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Economic Value of Multi-Market Bidding in Nordic Frequency Markets

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***Abstract*—Battery energy storage systems (BESS) can be used for ancillary services like frequency containment reserve (FCR), which can generate a significantly higher revenue than energy arbitrage. Different FCR services differ in revenues and energy throughput, which induces costs due to conversion losses, tariffs, but it also leads to a significant number of battery cycles that reduce the battery capacity over time. The normal operation reserve (FCR-N) had the highest revenues in the past years, but comes along with a higher energy throughput than the disturbance reserve (FCR-D) which also has a lower price. - Based on the Nordic regulatory frame work with 5 years of market and tariff data, the present study demonstrates that by choosing the most profitable service for each hour it is possible to reduce the number of charge cycles with 51% and increase the operating profit with 22% compared to delivering pure FCR-N.**

***Index Terms*—Ancillary Services, Battery Degradation, Frequency Control, Bidding Strategy, Stationary Storage**

I. Introduction

The Transmission System Operators (TSOs) of the Regional Group Nordic (RG-N) synchronous zone, which Eastern Denmark (DK-2) is a part of, have a shared set of grid codes with the purpose of maintaining system stability. The first ancillary service activated for the stability of the power system is frequency containment reserve (FCR), which maintains system frequency close to its nominal value by balancing production and consumption on a seconds time scale [1]. Battery energy storage system (BESS) offering fast power response could replace the frequency regulation requirements of significantly larger generating units with slower ramp rates, as the generation is transitioning towards renewable production [2].

FCR consists of three services, frequency-controlled normal operation reserve (FCR-N), activated for frequency deviations up to ± 100 mHz, frequency-controlled disturbance operation reserve (FCR-D) up regulation activated when frequency falls below 49.9 Hz, and down regulation when frequency exceeds 50.1 Hz and fast frequency reserve (FFR) which is activated below 49.7 Hz [3].

Frequency regulation remunerates availability of power capacity and not the delivered energy. Hence, it is suitable for BESS applications as an inverter-coupled resource can have a fast power response but a limited energy capacity [4]. Delivering the different FCRs is the most profitable application of a BESS in the Nordic market, between 2015-2020 the average yearly capacity payment of FCR-N was $222\,$k€/MW [5]. For a 1C system (1 MW/1 MWh) and price of $700\,$k€/MWh, the payback time would be three years excluding operation costs [6].

The operation costs are proportional to the amount of activation as both charging and discharging results in respectively import and feed-in tariffs in addition to conversion losses in the inverter. When active in FCR-N, the BESS acts as a power-buffer to the grid in alternating charging and discharging periods [7, 8]. If the frequency deviations are normally distributed, then the overall energy exchange between the BESS and the grid cancels out, but can lead to large energy exchanges [9]. It adds up to the energy throughput (i.e. the integral of the absolute power during both charging and discharging periods) of the BESS. A high energy throughput increases accelerates battery degradation, resulting in a reduced energy capacity [10–12]. Empirically, delivering FCR-N with 1 MW generates on average an energy throughput of 3 GWh over a year, which is equivalent to 1.493 full cycles for a 1C system with an energy capacity of 1 MWh [5]. This is significant even for the cell chemistry with the highest cycle life commercially available, Lithium iron phosphate (LFP), with 8000 cycles [13].

Compared to FCR-N, delivering FCR-D reduces the throughput by 99.7% [14]. Hence, the tariffs and charge cycles are negligible compared to FCR-N. Historically FCR-N has offered significantly higher capacity payment than FCR-D. However, the large energy throughput of FCR-N generates additional costs (i.e. conversion losses and tariffs) as well as accelerated battery degradation due to the high cycle numbers.

Hence, evaluation of the most lucrative service considering all aspects, from revenues over energy costs to costs of shorter lifetime is crucial for BESS business case evaluation. The present paper will address this question by comparing the costs and revenues for the different services, using historical frequency and market data. The paper is structured as follow; Section II provides an overview of the different frequency regulation services, followed by a detailed description of the delivery requirements, as well as settlement and operational costs of delivering the services. Section III presents the results of the comparison of the market strategies and Section IV draws the conclusions.

II. Method

A. Overview and specifications of services

Frequency regulation in RG-N consists of three services; FFR, FCR-D (up and down) and FCR-N. These services are paid for availability per power capacity [€/MW] per hour, independently of the actual amount of activation. The different market characteristics are shown in Table I. The energy throughputs of the services are calculated as a percentage of FCR-N throughput.

Some ancillary service markets require a balance responsible party (BRP) to bid and be responsible for its imbalances in the electricity market.

The FCR-D down regulation introduced in 2022 in Denmark and Sweden as a supplement to the existing FCR-D up regulation is not included in this study as market data is still very limited. In this work FCR-D therefore only refer to the up regulation counterpart.

	FFR	FCR-D	FCR-N
Reaction time	0.7, 1, 1.3 s	50% in 5 s 100% in 30 s	150 s
Implementation	Step function	Linear	Linear
@Hz	49.5, 49.6, or 49.7	49.5-49.9 50.1-50.5	49.9-51.1
Min. Delivery	10 s	N/A	N/A
Relaxation time	15 min	N/A	15 min (exemption)
Energy throughput	0%	0.3%	100%
Minimum bid	0.3 MW	0.3 MW	0.3 MW
Bid steps	0.1 MW	0.1 MW	0.1 MW
Up/Down regulation	Up	Up and down	Symmetric
Pricing	Marginal	Pay as bid	Pay as bid
Market	DK	DK-SE	DK-SE
Volume [MW]	0-23	624	258
Energy Settlement	imbalance	imbalance	up/down reg. power prices
Requires BRP	No	No	Yes

TABLE I: Service description of FFR, FCR-D and FCR-N

Power availability for FCR-N and FCR-D is settled with the pay as bid mechanism, but only volume-weighted average market prices in €/MW per hour are published [15]. The individual bids (i.e. volume, price) are not published. In this study it is assumed that it is possible to achieve the average market price when bidding FCR-N and FCR-D. FFR is settled with the marginal price mechanism, and the transmission system operator (TSO) publishes the marginal price.

Service providers are subject to tariffs when importing and exporting energy from/to the grid. Tariffs for customers connected to the 10 kV grid importing energy from the grid in the Radius Elnet distribution system operator (DSO) of Denmark are shown in Table II. The specific time of use tariffs are compared with the tariffs of customers connected to the 0.4 kV grid [16].

In addition to the DSO tariffs on import, TSO tariffs apply both for energy imports and exports (Table III) [17].

The total amount of tariffs charged to a BESS connected to the 10 kV grid after charge and discharge of 1 MWh is between 21.68 € in a low load hour and 35.77 € in a peak hour, with 26.39 € in an average hour.

	Low	High	Peak	Average
Hours/year	4438	2645	1677	8760
10 kV	6.05	12.72	20.15	10.76
0.4 kV	8.59	17.02	26.03	14.47

TABLE II: Import tariffs paid to the DSO Radius Elnet in €/MWh for a 10 kV and 0.4 kV connected customer [16]. The description of the low, high and peak load periods can be found in [16].

	Transmission grid	Balance	System	Sum
For consumption	6.58	0.31	8.19	15.08
	Feed-in	Balance		
For production	0.4	0.16		0.56

TABLE III: TSO tariffs in €/MWh [17]

B. Fast Frequency Reserve (FFR)

The Nordic TSOs introduced FFR in 2020 to handle situations of low inertia, which have become more frequent in the Nordic power system as a consequence of low hydro power generation during the summer. hence, FFR is only purchased for some hours of the day in the summer period. In the low inertia situations are FCR-N and FCR-D not fast reactive enough to ensure system stability.

FFR requires full activation when frequency drops below a certain threshold; power must be maintained for 10 s. Units with an activation time of 1.3 s, 1.0 s, and 0.7 s are triggered respectively at 49.7 Hz, 49.6 Hz, and 49.5 Hz. The lower the activation time the lower is the threshold and the less often the asset is activated. For example an asset activated in 0.7 s, has an activation probability close to 0 (no activation in the last 6 years). The activation period is typically so short that there is virtually no energy throughput (and consequently costs associated with losses). Consequently, FFR can be delivered by a non-BRP, and when activated it is settled as a regular imbalance.

The service is paid in €/MW per hour of power availability. Profit P_h^{FFR} at hour h is calculated as the reserve capacity r_h^{FFR} multiplied with the marginal price per MW p_h^{FFR} as

$$P_h^{\text{FFR}} = r_h^{\text{FFR}} \cdot p_h^{\text{FFR}} \tag{1}$$

C. Frequency Containment Reserve Disturbance operation (FCR-D)

An asset bidding in FCR-D should deliver power linearly when frequency is between 49.9 and 49.5 Hz. It should be able to deliver 50% of the full power capacity within 5 s and the remaining 50% of the capacity within another 25 s. An initial response delay of up to 2 s is tolerated [18].

For a frequency value f_t at time step t of a given day, the normalised response y_t is calculated as in (2). This is using the load convention, where y_t is negative for under frequency events where the unit exports (produces) energy.

$$y_t = \begin{cases} -1, & \text{if} \quad f_t < 49.5 \text{ Hz} \\ \frac{f_t - 49.9 \text{ Hz}}{0.4 \text{ Hz}}, & \text{if} \quad 49.5 \text{ Hz} \leq f_t \leq 49.9 \text{ Hz} \\ 0, & \text{if} \quad f_t > 49.9 \text{ Hz}. \end{cases} \tag{2}$$

The power delivered by the service provider at time step t of hour h is calculated as

$$Y_{t|h} = r_h^{\text{FCR-D}} y_t + B_h. \tag{3}$$

B_h is the scheduled power at hour h, based on the traded energy in MWh/h at the day-ahead spot market. $r_h^{\text{FCR-D}}$ is the reserve capacity contracted for FCR-D at hour h. System frequency is rarely below $49.9\,\text{Hz}$ (i.e. 1.1% of the time) [5]. The energy delivery of FCR-D is therefore negligible, and thus it not necessary to be a BRP to deliver the service. When activation occurs, it is settled as a regular imbalance. The service is paid in €/MW per hour of power availability. Profit $P_h^{\text{FCR-D}}$ at hour h is calculated as reserve capacity $r_h^{\text{FCR-D}}$ multiplied with the average price per MW $p_h^{\text{FCR-D}}$ as

$$P_h^{\text{FCR-D}} = r_h^{\text{FCR-D}} \cdot p_h^{\text{FCR-D}}. \tag{4}$$

D. Frequency Containment Reserve Normal operation (FCR-N)

FCR-N participation requires a full response within $150\,\text{s}$ with an acceptable initial response delay of up to $10\,\text{s}$ [18]. Due to the less strict response time requirements FCR-N can be be delivered with distributed electric vehicles with both unidirectional and vehicle to grid (V2G) chargers [1]. FCR-N must be provided linearly, with full activation for deviations of $\pm 100\,\text{mHz}$, without a dead-band. FCR-N is a symmetrical service which means that the provider must offer the same power capacity for upwards and downwards regulation. For a frequency value f_t at time step t of a given day, the normalised response y_t is calculated as

$$y_t = \begin{cases} -1, & \text{if} \quad f_t < 49.9 \text{ Hz} \\ \frac{f_t - 50 \text{ Hz}}{0.1 \text{ Hz}}, & \text{if} \quad 49.9 \text{ Hz} \leq f_t \leq 50.1 \text{ Hz} \\ 1, & \text{if} \quad f_t > 50.1 \text{ Hz}. \end{cases} \tag{5}$$

The power required by the service provider at time step t and hour h is calculated as

$$Y_{t|h} = r_h^{\text{FCR-N}} y_t + B_h. \tag{6}$$

$r_h^{\text{FCR-N}}$ is the reserve capacity contracted for FCR-N at hour h. Due to the significant energy delivery of FCR-N, it is required that the aggregator is either a BRP, or bids through a BRP. To avoid large energy imbalances from service provision, the TSO is compensating the BRP by buying the energy content delivered and selling the energy received. This energy content is calculated by integrating the consumption response ($y_t^{\text{c}} = \max(\text{y}_t, 0)$ and production response ($y_t^{\text{c}} = -\min(\text{y}_t, 0)$ for each hour with a resolution $\text{t}^{\text{s}} = 1\,\text{s}$, assuming zero response delay. The corresponding production e_h^{p} and consumption e_h^{c} at hour h with $\text{N}^{\text{s}} = 3600\,\text{s/h}$ are given by

$$e_h^{\text{p}} = \frac{1}{\text{N}^{\text{s}}} \sum_{t=\text{N}^{\text{s}}(h-1)+1}^{h\text{N}^{\text{s}}} y_t^{\text{p}} \text{t}^{\text{s}}\ ,\ e_h^{\text{c}} = \frac{1}{\text{N}^{\text{s}}} \sum_{t=\text{N}^{\text{s}}(h-1)+1}^{h\text{N}^{\text{s}}} y_t^{\text{c}} \text{t}^{\text{s}}. \tag{7}$$

The energy content is given *per unit* so the energy in MWh is found by multiplying with $r_h^{\text{FCR-N}}$. The energy content as production and consumption is bought and sold with the up and down regulation price respectively. The price for the energy uptake is generally lower than the spot market price, while the price of energy delivered to the grid is generally lower than the spot market price. The compensation scheme is therefore beneficial to the service provider, resulting in an average additional revenue of 3.5% of the capacity payment [5]. The total revenue $R_h^{\text{FCR-N}}$ for hour h, not conversion losses and tariffs, is found by (8), where c_h^{u} and c_h^{d} are the up and down regulation power prices respectively, and $r_h^{\text{FCR-N}}$ is the capacity payment per MW for FCR-N.

$$R_h^{\text{FCR-N}} = r_h^{\text{FCR-N}} (p_h^{\text{FCR-N}} + e_h^{\text{p}} c_h^{\text{u}} - e_h^{\text{c}} c_h^{\text{d}}). \tag{8}$$

The service requires 100% guarantee of delivery independent of the duration of the frequency deviation but the Danish TSO currently offers operators of systems with limited energy storage capacity (e.g. BESS) an exemption agreement, which applies to the condition for continuous service delivery. The agreement requires the service to be continuously active and contains functionalities which can guarantee $100\,\%$ delivery of power for a minimum of 15 minutes. Then, the BESS operator has the opportunity to restore reserves within the following 15 minutes. [19] shows that when following the specifications of the exemption agreement, a $1\,\text{MW}/1\,\text{MWh}$ battery with a round-trip efficiency of $90\,\%$ can allocate $90\,\%$ of its power capacity to continuously perform FCR-N service. Hence, in the present study the maximum $r_h^{\text{FCR-N}}$ value was set to $90\,\%$ of BESS power capacity.

Unlike the other two services, delivering FCR-N entails significant costs associated with conversion losses and energy exchanges. Therefore, equation (8) is augmented to include the cost associated with tariffs C_h^{tar} given by

$$C_h^{\text{tar}} = r_h^{\text{FCR-N}} (e_h^{\text{p}} t^{\text{TSO,p}} + e_h^{\text{c}} (t^{\text{TSO,c}} + t_h^{\text{DSO}})), \tag{9}$$

where t_h^{DSO} is the import DSO tariff at hour h, and $t^{\text{TSO,c}}$, $t^{\text{TSO,p}}$ are respectively the TSO consumption and production tariffs. The increased energy consumption due to conversion losses are found by multiplying the required energy consumption with one minus the average round-trip efficiency, $(1 - \eta)$. The increased consumption is multiplied with the balancing price c_h plus import tariffs for the specific hour. For simplicity energy conversion loss is assumed to be recharged within the same hourThe cost associated with losses C_h^{los} is given by

$$C_h^{\text{los}} = r_h^{\text{FCR-N}} \cdot e_h^{\text{c}} \cdot (1 - \eta) \cdot (c_h + t^{\text{TSO,c}} + t_h^{\text{DSO}}). \tag{10}$$

Profit $P_h^{\text{FCR-N}}$ can then be written

$$P_h^{\text{FCR-N}} = R_h^{\text{FCR-N}} - C_h^{\text{tar}} - C_h^{\text{los}}. \tag{11}$$

E. Multi-market bidding

It is not always the same market that generates the highest profit. Instead of only delivering one service continuously we propose to evaluate each hour by itself to determine which market generates the highest profit. In the same hour, a BESS can be bid in one of the three aforementioned services. Hence, for each hour the potential profit can be estimated based on price forecasts (in this work perfect forecast of the average market value is assumed) and expected cost of losses and tariffs. Moreover, only 90% of the available power can be bid in FCR-N, to allocate the remaining 10% to cover conversion losses while 100% can be bid for the other two. For each hour h, the service provider bids in the ancillary service market that yields the maximum profit. The decision is made latest at

18:00 on the day before operation, which runs from midnight to midnight.

$$\max(0.9P_h^{\text{FCR-N}}, P_h^{\text{FCR-D}}, P_h^{\text{FFR}}). \tag{12}$$

The implementation should involve FFR, but due to limited historical data is the value of the multi market bidding only evaluated for FCR-D and FCR-N, which is presented in the results section.

III. Results

A. Frequency services market prices

Few assets comply with FFR, resulting in the highest capacity payments of all services. During 2020, the service was introduced and procured monthly with total yearly earnings of 175 k€/MW. Since 2021, the service is procured daily with hourly bids. In 2021, 6.8 MW per hour were purchased on average (when active) for a total of 1,572 hours with an average price of 303 €/MW, resulting in a yearly capacity payment of 476 k€/MW for the whole year. Over the active period from May to September 2021, it was procured for 20% of the hours of the day and 38% of the hours at night.

The TSO purchases constant volumes of FCR-N and FCR-D throughout the year. Fig. 1 shows the total monthly capacity payment per MW for these services. Since prices have an increasing trend, the paper focuses on the full years of 2017 through 2021 to compare the services (see table IV). The introduction of new services (i.e. FCR-D down regulation, FFR) indicates the TSOs growing need for ancillary services. For fast-reacting BESSs, significant revenue increases can be achieved by delivering FFR, given the higher compensation per MW. FCR-D down regulation, introduced in 2022, can be delivered at the same time as the up regulation counterpart, and in the first three months of 2022 has a payment equal to 40% of the up regulation service.

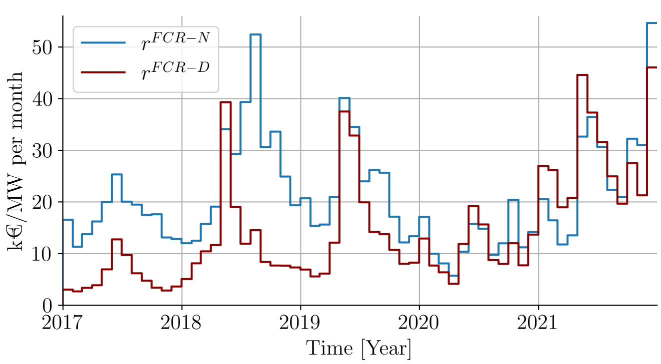

Fig. 1: Monthly capacity payment in k€/MW FCR-N and FCR-D capacity.

	2017	2018	2019	2020	2021	Average
FCR-N [k€]	203	323	266	149	324	253 k€/MW
FCR-D [k€]	63	151	176	128	346	173 k€/MW
FFR [k€]	N/A	N/A	N/A	175	476	326 k€/MW

TABLE IV: Historical yearly capacity payment in k€/MW. FFR has only been introduced in 2020

B. Economic potential of frequency regulation with a 1 MW/1 MWh BESS

Profits are calculated for a 1 MW/1 MWh BESS located in the Capital Region of Denmark in price area DK-2 to compare FCR-N and FCR-D. The system is assumed to have an average round-trip efficiency of $\eta = 0.9$. For a 1 MW BESS it is possible to bid 1 MW in FCR-D but only 0.9 MW in FCR-N. Additionally, the continuous charging/discharging results in a cost of both import/export tariffs and conversion losses that should be subtracted from revenue. The monthly profit margin is shown as a share of the capacity payment for the considered system, biding in FCR-N for the years 2017-2021 in Fig. 2.

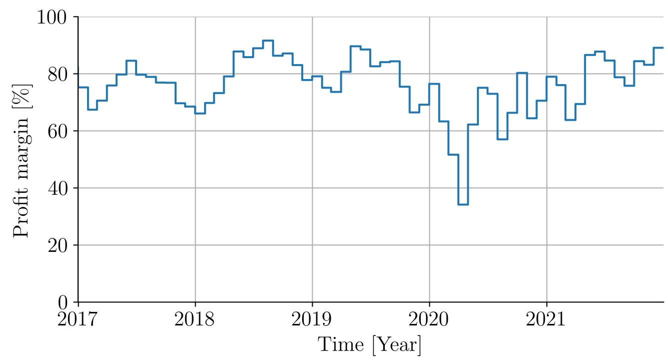

Fig. 2: Monthly profit margin of delivering FCR-N.

In Table V the yearly revenue, operation cost and profits for continuously bidding 0.9 MW FCR-N are presented over five years. Out of the average yearly cost of 44 k€/MW, on average 36 k€/MW is attributed to import/export tariffs. The conversion loss adds up to 149 MWh/year with a cost of 8 k€/MW.

	2017	2018	2019	2020	2021	Average
$R^{\text{FCR-N}}$ [k€]	57	136	159	115	312	156 k€/MW
$C^{\text{FCR-N}}$ [k€]	42	44	43	42	49	44 k€/MW
$P^{\text{FCR-N}}$ [k€]	141	247	197	93	243	184 k€/MW

TABLE V: Yearly revenue, $R^{\text{FCR-N}}$, cost, $C^{\text{FCR-N}}$, and profit, $P^{\text{FCR-N}}$, for continuously delivering 0.9 MW FCR-N with a 1 MW BESS.

The average FCR-N profit of 184 k€ is higher than the 173 k€ profit from FCR-D provision. A BESS with a cost of 700 k€ could be paid back in 4 years by delivering either service. This is without considering the cost of maintaining the operation by an aggregator and BRP. FCR-N participation results in a significant energy throughput, which affects BESS lifetime. The BESS will experience an energy throughput of 2.7 GWh per year due to FCR-N provision, which corresponds to 1,341 full equivalent charge cycles per year. For an LFP BESS as the one provided by CATL [20], the 8,000 full equivalent cycles included in the warranty would be used after 6 years.

C. Multi-market bidding results

By choosing the most profitable service in each hour, it is possible to increase BESS profits. In Fig. 3 is shown the monthly profit for the three cases where the battery is either providing FCR-N or FCR-D in all hours of the day and the multi-market case where the aggregator chooses the optimal market throughout the day with the multi-market bidding method presented in section II-E. The multi-market method

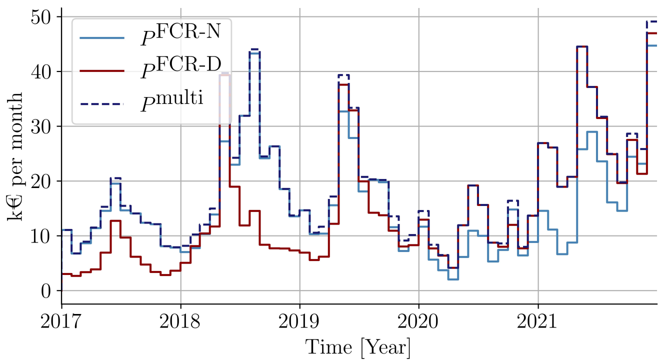

Fig. 3: Monthly profit if the 1 MW BESS either delivers FCR-N, $P^{\text{FCR-N}}$ or FCR-D, $P^{\text{FCR-D}}$ for all hours or if the multi-market method chooses the best market for each hour, P^{multi}.

achieves at least the same result as the best of the individual markets in every month of the period. Table VI shows the share of the hours over the year where the battery participated in each markets, together with the yearly profit. The ratio of time in the different markets shifts from year to year where FCR-N would be provided in 78% of the hours in 2017 to only 9% of the hours in 2021.

	2017	2018	2019	2020	2021	Average
FCR-N hours	86%	76%	55%	18%	12%	49%
FCR-D hours	14%	24%	45%	82%	88%	51%
P^{multi} [k€]	144	269	221	136	355	225 k€
$P^{\text{multi}}/P^{\text{FCR-N}}$	102%	109%	112%	146%	146%	122%
$P^{\text{multi}}/P^{\text{FCR-D}}$	228%	178%	125%	106%	102%	130%

TABLE VI: Distribution of hours providing FCR-D and FCR-N for multi-market bidding, profit, and bench-marking of the profit of the multi-market against delivering FCR-N or FCR-D for all hours of the year.

Multi-market bidding out-performs the individual FCR-N and FCR-D markets every year from 2% up to 46% for FCR-N and 2% up to 128% for FCR-D. On average over the 5 years, multi-market bidding achieves 22% higher result than FCR-N alone and 30% higher than FCR-D. An equally important result is that the multi-market bidding results in 51% fewer charge/discharge cycles since FCR-N only is provided in 49% of the hours throughout the years. During an average year the battery would operate only 659 charge cycles. It corresponds to 12 years for a battery with 8,000 charge cycles, so doubling the lifetime compared to the base case (6 years).

IV. Conclusion

Historically, FCR-N has the highest prices among the frequency regulation services in the Nordic power system. By delivering FCR-N it was possible to earn on average in 184 k€ per year with a 1 MW/1 MWh BESS, which could pay back a system in 4 years. However, the frequency behaviour results in a significant energy throughput when providing FCR-N, which reduces the BESS lifetime. The service causes 1,343 full equivalent charge cycles per year. A BESS with 8,000 full equivalent cycles included in the warranty would reach this limit in 6 years. It caps the potential earnings of the BESS in the lifetime, which could be up to 15 years. FCR-D gives a lower revenue but involves almost no energy throughput.

By switching between the two markets when it is most profitable it is possible to out-perform the individual FCR-N and FCR-D markets every year. On average over 2017 – 2021 multi-market bidding would have achieved 22% higher result than FCR-N alone and 30% higher than FCR-D. Moreover, the multi-market bidding strategy results in 51% fewer charge/discharge cycles and would double the lifetime from 6 to 12 years.

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