Techno-Economic Analysis of a Stationary Battery Storage Operating on Frequency Regulation Markets in a Church Powered with PV System

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Abstract

In Sweden, Svenska Kyrkan (the Church of Sweden) has over 3300 churches. A majority of the churches are electrically heated. The usage pattern of the church leads to a power peak during church heating, creating problems for the grid and the church organization through increased grid fees. Simultaneously, interest in deploying Battery Energy Storage Systems (BESSs) is growing. A significant challenge is determining the specific services the BESS should provide to maximize profits for the owner. For church load profiles, with the help of a battery, the church consumption peaks can be shaved. Additionally, when the Battery Energy Storage System (BESS) is not used for this purpose, it can instead be employed to support the grid through participation in the frequency regulation market. Frequency control services are activated in response to changes in the electricity grid frequency, with the BESS providing support during frequency fluctuations. The objective of this study is to investigate the economic value of installing BESS in a church powered by a PV system. Various frequency regulation services, with a focus on frequency containment reserve (FCR) are explored. The model operates on other energy markets, which are local flexibility and day-ahead markets. The inputs include selected services, feed-in and feed-out profiles, historical frequency data, and frequency regulation and energy market prices over the year 2023. The case study involves real data from Kila Church, equipped with a 60 kWp solar power system, located in mid-western Sweden. The economic metrics are net present value and payback period, whereas technical and environment metrics are the battery degradation and CO2 emissions equivalents, respectively. This study indicates that the investment in BESS is profitable if the BESS operates on frequency stability services together stacked with Peak Shaving (PS). The results show a 1.6-year payback period for a 120 kWh/60 kW BESS. A sensitivity analysis exploring future changes in prices of the frequency regulation market and BESS shows that Upward FCR for Disturbance (FCR-D Up) is more sensitive than Downward FCR for Disturbance (FCR-D Down) if a drop in the prices will occur in the future. Conclusively, BESS would be a beneficial investment for the churches and other commercial industrial load, from an economic, environmental, and societal perspective.

Keywords: Stationary Battery Storage, Frequency Regulation Markets, Ancillary Services, Techno-economic Analysis

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1. Introduction

This In 2015, the United Nations launched Agenda 2030 to promote sustainable development through goals aimed at reducing poverty, addressing climate action, and ensuring affordable and reliable energy for all (Swedish UN Association, 2015). At the European level, the European Green Deal targets a 55% reduction in emissions by 2030 and aims for carbon neutrality by 2050 (European Comission, 2015). Additionally, the European Commission has implemented the REPowerEU plan in response to disruptions in fossil fuel imports, aimed at enhancing energy savings, diversifying energy supplies, and promoting clean energy (European Commission, 2022). Sweden has set a goal to achieve completely renewable electricity production by 2040 (IRENA, 2020). Consequently, wind and solar power capacities in Sweden have increased in recent years (Lindahl et al., 2022). However, these energy production technologies are weather-dependent, posing challenges for integrating them efficiently into the electric grid and ensuring power system stability. These objectives drive the growth of renewable energy production and

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environmentally sustainable solutions, necessitating change. To advance these goals, the Church of Sweden has installed PV and battery storage systems and is leading pilot projects (The Church of Sweden, 2023). As one of the largest property owners in Sweden with over 20,000 buildings and extensive forest land, the Church of Sweden plays a crucial role in promoting the transition to renewables (in addition the total installed PV capacity in 2023 is 7.5 MW (The church of Sweden, 2024). It has set ambitious targets to achieve climate neutrality by 2030, focusing on sustainable development.

Globally, renewable energy generation capacity additions in 2023 exceeded 440 GW, with solar PV accounting for two-thirds of this capacity (IEA, 2023). The installed capacity of Battery Energy Storage System (BESS) integrated into the power sector globally doubled year-on-year from 2019 to 2023, reaching a total of 90 GW (65% utility-scale and 35% behind-the-meter) (European Commission, 2023). In Sweden, an estimated 3.5 GWh of BESS capacity is anticipated, according to the local newspaper "NyTeknik" (NyTeknik, 2024). Utility-scale battery storage refers to large systems connected directly to transmission or distribution networks, typically ranging from several hundred kWh to multiple GWh. In contrast, behind-the-meter battery storage systems are installed at residential, commercial, or industrial locations without direct grid connections.

Studies have explored utility-scale BESS operating on ASM alone or together with DAM (He G Chen Q Kang C Pinson P Xia Q, 2015). The BESS has been examined in the Ancillary Service Market (ASM) and Day-Ahead Market (DAM). either through a business case (Hameed Z Træholt C Hashemi S, 2023; Martins J Miles J, 2021) or using a Techno-Economical Analysis (TEA) framework (He G Chen Q Kang C Pinson P Xia Q, 2015) . It can also be a combination of operational bidding control and TEA (Merten et al., 2020). Behind-the-meter battery systems can operate similarly to utility-scale systems if aggregated as a virtual power plant. A virtual power plant is an aggregation of Behind The Meter (BTM) systems that can provide many of the same services as larger utility-scale systems (IEA, 2024). Additionally, BTM systems can offer services to consumers, such as frequency regulation and energy arbitrage, such as increasing self-consumption and self-sufficiency (Luthander et al., 2016), providing backup power (IRENA, 2019), enhancing energy resiliency, saving on electricity bills, and deferring demand change network investments. Thus, the increase operation of the battery could improve the economic value of BESS storage by staking multi-service and delivering the most value to customers and the grid.

For behind-the-meter battery storage, additional services beyond energy arbitrage include lowering electricity bills by taking advantage of variable tariffs or reducing peak demand, as well as increasing self-consumption and self-sufficiency of their systems (IEA, 2024). In this study the term BESS is referred to as BTM battery. Additionally, one of the focuses of this paper is on demand charge reduction, also known as Peak shaving (PS). PS and maximizing self-consumption and self-sufficiency have become increasingly interesting in recent years, as the battery's potential to reduce emissions and save costs through peak shaving and maximizing self-consumption is being recognized (Fares and Webber, 2017; Ollas et al., 2018; Oudalov et al., 2007). BTM batteries can also provide other services when connected to an aggregator. Investigating battery storage for more energy trading and frequency regulation can also be interesting (Merten et al., 2020). This study focuses on commercial and industrial loads and investigates the benefits of applying peak shaving when the BESS is connected to Local Flexibility Market (LFM), Frequency Regulation market (FRM), and DAM. Stacking services can increase the revenue streams and profitability of the BESS system (Berg K Resch M Weniger T Simonsen S, 2021; Braeuer et al., 2019).

Different country applications of industrial and commercial load PS, such as in Germany and Norway, have shown varying potential economic revenues compared to other cases. In the German case, the operation of the frequency market stacked with peak shaving increased the revenue. However, feasibility was only possible with the operation of the BESS on Frequency Containment Reserve (FCR) market (Braeuer et al., 2019). In Norway, feasibility increased with self-consumption and energy arbitrage; performing all possible services, including peak shaving and arbitrage, was feasible (Berg K Resch M Weniger T Simonsen S, 2021). Additionally, Shafique et al. (2021) investigated the connection between FRM, namely FCR Normal (FCR-N), and PS, showing the benefit of performing both in three Swedish case studies, with a return on investment of 24% in the case study for the year 2020 and around 13% PS achieved using real-time operation and prognosis modules. However, the authors did not evaluate other FRM like FCR for Disturbance (FCR-D) and did not estimate the individual effects of one service alone. Hjalmarsson et al. (2023) investigated the control operation of stacking Upwards FCR for Disturbance (FCR-D Up), DAM, and LFM, showing the optimization control possibility within one framework. This study explored the possibility of investigating different services, including FCR-D, the day-ahead market, and a local flexibility market, in addition to peak shaving. To the best knowledge of the authors, a techno-economic assessment of these services combined with peak shaving has not been considered before, which is the focus of this study. This study has the following aims:

- Investigating the economic benefit of peak shaving using a load profile for a church generation and consumption profile.
- Assessing how stacking another service with peak shaving can increase the economic value of battery storage. The additional stacked services are LFM, FRM, and EA.
- Identifying the percentage price drop in the FRM and the battery storage investment cost at which the cash flow breaks even.

2. Methodology

This section outlines the techno-economic framework for the BESS, covering the simulation cases and key performance indicators. The framework is divided into two categories: BESS single services and BESS service stacking. The key performance indicators, which include economic, environmental, and technical metrics, are the outputs of the TEA.

2.1 Techno-economic framework overview

The operation of BESS can be categorized as a single service or service stacking. These services consist of peak shaving, local flexibility market, frequency regulation services, and energy arbitrage. The FCR involves five individual services, including FCR-D Up, FCR-D Down, and FCR-N, while energy arbitrage is on the DAM. In addition, maximizing self-consumption has used as well. The stacking of services has been combined with peak shaving. The goal of the peak shaving service is to reduce the cost for customers linked with energy storage to create cost savings in electricity bills (Chua et al., 2016). Additionally, there are three service stacking cases that include the operation of BESS for multiple services on the same day or hour. For example, Fig. 1 shows both the single and stacking operation. FCR-D operation includes both FCR-D Up and FCR-D Down operations in the same hour, while other services are operated exclusively for a complete hour, and other operations are not allowed in the same hour.

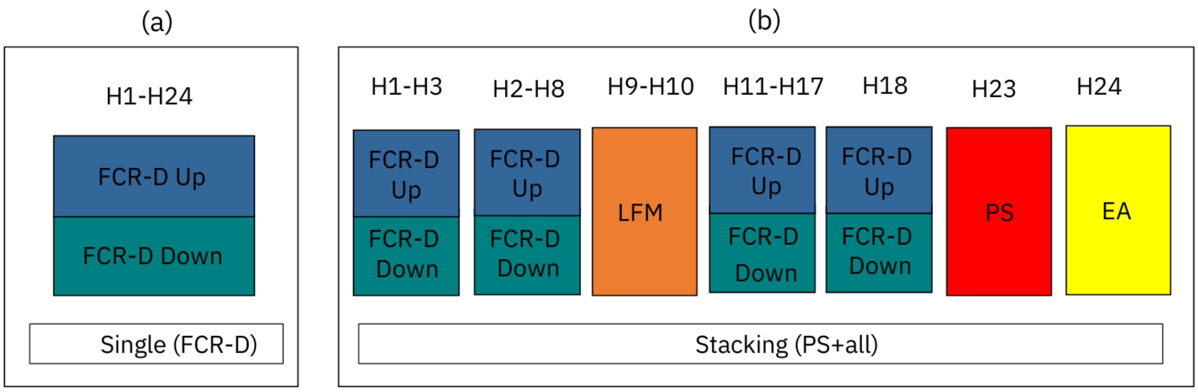


Fig. 1 Examples across various operational hours throughout the day: (a) illustrates the single service (FCR-D), while (b) depicts the stacking (All services).

The objective function for the BESS is economical. For peak shaving, the cost saving from the existing bill is considered as savings. Other objectives include the economic revenue from energy arbitrage, FRM, and LFM. Section 3.4 explains the markets input prices in the optimization. Section 3.2 explains each objective. Section 2.2 summarizes all the simulation scenarios conducted. The outputs of the optimization are then evaluated economically, technically, and environmentally. Economically, using the simple payback period and net present value calculation and annual savings of the base case; technically, through calculating the loss of capacity (LOC); and environmentally, by calculating CO2 emissions equivalents. Section 2.3 explains all the key performance indicators parameters for the TEA framework. The results of the TEA framework are shown in Section 4.1.

2.2 Simulation cases

The simulation cases were conducted on Kila Church and were split into two categories: BESS as a single service and BESS as a stacking service from A1-A5. For the single services, these included: self-consumption, peak shaving, energy arbitrage, and FRM (including FCR-N and FCR-D). For stacking, peak shaving was combined with the other services into four cases B1-B4. All the cases had the same PV system (60 kWp) and BESS (60 kW/120 kWh). The simulations were conducted for the year 2023. The simulation cases are shown in Tab. 1.

Tab. 1 Summary of simulation cases conducted on Kila Kyrka

Case No.	Service Type	Case Description	Fuse limit	PV size [kW]	BESS (P [kW], Cr)
R0	-	Base case no battery storage	63 A	60	-
BESS Single Service					
A1	SC	maximizing self-consumption	63 A	60	(60,0.5)
A2	PS	reducing peak electricity demand	63 A	60	(60,0.5)
A3	EA	Performing energy arbitrage	80 A	60	(60,0.5)
A4	FCRN	participates in FCR-N	80 A	60	(60,0.5)
A5	FCRD	participates in FCR-D	80 A	60	(60,0.5)
BESS Stacking Services					
B1	PS+EA	reducing electricity bill with arbitrage optimization.	80 A	60	(60,0.5)
B2	PS+EA+LFM	peak shaving and energy arbitrage including local energy markets.	80 A	60	(60,0.5)
B3	PS+FCRD	peak shaving and FCRD.	80 A	60	(60,0.5)
B4	PS+All	peak shaving, energy arbitrage and local energy market with FRM.	80 A	60	(60,0.5)

2.3 Key performance indicators

The key performance indicators of the cases are split into three categories: economical, technical, and environmental. The economic parameters include the annual savings relative to the base case without battery storage, net present value, *NPV*, and payback period, *PB*. The technical parameters include the battery capacity at the end of project life, E_{EOL}, equivalent cycle count, *EC*, and the relative battery usage, *RBU* (Berg et al., 2021). The environmental impact is calculated based on the amount of CO2 emissions equivalents, *CO2eq* per kWh, measured in tCO2eq. The key performance indicators parameters are estimated using the equations below:

$$NPV = \sum_{j=1}^{J} \frac{C_j}{(1+r)^j} \qquad \textbf{(Eq. 1)}$$

$$PB = \sum_{j=1}^{PB} \frac{C_j}{(1+r)^j} = 0 \qquad \textbf{(Eq. 2)}$$

$$E_{EOL} = (1 - LOC)E_N \qquad \textbf{(Eq. 3)}$$

$$RBU = \frac{\sum_{d=1}^{D} \sum_{t=1}^{T} \mathbb{I}(P_{dch}^{cons}(t,d) \neq 0)}{8760} \qquad \textbf{(Eq. 4)}$$

$$EC = \frac{\sum_{t=1}^{T} |E(t) - E(t-1)|}{2\, E_{net}} \qquad \textbf{(Eq. 5)}$$

$$CO2_{eq} = \left(P_{ch}^{PV}(t,d) - P_{dch}^{load}(t,d)\right) PV_{eq} + \left(P_{ch}^{grid}(t,d) - P_{dch}^{grid}(t,d)\right) Grid_{eq}(\text{t},\text{d}) + E_N BESS_{eq}. \quad (\boldsymbol{Eq.6})$$

Eq. **1** represents the NPV, where C_j denotes the net cash flow at year j . J and r are the economic analysis period and the discount rate, respectively. Eq. **2** is used to determine the payback period of the BESS, where the payback period is the time taken for the cumulative discounted net cash flow to reach zero. The total BESS loss of capacity, LOC can be estimated using the semi-empirical model (Xu et al., 2018). The remaining energy capacity of the initial BESS energy capacity E_N at the end of the project E_{EOL} is estimated using Eq. **3**. Relative battery usage, RBU, is the estimate of the number of hours during which the BESS was used to cover a load, divided by the number of hours in a year as shown in Eq. **4** (Berg et al., 2021). EC can be estimated using Eq. **5**. The net energy storage capacity, E_{net}, is calculated by multiplying the allowable SOC limit by the rated energy capacity, E_N. E_{net} can be calculated as:

$$E_{net} = E_N(SOC_{max} - SOC_{min}) \quad (Eq.7)$$

Eq. **6** calculates CO2 emissions equivalents, $CO2_{eq}$, from battery operations, relative to a scenario without battery storage. it integrates contributions from solar and grid power with respective emissions which is the emissions of the Nordic energy mix. where E(t) is the energy at time t. $P_{ch}^{PV}(t,d)$ and $P_{ch}^{grid}(t,d)$ represent the charging power of the BESS from the PV system and the grid, respectively. $P_{dch}^{load}(t,d)$ and $P_{dch}^{grid}(t,d)$ refer to the discharge power from the battery to the load or to the grid. PV_{eq}, and $BESS_{eq}$ represent the associated emissions factors contributions from PV, and the BESS, respectively. $Grid_{eq}(t,d)$ is the emissions of the Nordic energy mix.

3. Models and inputs

3.1 Battery storage model

The BESS model is applied to the church load profile of year 2023. The BESS model consists of optimization, economic, degradation, and operational models. The operational model aims to identify the optimal service to operate the BESS by evaluating their potential in the DAM, LFM and FRM and peak shaving detailed further in Section 2.2.

Tab. 2 Summary of technical parameter of the BESS, PV, and the Load.

Technical Specifications	Value
BESS	
Power ratings (P_N) [kW]	60
Energy ratings (E_N) [kWh]	120
C-rate (C_r)	0.5
Allowable SOC (SOC_{min} – SOC_{max}) [%]	5 – 95
Charging efficiency (μ_{ch}) [%]	95
Discharging efficiency (μ_{dch}) [%]	95
BESS technology	LFP
BESS end-of-life criterion [%]	80
PV	
Nominal power [kW]	60
Annual residual PV energy [kWh]	24489
Profile type	Measured hourly data (2023)
Load	
Annual residual load energy [kWh]	62974
Profile type	Measured hourly data (2023)

The operational model aims to identify realistic operations with an energy management system for charging and discharging the battery while respecting the national technical requirements (ENTSO-E, 2023a). The outputs from the operation model feed into the economic and degradation models. The financial and technical assumptions of the BESS are provided in Tab. 2, where the physical quantities are in parentheses. The financial model calculates two main investment criteria NPV, and payback period. The degradation model is semi-empirical and has been formulated in ref. (Xu B Oudalov A Ulbig A Andersson G Kirschen DS, 2018). This model helps estimate the BESS's capacity loss over the economic analysis period.

3.2 Optimization model

This section focuses on optimization strategies where the objective varies across simulation cases. It encompasses four key terms: PS, used as a cost-saving term compared to the base case without a battery (case R0), similar to ref. (Shafique et al., 2021). Additionally, Energy Arbitrage (EA) and FCR-D, as modeled as in ref. (Argiolas L Stecca M Ramirez-Elizondo LM Soeiro TB Bauer P, 2022), are selected based on revenue optimization between these two markets. EA and LFM are employed similarly as described in ref. (Hjalmarsson et al., 2023) by assuming bids are sent a day ahead of the operation.

3.3 Case study

One of the churches with intermittent energy use is Kila church in Karlstad Sweden (59° 24' 36.36" N, 13° 30' 45.29" E), which since September 2022, has solar PV panels distributed on different direction and are connected to two inverters. Moreover, the church is also a pilot project to implement a battery storage system (The Church of Sweden, 2023). The technical requirement of the PV system as well as the load and BESS are shown in Table 2. The residual load and excess PV power is shown in Fig. 2.

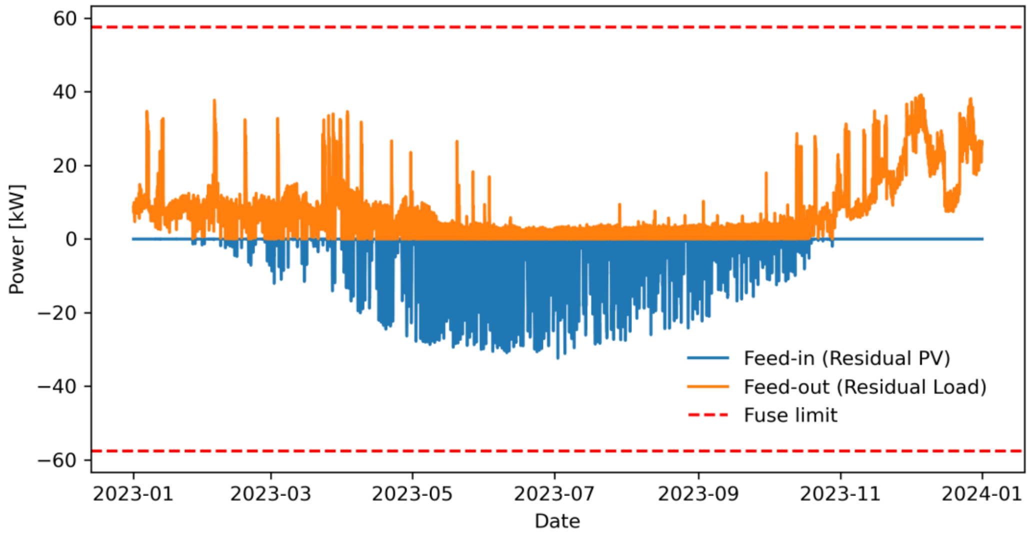
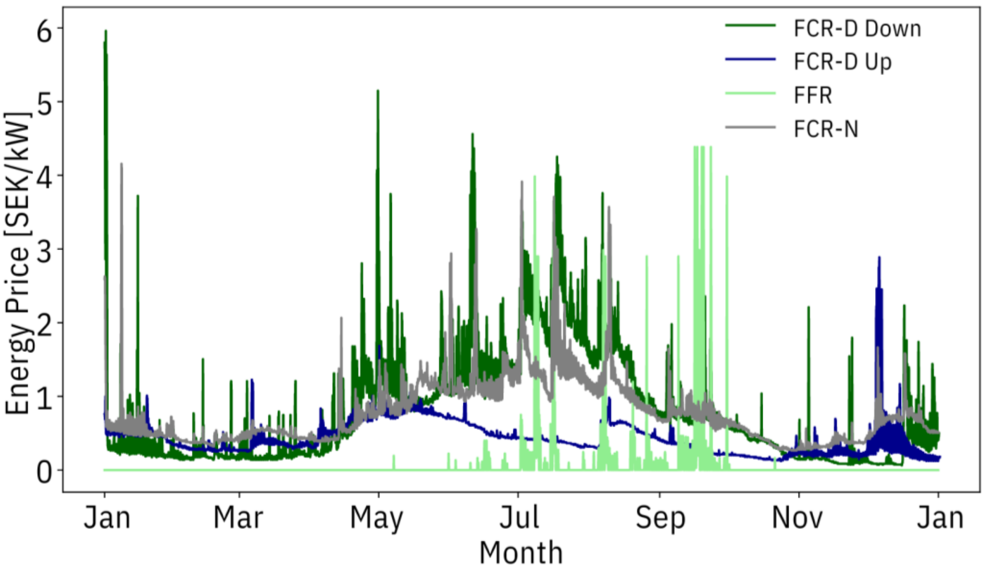


Fig. 2 Feed-in (residual PV power) and Feed-out (residual load) for the Kila church for the year 2023. Positive values are the residual consumption and negative values are the excess production.

3.4 Market prices

In the Nordic power network, electricity trading takes place on the Nord Pool market. This market consists of two types of auctions for power exchange: the DAM and the Intraday Market (Nord Pool, 2023). The spot prices for electricity in bidding area SE3 were chosen for the case study, where the case study is situated (see Section 3.3). The day-ahead and regulating prices were retrieved from ENTSO-E (European Network of Transmission System Operators for Electricity) Transparency Platform (ENTSO-E, 2023b, 2023c).The intraday market auction was not considered. LFM have been established and run as pilot projects in Sweden from 2021 to 2023 during the winter months (POWER CIRCLE, 2022). The data used are from CoordiNet in Uppland during Winter 2021/2022. The DSO is the main buyer of this flexibility the activation is considered 100% during the operation as the average activation is approximately 92% of the available data. The revenue from this market is split into capacity revenue and energy revenue (Real-time control of Battery storage for the Future Flexibility needs, 2022). The energy cost of DAM buy and sell and local flexibility market is shown in Fig. 3. In Sweden, FRM trading takes place on a platform, provided by SvK, which is the only transmission system operator. The data used in this study are for the weighted average price of ASM. However, the pay-as-cleared mechanism was introduced on the 1st of February 2024 for Sweden. Historical prices for procured FCR capacity were retrieved from SvK's database Mimer (Mimer database, 2023) for the years 2021 to 2023. When operating on FCR-N, the resource must be capable of delivering the specified power for at least 1 hour, whereas, for FCR-D, it must sustain the specified power delivery for at least 20 minutes(Svenska Kraftnät, 2023).

(a)



(b)

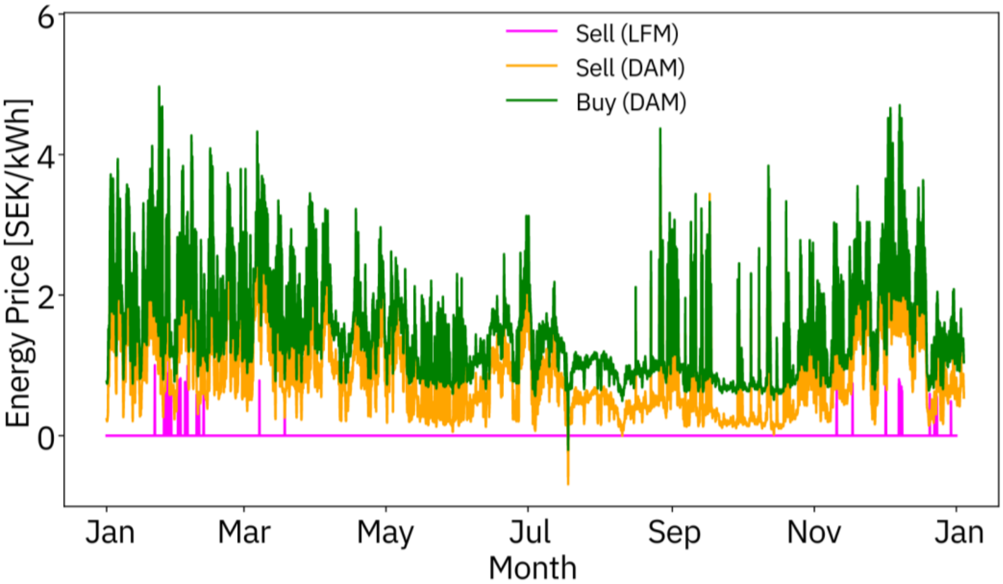


Fig. 3 (a) shows the ancillary services prices (b) shows the energy prices for selling and buying from day ahead market and local flexibility market (ENTSO-E, 2023; Mimer database, 2023; Svenska Kraftnät, 2023).

3.5 Emissions parameters

The CO2 emissions equivalents for the PV system, P Veq, are set to 25 gCO2eq/kWh, which was the emission value for PV in 2023 as shown in (Swedish Energy Agency, 2019). The battery's CO2 emissions equivalents are derived from the Swedish Energy Agency and specified as the amount of CO2 emissions equivalents per installed kWh. Considering that the emission varied between 61 to 106 kgCO2eq per installed capacity, an average of 83.5 kgCO2eq/kWh is assumed in this study (Vattenfall, 2022). The total CO2 emissions equivalents for the Nordic energy mix, is weighted according to the production mix among the Nordic countries retrieved from the Electricity Map for the year 2023 over each hour (Electricity Map, 2023).

3.6 Distribution subscription tariff

The subscription tariff for Kila church is connected to a distribution network managed by Vattenfall Eldistribution. The N3 tariff was chosen for this study due to its lower feed-out fee compared to the other available tariffs. The tariff structure includes an energy fee and a power fee. The energy fee for consumption is based on usage during peak hours (6:00 to 22:00) in the winter months (January, February, March, November, and December), with off-peak pricing for other hours throughout the year. The power fee is based on the highest mean power each month. Electricity production incurs compensation, with higher rates during the winter (Vattenfall Distribution, 2023).

4. Results

The results section is composed of the key performance indicators on economic technical and environmental shown in 4.1. The sensitivity analysis on BESS cost and FCR-D market prices is shown in Section 4.2.

4.1 Key performance parameters results

The BESS has been simulated over the year 2023 and compared with the base case where the system does not have BESS. The simulations are split into two categories: A for single service, shown in Tab. 1, and B for stacking two or more services, shown in 0 Economically, investing in the BESS for only PS, SC, or EA is neither profitable nor feasible. However, operating on Frequency Regulation Service over the year 2023 is feasible with a 2.5-year payback period when operating on FCR-N and a 1.6-year payback period when operating on FCR-D. For the single services, economically and technically, FCR-D is more beneficial to operate on. Technically, the battery performed with a 13 % loss of capacity after 10-year period (LOC) when BESS operate on FCR-D. In contrast, FCR-N and Energy Arbitrage have the highest average peak. Regarding relative use, the battery's utilization is highest when operating on EA and results in the lowest CO2 emissions equivalents over one year when used for self-consumption.

Tab. 3 Summary of technical and economic metric results BESS single service year 2023.

Metric	**A1**	**A2**	**A3**	**A4**	**A5**
Economic metrics					
Net present value (*NPV*) [kSEK]	-514.6	-554.3	-533.7	1887.3	3764
Payback period (*PB*) [years]	N/A	N/A	N/A	2.5	1.6
Annual saving [kSEK]	13.95	6.6	17.6	303.5	505.5
Technical metrics					
Relative battery usage (*RBU*) [%]	19.4	26.5	37.3	0	0
Loss of capacity (*LOC*) [%]	14	13.3	16.7	16	13
Equivalent cycle count (*EC*) [cycle/year]	140.4	65.6	350	299	0.5
Average Peak [kW, month]	25.2	14.8	58	35.5	27
Environmental metrics					
CO2 emissions equivalents (*CO2eq*) [tCO2eq]	8.9	10.4	12.5	12.1	10

For stacking services, it is also economically non-feasible as the NPV is negative for cases B1 and B2, where the battery stacking involves peak shaving, energy arbitrage, and participation in the local flexibility market. The stacking of services has not significantly increased the operation; while some savings have been added to the service, they do not significantly contribute to economic feasibility. The equivalent cycles have increased for cases B1 and B2, while in cases B3 and B4, the operation is mostly FCR-D. it is clear that the average peak has decreased when multi-objective uses are applied, as in case B4 compared to A5. The CO2 emissions equivalents for cases B1 and B2 are the highest and are similar to operating only in A3, as the battery operates on arbitrage.

Tab. 4 Summary of technical and economic metric results with BESS stacking services year 2023.

Metric	B1	B2	B3	B4
Economic metrics				
Net present value (*NPV*) [kSEK]	-419.5	-298.5	3851.3	3970.3
Payback period (*PB*) [years]	N/A	N/A	1.6	1.6
Annual saving [kSEK]	30.1	43.3	524.8	538.6
Technical metrics				
Relative battery usage (*RBU*) [%]	33.8	41.2	0	0
Loss of capacity (*LOC*) [%]	16.5	16.5	13	13
Equivalent cycle count (*EC*) [cycle/year]	319.8	315.5	1	5
Average Peak [kW, month]	21.3	20.9	24.7	24.7
Environmental metrics				
CO2 emissions equivalents (*CO2eq*) [tCO2eq]	12.0	12.0	10.0	10.0

4.2 Sensitivity analysis

The sensitivity analysis assesses the impact of changes in FCR-D and battery prices on the feasibility of the BESS at the break-even investment point, where NPV equals 0. A break-even investment implies that while the investment does not generate profit, it also avoids losses for the investor. The sensitivity analysis examines price changes ranging from 1 to 90% drop in FCR-D prices as shown in Fig. 4. In addition, changes where FCR-D Down prices decrease are indicated in red, while FCR-D Up is shown in blue. FCR-D Up shows more sensitivity in the prices for the profitability of the BESS while FCR-D Down shows that it is more beneficial and more economical to operate on even for the high price of BESS market prices. Additionally, the figure illustrates that purchasing batteries at higher prices remains feasible in 2023. However, a significant drop in service prices in the future could challenge feasibility, as shown by a potential 90% decrease from 2010 to 2023 in battery prices (IEA, 2024), particularly with current BESS prices (including labor cost) needing to stay below 200 kSEK/kW, which is not expected in the foreseeable future.

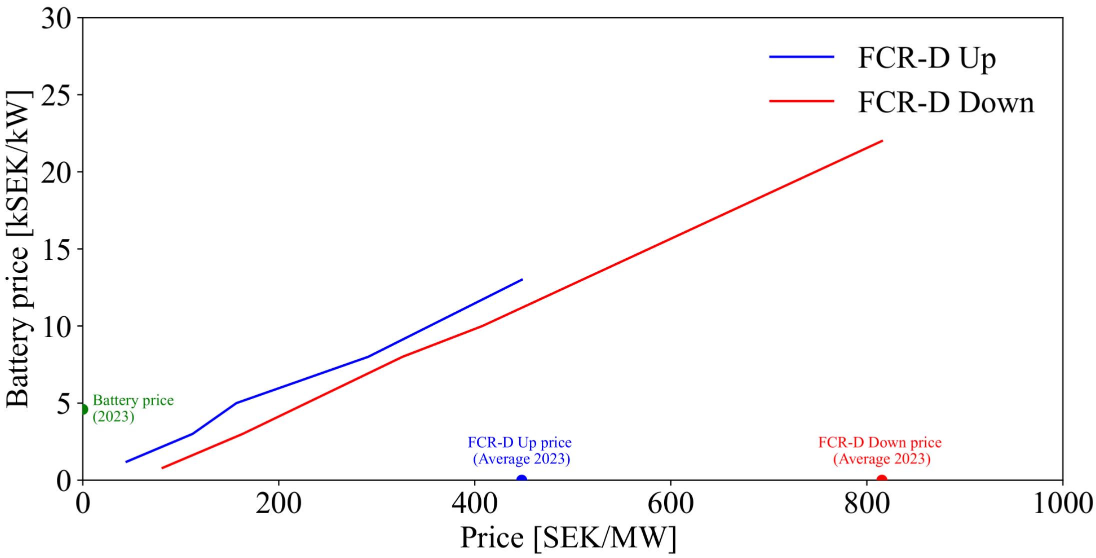


Fig. 4 Break even investments with sensitivity analysis for FCR-D prices and battery prices. Break-even investment means net present value equals zero.

5. Conclusion

In Sweden, the Church of Sweden (Svenska Kyrkan) owns more than 3,300 churches. A majority are used irregularly, typically only a few times a month, remaining unused between these sessions and A majority of the churches are electrically heated. This usage pattern results in electric peak power demand during church heating, posing challenges for both the electrical grid and the church organization due to higher grid fees. Many parishes have installed PV solar energy systems as part of the Church of Sweden's commitment to transitioning towards renewables, with goals set for climate neutrality by 2030. This study evaluated BESS operating various services including self-consumption, peak shaving, frequency regulation market, local flexibility market, and energy arbitrage. Stacking strategies included peak shaving, with FRM services encompassing FCR-N and FCR-D. Key performance indicators included technical metrics such as equivalent cycle count and loss of capacity, and economic metrics such as payback period and net present value, alongside environmental considerations like CO2 emissions equivalent.

The results indicate that battery operation is not economically feasible when BESS not operating on frequency regulation market. The highest annual average peaks were observed in FCR-N and energy arbitrage cases, while the lowest cycle and the highest NPV were associated with FCR-D operation. The lowest CO2 emissions equivalent were achieved with SC operations. For stacking FCR-D with other services, revenues are driven by FCR-D capacity revenue and the payback period was approximately 1.6 years, which is similar to the single service operation FCR-D. This shows that single service FCR-D and stacking other services with FCR-D is profitable during few hours of the year. Sensitivity analysis examined changes in both battery prices and FCR-D prices, revealing that a drop in FCR-D prices from 0 to 90% implies installing batteries with prices below 200 kSEK/kW, which is not feasible in the foreseeable future if a significant price drop occurs.

Future directions for this study could involve estimating the operation of churches combined with electric vehicle charging stations, and heating systems combined with BESS.

6. Acknowledgments

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