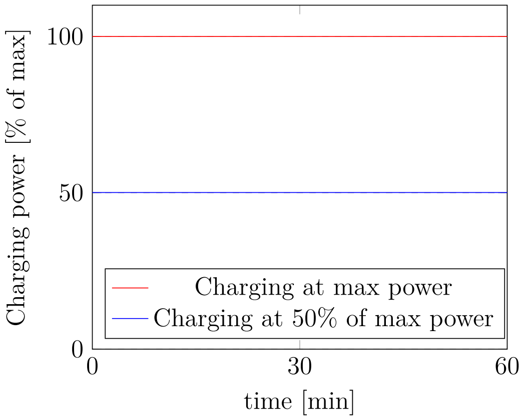
	FCR-N	**FCR-D**
Minimal bid size	0.1 MW	0.1 MW
Activation frequency	deviation from 50.00 Hz.	$\leq$ 49.90 Hz
Maximum activation at	$\leq$49.9 Hz (up) $\geq$50.1 Hz (down)	$\leq$49.50 Hz
Activation type	automatic	automatic
Activation start-up time	63%: 60 s and 100%: 3 min	50%: 5 s and 100%: 30 s
Minimal total volume in Sweden	200 MW	400MW
Symmetric	Yes	No
Capacity payment	Yes (pay-as-bid)	Yes (pay-as-bid)
Energy compensation	Yes (up/down regulating price)	No

FCR-N supplying units should activate FCR when the frequency deviates from 50 Hz. All settled FCR-N power must be available during the whole settled period under normal operation, and hence the endurance must be of a size which makes it possible to supply maximum activation of FCR-N during the whole period. FCR-D needs to be able to supply the requested power for 20 minutes [19] [26].

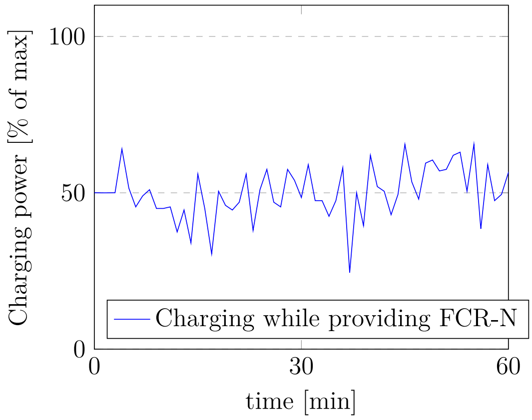
Table 2.5: Capacity payment in average over year for accepted bids [27]. Note that energy payments are excluded.

Year	**FCR-N** [SEK/MW/h]	**FCR-D** [SEK/MW/h]
2018	397	189
2017	227	72
2016	244	59
2015	128	65
2014	208	60

Each bid is either in the form of production or in the form of consumption [28][25], and each FCR supplying unit has to be either an electricity consumption unit or an electricity production unit during each settlement period [29]. This means that if a battery is to supply FCR, it has to either only charge or only discharge (feed electricity to the grid) during each settlement period. An example of how this is possible and how it might affect the charging power are presented in figure 2.6.



(a) Without FCR



(b) With FCR-N

Figure 2.6: Illustrative example of how charging power might look like without respectively with FCR-N activation (Calculated using 50% of maximum charging power as FCR-N capacity bid, using frequency data provided by Svenska kraftnät.)

2.4.3 Arising changes in the FCR market structure

An investigation made by Swedish smart grid [30] states that roles and responsibilities need to be clarified when it comes to energy storage, load adjustments and aggregation in the electricity market. The report also states that aggregation of distributed units should be made easier, and emphasizes the importance of economic incentives for demand response. In a report about challenges for the energy system [4], the Swedish Energy Agency states also that stated that a sufficient degree of electricity price variations are needed to promote the development of demand response as well as for making energy storage profitable. They further stare that today's reserve market is designed to suit large conventional production units, which is also supported by Swedish smart grid, who considers the reserve regulations not being fair to alternative technologies, regarding for example prequalification and pricing. They argue that this must change to enable new technology types (energy storage among others) to participate on the automatic reserve market. The development of those electricity balance market requirements, together with the development of price variations (including taxes and tariffs), will be crucial for the development of grid-connected storage technologies. To facilitate larger shares of intermittent renewable electricity production, storage technologies will make an important contribution and should therefore be promoted, they argue.

One important question is if energy storage's will participate in the market as production units, consumption units or as a new type, i.e. storage units. A draft of new requirements for the FCR market in the Nordic system [31] suggests that there will be three kinds of possible participant types on the FCR market, called generation based, load based and energy storage-based resources. The draft also states that a FCR-D for down-regulation will be introduced, which will be activated at 50.1 Hz and reach its maximum activation at 50.5 Hz. According to Svenska kraftnät [3], one of the possible actions to handle a decreasing amount of rotating mass in the system could be to introduce a new frequency support type called Fast frequency response (FFR). FFR should have stricter requirements on activation time than FCR and have an activation time of only one or a few seconds [32][33]. FFR would only be for up-regulation [34]. Svenska kraftnät sees batteries as one of the possible providers of FFR [34].

Another future change on the FCR market is the introduction of a new role called Balance service provider (BSP), which is to be introduced on the Swedish market 2020 at the earliest [21]. The introduction of this role entails that all balance providing actors will be able to provide the service directly to Svenska Kraftnät, and that balance services will no longer have to be provided by or via balance responsible parties [35]. During 2019, Svenska kraftnät will do an investigation of the benefits of changing the pricing system to marginal pricing in the FCR market [34]. The balance market settlement period is planned to be changed from 60 to 15 minutes in the future [36].

3

Description of the simulation model

To model the material handling sites, an already existing model was used (hereafter referred to as the forklift site model). The forklift site model calculates how much power that is available for FCR but does not simulate the activation of it. To simulate the impact of making forklifts available for FCR, an add-on functionality to Alelions forklift site model was developed. The add-on functionality simulates the activation of FCR power and investigate how it impacts the ordinary operation of the forklifts.

3.1 Alelions forklift site model

The forklift site model simulates 10 material handling sites of different sizes, having 1000 forklifts in total. The model can optimize the charging based on cost, CO_2 emissions or power available for FCR. The cost and CO_2 optimization algorithms are using electricity cost data and electricity production emission data from Germany. When optimizing the amount of power available for FCR, simple heuristics is used to make it possible to deliver both up-regulating and down-regulating FCR power. That is, to be able to either charge more or charge less or even feed electricity to the grid. To make this possible, the forklifts cannot charge at their full charging capacity since that would make it impossible to deliver down-regulating FCR power. Therefore, the forklifts in this mode are charged at half of their maximum capacity until they reach 50% State of Charge (SOC). Thereafter, in case they are off-shift, the forklifts are resting until 2 hours before the next shift starts. At this time, the forklifts start charging and charges faster (SOC*P_{max}/100) until they reach 90% SOC and thereafter they stop. At 90% SOC they are still be able to deliver down-regulating FCR power, which they are not if they are charged to 100% SOC.

The time resolution of the model is 1 minute. The initial value of the forklift batteries state of charge is 90%. The forklifts can either be parked and connected to a charger, or in operation. The sites can be set to have spare batteries with the total capacity corresponding to a certain percent of the total forklift battery capacity. The spare capacity is constant, and the spare batteries do nothing in the forklift site model.

The behaviour of the individual forklifts in the forklift site model are partly random. During a shift the forklifts consume as much energy as a fully charged battery in average, but their consumption is varied randomly between +-5 % of that value. In case the SOC gets too low for a forklift battery, i will connect to a charger.

Output from the forklift site model, for each site and minute, includes the following;

- State of charge.
- Total forklift battery power, i.e. sum of power on grid connection and operation power (P_{tot}).
- Charging power (P_{Ch}).
- Power on grid connection (Equal to P_{Ch} in original model. With FCR activation it is the sum of base charging power and activated FCR power, P_G).
- CO_2 produced from generation of electricity for charging.
- Cost of electricity for charging.
- Shift status (on shift or off shift).
- Number of working forklifts.
- Number of connected forklifts (F_C).
- Number of spare batteries (sum of B_S).
- Power that is available for FCR for up-regulation and down-regulation ($PA_{FCR,up}$ and $PA_{FCR,down}$).
- Minimum available FCR power for up-regulation and down-regulation that day (minimum of $PA_{FCR,up}$ and $PA_{FCR,down}$ during the day).

The available FCR power for up-regulation and down-regulation ($PA_{FCR,up}$[kW] and $PA_{FCR,down}$[kW]), at each minute and site, is calculated according to the following equations;

$$PA_{FCR,up}(t, site) = \sum_{B_F \epsilon site} min\Big(\frac{SOC(t, B_F)}{100} * \frac{C}{F}, \frac{P_{max}}{1.25} + P_{ch}(t, B_F)\Big) + \sum_{B_S \epsilon site} \frac{C}{2F} \tag{3.1}$$

$$PA_{FCR,down}(t, site) = \sum_{B_F \epsilon site} min\Big(\frac{100 - SOC(t, B_F)}{100} * \frac{C}{F}, P_{max} - P_{ch}(t, B_F), \frac{P_{max}}{1.25}\Big) + \sum_{B_S \epsilon site} \frac{C}{2F} \tag{3.2}$$

for all connected forklifts at time t[min], where B_F and B_S are forklift and spare batteries, C [kWh] is storage capacity of each battery, P_{ch}[kW] is the charging power and P_{max}[kW] is maximum charging/discharging power. F [kWh/kW] is a factor that is used to make the available power such that the battery can supply that power for at least 35 minutes, which is a requirement in Germany where the simulation model was developed. Likewise, the factor 1/1.25 is a requirement in Germany, where the battery owner needs to have 1.25 times more power available than what it gets paid for. The spare capacity for each battery is divided by 2 since the spare batteries are assumed to be at 50% SOC. The power endurance of 35 minutes could be changed to 20 minutes when calculating power available for FCR-D. Using 35 minutes as the endurance requirement when calculating the bids will add extra safety margin.

For FCR-N, the power needs to be able to be delivered for the whole settled period, which makes it more difficult to calculate a suitable bid. A power endurance requirement of 35 minutes is used in these bid calculations as well, and the resulting bid is multiplied with a bid factor (described in the next section) to try different bid sizes.

Except for the parts just described, the reader can think of the forklift site model as a black box, which was used for the simulations together with the add-on functionality described below.

3.2 Development of FCR operation impact model

The FCR operation impact model uses FCR power availability data from the original forklift site model and simulates the activation of FCR power using real historical frequency data from Sweden. The model can simulate activation of FCR-N or FCR-D separately (it can also simulate FCR-D for down-regulation but that is not made in this study) and has the time resolution 1 min. An illustrative overview of the simulation structure is given in figure 3.1.

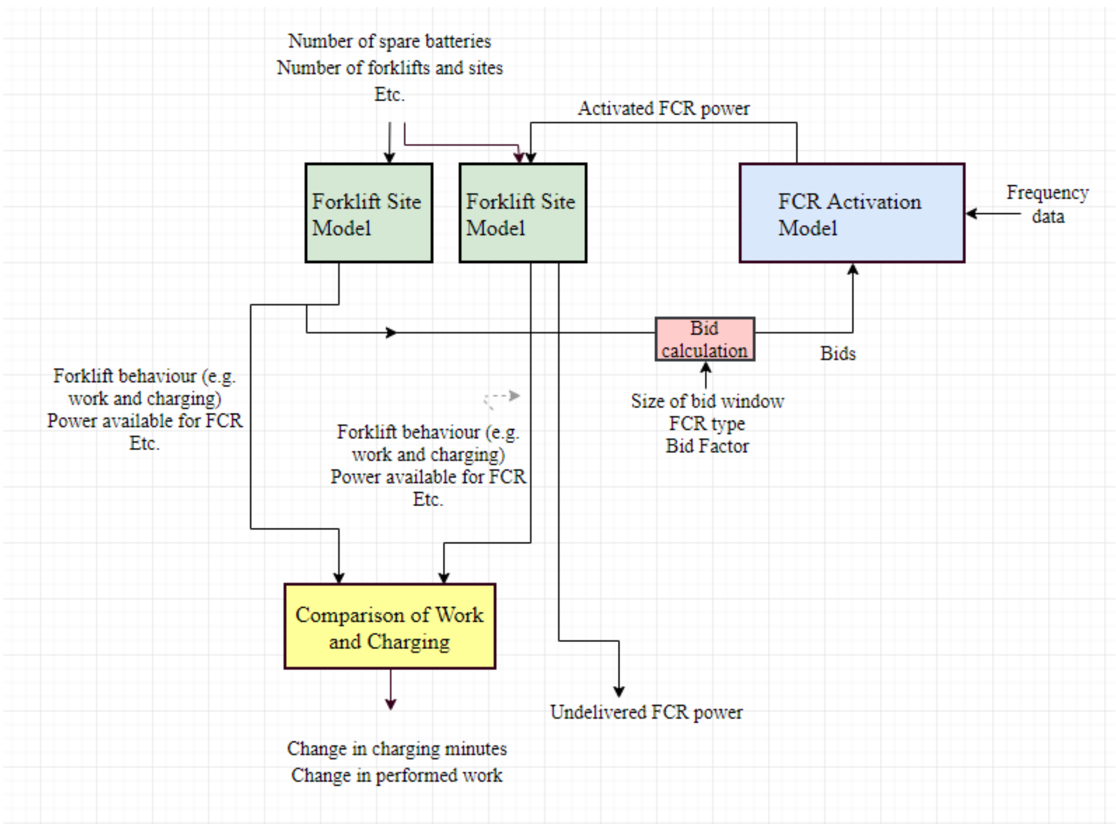


Figure 3.1: Flow chart illustrating the simulation model structure.

It is assumed that it is possible to deliver both positive and negative net power during the same settlement period. It is also assumed that FCR is activated whenever the frequency deviates, i.e. that all bids are accepted. This simplification is made because the purpose is to investigate if activation of FCR will have an impact on the ordinary operation. Assuming that all bids are accepted makes it possible to investigate the "worst-case", i.e. the case that would have the largest impact on the ordinary forklift operation. It is also assumed that there are no limits in how much energy that needs to be delivered during a certain period. However, as mentioned before, the available FCR power calculated in the forklift site model is of such a size that the power should be able to be delivered for 35 minutes. That value is used as base value of the bid, but capacity bids of other sizes are also used in the simulations, by multiplying the value from the forklift site model with a factor called bid factor (f). If the bid factor is 0, the bid will be 0. When this factor is set to 1, it is expected that the sites might not be able to deliver all FCR power for all hours due to that there is no limit in how much FCR that can be requested in normal mode (except for maximum activation during all minutes). The randomness of the model and the energy constraint of the batteries can also contribute to that all requested FCR power is not able to be delivered. Output from the model will include information about how often this appear.

3.2.1 Available capacity and bids

As mentioned, the forklift site model calculates how much power that are available for FCR for up-regulation and down-regulation for every minute at every site. The lowest of these values during the settlement period is used as the capacity bid for that period and site, after division with the frequency deviation from the activation limit corresponding to maximum activation (0.4 Hz for FCR-D and 0.1 Hz for FCR-N). For FCR-D, the capacity bid for each period will be

$$CBid_{FCR-D}(t_{set}, site) = f * \frac{1}{0.4} \min_{t \epsilon t_{set}} PA_{FCR,up}(t, site) \tag{3.3}$$

Where f is the bid factor, $CBid_{FCR-Dup}(t_{set}, site)$ [kW/Hz] is the capacity bid that is assumed to be accepted for settlement period t_{set}[min], $PA_{FCR,up}(t, site)$ [kW] is the amount power available for up-regulation at that site at time t.

For FCR-N, which needs to be symmetric as mentioned in the FCR-section, the lowest of the two numbers for up-regulation and down-regulation are used. That power is then divided by 0.1 to get the right unit ([kW/Hz]), giving

$$CBid_{FCR-N}(t_{set}, site) =$$

$$f * \frac{1}{0.1} min\Big(\min_{t \epsilon t_{set}} PA_{FCR,up}(t, site), \min_{t \epsilon t_{set}} PA_{FCR,down}(t, site) \Big) \tag{3.4}$$

Note that all sites operate, offers FCR and activates FCR independently of each other, and that it is not possible for the sites to cooperate to deliver the requested FCR power.

3.2.2 Activation of FCR power

The FCR activation model makes it possible to choose between simulating the activation of FCR-D (up or down) or FCR-N. It is assumed that the activation time is zero and that FCR is always activated when there is a frequency deviation larger than the activation limit. A summary of the assumptions made in this study is presented in table 3.1.

Table 3.1: Summary of assumptions made in the analysis. Assumptions made in the original forklift site model are excluded here.

Part of model	Assumptions
Forklift site	• No charging or discharging losses. • Maximum discharging power is equal to (-) maximum charging power.
Bid calculation	• All bids are accepted. • Batteries can not break, and spare batteries can therefore be used for FCR at all moments. • Spare batteries have no energy limitations (i.e. they can recharge or serve a load, or are allowed to stop deliver FCR after delivery of an energy quantity which corresponds to maximum FCR activation during 35 min which is used as the power endurance requirement when calculating the bid). The spare batteries in the model cannot fail to deliver requested FCR.
FCR activation	• FCR is always active when there is a frequency deviation. • No activation delay.
Regarding market participant requirements	• It is allowed to deliver both positive and negative net power during different periods in the same settlement period. • Each site operate independently and cannot cooperate with other sites.

The amount of FCR power that gets activated is calculated from the frequency and the size of the accepted capacity bid, as follows [25][28];

$$P_{FCR}(t, site) = -CBid(t_{set}, site) * (f(t) - f_0) = -CBid(t_{set}, site) * \Delta f \quad (3.5)$$

Where P_{FCR}(t, site)[kW] is FCR power delivered to the grid from the site at time t [min], $CBid(t_{set}, site)$ [kW/Hz] the accepted capacity bids for that site and that kind of FCR at settlement period t_{set}, f [Hz] is the frequency and f_0 [Hz] is the activation point for that kind of FCR, i.e. 50.0 Hz for FCR-N and 49.9 Hz for FCR-D. If the frequency drops below or goes above the value corresponding to maximum activation of the reserve, $f(t)$ is set to the value equal to the maximum activation frequency (49.9 or 50.1 for FCR-N and 49.5 for FCR-D).

Provided that all FCR power can be delivered, the electricity consumption level at the site will be

$$P(t, site) = P_{ch}(t, site) - P_{FCR}(t, site) = P_{ch}(t, site) + CBid(t_{set}, site) * (f(t) - f_0) \quad (3.6)$$

Where P(t,site) [kW] is the total net power on the grid connection (from grid to site) at time t [min] and $P_{ch}(t, site)$[kW] the charging power that the site will consume if the frequency is at its nominal value.

Note that the accepted capacity bids can be of either type, i.e. FCR-N or FCR-D. Also note that if $P_{ch}(t, site) \geq P_{FCR}(t, site)$ and $P_{FCR}(t, site) > 0$, then the site will deliver positive FCR without feeding electricity to the grid, i.e. by simply charging less than what it would have done otherwise.

The forklift batteries can only be used to supply FCR power when they are parked. Since the forklifts should be affected as little as possible of the FCR operation, the forklifts in operation do not adjust their behavior to prioritize the FCR, i.e. only parked forklifts are affected by the activation of FCR.

3.2.3 Integration of FCR power activation into the forklift site model

Since the FCR activation power affects the power on the gird connection and the state of charge, it needs to be integrated into the original forklift site model. The amount of activated FCR power ($P_{FCR}(t, site)$) at every site gets assigned to the individual forklifts one by one until the need for FCR power is fulfilled, or until all forklifts at the site delivers as much FCR power as they possibly can. This means that if the first forklift can supply all FCR power that minute then it will do so, and the other forklifts will not be affected by the FCR activation. Available up and down regulating power from each connected forklift is used as the maximum value for how much FCR power each forklift can supply at each moment. It is expressed as follows;

$$P_{FCRup,max}(t, B_F) = P_{ch,max}(t, B_F) + P_{ch}(t, B_F) \quad (3.7)$$

$$P_{FCRdown,min}(t, B_F) = -P_{ch,max}(t, B_F) + P_{ch}(t, B_F) \quad (3.8)$$

$P_{FCRup/down,max/min}$ (t,B_F) [kW] is maximum or minimum FCR power available to supply to the grid, $P_{ch}(t, forklift)$[kW] is the charging power that the forklift would consume if the frequency was at its nominal value at this time t and $P_{ch,max}(t, forklift)$ [kW] is maximum charging power for the forklift battery. Maximum discharging power is assumed to be equal to maximum charging power.

For each time t, the activated FCR power is allocated to the forklifts according the above description. This activation is integrated into the original forklift site model, to simulate the new behavior of the forklifts. Output from this part of the simulation will, in addition to the output from the original forklift site model, include

FCR power delivered from the forklift batteries every minute and site. This can be the same amount as calculated from equation 3.5, or another value if the connected forklifts are not able to supply all activated FCR power. Since the activation of FCR will affect the power on the grid connection and the charging and SOC level of the forklifts, the activated FCR power must be integrated into the forklift site model. The power from the grid connection to the site is now calculated as follows;

$$P_G(t, site) = \sum_{B_F \epsilon site} P_{ch}(t, B_F) - \sum_{B_F \epsilon site} P_{FCR}(t, B_F). \tag{3.9}$$

If the sites are set to have spare batteries, the spare batteries are prioritized above the forklift batteries for delivering FCR. The spare batteries are assumed to always be available and able to supply the power according to their contribution in equation 3.1 and 3.2, which means that their maximum power supply will be equal to the maximum power which they can supply for 35 minutes without getting discharged or fully charged. The assumption was made to get a first simple idea of how much spare battery capacity would impact the result, without developing more complete model for the spare batteries. Such a model would require new charging algorithms since FCR-N units always needs to be able to deliver the settled capacity. Note that the German requirements affect the result for simulations were the site has spare batteries. For the base case simulations there are no spare batteries, and the bid size are varied which makes the result independent of these German requirements.

In case the sites have spare batteries, the FCR power delivered by forklift batteries will be

$$\sum_{B_F \epsilon site} P_{FCR}(t, F_B) = P_{FCR}(t, site) - \sum_{B_S \epsilon site} P_{FCR}(t, B_S) \tag{3.10}$$

This expression is later used together with other output from the forklift site model to calculate the performed work (equation 3.11). Having spare batteries that are prioritized over forklift batteries for delivering FCR power will result in that the forklift batteries will have to deliver considerably less FCR power. Since the amount of FCR power that is activated will be much lower that the capacity bid, the spare batteries will often be able to deliver all activated FCR power them self for minutes. This also means that the spare batteries will deliver a higher share of the activated FCR power than their share of the capacity bids.

For the FCR operation impact simulations, the forklifts will initially behave the same as in the original forklift site model, since the seed number (i.e. the "start number" for the random number generator) in the simulation will be the same. However, since the activation of FCR will affect the battery energy level, the behavior of the forklifts will soon start to differ from the behavior in the original model. Since 56 days are simulated, the fact that the same seed number is used in the second pass through the forklift site model will likely not have a large impact on the result. The randomness of the model makes the forklifts behave partly random, which makes the available power difficult to predict exactly. This will lead to that the available FCR power calculated in equation 3.1 and 3.2 not always will be available, which can lead to inability to deliver all requested FCR. The calculated amount of available FCR power for a site might, for example, be impacted by the fact that there were always 2 or more forklifts parked in the simulation result from the forklift site model (note that there is a random behavior of the forklifts in the simulation that affects this), and when the FCR impact model runs there might at some time be only 1 or 0 forklifts connected to the charger which will lead to inability to deliver the requested FCR. Another situation that can lead to inability to deliver all requested FCR is if down-regulating power gets activated many minutes in a row to such an extent that all connected forklifts at the site become fully charged. The opposite, i.e. that connected forklifts gets discharged due to activation of up-regulating power is not as likely to happen since the forklifts will start to charge when the state of charge gets too low, while forklifts with 100% SOC cannot discharge (except for when delivering positive FCR) while standing still and connected.

3.2.4 Comparison of work and charging

The result from simulations where FCR was activated is compared to the output from the original forklift site model by comparing performed forklift operation work and number of forklift charging minutes in the two different cases. Output from the FCR activation simulation also include FCR power delivered from the forklift batteries every minute and site and average number of minutes per day and site for which all requested FCR could not be delivered. The work delivered by the forklifts with and without FCR power activation are compared in equation 3.11.

$$I_P = \frac{\sum_t \sum_{site} \Big(P_{tot,withFCR}(t, site) - P_{G,withFCR}(t, site)\Big)}{\sum_t \sum_{site} \Big(P_{tot,noFCR}(t, site) - P_{G,noFCR}(t, site)\Big)} \tag{3.11}$$

Where $P_{tot}(t, site)$[kW] is the total power consumption and $P_{G,withFCR}(t, site)$[kW] the power on the grid connection at the site, both with or without FCR operation.

The amount of connected time is compared according to equation 3.12.

$$I_C = \frac{\sum_t \sum_{site} F_{C,withFCR}(t, site)}{\sum_t \sum_{site} F_{C,noFCR}(t, site)} \tag{3.12}$$

$F_C(t, site)$[-] is the number of connected forklifts at the site at time t, with respectively without FCR operation.

Note that these numbers are comparing the cases with and without activation of FCR, where the difference is in whether FCR power is actually requested and delivered. In both cases, the base charging power of the forklift will be the same as in the optimization "with FCR", and in the case without FCR activation the power on grid connection will be equal to the base chairing power, i.e. as if the frequency is always at its nominal value and no FCR needs to be activated.

The number of extra connected minutes per forklift and day is calculates as follows;

$$ECM = \frac{\sum_t \sum_{site} \Big(F_{C,withFCR}(t, site) - F_{C,noFCR}(t, site)\Big)}{Forklifts * Days} \tag{3.13}$$

Where ECM stands for Extra Charging Minutes [min/day/forklift], $F_C(t, site)$ is number of connected forklifts at the site at time t, forklifts is the total number of forklifts and Days is the number of simulated days.

3.3 Performed simulations

An overview of the performed simulations is presented in table 3.2. First, an investigation of the ability to actually deliver the offered FCR was made, together with an investigation of the impact of randomness in the model compared to the impact of the FCR activation. For this base case, the bidding block time was set to be 24h. There were no spare batteries in the base case, since the main purpose of the study is to investigate how the forklifts are affected by doing FCR and since having spare batteries, that are prioritized over the forklifts for doing FCR, will mitigate the FCR impact on the operation. Simulations were made for different bid factors. For FCR-N, simulations were made for bid factors 0.01, 0.2, 0.5 and 1.0, and for FCR-D the bid factors 0.5, 1.0 and 2.0. The latest because FCR-D is activated more rarely and was expected to have lower impact on the operation and fewer problems with delivering requested FCR power. Note that a bid factor of 1 will make the resulting bid be of a size such that the maximum FCR power is predicted to be able to be delivered for 35 minutes, as described in section 3.1. All simulations were run several times with different result due to the randomness of the model, i.e. simulations were made using different seed numbers, to make sure that the result shows the actual impact of the FCR activation, and that differences in the result is not caused by the randomness in the simulation model.

The impact of having spare batteries were investigated by running the simulation for spare battery capacities corresponding to different percent of the forklift battery capacity. As mentioned, the spare batteries are prioritized above the forklift batteries for providing FCR power. Simulations for activation of FCR-N were performed for two different bid window sizes (1h and 24 h), which is for how long each bid is placed. A bid window of 24 hours means that the same bid is placed for 24 hours, while a bid window of 1 hour means that different bids can be placed for different hours during the day.

The above described simulation compares the result from simulating the operation with and without *activation* of FCR power. If the forklift batteries are not used for providing FCR, they can charge at full power. However, to be able to activate FCR for both up and down regulation, the forklift batteries cannot charge at full power, as described earlier. Therefore, when running the model in FCR mode (descried in the beginning of the part about the original forklift site model), they will charge at a lower power. In the simulations described above, it is only the actual *activation*

Table 3.2: Simulation scheme.

	Type	Days	Spares (%)	Bid period (h)	Bid factors	Repetitions
Base case	FCR-N	56	0	24	0.01 0.2 0.5 1.0	3
	FCR-D	56	0	24	0.5 1.0 2.0	3
Spare capacity impact	FCR-N	56	0 2 5 10 15	24	1.0	3
	FCR-D	56	0 1 2 5	24	1.0	3
Bid window impact	FCR-N	56	0	1 24	1.0	3
Impact of lower charging power	-	56	-	-	-	4

of FCR that is different (when comparing "with FCR" and "without FCR"). The base charging level for the cases in the numerator and denominator in equation 3.11 and 3.12, will not be full charging capacity. This is the case for all simulations in table 3.2 except for the simulations of Impact of lower charging power. To better understand this explanation, look at figure 2.6. The FCR activation model compares charging similar to the blue line in figure 2.6a (however is varies between 50% and 90% of maximum charging power, as described section 3.1) with the charging when activating FCR as in figure 2.6b. Because of this, additional simulations were made with the purpose of comparing the operational effect of charging at a lower charging power than maximum charging power. This was made by comparing the result from simulations made with optimization mode "fcr" (described in the beginning of this chapter) with the simulation result from simulations made with no optimization i.e. just charging directly when parked and at full power. This would correspond to comparing the result from charging like the blue line in figure 2.6a with charging at full power i.e. the red line in that figure. The result from these simulations is presented in section 4.2.4.

3.4 Frequency data for the simulations

Simulations were made using real historical frequency data, with the time resolution 1 minute, for one week per season during the last two years. Data from the first week of January, first week of April, first week of July and first week of October were used for each year. This data was provided by Svenska kraftnät on request. The values have 3 decimals. In the data from these 56 days, 7 values were missing. To get matching matrix dimensions in the simulation program and to be able to make the simulations for 56 whole days, 7 frequency values with the value 50.0 Hz were added in the end on the frequency list.

An analysis of the frequency data was made to see how the large part of the frequency values during these days that were higher than 50.0 Hz compared to how many frequency values during these days that were lower than 50.0 Hz. Number of minutes when the frequency deviated more than 0.1Hz from the nominal value was calculated, as well as the duration of the deviation.

4
Simulation results

4.1 Result from frequency data analysis

Frequency value distribution during the period is presented in table 4.1. During these 56 days, the frequency was higher than 50 Hz for about as many minutes as it was lower than 50 Hz. Note that the analysis is made with frequency values with the accuracy of three decimals, and that some of these values are equal to 50.000Hz which makes the first 2 values in column three add up to less than 100 %. Also note that the frequency drops below 49.9 Hz for about 1.26 % of the minutes, which confirms that FCR-D is activated much more rarely than FCR-N which is continuously active.

Table 4.1: Frequency values during the time period of 56 days.

Type of deviation	**Number of minutes [min *(56 days)$^{-1}$]**	**Percent of time** [%]
f $<$ 50.0 Hz	39 756	49.3
f $>$ 50.0 Hz	40 168	49.8
f$\leq$49.9 Hz	1 013	1.26
f$\geq$50.1 Hz	1 146	1.42

Since FCR-N is used for both up-regulation and down-regulation, it is of interest to know not only for how large part of the time it is active in each direction, but also how much relative energy quantity that is activated in each direction. As mentioned earlier, the average activated power for FCR-N is zero according to Svenska Kraftnät [21]. The relative activation of energy volumes for FCR-N during these 56 days are shown in table 4.2. The share of activated energy volumes is, as expected, about 50 % in each direction. The same goes for the number of minutes with a frequency higher respectively lower than 50 %, which was shown in table 4.1.

FCR-D gets activated for up-regulation when the frequency drops below 49.9 Hz. Note that there is no FCR-D product on the Swedish market today for frequency down-regulation (which, if it existed, might have had the activation frequency 50.1 Hz). As is seen in table 4.1, about thousand minutes of each of those kinds of deviations occurred during the time periods. Table 4.3 presents information about the

Table 4.2: Share of activated FCR-N energy volume for up-regulation and down-regulation during the time period.

Type of regulation	**Share of activated energy volume** [%]
Up-regulation (discharging)	49.10
Down-regulation (charging)	50.90

duration of frequency deviations larger than 0.1 Hz. As can be seen, the deviations during this period did not last very long.

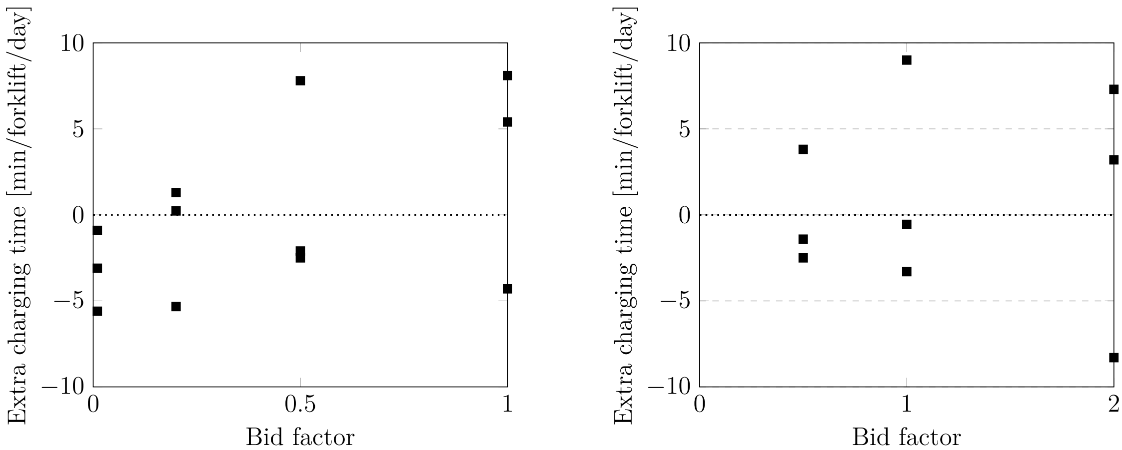
Table 4.3: Duration of frequency deviations larger than 0.1 Hz during the time period.

Duration of deviations [min]	**Occurrence** [(**56 days**)$^{-1}$]	
	f≤49.9 Hz	**f≥50.1 Hz**
1	397	499
2	89	80
3	32	28
4	17	23
5	11	8
6-10	22	16
11-15	5	5
16-20	0	2
21 ≤	0	1
Sum	573	662

4.2 Impact of FCR on ordinary operation

4.2.1 Base case: no spare batteries and 24h bid window

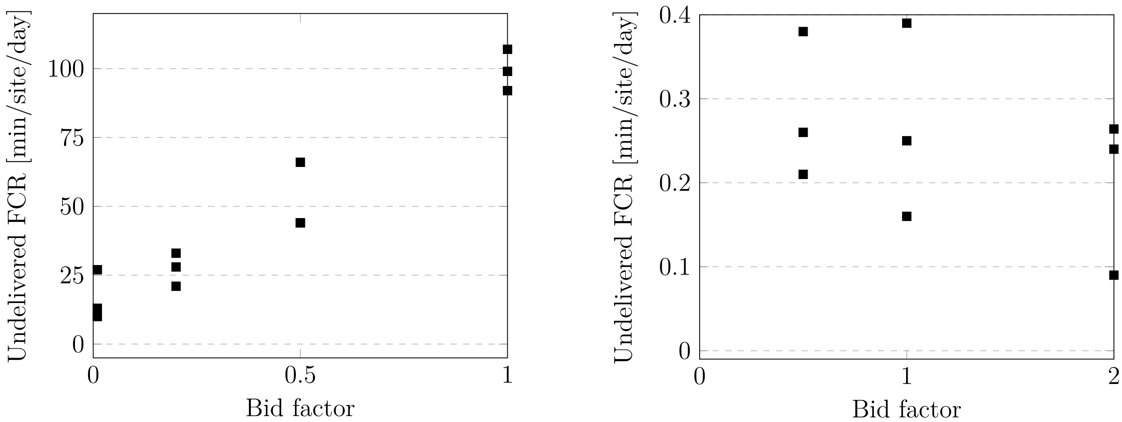
Simulations were run for different bid sizes by varying the bid factor. The bid window was set to 24 hours and number of spare batteries was set to zero. As for all simulations in this study, 56 days were simulated. Simulations were performed for both FCR-N and FCR-D. Number of parked minutes and amount of performed work were compared with the case with no FCR power activation. The base charging pattern for both these compared cases are the same (lower than 100%). Figure 4.1 shows the result in terms of share of extra parked minutes due to the activation of FCR. The hypothesis was that a need for extra charging due to FCR activation could be caused by for example batteries delivering up-regulation when charging during a work shift, and therefore having to charge some extra minutes before getting fully charged. However, no clear correlation between extra charging time and bid factor seem to appear. Even though FCR power is activate much more often for FCR-N than for FCR-D, the simulation results in terms of extra charging minutes and performed work do not differ markedly between the two FCR types, which supports the idea that the result is affected by randomness more than by the activation of FCR power. Simulation data can be found in Appendix, table A.1.



(a) FCR-N

(b) FCR-D

Figure 4.1: Extra charging minutes for different bid factors in the base case. (Note that each case was simulated 3 times with different results due to the randomness of the model.)



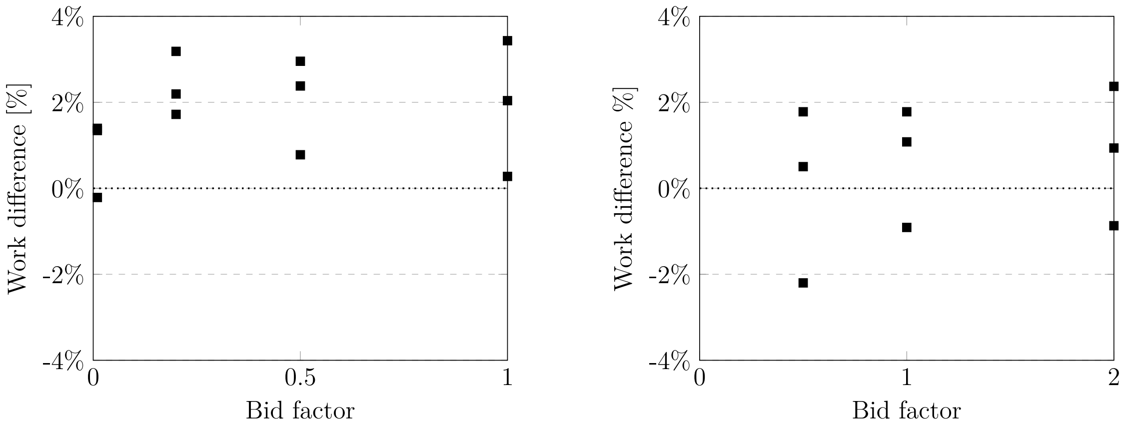
(a) FCR-N

(b) FCR-D

Figure 4.2: Number of minutes per day and site in which requested FCR power failed to be delivered for different bid factors. Note the scale difference between the two plots. (Also note that each case was simulated 3 times with different results due to the randomness of the model.)

Number of minutes in which the site was not able to deliver all requested FCR power is shown in figure 4.2. For FCR-N, most of the failures occurred because some of the forklift batteries got fully charged due to activation of FCR power for down-regulation. The site was then not able to deliver enough down-regulating FCR power until either more forklifts got parked or the batteries got discharged due to activation of up-regulating FCR power. Another cause of failure to deliver requested FCR power was that too many forklifts were in operation while too few were parked. Problems with FCR power delivery can occur when the number of parked forklifts at a certain moment is fewer than what was predicted when calculating the capacity bid, caused by the partly random behaviour of the forklifts. This is what caused most failures for activation of FCR-D power. There seems to be a quite clear correlation between inability to deliver FCR and bid factor (bid size) for the case of FCR-N, but not for FCR-D.

FCR-N is active almost every minute, while FCR-D is activated in only 1.26 % of the minutes during simulated period, which corresponds to about 18 minutes per day in average . This means that the failure to deliver FCR is less different between the two FCR types than one can think by view figure 4.2. For example, 50 minutes of undelivered FCR-N for an average day corresponds to failure to deliver the requested FCR-N for 3.5 percent of the minutes. Failure to deliver FCR-D power for 0.2 minutes during an average day corresponds to 1.1 percent of the requested minutes.



(a) FCR-N **(b)** FCR-D

Figure 4.3: Difference in performed work compared to without FCR activation (average per day and forklift) for different bid factors. (Note that each case were simulated 3 times with different results due to the randomness of the model.)

Figure 4.3 shows the difference in performed work between the case with FCR activation and the case without FCR activation. In almost all FCR-N simulations, the forklifts perform more work in the simulations for which FCR is activated than when it is not, which an unexpected result. The same trend does not seem to appear in the simulations of FCR-D. However, there is no clear correlation between bid factor and performed work for any of the two types. Also note that the result does not differ very much between result from simulations of FCR-N compared with result from simulations of FCR-D, i.e. the difference in performed differ at the most about 3 % for both types.

4.2.2 Influence of spare battery capacity

As mentioned, spare batteries will be prioritized over forklift batteries for delivering FCR. Having more spare batteries also implies a higher bid since more power is available. The spare batteries also increase the battery availability since they are always available for delivering FCR. Figure 4.4 show the average bid size as function of amount of spare batteries. The average bid size increases linearly with spare batteries, since spare batteries are always available for FCR and the bids are calculated as described in equations 3.1 and 3.2.

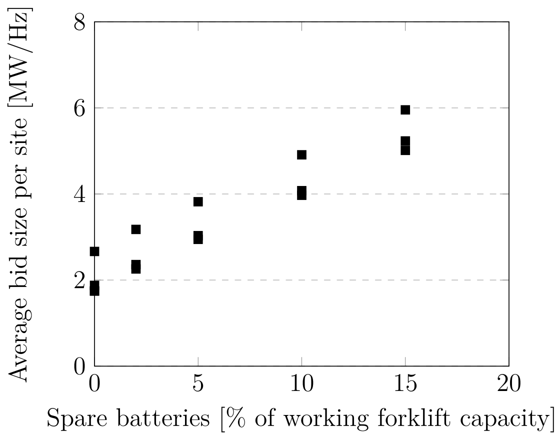
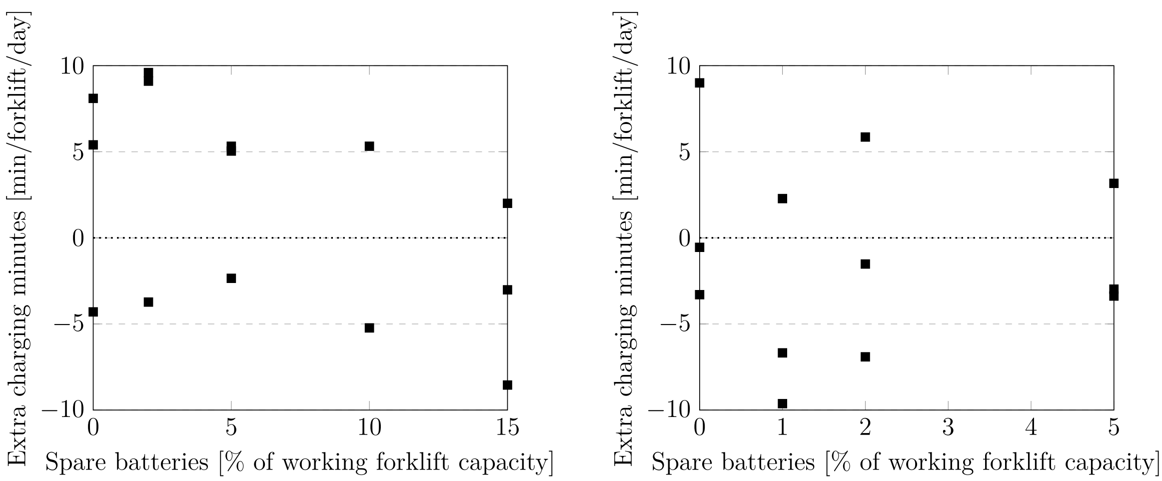


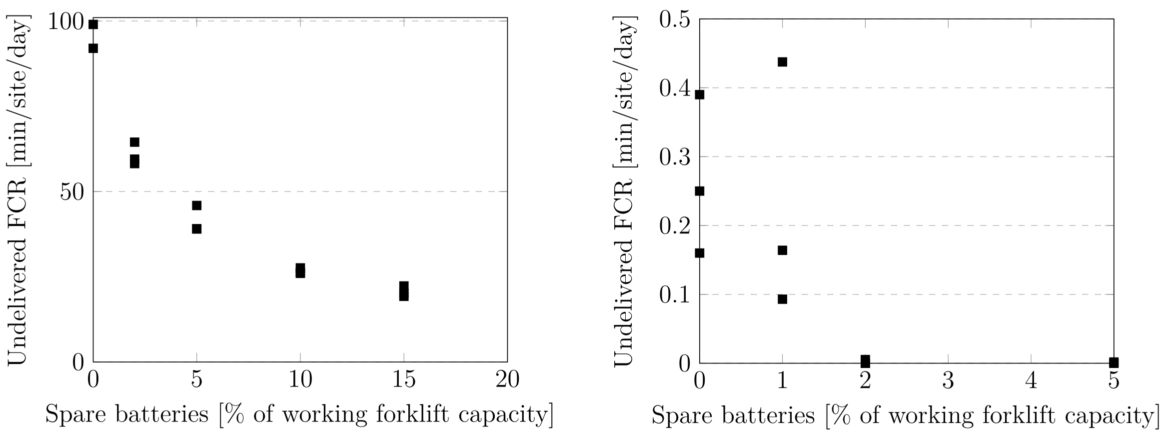
Figure 4.4: Average bid size per day and site for FCR-N and different spare battery capacities. Note that the capacity bid in [MW/Hz] is 10 times as high as the available capacity. (Also note that each case was simulated 3 times with different results due to the randomness of the model.)



(a) FCR-N **(b)** FCR-D

Figure 4.5: Extra charging minutes for different spare battery capacities. (Note that each case was simulated 3 times with different results due to the randomness of the model.)

Figure 4.5 presents the result in terms of extra charging minutes. Just like in the base case (figure 4.1), the result looks about random and no clear correlation between extra charging minutes and number of spare batteries appear. While there is no clear change in number of extra charging minutes, the ability to deliver FCR is affected considerably by the spare batteries. This is presented in figure 4.6, which can be compared with the base case by looking back at figure 4.2. Inability to deliver FCR increases considerably with bid factor but decreases with spare batteries. For example, 5 % spare batteries and a bid factor of 1 will result in about the same ability to deliver FCR as no spare batteries and a bid factor of 0.5. However, it should be emphasized that the spare batteries in this simulation are subject to several simplifications, as described in section 3.2.3. Data from simulations presented in this section can be found in appendix A, table A.3.



(a) FCR-N **(b)** FCR-D

Figure 4.6: Number of minutes per day in which requested FCR power failed to be delivered for different spare battery capacities. Note the scale difference between the two plots. (Also note that each case was simulated 3 times with different results due to the randomness of the model.)

4.2.3 Influence of number of bidding blocks per day

To investigate the impact of bid window size, simulations were performed for a bid window of 1 hour, and the result compared with result from having a bid window of 24 hours. The bid window size is for how long time period each bid is for. A bid window of 1 hour seem to enable considerably larger average bids compared to a bid window of 24 hours, as shown in figure 4.7. This was an expected result. A shorter bid window will enable larger bids for example during the night when there is no material handling operation. If the bid window is 24 hours, the lowest amount of available power during that time will limit the bid.

More FCR failed to be delivered for the 1 hour bid window, as shown in figure 4.8b. However, the increase in delivery failures was smaller than the increase of average bid size. For the 1 hour bid window, the average bid was about twice as high as for the 4 hours bid window, while the number of failures to deliver requested FCR power is only 150% as high.

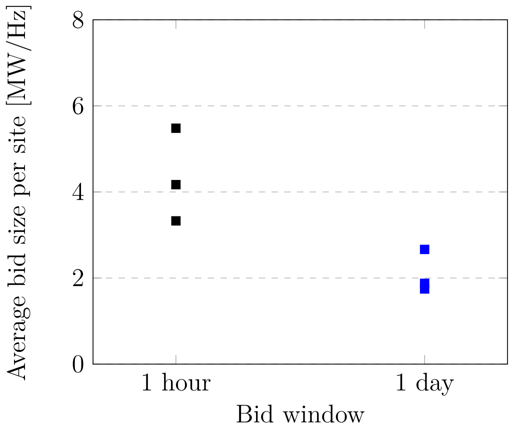
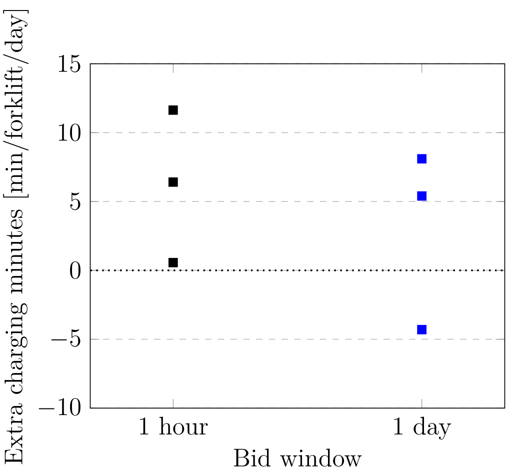
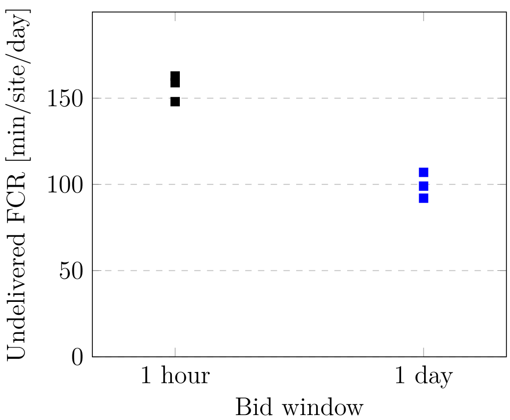


Figure 4.7: Average bid size (average per day and site) calculated from forklift site model for FCR-N with bid windows of 1 respectively 24 hours. (Note that each case was simulated 3 times with different results due to the randomness of the model.)

Figure 4.8a shows the number of extra charging minutes when having a bid window of 1h respectively 24 h bid window. As can be seen, the average number of extra charging minutes is slightly higher for a 1 hour bid window. However, the result between different simulations of the same type is large. Simulation data from this part of the analysis can be found in table A.4.



(a) Extra charging



(b) Failure of activation

Figure 4.8: Extra charging minutes and number of minutes per day in which requested FCR-N power failed to be delivered, for a bid window time of 1 respectively 24 hours. (Note that each case was simulated 3 times with different results due to the randomness of the model.)

4.2.4 Impact of lower charging power

The impact of lower charging power (described in the end of section 3.3) was simulated four times, of which three resulted in an increased charging time and less performed work when charging at lower average power due to the need of having power available for delivering down-regulating FCR power. The fourth simulation resulted in the opposite, which was unexpected. Simulation results are presented in figure 4.9. Note that no FCR is offered or activated in these simulations. It is the simulation result from different charging power levels that are compared.

When viewing figure 4.9, the work difference appears considerably larger than the change in charging time. However, since all parked time is considered charging time, the total amount of charging time will be longer than the time when the forklifts perform work (only during shifts), making the change in work more sensitive to changes. Something else worth noticing is that for FCR-D, only up-regulation is made, implying that it is possible to charge the forklifts at maximum capacity while being ready to provide FCR-D. Therefore, this result is only relevant when considering the impact of FCR-N.

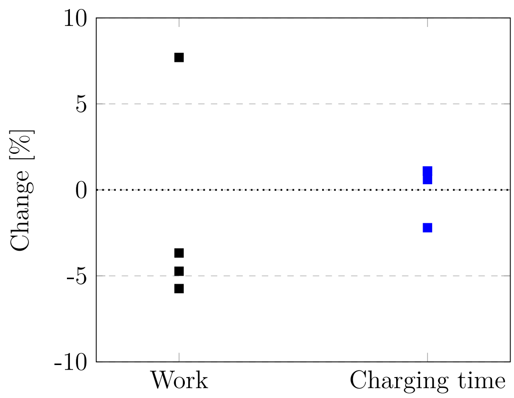


Figure 4.9: Illustration of the difference in performed work and charging time due to lower charging power. Result data from each of these simulations can be found in Appendix A, table A.5.

5
Analysis and discussion

5.1 Discussion of simulation results

Regarding parked time and performed work, no clear correlation with bid size are observed. See for example figure 4.1 and 4.3, where the result looks about random. The randomness of the model seems to affect the result to a larger extent than the activation of FCR power. No clear correlation between change in performed work and parked time, or between one of them and other parts of the result, seem to appear. The numbers from the simulations of FCR-N and FCR-D is in the same range, despite the fact that the activation of FCR power is much less for FCR-D, which also indicates that there is no clear correlation between bid size (or FCR power activation) and amount of extra charging time or performed work. Since the frequency is 50 Hz in average, and since about the same amount of energy is activated for up-regulation as for down-regulation for FCR-N, this is not an unpredictable result. The activation of FCR will alternately imply a higher or a lower charging power, which results in an average charging power about equal to what it would be if no FCR were activated. This is in the long run though, and it is likely that down-regulation or up-regulation dominates shorter time periods, leading to extra charging or discharging of the batteries during that time.

As described in the chapter about the simulation model, it is not only the *activation* of FCR-N power which can affect the forklift operation, but also the fact that the forklift batteries has to charge at a lower charging power to be able to deliver FCR-N power for down-regulation. The impact of lower charging power seems to be a potential cause of lower work performance and longer charging times due to letting the forklift batteries be available for down-regulation. Three of four simulations performed in this study resulted in less performed work and longer charging time. However, more simulations need to be run to improve the statistical validity of this result. The fact that the amount of FCR-N power activated for up-regulation seems to be about equal to the amount of FCR-N power activated for down-regulation indicates that simulations of this type, i.e. only considering average power and not activation of FCR-N power, is enough when studying the impact of supplying FCR-N power on the ordinary operation in normal cases. However, these simulations cannot give indications of whether the requested FCR power will be able to be delivered or not.

The number of minutes when the sites fail to deliver requested FCR power is surprisingly high. This likely has to do with the fact that in the FCR activation model there is no limit in how much energy the sites can be requested to deliver, while an energy-limit is assumed when calculating the bids in the original forklift site model. Figure 4.2a show a clear correlation between bid size and the ability to deliver FCR-N. For FCR-D (figure 4.2b) this correlation does not seem to appear, which is likely due to the fact that FCR-D is activated much more rarely than FCR-N, making problems with energy delivery considerably smaller or non-existing. When observing output data from the simulations, observed reasons for why FCR-N failed to be delivered were that the parked forklift batteries got fully charged, or that there were not enough forklifts parked to deliver the requested FCR. Most failures occurred due to a combination of these two causes. No failures due to discharged batteries were observed, which probably is because the SOC level of the batteries rarely is near 0%, while it is often near 100 %. Note that for FCR-D, it is not a problem if the forklifts are fully charged, which is an advantage. Failure to deliver FCR-D were, in all observed cases, caused by too few parked forklifts at moments when much FCR power were requested. For example, if the prediction says that there will be two forklifts parked at a certain period and the bid is calculated for those circumstances, then there might be too few or zero forklifts parked when the FCR is to be delivered. This is caused by the randomness of the forklift behaviour, which makes the forklifts behave a little bit different in the prediction compared to in the "real" case when FCR activation power is included in the simulation. This is since the forklift site model is used twice during each simulation, according to the scheme in figure 3.1. The forklift will not behave exactly the same in these two passes. The first (left) Forklift site model box in figure 3.1 corresponds to the prediction of the forklift behaviour and the second Forklift site model box (to the right) in the picture corresponds to the "real" case, i.e. where FCR actually gets activated and affects the power and SOC of the forklift batteries.

As is shown in figure 4.2a, the number of minutes per day when parts of the requested FCR-N failed to be delivered is about 25-120, which is very high. This issue must be solved if the forklift batteries are to participate on the FCR market. One possible action to decrease the number of delivery failures are to place smaller bids, especially for hours of the day when it is unsure how many forklifts that will be parked. When studying output data from the simulation, it was observed that the risk of failing to deliver FCR-N seemed to be high when there are few forklifts parked. This is likely due to the fact that if, for example, only two forklifts are predicted to be parked at a certain moment, then the ability to deliver FCR is very sensitive to changes in number of parked forklifts and will be heavily affected if only one of the forklifts leave to operate.

The charging and FCR-N power allocation algorithms needs to be further developed. The charging algorithms deciding FCR-N activation allocation to the forklifts most likely have a considerable large effect on the result and the ability to deliver requested FCR-N. In the FCR activation model developed in this study, activated FCR power is allocated to the forklift batteries one by one until the required power is reached. This decision was made to make the FCR activation affect as few forklifts as possible. However, the result from this study suggests that the activation of FCR-N power does not have more than a minor long-term effect on the charging. As mentioned, observations made when studying output data from the simulations is that problems occurs with forklift batteries getting fully charged during periods when down-regulating power dominates the FCR-N activation. When some of the batteries are fully charged, they cannot participate in delivering more down-regulating power, leading to a decreased maximum available power for down-regulation. It is therefore recommended to consider alternative allocation strategies, e.g. allocating the activated FCR power equally over all available batteries. Such an allocation will likely solve some of the FCR power delivery problems.

Another way of decreasing the number of failures caused by batteries getting fully charged is to let the charging of the batteries stop at a lower state of charged. The charging could for example stop after a state of charge of 80% is reached, instead of at 90%. However, this could imply increased impact on the material handling since it would take less time before the batteries got discharged.

Note that the number of failures to deliver FCR-D is very much smaller than the same number for FCR-N, as shown in figure 4.2b. As mentioned, the failures was observed to most often be caused by that to few forklifts were parked. Just like for FCR-N, it is recommended to only place FCR-D bids for periods when it is sure that enough forklifts will be parked and hence enough power available to deliver the settled FCR-D power.

As expected, spare batteries increase the ability to deliver requested FCR, as shown in 4.6. Since spare batteries are constantly ready to deliver FCR, they increase the overall availability of FCR power at the site. This will also significantly mitigate the risk of having to few or no forklifts parked at certain moments due to the random behaviour of the forklifts. Since the FCR power activation level is rarely near its maximum, the spare batteries will often be able to deliver all requested FCR power by themselves. However, if bids are calculated as if a certain number of forklifts are parked at a certain moment, it will still be a problem that all that power might not be available when that moment occurs in reality (corresponding to the second forklift site model pass), which can cause inability to deliver requested FCR power if it is high. Since the settled power has to be available during the whole settled period, having spare batteries will not help solve all delivery failures caused by the random behaviour of the forklifts. However, spare batteries can help mitigate the energy and SOC level problems, which causes most delivery failures for FCR-N. Since spare batteries do not perform other services than FCR, the target state of charge level can be kept around 50 %, implying a considerably lower risk of energy problems than the forklift batteries which are often charged to a state of charge of 90 % and then risks being fully charged due to down-regulating FCR activation as described earlier in this section.

5.2 Method limitations and accuracy

Two extra important assumptions made in this study are that all FCR bids are accepted and that FCR is activated whenever the frequency drops during the bid period. They both contribute to making the activation (and impact) of FCR as high as possible for each bid. FCR is activated all minutes when the frequency deviates, while the bids are calculated as if an energy level corresponding to 35 minutes of full activation is what needs to be available, which likely is one of the causes for inability to deliver requested FCR as discussed in section 5.1.

Another important assumption is that FCR units are allowed to deliver both positive and negative net power at different moments during the same settlement period, which is not the case in Sweden. The result will be affected by the fact that this assumption puts less strict requirements on charging patterns. For example, according to the current Swedish participant requirements, it would not be possible to stop charging at 90 % SOC and thereafter deliver FCR power for both up-regulation and down-regulation by alternating charging and discharging. The assumption was made to make the model less dependent on current market participant rules and to get a result valid for a more general case, and valid in a future market with FCR market participant requirement adjusted to better fit these new kinds of suppliers.

The main purpose of having spare batteries at the site is that they should be able to replace broken forklift batteries. Such an occasion can coincide with an ongoing FCR offer, which will force a decision about if to prioritize FCR delivery or the material handling operation. If FCR is prioritized, the forklift will not be able to operate until a later day when the bid has had time to be replaced with a lower one. If the material handling is prioritized, some requested FCR power might be unable to be delivered which can risk the ability and legitimacy of being an FCR supplier. Spare batteries, however, are not the only way to increase power availability and decrease FCR delivery failure. Making it possible for sites to cooperate could probably imply a sufficient increase of power availability, since the sites could support each other. For example, if no forklift is parked at one site at a moment, other sites where enough forklifts are parked could help deliver the requested FCR power. At least this could help mitigate the delivery failures caused by not having enough parked forklifts to supply the requested power. Unfortunately, it will probably not solve many of the delivery failures for FCR-N since those are most often caused by energy problems rather than forklift battery availability, and since problems with batteries getting fully charged likely will coincide at different sites when much FCR for down-regulation is activated. Even though the exact potential of improving the ability to deliver FCR by letting sites cooperate is unknown, it can be stated that it will imply some improvement. Especially if the site operations are scheduled differently, the potential might be large.

The assumption that requested FCR from spare batteries are limited by the amount of power which could be delivered for 35 minutes was made to get a first simple idea of how much spare batteries would impact the result. The bids calculated from the forklift site model uses the 35 minute rule for the power endurance, due to a requirement valid in Germany were the model was developed. The same rule was used to calculate available for FCR activation power from spare batteries. The 35 minute rule resulted in a maximum charging and discharging power of the spare batteries equal to about 0.89 times the maximum forklift battery power. The assumption was made to be able to do a simple model of the activation of FCR power from the spare batteries, without a complete model of the charging level of the batteries (similar to the forklift battery model). For future studies of the Swedish market, it is recommended to to improve the model by changing this number to 20 minutes for FCR-D. For FCR-N, a more complete model of the spares and their state of charge would need to be developed.

An alternative way of modeling the spare batteries would be to let the them be able to charge and discharge to balance the state of charge. For example, if a spare battery does a lot of up-regulation for a period of time and the SOC level gets low, charging of the battery is needed to enable the battery to continue to deliver FCR for up-regulation when requested. Charging (or discharging) the battery will lead to reduced ability to deliver FCR power for down-regulation (or up-regulation), which should be taken into consideration when calculating the bids.

In the Swedish market, rules of energy endurance for FCR units is different for FCR-N and FCR-D, which is not considered in the model. The model assumes that FCR for the forklift batteries always are activated when the frequency deviates, which is in line with the Swedish market requirements on FCR-N under normal operation. For FCR-D, none of the frequency deviations with a frequency lower than 49.9 Hz during the whole simulated period lasted for longer than 20 minutes (table 4.3) which inidicates that the simulation result will the same as it would have been if the limit of 20 minutes as maximum full activation time were considered in the model.

Other assumptions include no activation delay, a maximum discharging power equal to maximum charging power, and neglecting charging and discharging losses. These assumptions are considered to, compared to the other ones, only have a minor effect on simulation result in terms of general behaviour of the forklifts and ability to deliver FCR.

The impact of the randomness of the model appears to have a larger effect on the result than what the activation of FCR power do. This makes it more difficult to get a clear result. To get a more accurate result, more simulations should be performed to get more precise average numbers and confirm the result from this study. However, forklift operation will be somewhat random in reality as well. It is of great significance to consider the random or unpredictable behaviour of the forklifts when planning what bids to place. Bids of FCR should not be placed if it is not sure that enough power and energy will be available. As discussed in chapter 5.1, this could be managed by placing smaller bids during hours of the day when the uncertainty is high. For the FCR operation and availability, it is favorably to have a well planned operation schedule at the site.

The frequency data used for the simulations seem to represent normal frequency data well since near half (49.8%) of the values are higher than 50 Hz while about half (49.3%) are lower than 50 Hz. Activated energy level is also near half in both directions, which supports the idea that the values are representative. Even though the frequency data seem to be representative for normal periods, it could have been good to do the analysis for extreme data to get an enhanced understanding of how the FCR activation can affect the material handling site. When discussing the frequency data used in the simulations it is also worth mentioning that seven missing frequency values were set to 50 Hz, which will have an extremely low impact on the result since the total number of frequency values are high.

5.3 Participation on the Swedish FCR market

The Swedish FCR market seems to be designed for traditional suppliers and not well adjusted to promote new types of suppliers such as energy storage units. One requirement that might hold back these new suppliers is the rule that it is not allowed to deliver positive and negative net power to the grid at different times during the same settlement period. It is therefore not possible to do up-regulation by discharging to the grid and, in the same settlement period, down-regulation by charging. However, it is still possible for batteries to participate as either production units or consumption units. When available for FCR-D, batteries could either charge and hence activate FCR-D by charging less, or they could be still and activate FCR-D by feeding electricity to the grid. Since FCR-N is a symmetrical product, it is the regulation direction with the least available FCR power or energy which limits the bid. FCR-N can be delivered while, for example, charge or discharge on half of the maximum charging power, and charge or discharge less or more depending on the frequency, while still avoid switching between charging and discharging. An example of this is shown in figure 2.6b. However, the battery will eventually get fully charged or discharged. One strategy to handle this could be to let the batteries alternately act as production and consumption units. Another way would be to use batteries which have some way of charging or discharging locally. However, regardless of charging strategy the charging algorithms must make sure that the forklifts are charged and ready to operate when needed. Together with the rule of not delivering net positive and net negative power during the same settlement period, and the fact that the batteries cannot be charged at maximum charging power, this puts large requirements on the charging algorithms. Operation and charging of the forklift batteries must be well planned and controlled so that they are available both for FCR power delivery and the material handling operation. When supplying FCR-D, charging can be done at maximum power and it is not a problem if batteries reach 100 % SOC, since FCR-D is only for up-regulation. This suggest that FCR-D is easier to implement and would require less advanced adjustments of the charging algorithms.

Since FCR-N needs to have an endurance equal to maximum activation during the whole period for which it is settled, energy limitations are very important to consider when calculating bids. A lower maximum activation time requirement would likely promote the entrance of energy storage units as FCR-N units. FCR-D, on the other hand, only needs to be able to supply an energy quantity corresponding to 20 minutes of maximum activation. Considering the energy requirements, this indicates that it is possible to give larger capacity bids for FCR-D than for FCR-N provided the same circumstances. The possibility to charge at maximum power wile supplying FCR-D, together with the requirement of not delivering net positive and net negative power during the same settlement period, will also contribute of making a higher bid possible. If only considering the power available for FCR while charging, it can be assumed that a bid twice as high can be offered for supplying FCR-D compared to FCR-N. In addition to this, FCR-D can also be delivered when the forklift batteries are fully charged, which also could contribute to making a higher capacity bid possible for FCR-D. Looking at the average capacity payments in table 2.5, it is seen that capacity payments for FCR-D historically have been about half or one third of the capacity payments for FCR-N. These observations together indicate that potential payments might not differ very much between FCR-D and FCR-N in the forklift battery case, and that it is not obvious which FCR type would imply the most revenues from capacity payments. However, revenues from supplying FCR-N is not only from capacity payments but also from energy payments in terms of up-regulating or down-regulating payments for supplied energy. A further investigation of potential revenues from the two FCR types are needed to tell which type would be most profitable.

The frequency reserve market seems to be under evaluation and development, which implies that the prerequisites of participating with energy storage units might change in the near future. Actors that are interested in participating in the frequency reserve market should be aware of this and keep themselves informed. Hopefully, coming requirements on FCR units will be better adjusted to energy storage units to enable them to more easily participate on the market. Implementation of new types of frequency reserves can also imply a higher flexibility for frequency reserve supplying units, since it will create more alternatives. For example, FCR-D for down-regulation would be the first frequency containment reserve product on the Swedish market that is only used to provide down-regulating power. For a battery, down-regulating power is provided by charging, and would have the benefit of not implying additional charging cycles and deterioration of the battery, since the battery would charge anyway. However, FCR-D for down-regulation would imply the same kind of problems as discussed for FCR-N regarding possible charging power and maximum SOC level for which FCR still can be provided. Another potential future market for battery reserve power is the frequency regulation product FFR. Implementation of FFR on the Swedish market could likely promote for example batteries as participants, since batteries have the advantage of having a fast activation time, which would be one of the requirements on FFR suppliers.

Market characteristics that are extra critical for batteries as FCR includes the following;

- Whether it is allowed to deliver positive and negative net power during the

same settlement period. If allowed, it can enable larger bids and hence larger profits for the FCR provider.
- Energy requirements, i.e. for how long time maximum power can be required.
- Introduction of the new role Balance Service Provider, which can make it easier for smaller and new kinds of actors to participate on the frequency reserve market.
- For how long in advance the operation needs to be planned.
- Battery prices, electricity spot price and its variations, and frequency reserve payments.
- Size of bid window is also important, although the coming change from 1 hour to 15 minutes is not very critical for having batteries as FCR. The current bid window size of 1 hour is enough to not hold back units with varying amount of power available for FCR.

Regarding the first item on the list, the problem of not being able to charge at maximum power while providing down-regulating power would remain. This is one of the factors which limits the FCR-N bid while charging. However, allowing positive and negative net power to be delivered during the same settlement hour would significantly increase the potential of providing FCR-N from batteries anyway, since it would enable market participation also when the units are not charging.

5.4 Potential of forklift batteries as FCR

Forklift batteries do have potential to serve as frequency containment reserves. It is extra important to consider the following two requirements;

1. Maximum allowed impact on material handling
2. All FCR should be able to be delivered

Since the bid widow size in Sweden is 1 hour, it would be possible to participate on the market for only parts of the day or week, such as during the night or during the weekend when there is no ongoing material handling operation. FCR-D will likely require less advanced charging software than FCR-N. The forklift battery can be fully charged before the period starts and FCR-D bids can be placed based on how much power the batteries can deliver. For FCR-N, more advanced software is needed since it is not allowed to deliver positive and negative net power during the same settlement period, which implies that the battery would need to alternately charge and discharge to the grid during different settlement periods, or only provide FCR-N while charging. This leads to that the charging needs to be carefully planned if FCR-N is to be offered, especially during hours when the forklifts are in operation.

Requirements in the current Swedish FCR market limits the possible bids and hence the revenue for energy storage units. Future and ongoing market changes and adjustments to energy storage units, together with the decreasing cost of battery systems, indicates that FCR supplied by batteries likely will be more profitable in the future. Further, the development will be affected by electricity spot price, level of price fluctuations and of course frequency reserve revenues. Revenues will depend on the bid since payment is of pay-as-bid type. The bid should cover not only cost of additional hardware, software and disturbed material handling, but also administrative costs and costs of increased battery cell deterioration. Another potential cost could be caused by higher charging costs due to limitations of charging to certain times, since cost optimization of the charging might be hindered. However, a cost optimization can be made over the whole system including FCR possibilities. Unlike ordinary stationary batteries, forklift batteries are already invested in and could supply FCR while avoiding large incremental costs that would be needed for purchasing stationary batteries with the only purpose of supplying FCR.

5.5 Future work and model development

To further investigate the potential of forklift batteries as FCR, the following actions and topics for investigation are suggested;

Further adjustments to the Swedish market:

- Adjust the calculation of available FCR power to the endurance requirements in the Swedish market.
- Adjust the model to not deliver both positive and negative FCR power at different moments during the same settlement period.
- Further investigate how need of planning of operation and charging will affect the FCR potential.
- Investigate the possibilities for sites to cooperate, i.e. investigate if aggregation is possible.
- Investigate if it under some circumstances can be allowed to fail to deliver requested FCR power, and if future requirements might allow this for energy storage units which participate on the FCR market.

Development of optimization and charging algorithms:

- Optimize the charging level. Higher charging power implies lower impact on material handling operation while lower charging power enables a higher FCR-N bid (considering power only, maximum bid will be at around 50% of maximum charging power).
- Make sure that bids are not higher than that the site can handle some random variations during shifts without failing to deliver requested FCR.
- Optimize which forklifts that are used for FCR, to avoid unmanageable bids. Even a simple change, such as allocating FCR activation in a way such that activated FCR is allocated equally to all parked forklift batteries, could likely decrease the number of activation failures significantly.
- Improve the simulation code to make the simulation run faster.
- Model SOC level of spare batteries so that their energy limitations can be considered.

Further analysis:

- Run more simulations to see if the average performed work difference gets closer to zero. If not, study the forklift site model to find what causes a power

minutes index larger than 0.
- Repeat the simulations to see if more correlations appear and to confirm the result from this study, i.e. to increase the statistical validity of the result.
- Run the simulation for critical or unusual frequency data to see how the operation is affected during extreme occasions.
- Use the FCR activation and bid output from the model to simulate potential revenues from FCR.

6
Conclusions

The main purpose of this study was to investigate how the activation of FCR affects the ordinary forklift operation. The results indicate the *activation* of FCR power does not have any considerable large impact on the ordinary forklift operation. This has to do with that FCR-N is activated in approximately equal amounts in each direction, implying that the activation of FCR-N does not affect the average power. FCR-D is only for up-regulation and is only active for about 1.26% of the time during the simulated period, leading to only a small decrease in average charging power due to the activation. However, stating that the activation of FCR do not have a large impact on the ordinary operation is really only relevant to do provided that parked forklifts are able to provide all requested power, which was not the case in the result from this study. The result clearly demonstrates that it is important to make sure not only that FCR will not affect the material handling, but to also make sure that all requested FCR power are available and can be delivered. Bid calculation strategy and charging algorithms play an important role in making sure that all offered power are available and that no energy quantity problems occur.

Occurrence of energy problems are also closely related to the market requirements. The Swedish FCR market do not seem to be well adjusted to energy storage units. The rule that it is not possible to deliver positive and negative net power during the same settlement period is an example of this. The absence of limits for how long time FCR-N power needs to be able to be delivered during normal operation is another example. However, there are ongoing changes in market structure and requirements, which hopefully will promote energy storage as FCR providing units.

It is not only the activation which affects the charging. Lower charging power caused by down-regulating power availability could lead to increased charging time and less performed material handling. This is only an issue for FCR-N. FCR-D only do up-regulation and can therefore charge at the same level as it would do otherwise. Together with the rules on the current Swedish market and the fact that FCR-D is activated more rarely, this leads to a recommendation of FCR-D over FCR-N if the ordinary material handling not should be affected and all requested FCR power is to be delivered. However, further investigations of charging strategies and potential revenues from the two FCR types are suggested.

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A

Appendix 1

Table A.1: Result from Base Case simulations.

Base case: Spare capacity=0, Bid Window =24h								
Type	**Spares** [%]	**Bid period** [h]	**Bid factor**	I_p	I_c	**ECM per forklift and day**	**Not delivered min (avg / day / site)**	**Seed**
N	0	24	0.01	1.0140	0.9988	-0.9	13	(2234)
N	0	24	0.01	0.9979	0.9945	-3.1	27	(1222)
N	0	24	0.01	1.0134	0.9938	-5.6	10	(1234)
N	0	24	0.2	1.0172	1.0023	1.3	33	(1222)
N	0	24	0.2	1.0219	0.9941	-5.3	21	(1234)
N	0	24	0.2	1.0319	1.0003	0.23	28	(2234)
N	0	24	0.5	1.0296	0.9977	-2.1	44	(1234)
N	0	24	0.5	1.0238	1.0110	7.8	44	(2234)
N	0	24	0.5	1.0078	0.9954	-2.5	66	(1222)
N	0	24	1.0	1.0343	0.9952	-4.3	99	(1234)
N	0	24	1.0	1.0204	1.0077	5.4	92	(2234)
N	0	24	1.0	1.0028	1.0147	8.1	107	(1222)
D	0	24	0.5	0.978	1.007	3.8	0.38	(1222)
D	0	24	0.5	1.0178	0.9980	-1.4	0.26	(2234)
D	0	24	0.5	1.0050	0.9973	-2.5	0.21	(1234)
D	0	24	1.0	1.0108	0.9990	-0.55	0.39	(1222)
D	0	24	1.0	1.0178	0.9963	-3.3	0.16	(1234)
D	0	24	1.0	0.9909	1.0127	9.0	0.25	(2234)
D	0	24	2.0	0.9913	1.013	7.3	0.26	(1222)
D	0	24	2.0	1.0237	0.9908	-8.3	0.09	(1234)
D	0	24	2.0	1.0094	1.0046	3.2	0.24	(2234)

Table A.2: Average bid size for base case simulations with Bid factor=1.

Base Case: Spares=0, Bidding Window =24h					
Type	**Spares [%]**	**Bid period [h]**	**Bid factor**	**Average bid size per site [kW/Hz]**	**Seed**
N	0	24	1.0	2665	(1234)
N	0	24	1.0	1877	(2234)
N	0	24	1.0	1746	(1222)

Table A.3: Result from sensitivity analysis of spare batteries.

Spare batteries varied: Bid factor=1, Bid window= 24h									
Type	**Spares [%]**	**Bid period [h]**	**Bid factor**	I_p	I_c	**ECM per forklift and day**	**Not delivered min (avg / day / site))**	**Average bid size [kW/Hz]**	**Seed**
N	2	24	1.0	1.04	0.996	-3.73	59.5	3177	(1234)
N	2	24	1.0	1.0162	1.0128	9.10	64.5	2366	(2234)
N	2	24	1.0	0.9862	1.0174	9.60	58.2	2258	(1222)
N	5	24	1.0	1.0230	0.9974	-2.35	39.0	3820	(1234)
N	5	24	1.0	1.0240	1.0075	5.32	39.1	3033	(2234)
N	5	24	1.0	1.0097	1.0092	5.04	45.9	2946	(1222)
N	10	24	1.0	1.026	0.994	-5.23	26.0	4910	(1234)
N	10	24	1.0	1.02	1.0084	5.93	26.3	4077	(2234)
N	10	24	1.0	0.988	1.0129	7.10	27.6	3969	(1222)
N	15	24	1.0	1.018	0.9966	-3.02	20.2	5954	(1234)
N	15	24	1.0	1.0174	1.0028	2.01	19.3	5232	(2234)
N	15	24	1.0	0.998	0.9845	-8.55	22.3	5013	(1222)
D	1	24	1.0	1.012	0.993	-6.68	0.093		(1234)
D	1	24	1.0	1.011	1.0032	2.28	0.164		(2234)
D	1	24	1.0	0.9918	0.9825	-9.63	0.438		(1222)
D	2	24	1.0	1.0037	0.9923	-6.91	0.0		(1234)
D	2	24	1.0	1.0125	0.9978	-1.52	0.0		(2234)
D	2	24	1.0	0.9817	1.0106	5.86	0.005		(1222)
D	5	24	1.0	1.0103	0.996	-3.38	0.0		(1234)
D	5	24	1.0	0.9987	1.0045	3.17	0.002		(2234)
D	5	24	1.0	0.9876	0.9946	-2.98	0.0		(1222)

Table A.4: Sensitivity analysis of size of bid window.

Bid window varied: Bid factor=1, Spare capacity = 0									
Type	**Spares** [%]	**Bid period** [h]	**Bid factor**	I_p	I_c	**ECM per forklift and day**	**Not delivered min (avg / day / site)**	**Average bid size** [kW]	**Seed**
N	0	1	1.0	1.0118	1.0071	6.41	159.7	5475	(1234)
N	0	1	1.0	1.0226	1.0165	11.64	148.0	4170	(2234)
N	0	1	1.0	1.0149	1.0010	0.5646	162.9	3328	(1222)

Table A.5: Effect of charging at lower power.

Compared result from "FCR" vs "none" optimization			
I_p	I_c	**ECM per forklift and day**	**Seed**
0.9426	1.011	10.2	(1234)
0.9527	1.006	4.2	(2234)
0.9633	1.011	9.2	(2222)
1.077	0.978	-18.2	(5555)

B
Appendix 2

B.1 Electricity spot price variations

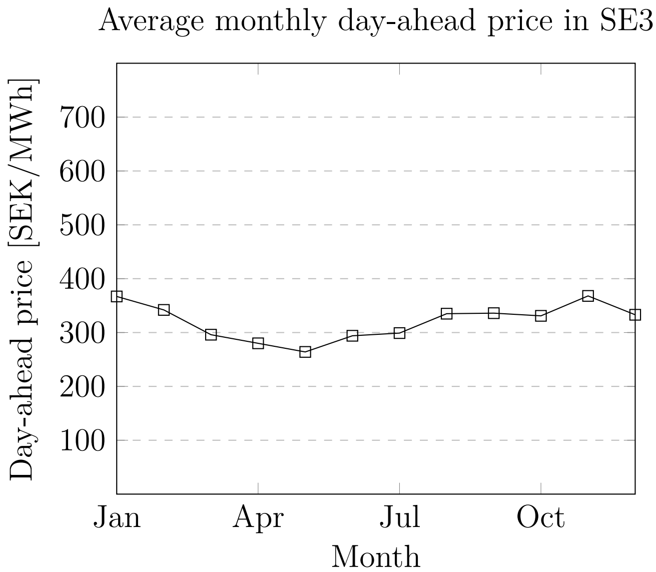

Figure B.1: Average day-ahead spot prices per month in SE3 April 2015 - Mars 2019, calculated using Nordpool data [23].

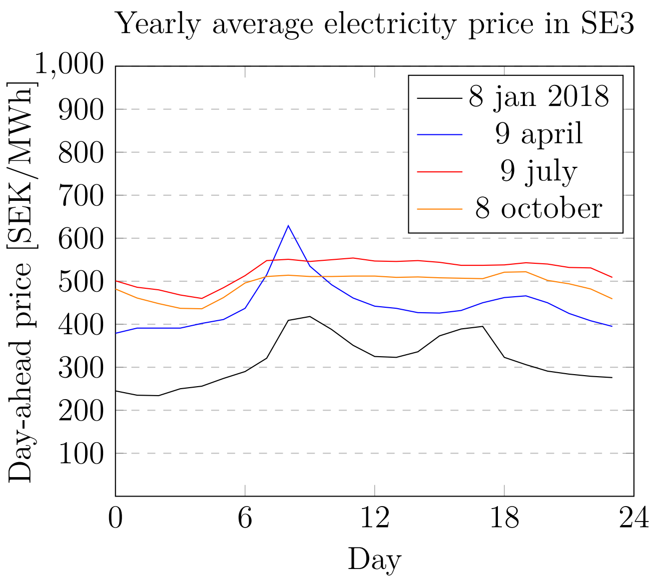

Figure B.2: Hourly prices in SE3, second Monday every third month in year 2018 [23].

B.2 Global energy storage

Energy storage technologies are under continuous development and the energy storage market is growing larger [7]. In 2017, there were approximately 129 MW stationary storage capacity connected to the grid globally. [7] The majority of this capacity is pumped hydro power plants, as is shown in table B.1. The rest of the capacity come from electro-chemical storage (e.g. batteries), electro-mechanical storage (e.g. flywheels and compressed air), thermal storage (mostly molten salt at CSP plants) and other types.

Table B.1: Global storage capacity of different types [7].

Global storage		
Storage type	**Capacity [GW]**	**Percent of capacity [%]**
Pumped hydro	153	96.2 %
Electro-chemical	1.3	1.4%
Electro-mechanical	2.3	0.8%
Thermal	2.3	0.8%
Others	5.9	3.7%