Energy Storage for Export Limitation Mitigation and Capacity Factor Enhancement in GB: A Case Study

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***Abstract*—Local distribution network-driven limitation of distributed generation is an increasing problem for the Great Britain distribution network. This paper presents for the first time a novel case study on the implementation of Energy Storage Systems for increasing the capacity factor of sites subject to such export limitation schemes. This includes a technical performance comparison and sensitivity study between Battery Energy Storage Systems (BESSs) and Flywheel Energy Storage Systems (FESSs), where it is shown that despite both mediums delivering effective support for this application, the cycling intensity is in excess of what a BESS can reasonably handle leading to excessive degradation. Conversely, the FESS is able to handle the required cycle rates easily with only a small drop in performance compared to the battery. In terms of economic performance, it is shown that a FESS can provide a positive economic impact up to and including a total capital cost of £1500/kW, whilst a BESS can provide a positive economic impact up to a value of £500/kW.**

***Index Terms*—energy storage, flywheels, batteries, wind generation**

I. Introduction

Distributed Generation (DG) now constitutes 35% of the total generation capacity within Great Britain (GB), introducing new challenges to the local distribution network and the viability of deploying new DG sites [1]. DG is defined as an electricity generating plant that is connected to the distribution network, rather than to the higher voltage transmission network. A 2016 report from the U.K. Government highlighted that new connection requests continued to rise rapidly along with concerns for geographical variations in costs for these connections [2]. Within GB, there are 6 major Distribution Network Operators (DNOs) covering a total of 14 geographical areas. They are responsible for operating and maintaining the distribution infrastructure within their geographical area such as substations, transmission lines, and new connections. The largest of these DNOs is National Grid Electricity Distribution (NGED), which makes the status of their substations publicly available to assist in planning [3].

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56.4% of the substations operated by NGED are rated 'Red' on their online capacity map [3] meaning a connection is unlikely to be achieved without significant investment. The impact of this can be seen primarily in the increasing prevalence of Export Limitation Schemes (ELSs) agreed by local DNOs to limit the export power of a DG site below an agreed value. This could be driven by equipment limitations such as substation, transformer or distribution cable capacities [4].

Additionally, 16.93% of sites on the Embedded Capacity Register (ECR) across all of the UK DNOs have an agreed export capacity that is lower than their registered connected capacity [5]–[9]. Whilst this is not necessarily due to an ELS being in place, it gives an indication of the scale of the issue of sites being unable to export to their full capability. The main issue that is being addressed by this paper is the alleviation of the effects of local grid-constraint-driven limitation of export capability, resulting in the restoration of the capacity factor back to intended levels.

The work presented in this paper seeks to utilise Energy Storage Systems (ESSs) to assist in alleviating this issue and increasing the capacity factor of a given site. For the first time, a novel techno-economic case study into the feasibility of deploying both Battery Energy Storage Systems (BESSs) and Flywheel Energy Storage Systems (FESSs) is presented. The relative merits of each ESS are discussed firstly with a focus on technical performance for this application, followed by an extensive economic analysis showing how the technical performance translates into viability for deployment in this application.

II. Literature Review

BESSs are a mature technology that is widely deployed for a range of energy storage applications across the world [10]. They offer an excellent balance between power and energy capacities and are technically well understood with much of the literature discussing aspects such as charge management and degradation [11] [12]. However, one of the key drawbacks is their susceptibility to cycle-based degradation with the

TABLE I
HIGH-LEVEL FESS AND BESS CHARACTERISTICS

Characteristics	FESS	BESS (Li-Ion)
Energy storage capability	Generally low, although higher energy systems are being developed	High
High power applications	Highly suited	Capable, but results in faster degradation
Application duration	Seconds to minutes	Hours to days
Self discharge rate	20-100% per day	1-10% per day
Cycle life	100,000+	2,000-10,000
Calendar life	20 years+	10-20 years

majority of the literature placing this in the region of 5,000-10,000 cycles before failure [13] [14] [15].

Conversely, FESSs are significantly less affected by cycle-based degradation with a general agreement in the literature that they can handle in excess of 100,000 cycles [16] [17]. However, it should be noted that many of the current flywheel manufacturers advertise unlimited cycle capacity [18] [19] [20]. Flywheels do suffer from significant levels of self-discharge however this is less relevant in applications when there are almost constant levels of charge and discharge being demanded of the FESS. A comparison of the main characteristics of the two energy storage technologies is shown in Table I.

As the issue discussed within this paper is an emerging one, there is little available literature to discuss. The literature available that aligns most closely with this work is discussed in studies such as [21] and [22] which look at network improvements, incentives and stakeholder engagement to alleviate local distribution issues. Neither of these studies considers utilising energy storage on a targeted level. Additionally, [23] discusses a pilot project to assist with local limitations called 'Flexible Plug and Play' which was trialled in the U.K between 2012 and 2014, however once again this does not consider energy storage. It is clear then that a significant gap exists in the literature, and this work will look to investigate this unexplored application.

III. STUDY OVERVIEW

This study looks at a specific wind generation site facing the issue of ELS restricting the generation and income potential of the site. This allows the economic conclusions to be assessed in a real-world scenario, which can provide greater clarity on the required techno-economic specifications for a FESS to be deployed for this application. The site in question has the following main operational criteria;

- The turbine is rated to deliver a maximum power output of 300kW
- The site export limit is 250kW.
- The turbine can be set via pitch control to modify the output power of the turbine. The set point for the output power is referred to in this study as 'Targeted site output'.

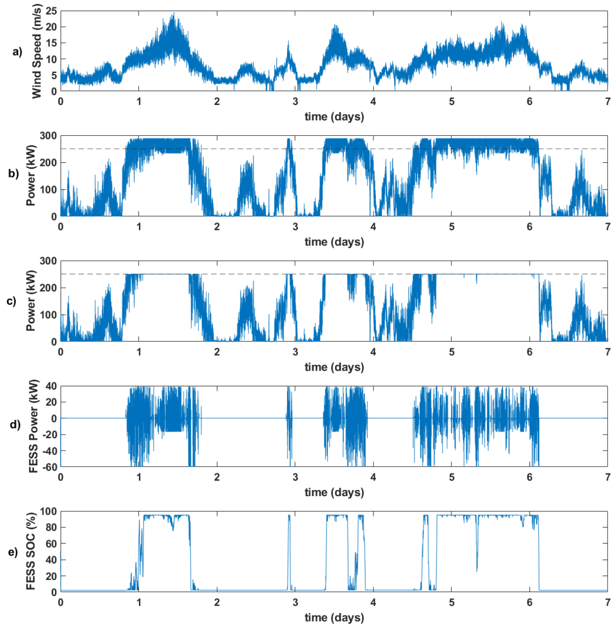

Fig. 1. Example simulation output showing FESS operating to reduce export limitation issues showing a) Wind Speed b) Site Output without ELS c) Site Output with ELS and FESS d) FESS Power e) FESS State of Charge

Wind speed data for the site was made available at a resolution of 10 seconds. This data was linearly interpolated to create data of 1-second resolution. Linear interpolation was chosen in line with the approach taken across multiple studies in similar areas [24], [25]. It is considered that within the 10-second time frame, the inertia of the system will not react sufficiently to any very short-duration fluctuations to a degree that would affect the validity of the simulation. An example simulation output showing a FESS operating to maintain the site output at 250kW is shown in Figure 1

With a site that has the ability to generate power far in excess of its agreed export limit, this study is an ideal opportunity to showcase the technical and economic benefits that can be achieved by introducing an ESS. For this case study, three configurations of FESS will be compared against three configurations of BESS to give an idea of the implications behind utilising the two different mediums for this application, and the effect that their relative strengths and weaknesses have on the operation of the system.

The case study has been conducted using the specifications of the OXTO Flywheel, an 8C 60kW, 7.5kWh modular steel FESS [26]. Table II summarises the configurations studied. The approach taken is to represent the installation of 1, 3 and 5 individual flywheel units at the site, and compare this against a range of different Lithium-ion BESS configurations. The BESS configurations have been chosen to represent small modular systems in the same way as the FESS configurations, across a range of power ratings that would be suitable for this application given the maximum additional power to be absorbed at any one-time is 50kW. It is not considered useful to utilise an 8C BESS for this comparison as such systems are

$$P_{dis} = \begin{cases} |P_{base} - P_{limit}| & SOC_{low} \leq SOC_{ESS} \leq SOC_{high} \text{ and } P_{base} \leq P_{limit} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

$$P_{cha} = \begin{cases} |P_{base} - P_{limit}| & SOC_{low} \leq SOC_{ESS} \leq SOC_{high} \text{ and } P_{base} \geq P_{limit} \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

TABLE II
ESS CONFIGURATIONS USED FOR ELS CASE STUDY

Reference	ESS Type	Energy Capacity (kWh)	C-Rate
F1	FESS	7.5kWh	8
F2	FESS	22.5kWh	8
F3	FESS	37.5kWh	8
B1	BESS	30kWh	1
B2	BESS	60kWh	1
B3	BESS	90kWh	1

The analysis has been carried out using a MATLAB/Simulink model developed and presented across multiple papers [27] [28] [29], with the data taken from a real-world generation site located in Great Britain (GB). The control philosophy contained within the model is that if the output power is higher than the limit, the system attempts to charge the ESS and if the output power is lower than the limit then it attempts to discharge the ESS. This is represented in Equations 1 and 2, where P_{dis} is the discharge power of the ESS in kW, P_{cha} is the charge power of the ESS in kW, SOC_{low} and SOC_{high} are the low and high limits of the ESS SOC range, SOC_{ESS} is the current SOC of the ESS, P_{base} is the output of the site before any adjustments due to ELS in kW, and P_{limit} is the export limit of the site in kW.

An economic study is then undertaken to determine the required Total Capital Cost (TCC) at which the FESS and BESS configurations would be viable for installation at the site based upon the requirement of providing a positive NPV change.

IV. Performance Analysis

The main performance statistics that will be considered are Limitation Time Proportion (LTP) and Capacity Factor Increase (CFI) whilst also considering the degradation that takes place on the BESS during the course of operation.

Capacity Factor (CF) is a common metric for measuring the overall output of a generation site as a proportion of the theoretical maximum a continuous peak-rated output of the site would yield and is calculated as given in Equation 3 where E_{actual} is the total amount of energy generated by the site in MWh and P_{rated} is the rated power of the site in MW. Capacity factor has been used extensively as a metric for improvements to generation sites throughout the literature [30] [31] [32]. CFI is defined as the difference between the base capacity factor achieved with no ESS installed and the new capacity factor achieved with ESS deployed.

LTP represents the amount of time that the wind generation site is limited under the terms of the ELS as a proportion of the total operational time, as shown in Equation 4 where t_{limited} is the duration of time that the export is limited and $t_{\text{operational}}$ is the total time the system is operational for. It can be used as a metric to determine how the introduction of the FESS is affecting the duration of time that the site is operating without any restrictions.

$$Capacity\ Factor = \frac{E_{actual}}{P_{Rated} \times 8760} \quad (3)$$

$$LTP(\%) = (1 - \frac{t_{limited}}{t_{operational}}) \times 100 \quad (4)$$

Each metric has been assessed over a range of targeted site outputs, with the aim of looking at whether the ESS can offer greater benefits if the site is continuously generating above the export limit. The ELS panel operates at the grid connection point, with any energy that is over 250kW instantaneous power and is not absorbed by the ESS being 'dumped' into a resistor bank to maintain the output within the export limit. This study aims to capture as much of that energy that would otherwise be wasted as possible.

Initially, looking at LTP for this site as shown in Figure 2, it is clear that the introduction of any ESS technology or configuration will result in an immediate reduction in LTP, with the effect slightly lessening as the target output is increased.

Comparing the two different ESS mediums it is apparent that in general terms the BESS is more adept at reducing the limitation experienced by the site, reducing by more than the best performing FESS in 2 of the 3 configurations. This is likely due to the greater levels of energy capacity available that enables the BESS to operate for longer durations of excess power duration before becoming fully charged. In fact, the only situation in which the FESS will work better than the BESS is when the FESS has a higher energy capacity when comparing configuration F3 with B1. From this standpoint, it appears that the application is largely technology agnostic with equal performance available depending on energy capacity.

CFI for the analysed configurations is shown in Figure 3, This metric is where the differences between the two technologies begin to become a bit more apparent with a clear, albeit relatively small, difference in the shape of the two sets of curves.

For all of the FESS configurations, the CFI peaks in the region of 270-290kW targeted site output before beginning

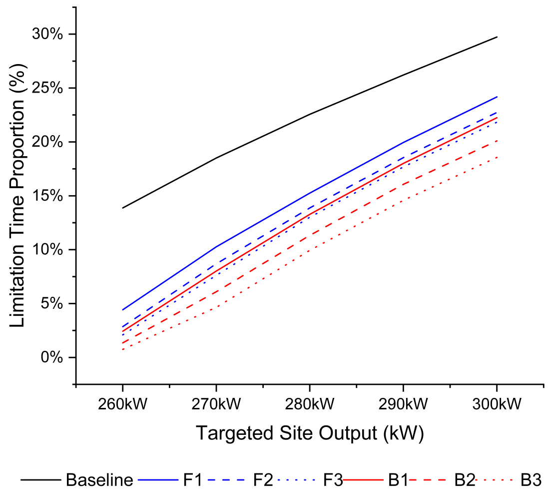

Fig. 2. Limitation Time Proportion for varying FESS and BESS sizes across different target outputs

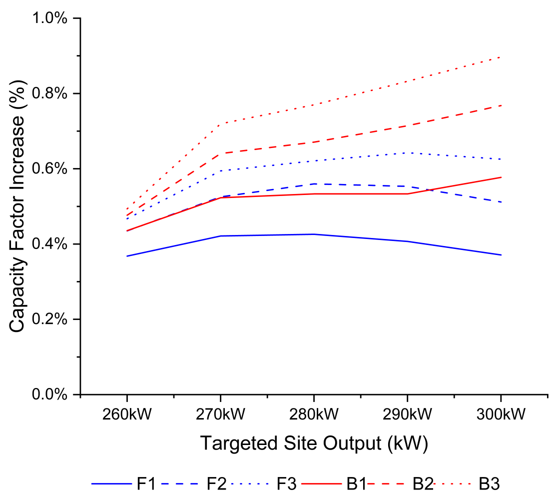

Fig. 3. Capacity Factor Increase for varying FESS and BESS sizes across different target outputs

to fall back down whilst for the BESS configurations there is a continuous trend upwards as the targeted site output is increased. The reason for this difference between the two systems is that because of their higher C-Rates, the FESSs charge much quicker when the export level is above the limit, meaning they reach fully charged status sooner and hence are able to manage the higher targeted site output less effectively than the BESSs.

Once again there is a clear correlation between the energy capacity and effectiveness in improving CFI, with the highest energy capacity BESS configuration (B3) achieving a peak increase of 0.9% (representing an additional 23.6MWh of energy over the course of a year), whilst the highest energy FESS configuration provides a peak increase of 0.63% (an additional 16.6MWh of energy over the course of a year).

TABLE III
BESS DEGRADATION EQUATION COEFFICIENT VALUES

	Coefficient values and units
a	8.61E-6
b	-5.13E-3
c	7.63E-1
d	-6.7E-3
e	2.35

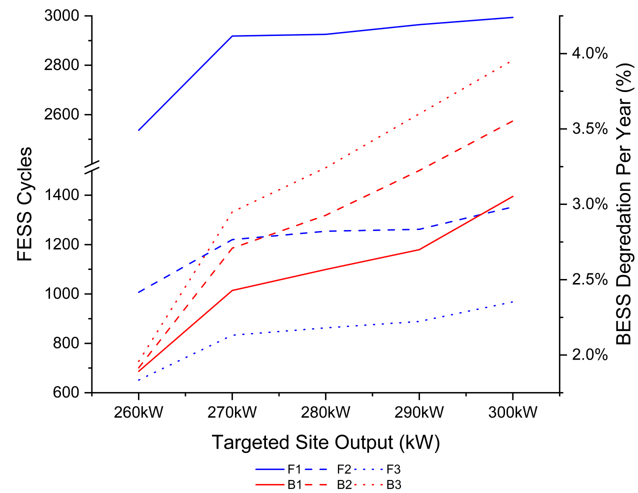

Fig. 4. Cycles and Degradation for varying FESS and BESS sizes across different target outputs

Finally, Figure 4 shows the cycles experienced by each FESS per year and how much degradation each BESS configuration experiences. The equation presented in [11] is used as part of the MATLAB/Simulink model to calculate the incremental degradation for a period Δt as shown in Equations 5,6 and 7. It is primarily based on instantaneous C-Rate and energy throughput, with temperature treated as a constant.

$$\Delta Q^{cycleloss}(t) = B_1.e^{B_2.I_{rate}}.A_h\Delta t \tag{5}$$

$$B_1 = a.T^2 + b.T + c \tag{6}$$

$$B_2 = d.T + e \tag{7}$$

Where $\Delta Q^{cycleloss}$(t) is the % degradation experienced over a given time period t due to cycling, the values of a, b, c, d, and e are constants as given in Table III, I_{rate} is the C-Rate for that period, A_h is the energy throughput over that period and T is the temperature.

First let us consider the FESS cycle numbers, which across all configurations peak at 2925 cycles across a single year (configuration F3 for 300kW target output). Extrapolating this across the expected 25-year lifespan would result in just over 73,000 cycles, well below the marketed cycle limit across the flywheel manufacturer industry which is generally specified as 100,000+. This suggests that all the configurations studied can easily handle this application without the need for anything more than standard levels of maintenance.

However, when considering the level of BESS degradation experienced each year, the lowest value is 1.9% per year for configuration B1 at a 260kW target output. Even at this lowest level of degradation, the BESS would still only be expected to last into its 11th year of operation before it would require replacement after falling to below 80% of its original capacity, the point generally considered within the literature to be the end of life for a BESS. In addition to this, at the worst levels of degradation, the BESS would last just over 5 years before requiring a replacement.

It is in this last set of analyses that the issue with installing BESSs over FESSs for this application becomes apparent. Whilst the BESS can perform technically better than the FESS, when we begin to consider the effect that this application has on the lifetime of the BESS the drawbacks become too great to be mitigated. This factor is particularly important when considering the economics of the site.

V. Economic Analysis

To further inform the results of the technical analysis and the comparison between BESSs and FESSs for this application, an economic analysis was performed. The metric used for this analysis is Net Present Value (NPV) which represents the present value of an installation when taking into account the future income and expenditure and is defined as in Equation 8 where $C_{investment}$ is the initial investment in the system, $C_{revenue}$ is the yearly income (£), N is system lifetime in years and d is the discount rate. In this work, the Net Present Value Change (NPVC) is discussed, which represents the difference between the base NPV with no energy storage installed and the new NPV with a FESS or BESS present.

Firstly, the NPV for each combination studied so far at a TCC of £500/kW and a discount rate of 5% is shown in Figure 5 to provide a baseline economic analysis to build from. The yearly income is based upon the amount of energy exported from the site, set in this work at a value of 6 pence per kWh [33].

$$NPV = \sum_{n-1}^{N} \frac{C_{revenue}}{(1+d)^n} - C_{investment} \quad (8)$$

It can be seen from Figure 5 that of the configurations assessed, configuration F1 (a 7.5kWh 8C FESS) is the best performing from the initial economic assessment. The low cost of installing just one of the modular FESSs coupled with the diminishing returns of installing further FESS modules results in the NPVC becoming worse as the FESS is increased in size. It is also important to note that configuration F1 peaks at 270kW target output, with any further increase in targeted output bringing the NPVC down rather than up. This is because the FESS is now sitting at 100% SOC for longer periods of time, rendering it less effective than when capturing more of the available additional energy at the lower target outputs. The key aspect to be aware of to explain why this impacts the NPV in this way, is that at the higher targeted site outputs, the base NPV that is being compared against is also increasing, and the resulting drop in NPVC at the higher target outputs is actually the result of the relative increase becoming smaller.

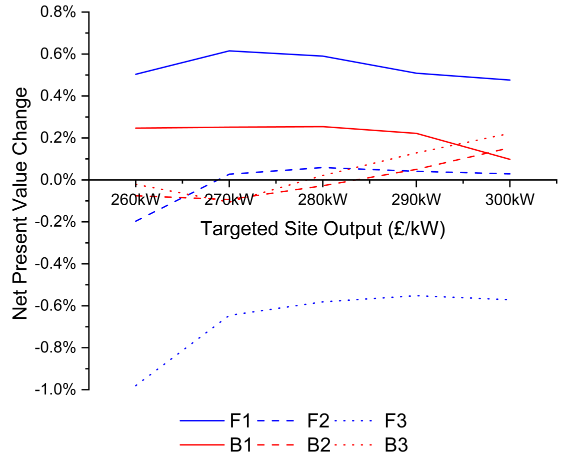

Fig. 5. NPVC for varying FESS and BESS sizes across different target outputs

When considering the BESS configurations, they are grouped together far more closely than the FESS configurations. B1 is the best performing by a narrow margin (£18,331 NPVC compared to £16,547 NPVC for B3), but is also the only configuration where the NPVC falls at the higher target outputs. This is due to the complex trade-off between increasing income from the additional energy available, and the resulting increase to degradation from the BESS being required to operate more frequently. Where for B1, an additional replacement BESS is required when the target output reaches £300/kW, this does not happen for B2 and B3, although it can be observed happening initially at the step between 260kW and 270kW target outputs. This is an important aspect to note, as it highlights the fine balance between positive and negative impacts in sizing these systems.

The best-performing combinations of both FESS and BESS were further analysed under a discount rate and TCC sensitivity study to investigate over what range of values each system can provide a positive economic impact. The two configurations being investigated further consisted of configuration F1 with a 270kW target output, and configuration B1 with a 280kW target output. For the FESS, the results of this study are shown in Figure 6.

As the TCC is increased, the related improvements to NPV are reduced, but even at a TCC of £1000/kW which represents a higher figure than commonly found throughout literature, there is still the potential for providing a positive NPVC all the way up to a discount rate of 7%.

Conversely, for the BESS sensitivity analysis, the picture does not look quite as promising. Referring back to the pre-

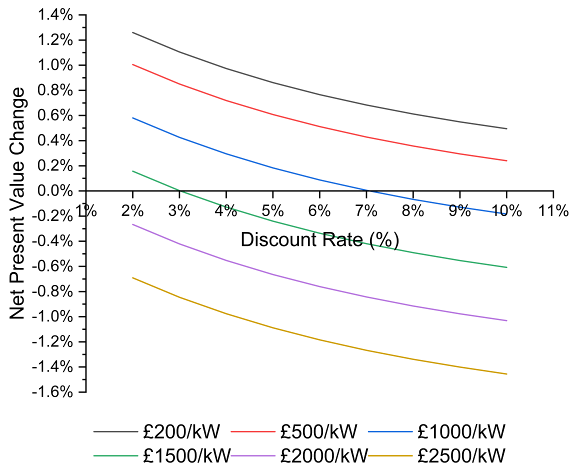

Fig. 6. NPVC for varying discount rates and TCCs for a 7.5kWh 8C FESS at a site with a targeted output of 270kW

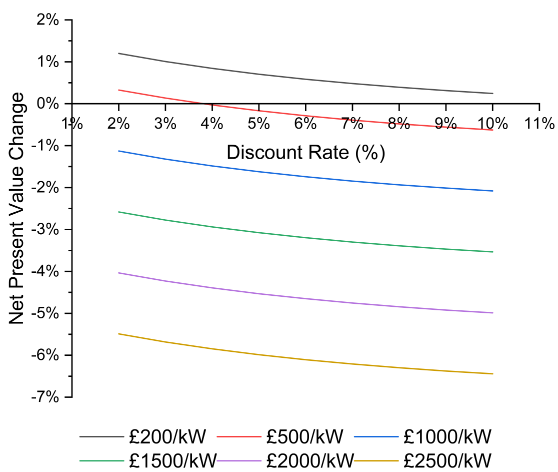

Fig. 7. NPVC for varying discount rates and TCCs for a 30kWh 1C BESS at a site with a targeted output of 280kW

vious subsection, it is clear that the impact of the degradation on the BESS is having a significant impact on the ability for the BESS to provide a positive economic impact.

Only under a £200/kW TCC does the BESS provide a positive NPVC across the entire range of discount rates, and will only provide positive NPVC at a TCC of £500/kW for a discount rate of 2% and 3%. In fact, it appears that unless the BESS can achieve a very narrow window of costing then it would have a negative impact on the economic performance of the site.

VI. Conclusions

From a technical perspective, the BESS configurations performed generally better than the FESS configurations owing this success mainly to the increased energy capacity from the configurations studied. However, the gap in performance is not significant enough to clearly indicate a preference for one ESS medium or the other. Additionally, there is the potential for different configurations from different manufacturers to perform either better or worse than those discussed in this study. The key takeaway from a technical perspective is the evidence that an ESS can be introduced to effectively assist an export-limited site on a smaller local scale with the potential to improve performance at many sites across GB currently operating under such schemes.

In terms of the economic sensitivity analysis, it has been shown that the excessive strain placed upon a BESS being used for this application and the subsequently required replacement rates of the BESS units has a significant impact on its ability to be economically viable. The FESS on the other hand can easily withstand the required cycle rates and provides a strong economic performance across a range of different TCC and discount rate values. This study provides real impactful data for both flywheel manufacturers and distributed generation owners to enable them to extract greater value from their products and sites.

The main drawback to the study presented in this paper is the lack of experimental validation on the system, which will be explored in future work. Additionally, this research looks at a single site and further research should be conducted for different geographic locations and generation sizes.

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