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Title:	Effects of Battery Aging on BESS Participation in Frequency Service Markets - Finnish Case Study
Year:	2022
Version:	Accepted manuscript
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Please cite the original version:

Khajeh, H., Parthasarathy, C. & Laaksonen, H. (2022). Effects of Battery Aging on BESS Participation in Frequency Service Markets - Finnish Case Study. In: *2022 18th International Conference on the European Energy Market (EEM).*
https://doi.org/10.1109/EEM54602.2022.9921139

Effects of Battery Aging on BESS Participation in Frequency Service Markets – Finnish Case Study

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***Abstract*—Increasing share of intermittent inertialess renewable power is being integrated into the power systems. This affects the power system dynamics and frequency stability. As a result, the systems need more resources that provide frequency control related technical services. In this regard, this paper proposes the participation of a Lithium-ion Battery Energy Storage System (Li-ion BESS) in providing frequency containment reserve for normal operation (FCR-N). The Li-ion BESS reacts to the frequency deviations from 0 to 0.1 Hz and -0.1 to 0 Hz in FCR-N operations. In addition, the paper presents a method to schedule the charging and discharging power of BESS while considering the effects of BESS cycling aging. In the simulation section, a 50-kWh BESS is supposed to react to the three-minute frequency changes and the corresponding outcome is estimated for three months. At the end, the paper assesses whether the cycling aging affects the BESS economic outcome when it provides FCR-N service.**

***Index Terms*—BESS, frequency regulation, BESS aging, cycle counting, FCR.**

I. INTRODUCTION

A large share of variable weather-dependent, renewable inverter-based generation is being connected into power systems. This adversely affects the power system dynamic behavior and stability, especially frequency stability, during different events and disturbances. To resolve this issue, future power systems need to adopt new sources of flexibility that can provide frequency control services for the system. Recent studies have proposed the utilization of BESS for this purpose since they are capable of responding to frequency changes very fast due to their controllability and flexibility features [1], [2]. However, the participation of BESS in providing frequency services should be profitable for its owner. In other words, BESS participation should not impose additional costs on the BESS owner. Thus, a thorough techno-economic study needs to be conducted including battery aging costs for Li-ion BESS.

In the literature, there are works trying to schedule a BESS in a way to provide frequency services. For instance, [3] proposed the optimal operation of a Li-ion BESS if it participates in Nordic FCR markets. The work mostly concentrated on one-day scheduling of the BESS and the battery aging effects were disregarded. Another thorough work conducted by [4] was to schedule a Li-iron phosphate battery to be in line with the regulation markets' needs and also proposed the simultaneous participation in energy markets. However, the type of services that the battery is scheduled for was not clearly specified. Each market has its own characteristic and needs its own technical requirements. For instance, the BESS cannot provide some frequency regulation services with energy at the same time meaning that its total capacity should be reserved for the frequency regulation and thus it is not allowed to participate in energy-related markets. In addition, the study tried to consider BESS aging effects in 24 hours but the capacity degradation cannot be estimated thoroughly in a one-day interval. Another daily analysis was conducted by [5] proposing the contribution of a BESS to the FCR as well as peak-shaving services. Again, cycling effects and the type of battery technology were not thoroughly considered. Study in [6] proposed a business model and regulatory frameworks considering the BESS as a service provider in Finland. The BESS technology includes a wide range of batteries such as lead, Li-ion, condenser and flow battery. The aging of the capacity was however disregarded in their analyses. Authors of [7] tried to schedule a vanadium redox BESS that provides frequency restoration reserves in a community environment and [8] proposed the provision of ancillary services by the household BESS without specifying the battery technology. Both studies did not take into account the effects of cycling on the BESS capacity. Although [9], [10] analyzed and schedule a Li-ion BESS based on its cycling aging effects, they do not consider these effects if the BESS provides frequency regulation services.

In this regard, this paper aims to conduct a three-month analysis to consider the effects of cycling aging if a Li-ion BESS participates in Nordic FCR-N provision. The contribution of the paper will be twofold:

1- It proposes a method and strategy to schedule the charging and discharging power of a Li-ion BESS that can count the cycle simultaneously and estimate the capacity based on the cycles.

2- It obtains the economic outcome of a 50 kWh Li-ion BESS that responds to the three-minute real measured frequencies and provides FCR-N. This outcome is calculated with and without cycling effects for comparison purposes.

The rest of the paper is organized as follows. Section II describes how a resource can provide the FCR-N service. Section III introduces the proposed method including cycle counting, capacity estimation, and Li-ion BESS scheduling. Section IV introduces the cases studies and implementation of the proposed scheduling methodology on a 50 kWh Li-ion BESS. Finally, Section V concludes the paper.

II. BESS PARTICIPATION IN FCR-N MARKET

Frequency Containment Reserves (FCR) are deployed to regulate frequency continuously. This service is categorized into FCR for normal operation (FCR-N) and FCR for disturbance situations (FCR-D). FCR-D is responsible to control frequency when it falls below 49.9 to 49.5 and when it goes above 50.1 to 50.5. The focus of this paper is on the FCR-N service which is designed for normal operation. FCR-N services should react to the frequency changes from 0 to 0.1 Hz and -0.1 to 0 Hz [11].

FCR-N is considered as a symmetrical service and market. This means that an FCR-N provider should be able to reserve both upward and downward services at the same time. Thus, a BESS that has the capability to be charged and discharged, can be an FCR-N provider. The full reserve capacity of the FCR-N provider needs to be activated when the frequency goes below 49.9 Hz. Correspondingly, in cases where the frequency goes above 50.1 Hz, the resource should be fully activated with its 100 percent capacity. When the frequency level is within the range of 49.9 to 50.1 Hz, The activated capacity needs to be proportional to the magnitude of the frequency changes. In addition, when the frequency deviation happens, the reserve should be activated in less than 3 minutes and it should not be delayed on purpose [11].

When a BESS is an FCR-N provider and it reaches the maximum or minimum level of its state-of-charge (SOC), the service activation needs to be interrupted until the direction of the frequency changes. A balancing service provider is responsible for scheduling the charging and discharging level of the BESS. The recharging power, SOC management and forecasting as well as scheduling timetable of BESS can be a challenge when it provides FCR-N services.

A reserve provider receives two types of payment if it contributes to the FCR-N provision. Firstly, it receives a capacity payment for the amount of capacity that is reserved to respond to the frequency deviations. Secondly, it is paid if its upward flexible capacity is activated. When the upward capacity is activated, the provider injects power into the grid. On the other hand, when the downward capacity is activated, the flexible resource increases its consumption. Although the reserve provider is paid in case its upward capacity is activated, it should pay for its consumption based on the downward regulation prices when it is providing downward flexibility. However, it is worth mentioning that the prices of downward flexibility are always equal to or lower than those of the spot market [8]. This means that it is always more beneficial for a consumer to consume power based on downward regulation prices rather than spot market prices. Correspondingly, the prices of upward regulation are always equal to or higher than those of the spot market. Hence, it is more beneficial for a producer to provide upward flexibility and sells it into the reserve markets rather than the spot market [8].

A BESS can be deployed as an FCR-N provider. In this way, the BESS is charged whenever the frequency increases from 50 to 50.1 Hz meaning that the system needs downward flexibility. The BESS is discharged in cases where the frequency falls between 50 to 49.9 Hz. In these cases, the system requires upward flexibility. The charging/discharging power needs to be proportional to the frequency deviation. In addition, there should be a local measurement device to direct the BESS towards the right amount and direction of power. Thus, the BESS is managed according to the local frequency measurement.

III. PROPOSED METHODOLOGY

This paper proposes the participation of a Li-ion BESS in providing FCR-N services. In this regard, we propose a linear optimization problem that schedules the BESS. However, in the process of BESS' scheduling, we need to determine the remaining capacity of the battery in each cycle. In addition, a fast Li-ion BESS cycle counting method is needed as a first step to calculate the cycles.

A. Li-ion BESS Cycle Counting

Li-ion BESS cycle is counted by modifying the method proposed by [12].

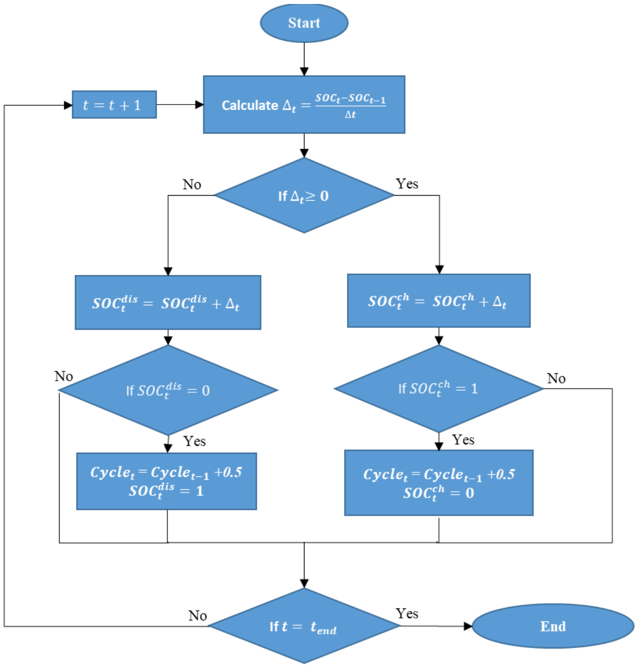

Figure 1. A flow chart representing BESS cycle counting

According to this method, the first step calculates the SOC change within the predefined time slot. If the SOC increases, it means that the Li-ion BESS was charging. Hence, it adds the

SOC increase to the value of a variable denoted by SOC_t^{ch}. It should be noted that this variable is totally different from the BESS SOC at t denoted by SOC_t. The variable SOC_t^{ch} is just used to calculate the Li-ion BESS cycle. If SOC_t^{ch} reaches its maximum level, which is one, the cycle increases by 0.5 and SOC_t^{ch} is reset to one. Otherwise, the algorithm continues with the current cycle.

Correspondingly, if the SOC decreases during one time slot, the battery was discharging. Hence, the change is added to another variable denoted by SOC_t^{dis}. This variable is just utilized to calculate the cycle. If SOC_t^{dis} approaches its minimum level, zero, the cycle increases by 0.5 and SOC_t^{dis} is reset to zero. This algorithm ends when the BESS stops being charged and discharged. Fig. 1 summarizes the method adopted to calculate the Li-ion BESS cycle counting.

B. *Li-ion BESS Capacity Estimation Considering BESS Cycling Aging*

Li-ion BESS capacity decreases with the cycle (age) increase. Thus, Li-ion BESS capacity can be defined as a function of cycle while the cycles reflect the age of the battery. In order to obtain capacity-cycle function, we use the field data on a 50 kWh Li-ion BESS. The field data is based on measured capacities of a 50 kWh Li-ion BESS after passing some cycles. Then, a polynomial regression is deployed to obtain the relationship between the Li-ion BESS capacity and the cycle. Finally, mean squared error (MSE) criteria is utilized to choose the best fitted function. Regarding our data, the best fitted function that models the Li-ion BESS capacity based on its charging/discharging cycle was a polynomial of degree 4. Fig. 2 depicts the curve fitted on the data. Fig. 2 illustrates the relationship between capacity and cycle for the studied BESS.

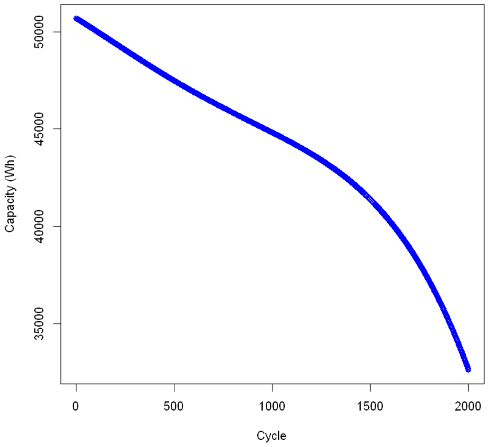

Figure 2. The curve representing studied Li-ion BESS capacity-cycle

As Fig. 2 states, the cycling of the BESS can affect its maximum capacity. For the case of 50 kWh of a Li-ion BESS, its maximum capacity falls to less than 35 kWh after 2000 cycles. Accordingly, it is necessary to consider the BESS cycling effects when the study aims to assess the Li-ion BESS long-term economic outcome.

C. *Li-ion BESS Scheduling*

BESS scheduling should be done according to the volume and direction of the frequency deviation. Moreover, the power of charging/discharging should not result in the Li-ion BESS SOC exceeding its predefined limits. Therefore, a scheduling problem can be developed with linear programming (LP) method. The problem is written separately for scheduling the charging and discharging power, as follows:

$$If\ FD_t \geq 0\ then\ the\ BESS\ is\ charging\ with\ P_t \geq 0:$$

$$\max_{P_t} P_t \qquad (1)$$

Subject to:

$$0 \leq P_t \leq \frac{FD_t}{0.1} \times P^{max} \qquad (2)$$

$$SOC_t = SOC_{t-1} + \frac{\eta_{ch} P_t}{Cap(Cycle_t)} \Delta t \qquad (3)$$

$$SOC^{min} \leq SOC_t \leq SOC^{max} \qquad (4)$$

$$If\ FD_t < 0\ then\ the\ BESS\ is\ discharging\ with\ P_t < 0:$$

$$\min_{P_t} P_t \qquad (5)$$

Subject to:

$$\frac{FD_t}{0.1} \times P^{max} \leq P_t \leq 0 \qquad (6)$$

$$SOC_t = SOC_{t-1} + \frac{P_t}{\eta_{dis} \times Cap(Cycle_t)} \Delta t \qquad (7)$$

$$SOC^{min} \leq SOC_t \leq SOC^{max} \qquad (8)$$

Where:

$$FD_t = freq_t - 50 \qquad (9)$$

Where, SOC^{min} is the lowest allowable SOC while SOC^{max} indicates the higher limit defined for the SOC. Also, η_{ch} and η_{dis} denote Li-ion BESS charging and discharging efficiencies, respectively. $Cap(Cycle_t)$ is the function that calculates the value of BESS maximum capacity based on the real-time cycle at t ($Cap(Cycle_t)$). This function was determined in subsection B. The cycle is also counted using the method proposed in subsection A.

P_t is the scheduled power determined by solving (1)-(8). If the frequency deviation at t, i.e. $FD_t \geq 0$, the BESS needs to provide downward flexibility by charging the BESS. Thus, P_t is also positive and the optimization problem (1)-(4) should be solved. Otherwise, if the frequency deviation is negative, the BESS should be discharged. The discharging power can be obtained by solving (5)-(8).

In the optimization problems, P^{max} is the absolute value of charging/discharging power. As previously stated, an FCR-N provider should be activated with the power that is proportional to the frequency deviation. Regarding FCR-N services, the ratio of the frequency deviation equals $\frac{FD_t}{0.1}$. This means that the charging power should be equal to or lower than $\frac{FD_t}{0.1} \times P^{max}$ and the discharging power should be equal to or higher than

$\frac{FD_t}{0.1} \times P^{max}$. If the BESS SOC does not limit the charging/discharging power, optimization problems (1-4) and (5-8) yield $P_t = \frac{FD_t}{0.1} \times P^{max}$. Otherwise, it gives us the highest absolute value of discharging/charging power that maintain the SOC within the permissible range.

IV. CASE STUDY

The proposed methodology has been tested on a 50 kWh Li-ion BESS. Table I illustrates the battery characteristics. Also, the frequency data from January 1st to 31st March, 2021, was extracted from "Fingrid Open Data on the Electricity Market and the Power System" [13]. Fingrid is the Finnish Transmission system operator (TSO). The frequency data measured in a three-minute intervals is depicted in Fig. 3.

TABLE I. BATTERY CHARACTERISTICS

Maximum Capacity for cycle =0 [kWh]	P^{max}[kW]	SOC^{min}/SOC^{max}	η_{ch}/η_{dis} [%]
50.69	100	0.05/0.95	90

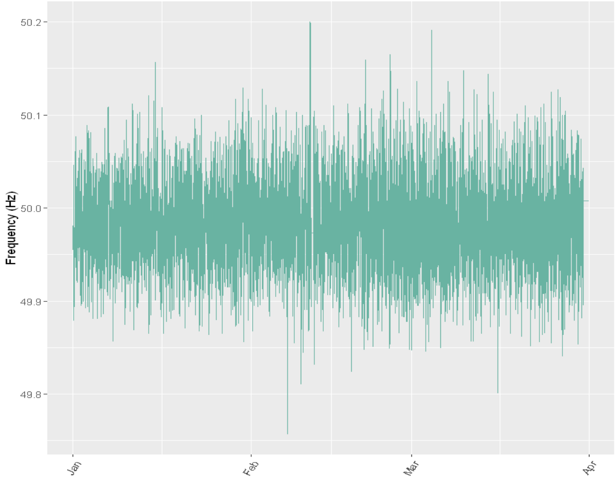

Figure 3. Frequencies measured for each three minutes in Jan-March 2021

R programming language was utilized to implement the methodology including data preprocessing, polynomial curve fitting, and solving the linear optimization problem. Fig. 4 explains the steps designed to schedule the charging and discharging power of the BESS as well as obtain the outcomes.

The charging/discharging power of the BESS was scheduled according to the proposed methodology. Fig. 5 and Fig. 6 indicate the charging power (negative values for discharging and positive values for charging) as well as the BESS SOC variations. As the Fig. 5 and Fig. 6 state, the BESS is continuously reacting to the frequency changes. The initial BESS SOC was considered 0.5.

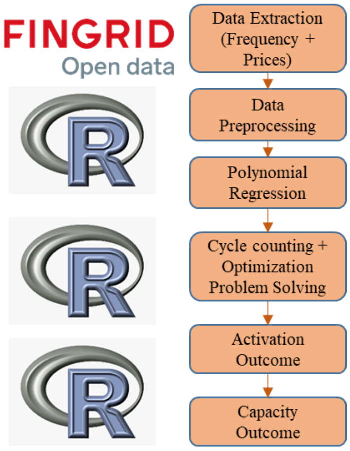

Figure 4. The steps to calculate the outcome of the BESS providing FCR-N

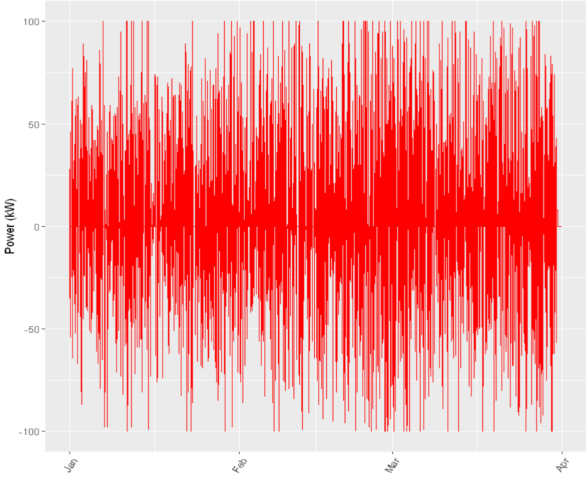

Figure 5. Charging/discharging power obtained after scheduling the BESS based on the frequency deviations

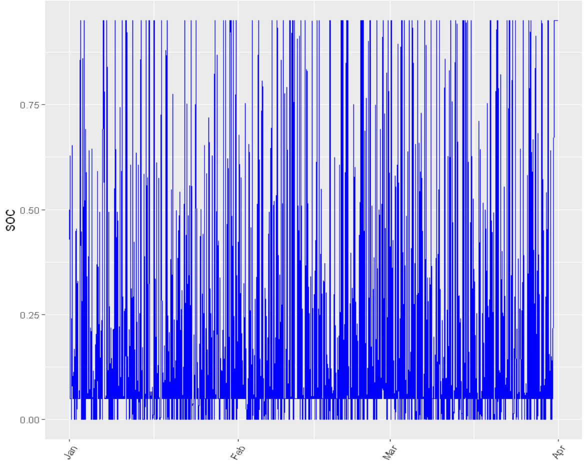

Figure 6. BESS SOC variations after responding to the frequency changes

A. *Economic Analysis*

This subsection analyzes the economic outcomes of the BESS participating in the FCR-N provision. As stated before, the BESS as an FCR-N provider has two resources of the outcome. It receives payment for the capacity it has reserved for providing FCR-N. In 2021, the capacity price for providing 1 kWh FCR-N was equal to 1.25 Cents [13]. The FCR-N is activated by charging and discharging the BESS. Regarding our case study, the BESS was being charged and paid the prices of downward regulations. It was being discharged and received the prices of downward regulations. Fig. 7 depicts the upward and downward regulation prices for the defined time period. The figure proves the fact that the prices of upward regulation are always equal to or higher than those of downward regulation.

The BESS makes profits by receiving the capacity payment and the upward activation payment. However, it should pay according to the downward prices for its charging power. The total activation outcome and the capacity outcome have been calculated for the BESS regarding the three-month period. The results are written in Table II.

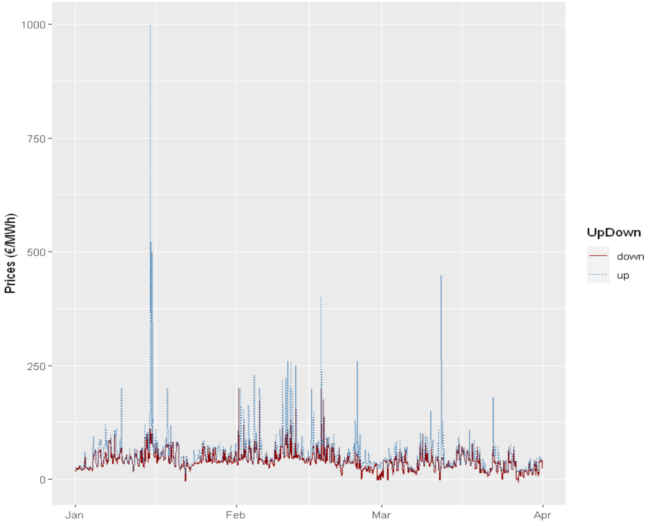

Figure 7. Upward and downward regulation prices during January to March 2021

TABLE II. RESULTS OBTAINED AFTER SCHEDULING THE BESS BASED ON THE PROPOSED METHOD

Capacity Outcome (cent)	Activation Outcome (cent)	The Number of Cycles	Total Outcome (cent)	Final SOC
134812.5	-16955.199	234	117857.3	0.95

The table shows a negative activation outcome which means that in total, the system needed more downward flexibility than upward one. Hence, the BESS should pay approximately € 169. On the other hand, the BESS receives a rather high payment equaling € 1348 for reserving its capacity for the FCR-N service. In total, the BESS is paid nearly € 1178 for its three-month participation in providing the FCR-N service.

B. *Effect of BESS Cycling Aging*

In our simulation results, we have considered the effects of BESS cycling aging in the process of BESS scheduling. In this subsection, we create another case where the cycling effects are disregarded. In this way, BESS capacity has a constant value and is not a function of the cycle. Accordingly, the charging/discharging power is scheduled and the outcomes are calculated. In order to analyze the effect of cycling in an economic way, we propose an indicator that calculates the total outcome for each cycle. The indicator is denoted by TOPC (Total Outcome per Cycle). This indicator is calculated for the BESS with and without BESS cycling effects. The results are shown in Table III. The table states that aging decreases the BESS profits by 6.06 Cent in each cycle.

TABLE III. TOPC INDICATOR WITH AND WITHOUT CYCLING EFFECTS

	With BESS cycling effects	Without BESS cycling effects
TOPC [Cent/kWh]	503.66	509.72

V. CONCLUSIONS

Renewable-based power systems require more flexible energy resources participating in the provision of frequency regulation services. In this regard, BESS is a very potential resource that can provide different types of technical ancillary (i.e. flexibility) services. FCR-N market needs a symmetrical flexibility service provision. This paper focused on the provision of the FCR-N service by a Li-ion BESS which had the ability to be charged and discharged, and was capable of being a FCR-N provider. Further, this paper discussed the participation of a Li-ion BESS in providing FCR-N, taking into account the effects BESS cycling aging, particularly on their degradation effects on battery capacity.

The paper proposed a methodology that schedules the BESS in a way to be proportional to frequency deviations. The charging/discharging power was based on frequency deviations' direction and volume. In addition, the methodology includes the effects of Li-ion BESS cycling on its capacity. Finally, the proposed method was implemented on a 50 kWh Li-ion BESS. The BESS was scheduled according to the real frequencies measured for three months and the economic outcomes were discussed. Also, the results demonstrate that aging can decrease the BESS profits by 6.06 Cent in each cycle.

REFERENCES

[1] E. Pusceddu, B. Zakeri, and G. Castagneto Gissey, "Synergies between energy arbitrage and fast frequency response for battery energy storage systems," *Applied Energy*, vol. 283, p. 116274, Feb. 2021, doi: 10.1016/j.apenergy.2020.116274.

[2] H. Alsharif, M. Jalili, and K. N. Hasan, "A Comparative Analysis of Centralised vs. Distributed Battery Energy Storage System in Providing Frequency Regulation," in *2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Brisbane, Australia, Dec. 2021, pp. 1–5. doi: 10.1109/ISGTAsia49270.2021.9715576.

[3] P. Hasanpor Divshali and C. Evens, "Optimum Operation of Battery Storage System in Frequency Containment Reserves Markets," *IEEE Transactions on Smart Grid*, vol. 11, no. 6, pp. 4906–4915, Nov. 2020, doi: 10.1109/TSG.2020.2997924.

[4] C. Wu, X. Lin, Q. Sui, Z. Wang, Z. Feng, and Z. Li, “Two-stage self-scheduling of battery swapping station in day-ahead energy and frequency regulation markets,” *Applied Energy*, vol. 283, p. 116285, Feb. 2021, doi: 10.1016/j.apenergy.2020.116285.

[5] H. Shafique, L. B. Tjernberg, D.-E. Archer, and S. Wingstedt, “Energy Management System (EMS) of Battery Energy Storage System (BESS) – Providing Ancillary Services,” in *2021 IEEE Madrid PowerTech*, Madrid, Spain, Jun. 2021, pp. 1–6. doi: 10.1109/PowerTech46648.2021.9494781.

[6] A. Ramos, M. Tuovinen, and M. Ala-Juusela, “Battery Energy Storage System (BESS) as a service in Finland: Business model and regulatory challenges,” *Journal of Energy Storage*, vol. 40, p. 102720, Aug. 2021, doi: 10.1016/j.est.2021.102720.

[7] H. Firoozi, H. Khajeh, and H. Laaksonen, “Optimized Operation of Local Energy Community Providing Frequency Restoration Reserve,” *IEEE Access*, vol. 8, pp. 180558–180575, 2020, doi: 10.1109/ACCESS.2020.3027710.

[8] H. Khajeh, H. Firoozi, and H. Laaksonen, “Flexibility Potential of a Smart Home to Provide TSO-DSO-level Services,” *Electric Power Systems Research*, vol. 205, p. 107767, Apr. 2022, doi: 10.1016/j.epsr.2021.107767.

[9] L. Zhang *et al.*, “Improved Cycle Aging Cost Model for Battery Energy Storage Systems Considering More Accurate Battery Life Degradation,” *IEEE Access*, vol. 10, pp. 297–307, 2022, doi: 10.1109/ACCESS.2021.3139075.

[10] Y.-R. Lee, H.-J. Kim, and M.-K. Kim, “Optimal Operation Scheduling Considering Cycle Aging of Battery Energy Storage Systems on Stochastic Unit Commitments in Microgrids,” *Energies*, vol. 14, no. 2, p. 470, Jan. 2021, doi: 10.3390/en14020470.

[11] Fingrid, “The technical requirements and the prequalification process of Frequency Containment Reserves (FCR),” no. January, p. 17, 2019.

[12] B. Gundogdu and D. T. Gladwin, “A Fast Battery Cycle Counting Method for Grid-Tied Battery Energy Storage System Subjected to Microcycles,” in *2018 International Electrical Engineering Congress (iEECON)*, Krabi, Thailand, Mar. 2018, pp. 1–4. doi: 10.1109/IEECON.2018.8712263.

[13] Fingrid, “Open data on the electricity market and the power system.” [Online]. Available: https://data.fingrid.fi/en/