Article:

Hutchinson, A.J. orcid.org/0000-0002-0342-0989 and Gladwin, D.T. orcid.org/0000-0001-7195-5435 (2023) Capacity factor enhancement for an export limited wind generation site utilising a novel flywheel energy storage strategy. Journal of Energy Storage, 68. 107832. ISSN: 2352-152X

https://doi.org/10.1016/j.est.2023.107832

Journal of Energy Storage 68 (2023) 107832

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Research papers

Capacity factor enhancement for an export limited wind generation site utilising a novel Flywheel Energy Storage strategy

Andrew J. Hutchinson [*,1], Daniel T. Gladwin

University of Sheffield, Western Bank, Sheffield, S10 2TN, United Kingdom

ARTICLE INFO

Keywords:
Energy storage
Flywheels
Wind generation
Capacity factor

ABSTRACT

The percentage of generation provided by wind power sites is ever-increasing, bringing with it additional challenges and benefits. An increasing number of wind generation sites in Great Britain are subject to export limitation schemes (ELS) that ensure generation does not exceed the rated capacities of distribution network infrastructure. This leads to reduced generation resulting in loss of revenue and increased costs. This export limitation is exclusively performed on a site-by-site basis, in contrast to large-scale curtailment to meet national distribution limits. This paper presents for the first time a study highlighting the increasingly common issue of ELS restrictions and how the capacity factor at such sites can be enhanced by deploying Flywheel Energy Storage Systems (FESSs). FESSs can enhance the system performance metrics by storing energy that would otherwise be wasted and using this to increase the capacity factor of the site. In this paper, a novel model is demonstrated by showing for the first time how a FESS can be utilised to enhance the performance of a site subjected to export limitation. A FESS integration and sensitivity analysis performed on a 1MW wind power site with varying degrees of export limitation in place show that the site could generate an additional 6.1–38.5MWh over the course of a year. Subsequent novel economic analysis of the installations showed that the system is economically viable across a wide range of scenarios, increasing the Net Present Value of the site by up to 1.25%. Finally, the performance of the FESS is compared to a Lithium-Ion Battery Energy Storage System (BESS), highlighting the novel contribution of using a flywheel for this application by showing the excessive cycling a BESS would experience and the knock-on effect this has on economic viability. This work can have a significant impact on owners of distributed generation across Great Britain and beyond.

1. Introduction

Export Limitation Schemes (ELSs) are becoming increasingly prevalent within the Great Britain electricity market and fall under the guidelines of Engineering Recommendation G100 [1]. They are used when the rated export power of a distributed generation site could exceed local distribution network limits, usually due to insufficiently sized equipment such as transformers or distribution cables. Many new wind and solar generation sites are choosing to construct installations in excess of the local network limit and using ELSs to manage the output until the local network is upgraded in order to avoid responsibility for the costs of such upgrades [2]. The main technical specifications of G100 are described below;

- The ELS must reduce the exported active power to less than or equal to the agreed export limit within 5 s
- The system must be fail-safe, both in terms of component failure and inadvertent breaches of the export limit. This means that if any component of the export limitation system fails then the exported active power will be reduced within 5 s.

As the drive towards net zero emissions gathers pace, it is imperative that renewable energy generation sites can be allowed to reach their full techno-economic potential. With a wide range of companies offering ELS services, this is commonly achieved in a variety of different ways ranging from changing the turbine blade pitch to reduce power capture from the wind to diverting portions of the generated power into dump loads such as heaters [3]. However, these approaches waste the extra energy that could have been utilised and decrease the overall capacity factor of the site, something that could potentially be exploited by introducing Energy Storage Systems (ESSs).

* Corresponding author.
E-mail address: ahutchinson1@sheffield.ac.uk (A.J. Hutchinson).

[1] The authors gratefully acknowledge the financial support of the Engineering and Physical Sciences Research Council (EPSRC), United Kingdom in the form of the 'Energy Storage and its Applications' Centre for Doctoral Training under grant code EP/L0168/18.

https://doi.org/10.1016/j.est.2023.107832
Received 12 January 2023; Received in revised form 30 April 2023; Accepted 22 May 2023
Available online 6 June 2023

The Capacity Factor (CF) is a common metric for measuring the overall output of a generation site as a proportion of the theoretical maximum that a continuous peak-rated output of the site would yield and is calculated as given in Eq. (1) 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 [4–6]. CF is one of the most crucial metrics for considering the viability of wind generation sites, and the work contained here concentrates on increasing this through the use of ESSs, thus increasing the techno-economic viability of the site.

$$Capacity\ Factor = \frac{E_{actual}}{P_{Rated} \times 8760} \tag{1}$$

Literature considering wind generation sites experiencing decreased capacity factor [7–10] mainly studies the transmission based curtailment of wind where the site is subjected to limitations based on grid wide levels of electricity supply and demand. This is opposed to export limitation, where site-specific local equipment sizing (for example, the size of a local substation) leads to restrictions being placed upon generation sites. Additionally, the export limitation is constant and is not affected in any way by the levels of demand and supply on the grid, with any site subjected to export limitation having their generation capacity permanently reduced until such a time that local infrastructure is upgraded. As this is an emerging issue, this paper seeks to highlight the challenges that it presents and present a detailed assessment on how energy storage can be used to mitigate its impact for the first time.

1.1. Motivation and impact

As renewable generation continues to reach record levels [11] local distribution network operators (DNOs) are coming under increasing pressure to manage local substation capacity. Fig. 1 shows an excerpt Network Capacity Map for the largest DNO in the United Kingdom (UK), Western Power Distribution (WPD) [12]. The image shows all of the substations that do not have any capacity for generation to be installed in excess of 1 MW. In total, 57% of the substations operated by WPD are rated as 'Red' meaning a connection is unlikely to be achieved without significant reinforcement.

This information suggests that this issue has the potential to cause widespread difficulties for the expected rapid increase in distributed generation sites across Great Britain. If the capacity is not available to connect a site to the distribution network, then it is highly likely an ELS scheme will be put in place to restrict the site output in order to allow the installation to proceed. When considering the number of such sites in Fig. 1, it becomes apparent that this is not an isolated issue.

Wind generation sites are often subject to large fluctuations in wind speed and therefore the output of these sites is often highly volatile. This volatility can cause the site to breach agreed export limits with local distribution network operators (DNOs) or conversely not fulfil the full generational potential of the site by setting the pitch to a conservative value in order to prevent these breaches [9].

Fig. 2 shows how an ELS works in practice, limiting the export of the site in real-time and preventing it from breaching the agreed limit. In this example, a site is limited to an export level of 0.2 MW despite being capable of generating power in excess of this, thus resulting in a significant reduction in energy exported (14.2% less energy over the course of the 4000s of operation in this example). When considering different levels of export limitation, the more limited the system is as a proportion of its maximum rated output, then the more potential for increasing the overall Capacity Factor there is. This is due to more excess energy being available for charging an energy storage device to then subsequently be discharged when the output drops back below the export level.

Export limitation on a local scale is only going to become more of an issue as the demand for more distributed generation installation increases. The UK Government is currently looking to loosen restrictions on the deployment of onshore wind [13,14] which will lead to increasing levels of deployment of wind generation. This work presents a timely investigation into allowing new installations to consider additional methods to extract the maximum amount of value from their existing or proposed generation site. It also allows previously discounted sites to be considered for the deployment of new onshore wind generation sites.

The key difference between the research presented in this paper and the previous extensive body of work that has looked into wind curtailment is that export limitation schemes are completely local with no involvement in forecasting or receiving payments for having their generation forcibly reduced. In essence, it represents a permanent enforced decrease in the capacity factor of the site. This work represents a crucial and novel step in increasing the understanding of an emerging issue and providing a viable energy storage-based solution for mitigating their impact and raising the capacity factor back to the intended levels.

1.2. Literature review

It is important to note that this research does not concern the traditional view of wind curtailment, and whilst some of the principles will be the same as this extensive body of research, the area of export limitation on a local scale has received very limited prior research. This is due to the fact it is still an emerging problem which will become increasingly relevant as local DNO networks reach their capacities.

1.2.1. ELS mitigation

Of the literature available, a focus is found on strategies for investing in both DG and DNO network improvements such as found in [15], which presents a modelling scenario where restriction rules, DNO incentives and local renewable generators are balanced according to the game theory principle. Whilst this is an interesting study and raises some good points about the balance between various stakeholders, there is no reference to ESSs which could be proposed as part of the solution. A similar theme is found in [16] where energy trading between generation sites is proposed as a solution to reducing constraints on local distribution networks, but once again there is no suggestion of utilising energy storage to assist in reducing such constraints.

The main previous work in locally limited DG is discussed in [17] which comments upon the fact that there has been very little exploration of the issues faced by DG sites. It proposes smarter connection schemes such as the Flexible Plug and Play scheme trialled by UK Power Networks from 2012 to 2014, which concentrated purely on connection-based innovation with no focus on deploying energy storage to assist in relieving distribution-restricted issues beyond a limited simulation trial [18]. This project was funded for almost £10 m back in 2011, suggesting that there is significant commercial interest in managing these issues. Clearly, there is a significant opportunity for the investigation of the novel use of ESSs to alleviate local distribution restrictions.

It should also be noted that whilst alternative solutions for alleviating local distribution restrictions are possible, this has not been considered as part of this study. An example of this method of alleviation would be increasing the self-consumption of the site with a process that can be controlled to utilise more power at times when the export is above the limit. In addition, many studies investigate ways of increasing the performance of a wind turbine itself such as in [19], which will also impact upon the ability of wind generation sites to maximise their capacity factor. However, in the case of the work undertaken in this study, the turbine would still be subjected to an ELS and hence these further gains in turbine output would still be limited by the local distribution restrictions.

Another significant aspect that impacts the deployment of ELSs is the Dynamic Thermal Rating (DTR) system. This system provides

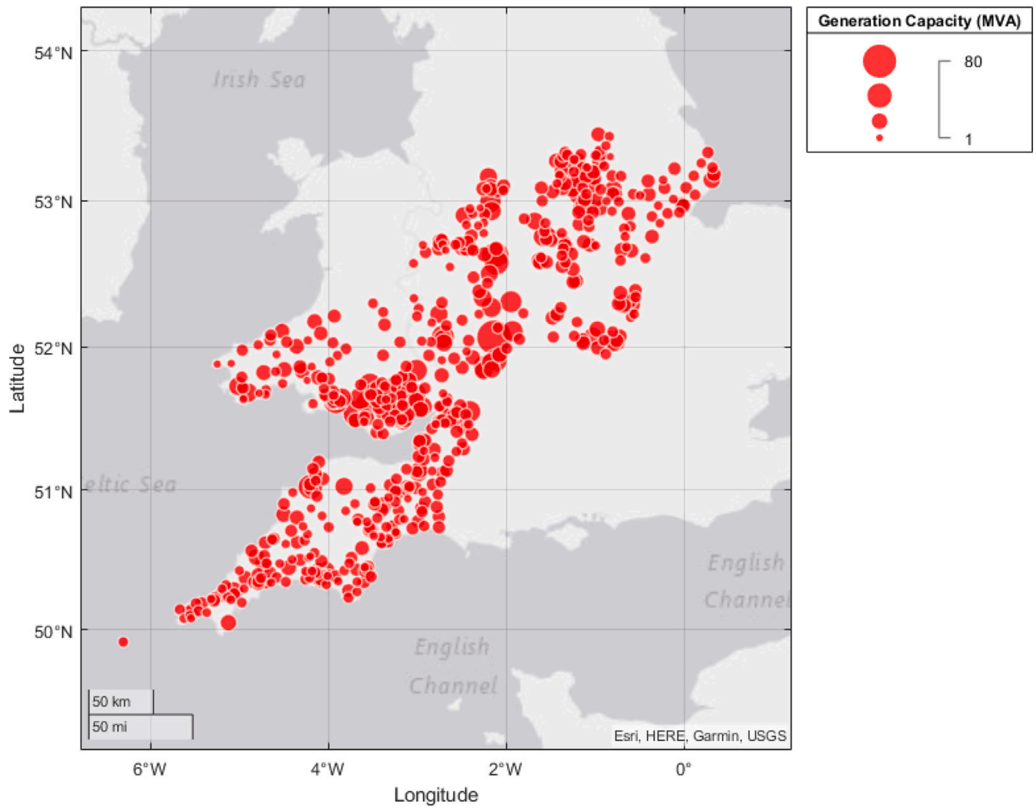

Fig. 1. WPD Network Capacity Map showing sites currently rated as 'Red' for a capacity of less than 1 MW.

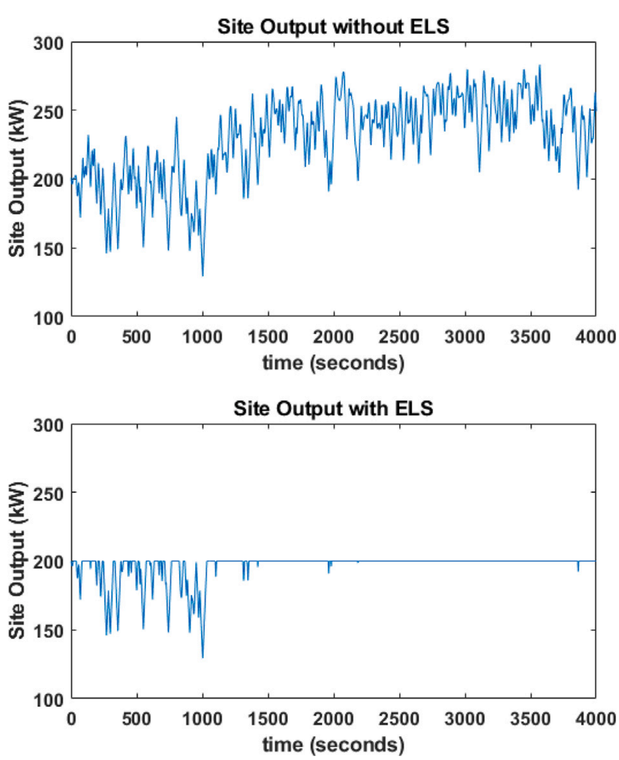

Fig. 2. Example site output showing how ELS affects site productivity for a site limited to a maximum export of 0.2 MW. The output with ELS exports 14.2% less energy.

the actual current carrying capacity of transmission lines in real-time, allowing the capacity to be maximised according to environmental conditions [20]. This study does not include this aspect instead focusing on sites that have already been subjected to ELSs despite the use of DTR, or due to aspects unaffected by DTR such as substation transformer capacity. Despite this, it is important to consider how ELSs and the DTR system can complement each other to alleviate further issues.

The studies contained in [21,22] discuss the reliability of a wind-integrated power system utilising DTR both with and without BESSs respectively, showing significant improvements in reliability and allowing greater penetration of wind generation. Additionally, [23] also explores these issues by performing an optimisation on the topology of a network accounting for the DTR system and BESSs and again concluding that higher levels of wind generation can be integrated into the grid when utilising these two aspects effectively. Finally, [24] discusses peak demand matching utilising BESSs considering the DTR system and demand response. This study shows that the combination of technologies can extend the lifetime and reduce the required BESS energy and power capacities whilst also improving the security of supply.

Overall, it is clear that the usage of the DTR system is a key part of the solution to allowing a higher level of wind penetration. Generally, sites will be subjected to ELSs for a range of different reasons, and if the primary reason is the transmission line capacity then the use of DTR can be effective in removing the requirement for an ELS. However, this work now concentrates specifically on sites that are already subjected to an ELS and situations where the transmission line is not the limiting factor. The work reviewed above, along with the work presented in this study, can work in tandem to provide a more resilient grid, wider deployment, and more effective utilisation of wind generation.

1.2.2. Energy storage systems for wind generation support

With so little previous work being conducted in the field of locally drive export limitation, it is important to review the extensive works undertaken in grid scale wind curtailment as this can help to inform and guide the decisions made on a local level. Additionally, the specific application of FESSs for increasing the capacity factor of a wind generation site has received minimal prior investigation beyond being a secondary objective in curtailment studies. Grid scale wind curtailment in the U.K. is increasing, with more than £500 m spent on paying wind farms to stop generating in 2021, a significant increase from over £200 m in 2020 [25].

An important area to note is the work presented by [26], which focuses solely on the control and operation of a wind turbine to directly reduce curtailment by variation in torque control in tandem with pitch angle modifications to good effect. Something that has not been discussed, however, is utilising this ability to vary the output of a turbine in order to maximise the effect of an ESS being introduced, combining the two methods to produce a better techno-economic solution.

In many studies, the aim of introducing an ESS to a wind generation site is to smooth the power output of the site, an objective that aligns well with restricting the output of a site to fall in line with export limitations such as in [27–29].

Firstly, in [27], a BESS integrated with a wind generation site is minimised in order to reduce costs and increase economic performance, whilst maintaining the correct level of technical performance. It also looks into the optimal topology of BESS installation at a large wind farm, concluding that a BESS that is distributed throughout the site rather than in one location is more effective. However, it neglects to discuss the effect that operating this service has on the lifetime of the BESS, which represents significant scope for further work in this field, something this thesis will build upon.

Within [29], a FESS is utilised for wind power smoothing. This study shows a significant benefit to utilising FESSs for wind smoothing applications, although the smoothing achieved is minimal due to the objective being more closely related to reducing the power spectrum variance when exporting to the grid. Despite this though, it shows that a FESS can effectively provide this type of support and thus warrants further investigation in this chapter.

In [8], Battery Energy Storage Systems (BESSs) are assessed for the mitigation of wind curtailment on a large scale and shown to be effective up to a ceiling cost of $780/kW, where anything above this cost would not be economically viable. Recently, a study outlined a method for determining the optimal size of a battery at the design stage of a hybrid wind-battery system to compensate for power fluctuations [30] but concluded that the lifetime under two different scenarios was 3–6 years due to the cycle and calendar ageing rates, which would not provide a viable economic return.

At a grid-scale level, the work in [7] shows that investment in energy storage (in the form of an electrolyser) produces a significantly quicker payback period than investment in the network infrastructure suggesting there is a potential for economic benefits on a lower scale as well as the grid level discussed in that study.

1.2.3. Flywheel energy storage systems

Responding to variations in wind power in the seconds-minute range requires significant amounts of cycling from an integrated ESS, as discussed previously in [31], with a small-scale wind generation site shown to require a FESS to be subjected to 350–1000 cycles per year. This high-intensity cycling would be detrimental to some forms of energy storage that are more susceptible to cycle-based degradation such as a BESS, however, a FESS can withstand cycles in excess of 100,000 across its lifetime [32].

For frequency regulation services, FESSs have been found to be a more cost-effective solution than competitors' lead–acid and lithium-ion batteries when considering whole life cycle costs [33]. This is due to FESSs being able to handle a higher number of cycles than other energy storage mediums, thus reducing the number of replacements required during the system lifetime that would incur additional costs. In [8], a FESS was found to have an annualised life-cycle cost of less than half of the equivalent cost for lithium-ion batteries.

Table 1
Selection of FESSs either commercially available or in development.

Manufacturer	Max C-Rate	Energy capacity per flywheel	Power capacity per flywheel
Amber kinetics	0.25	32 kWh	8 kW
OXTO energy	13	5 kWh	65 kW
Stornetic	23–65	2–2.3 kWh	60–120 kW
Vycon	240	0.52 kWh	125 kW

Flywheels suffer from a high self-discharge rate compared to other energy storage systems [34,35]. In applications such as renewable integration, this becomes less significant. Due to the rapid change of state between charge and discharge, there are rarely occasions when the flywheel will be 'idle' and hence a limited opportunity for it to freely self-discharge.

Another key characteristic of FESSs is a high efficiency generally quoted in excess of 90% and a wide operating temperature range, both of which lend themselves to the rapid power variations and often variable weather conditions of a wind generation site [36,37]. Existing and upcoming commercialised flywheels have a wide range of both power and energy densities, with selected manufacturers shown in Table 1.

1.2.4. Application of flywheels

Previous works [31,37–44] have discussed various implementations of a FESS into renewable energy generation scenarios with all reporting a positive impact provided by the FESS. [31] provided an initial commentary on a specific case study describing how varying sizes of FESS could be used to support a site subjected to an ELS and showed that significant reduction in breaches of the limit could be achieved. The overview presented in [37] provides a detailed assessment of various energy storage mediums for integration with renewable energy sources and demonstrates that the ESS being introduced needs to be specifically chosen for a given application to avoid negative impacts.

A MATLAB/Simulink simulation [40] shows an effective technique of ensuring the power and voltage delivered to a load is constant through flywheel power matching the inverse of the wind power delivered in a 30-second simulation and concludes that for short duration and power quality applications, flywheels can be utilised.

A key challenge in the specification and integration of FESSs into a wind generation system is ensuring that the chosen configuration will provide appropriate benefits dependent on the system owners' requirements, with previous studies determining that installing energy storage in certain scenarios is not cost-effective [45] while some studies have determined there to be value in introducing hybrid systems [46,47]. A detailed economic analysis is therefore key in providing value to any study, to lend context and a real-world perspective.

1.2.5. Economic analysis

A wide variety of studies have been performed to date which combines both technical and economic analysis of energy storage technologies [48,49]. They enable the real-world benefits of introducing an energy storage component into an existing system to be realised and assessed.

The analysis in [49] specifically concerns energy storage systems for wind generation sites and provides a techno-economic model for Australian wind farms. The cost model portion has been produced to both assess the overall cost of the ESS after n years and also to provide an indication of payback time for that ESS. However, the actual cost model itself is not presented with only the results of the study being shown.

Several other studies [50,51] include multiple cost elements often referred to with different terms such as PCS (Power Conversion System), BOP (Balance of Plant, defined as the related infrastructure required for the operation of the ESS such as transformers, foundations, cables etc.), storage cost etc. Cost items similar to these are often quoted throughout the literature, often being encompassed within a generalised '£/kW' or '£/kWh' figure for the overall ESS [32,33,50,52].

It is important to note the age of many of the available cost studies to ensure that up-to-date values are referenced as some studies with an excellent level of cost breakdown can now be considered to be out-of-date due to advancements in technology and reduction in costs [53]. It is therefore crucial to consider a range of economic values to appropriately reflect the variability of these costs.

Net Present Value (NPV) is a metric that seeks to represent the value of an investment by comparing the current value of cash inflow with the present value of cash outflow [7]. NPV is calculated using a generic formula (Eq. (2) and offers a standardised method for comparing the profitability of an installation which is used widely across different research areas [54–56]. It offers an easily comparable value for how economically viable an installation will be under set conditions. The return on investment required is controlled by changing the discount rate d. In this study, the discount rate has been set as 5% in line with figures used throughout literature [49,57–60].

$$NPV = \sum_{n-1}^{N} \frac{C_{revenue}}{(1+d)^n} - C_{investment} \tag{2}$$

where $C_{\mathrm{investment}}$ is the initial investment in the system, C_{revenue} is the yearly income (£), N is the system lifetime in years and d is the discount rate.

Taking into account these examples, this study will be conducted by analysing the economic impact of introducing a FESS into the wind generation system in terms of total NPV Change (NPVC) compared to the baseline NPV without a FESS and will be considered over a lifetime of 25 years (N=25 in Eq. (1)). Current literature places the overall total capital cost (TCC) in £/kW of a FESS in the 500-2500£/kW range [32,61–64] and a sensitivity analysis on how varying this TCC effects the NPVC of different FESS systems will also be performed.

1.3. Novel contribution

For the first time, a detailed assessment of using FESSs to alleviate export limitations caused by local distribution restraints is presented, an issue that is widespread throughout the GB network and which prevents wind generation sites from fulfilling their full generation potential. This enforced capacity factor reduction can be countered effectively with the results of the study presented here.

Whereas many previous studies regarding the integration of FESSs with wind generation have looked at short-duration simulations mitigating second-to-second oscillations, this study contains a novel use of extensive wind speed data to accurately model and simulate a FESS providing capacity factor improvements to a wind generation site over an extended period of operation for the first time, as well as showcasing why cycle resistant storage such as flywheels holds an advantage over storage mediums that are more susceptible to cycle based degradation like BESSs.

Whilst there has been widespread work conducted in the field of wind curtailment, there has been little to no activity in the field of locally driven limitations. This is a significant issue that will only rise further in prominence as distributed generation (DG) is further deployed. By providing the means to counter these issues at an early stage, this work represents a significant and timely overview of preventing export limitations from stopping further DG from being introduced to the grid. It can help unlock previously discounted sites for wind generation deployment, and enhance existing sites not reaching their full potential.

The financial benefits of utilising flywheels in this way are also presented for the first time. The work in this study can cause a significant impact on the viability of generation sites across the UK and other parts of the world.

1.4. Study overview

The key technical metrics that will be assessed within this study are as follows;

- Capacity Factor Increase (CFI) — For this study, the CF for the base site has been calculated followed by the CF for the site with the ESS introduced. The CFI is then determined by calculated the difference between the two values.
- Limitation Time Proportion (LTP) — The 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 Eq. (3) where t_{limited} is the duration of time that the export is limited and $t_{\mathrm{operational}}$ is the total time the system is operational for. It can be used as a metric to determine how the introduction of the FESS affects the duration of time the site is operating without any restrictions.
- FESS Cycles — The total amount of cycles experienced by the FESS, an important metric to monitor the lifetime of the system which has been set as a limit of 100,000 cycles before replacement for this study.

$$LTP(\%) = \frac{t_{limited}}{t_{operational}} \times 100 \tag{3}$$

In this study a 1 MW wind power site is investigated using real-world wind data to simulate a year of generation in a MATLAB/Simulink model as previously developed and discussed in [31,65]. The wind generation site has been modelled based on 4 co-located turbines using the publicly available power curves of the WindTechnik WTN250 [66].

The flywheel model has been developed in coordination with a flywheel manufacturer using provided performance characteristics. A sensitivity analysis is then conducted on the level of export limitation the site is subjected to. This consisted of limiting the output by 5%, 10% and 20% of the total site output. For instance, a 1 MW site subjected to 20% export limitation would be allowed to export a maximum instantaneous power of 0.8 MW. The technical performance of the system is then assessed when varying the energy-to-power ratio of the FESS, with three different power capacities considered (0.05 MW, 0.1 MW and 0.2 MW). Throughout this paper, FESSs that are specified with different power or energy ratings are referred to as different FESS configurations.

Energy to power ratio is referred to as C-Rate within this paper, in line with the definition commonly used for Battery Energy Storage Systems. C-Rate is defined as in Eq. (4), where P_{ESS} is the power rating of the ESS in MW and E_{ESS} is the energy rating of the ESS in MWh. This value is varied between maximum C-Rates of 1C and 20C.

$$C_{Rate} = \frac{P_{ESS}}{E_{ESS}} \tag{4}$$

Subsequently, an economic analysis is performed to evaluate the viability of introducing the FESS in terms of real-world benefit. The income generated by the site has been set as 6 pence per kWh in line with available data from both existing wind generation sites consulted as part of this study, and publicly available information [67]. With the current energy picture being uncertain, this value has been chosen as a conservative option in order to produce a more robust set of results. This is an important metric to consider as it can provide guidance to flywheel manufacturers about the specifications that they will be required to design products to in order to participate in different markets.

To demonstrate how the system operates within MATLAB/Simulink, Fig. 3 shows the simulation output for a 20% limited site, with a 5C 0.2 MW FESS installed to assist with export limitation.

The FESS is seen to be charging whenever the site output power is exceeding the ELS threshold until it reaches its SOC high limit, at which point the remaining excess power will be dissipated by an ELS panel. The FESS then discharges when the output power falls below the agreed export limit.

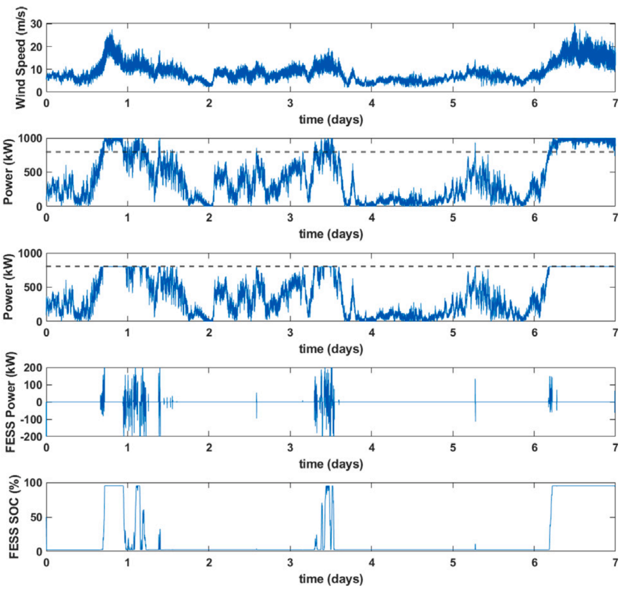

Fig. 3. Example simulation output for ELS site simulation showing (a) Wind Speed (b) Site output without any ELS scheme in place (c) Site output with ELS and integrated FESS (d) FESS output power (e) FESS SOC.

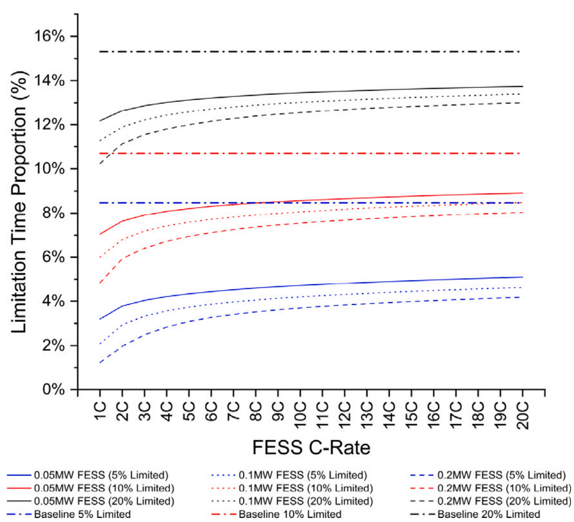

Fig. 4. Limitation Time Proportion (%) for different levels of limitation and FESS sizes over a range of C-Rates including baseline without any FESS for each limitation level.

2. Technical analysis

A sensitivity analysis was performed over a range of C-Rates for the three power capacities and varying levels of limitation. The first of the three technical criteria to be assessed is LTP.

2.1. LTP assessment

The results of the LTP assessment are shown in Fig. 4. This metric gives a good idea of how much the FESS is operating for a given set of conditions and how sensitive the system is to changes in C-Rate (and therefore energy capacity as the power is fixed).

From Fig. 4 it is clear that for all three levels of limitation, a significant reduction in the amount of time spent being limited can be achieved. It is also clear that regardless of the level of limitation, the lower C-Rate configurations perform best but then plateau rapidly to suggest that increasing the C-Rate further does not have a significant detrimental effect on performance, implying that the application could be taken on by a wide range of flywheel specifications.

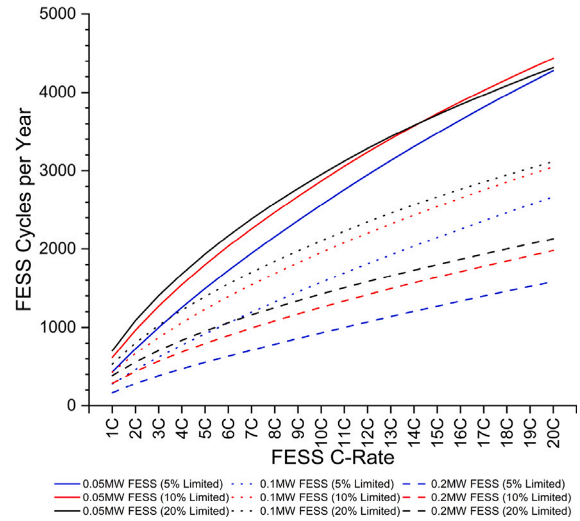

Fig. 5. Cycles per year experienced by the FESS for different levels of limitation and FESS sizes over a range of C-Rates including baseline without any FESS for each limitation level.

When the site experiences a smaller degree of limitation, then the impact of introducing a FESS becomes more apparent suggesting that the more oversized the generation in relation to the site export limit, the less potential there is for improving the site performance through this method. From a baseline of 8.47% LTP, introducing varying sizes of FESS reduces this to between 1.23% and 5.10% LTP. At the lowest point, the LTP of 1.23% suggests that the site is almost operating to its full potential. Even for higher levels of limitation, there is still a significant reduction available by using a FESS, with the 20% limitation level showing a reduction from 15.3% to a range of 10.24% to 13.74% depending on C-Rate and rated power.

Interestingly, in areas where the energy capacity is equal but with different configurations (for instance a 4C 0.1 MW FESS has the same energy capacity as a 2C 0.05 MW FESS) the higher power system performs better, as a 2C 0.05 MW FESS at a limitation level of 5% shows an LTP of 3.78% whilst the 4C 0.1 MW FESS at the same level of restriction has a LTP of 3.57%. This shows that whilst the energy capacity is important, a higher power rating also allows the system to contribute more effectively.

2.2. Cycle life assessment

In Fig. 5 the total amount of cycles that the FESS is subjected to per year is shown. From the literature review, it was found that a FESS can commonly withstand at least 100,000 cycles before the end of life whilst in some cases can be subjected to significantly more.

Considering the results with this in mind, it is clear that under all but 3 of the simulated scenarios, the FESS will not come close to reaching 100,000 cycles over a 25-year lifetime. However, the three configurations with a 0.05 MW flywheel would reach between 106,950 and 110,925 cycles within 25 years of operation. Even with these values, it is likely that a modern FESS would be able to be designed to withstand these levels of cycling as 100,000 cycles is generally quoted as the lower threshold of allowable cycles.

2.3. CFI assessment

The final metric to be discussed is CFI. This can give a good indication of the effect that the changing levels of limitation have on the overall CF of the site, and will subsequently lead to how much more

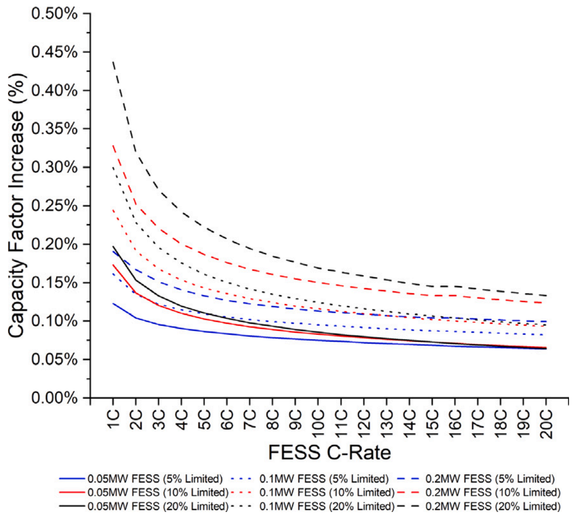

Fig. 6. Capacity Factor Increase (%) for different levels of limitation and FESS sizes over a range of C-Rates.

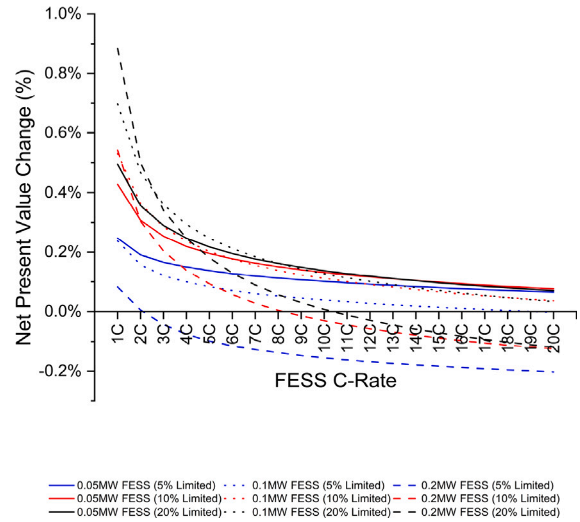

Fig. 7. NPV change for varying FESS and site configurations across a range of different C-Rates with discount rate of 5% and TCC of £500/kW.

income the site can generate. The results of this study are shown in Fig. 6

The relationship between CFI and the C-Rate of the system represents different degrees of inverse relationship depending on the level of limitation and energy capacity installed. However, there is a complex balance between these two metrics and the technical operation of the FESS, meaning that within the curve there are some areas where steeper-than-expected drops or rises in CFI occur from one C-Rate to the next.

For all of the studied FESS configurations and limitation levels, the CFI decreases as the C-Rate is increased with a significant decrease when comparing low C-Rate systems to higher C-Rate ones. However, after an initial rapid decrease in CFI as the C-Rate is increased from 1C, all of the configurations experience a plateau where further increasing of the C-Rate does not result in a significant reduction in CFI, suggesting again that a wide range of FESS configurations can be suitable for this application. Additionally, as limitation is increased, all systems experience immediate reductions in the CFI that they provide although this feature is again more prominent at lower C-Rates than higher ones.

It is interesting to note that whilst the 0.2 MW FESS achieves the two best CFI results under the 20% and 10% limitation scenarios, it is then the 0.1 MW FESS under the 20% and 10% limitation scenarios that produces the next best results rather than the 0.2 MW FESS under 5% limitation. This suggests that the 5% level of limitation does not contain a sufficient duration of time where the export is limited to provide scenarios where the FESS is justified.

At its peak, a CFI of 0.44% can be achieved. Whilst the numbers for these increases appear small, considering the scale of the site the value becomes clear. A capacity factor increase of 0.44% for a 1 MW site would result in an additional 38.5 MWh of generation over the course of a year. The lowest increase of 0.07% would lead to an additional 6.1 MWh of generation over the course of a year.

3. Economic analysis

In order to verify the real-world viability of the systems being analysed, an economic analysis was conducted. This economic analysis is based upon comparing the baseline NPV of the system without an energy store, and the new NPV after the system has been installed calculated as shown previously in Eq. (2) over a period of 25 years.

The income generated by the site by exporting energy has been set at a rate of £0.06/kWh in line with available data from both existing wind generation sites consulted as part of this study, and publicly available information [67].

3.1. Initial assessment

For the initial assessment, the Total Capital Cost (TCC) was set at £500/kW along with a discount rate set at 5%. This TCC has been set to provide an initial baseline result, with the TCC then varied to show the ranges of values for TCC that should be targeted by manufacturers in order to provide an economically viable product. The NPV change was then calculated for each C-Rate as shown in Fig. 7. The TCC is then varied to show the ranges of values for TCC that should be targeted by manufacturers in order to provide an economically viable product.

It is important to consider how the changing C-Rate will affect the NPV of the site. As the TCC is calculated in terms of £/kW, the kW rating of the site is determined by multiplying the kWh rating and C-Rate of the FESS. Thus, an increased C-Rate will lead to a higher power rating for the same energy capacity, impacting the NPV of the site.

It is clear that the lower end of the C-Rate spectrum creates the most favourable increase in NPV, before beginning to plateau around the 4–10C range depending on the configuration being assessed. Across the range of C-Rates studied, the level of limitation and energy capacity has a significant impact on which C-Rate will provide the most significant economic benefit, with the following configurations representing the greatest increase at the given C-Rate ranges;

- 1C-2C - 0.2 MW FESS (20% limited)
- 3C-7C - 0.1 MW FESS (20% limited)
- 8C-13C - 0.05 MW FESS (20% limited)
- 14C-20C - 0.05 MW FESS (10% limited)

These results are particularly interesting, as it shows that in the lower C-Rate ranges the larger FESS systems are more favourable, as well as there being a greater advantage from higher levels of limitation. However, as the C-Rate is increased the picture changes until at 11C a lower level of limitation coupled with the smallest FESS power rating becomes the best-performing configuration. Again these results show that at this TCC a wide range of different FESS configurations can be introduced to add value to a site.

However, the picture is not uniformly positive. The 0.2 MW FESS in a 5% limited system fares particularly badly with only a 1C and 2C FESS providing a positive NPV change under these conditions. Additionally, the other two levels of limitation for a 0.2 MW FESS fall into negative NPV change at different points. Here then we have at one end of the spectrum a 0.2 MW FESS (20% limited) providing the biggest NPV increase but at the other end providing a negative change to NPV

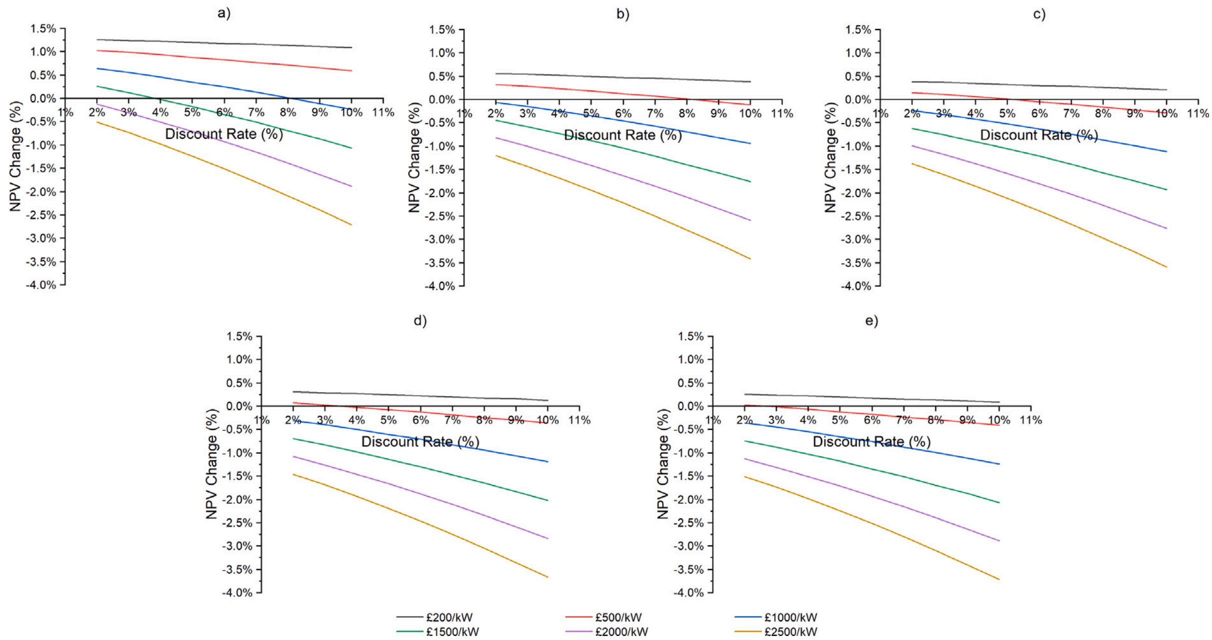

Fig. 8. NPV change for a 0.2 MWM FESS installed at a site limited by 20% based on varying levels of discount rate and TCC for (a) a 1C system (b) a 5C system (c) 10C system (d) 15C system (e) 20C system.

highlighting the fine line between positive and detrimental effects from deploying energy storage systems. It is therefore key that they are sized and deployed correctly to ensure positive outcomes.

3.2. TCC sensitivity analysis

Following this a TCC sensitivity analysis was conducted for the 0.2 MW FESS under 20% limitation, varying the TCC between £200/kW and £2500/kW and varying the discount rate between 2% and 10%. The results of this are shown in Fig. 8.

Firstly, consider the varying levels of TCC. An increased TCC will lead to a lower NPV, with this effect being increased further should the ESS being studied require replacement during its operational lifetime. This has a significant impact on the overall level and direction of NPV change compared to the baseline. If the TCC could be reduced to as low as £200/kW then the change to NPV would be positive regardless of the required discount rate or indeed C-Rate. However, all of the discount rate combinations for £2000/kW and above result in exclusively negative NPV changes.

An interesting point to note is that the lower the TCC gets the less vulnerable the system is to changes in discount rate. Taking the 1C system as an example, the £200/kW TCC only varies by 0.176% between its highest and lowest NPV change whilst the £2500/kW TCC varies by 3.21%. The discount rate, therefore, becomes a more important metric as the TCC of the system is increased.

Whilst the NPV increases are generally small, they still represent a positive impact and are dependent on the level of economic return that site owners require, as well as the level of risk they are willing to accept. These results provide the foundation for further analysis in this field, looking into increasing the impact of ESS deployment and enhancing the economic impact.

4. Alternative energy storage economic assessment

The most widely deployed energy storage devices behind pumped hydro energy storage are Li-Ion BESSs [68]. It is therefore prudent to analyse their economic performance for this application to determine whether the FESS can provide a legitimate advantage over the generally cheaper and more commonly deployed Li-Ion BESS.

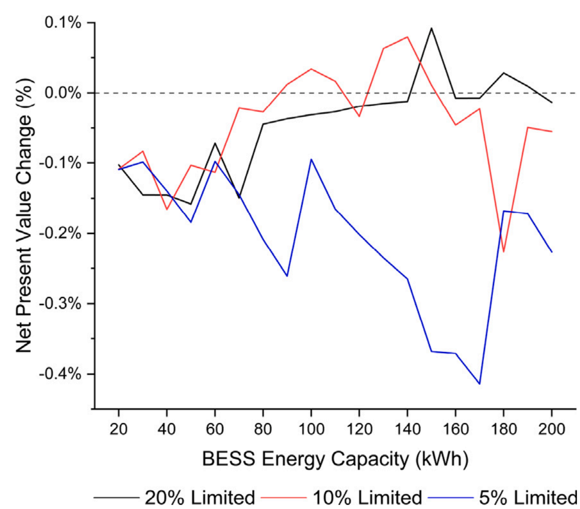

Fig. 9. NPV change for varying BESS energy capacities under differing levels of export limitation.

For this assessment, the BESS C-Rate was set as 1C to represent the most common type of system configuration with the energy capacity varied between 20 kWh and 200 kWh. The same simulations were then conducted as in the previous section, with the TCC of the BESS set as £400/kWh in line with current industry economic conditions, representing the whole TCC including aspects such as battery cells, power electronics and integration costs.

Fig. 9 shows the results of this study. Across the range of capacities studied and over all three levels of export limitation the BESS will actually cause a negative economic impact on the site apart from under a small number of specific combinations. This is in sharp contrast to the results from the FESS study, where multiple different combinations experienced a positive NPVC across the entire range of C-Rates studied.

When deployed in the lowest level of export limitation, the BESS does not provide a positive NPVC under any configuration. This is because the additional income generated does not outweigh the cost of multiple replacement systems being required over the operational

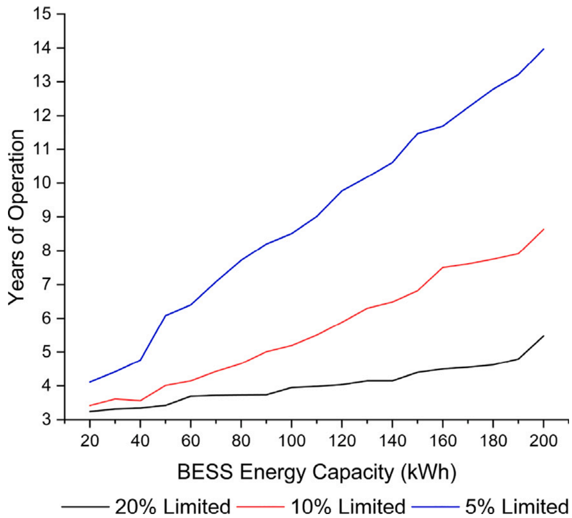

Fig. 10. Years of operation before BESS would need replacement due to excessive cycling.

lifetime due to excessive cycling. Under the 10% limited scenario, the BESS provides a positive NPVC for energy capacities of 90–110 kWh and 130–150 kWh, whilst in the 20% scenario a positive NPVC is provided for 150 kWh and 180–190 kWh. Even when the NPVC is positive, the peak value achieved is 0.09%, much lower than many values achieved by the FESS.

Rather than the smooth exponential lines from Fig. 7, the NPVC for the BESS configurations studied fluctuates significantly as the energy capacity is increased. This is due to the balance between additional income from the extra capacity and additional costs from the number of cycles experienced by the system. Fig. 10 shows the number of years that the BESS will be operational before requiring replacement.

Clearly, this application places a significant strain upon a BESS which results in a reduced lifetime. As previously discussed in Section 2.2, it is likely that all of the FESS configurations studied would not need replacement during the 25-year operational lifetime. This is the key area in which the FESS is shown to be a superior energy storage medium for use in this application.

However, there are specific scenarios under a 10% and 20% level of limitation in which a BESS will outperform a FESS. At a 10% limitation for example, a 140 kWh BESS will outperform a 0.2 MW FESS rated from 8C and above whilst at a 20% limitation, a 150 kWh BESS will outperform a 0.2 MW FESS rated from 11C and above.

5. Conclusion

A novel application of FESSs has been introduced and analysed from both a technical and economical perspective. The scale of the issue that this work seeks to address has been highlighted, showing how this application has the potential to generate additional income for thousands of new and existing sites across GB. Flywheels are ideally suited to perform this service due to their rapid response time, high power capabilities and resistance to cycle-based degradation.

In terms of technical performance, increases to the overall capacity factor of the site can be achieved up to 0.44% for a 1 MW site being limited by 20%. Additionally, the duration of time that the site is export limited for can be reduced dramatically under a wide range of FESS configurations and operational restrictions. The FESS is also shown to experience a number of cycles that it is more than capable of handling over the system's lifetime.

In terms of economic performance, a peak increase to the NPV of the site of 0.85% was achieved at a £500/kW TCC whilst a sensitivity analysis conducted shows that the relationship between the discount rate and TCC and the effect this has on the economic viability of introducing a FESS. The key takeaway from this section is that as the TCC is reduced the effect of increasing discount rates on the NPV change is reduced. From the analysis conducted it is clear that aiming for a TCC of £500/kW in the short term with an aim to reduce this as low as possible will provide the greatest range of options for deploying varying configurations of FESS.

It was also shown that whilst a BESS can provide a positive NPVC to the site, it can only do so under narrow and specific conditions, in sharp contrast to the wide range of configurations where a FESS can provide a positive economic impact. This has been shown to be due to the excessive cycling required of the BESS for this application, resulting in lifetimes ranging between 3.2–13.9 years before replacement is required.

Future work should concentrate on applying these generalised results to specific case studies, along with performing further analysis on how larger-scale sites are affected by this issue.

CRediT authorship contribution statement

Andrew J. Hutchinson: Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Daniel T. Gladwin:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Andrew J. Hutchinson reports financial support was provided by Engineering and Physical Sciences Research Council. Andrew J. Hutchinson reports a relationship with OXTO Energy that includes: funding grants.

Data availability

The authors do not have permission to share data.

References

[1] Energy Networks Association, Engineering recommendation G100 issue 1 amendment 2 2018 technical requirements for customer export limiting schemes, (1) 2018, pp. 1–39, [Online]. Available: www.energynetworks.org.

[2] The Association for Decentralised Energy, Technical guidance for customer export limiting schemes - engineering recommendation G100, 2022, [Online]. Available: https://bit.ly/3RqX6Ty.

[3] OMNI Generators, G100 export limitation panel, 2020, [Online]. Available: https://www.omni-generators.co.uk/electrical-panels/146-g100-export-limitation-panel.html.

[4] M. Yoon, S. Jung, An economic ESS design method based on wind system capacity factor for island power grid, Int. J. Eng. Technol. 7 (3.3) (2018) 368.

[5] J.G. Simpson, E. Loth, Super-rated operational concept for increased wind turbine power with energy storage, Energy Convers. Manag. X 14 (September 2021) (2022) 100194, [Online]. Available: https://doi.org/10.1016/j.ecmx.2022.100194.

[6] R.P. Praveen, K.V. Chandra Mouli, Performance enhancement of parabolic trough collector solar thermal power plants with thermal energy storage capability, Ain Shams Eng. J. 13 (5) (2022) 101716, [Online]. Available: https://doi.org/10.1016/j.asej.2022.101716.

[7] X. Yan, C. Gu, F. Li, Q. Ai, Cost-benefit comparison of different techniques for addressing wind curtailment, Energy Procedia 142 (2017) 1759–1764, [Online]. Available: https://doi.org/10.1016/j.egypro.2017.12.560.

[8] J.X. Johnson, R. De Kleine, G.A. Keoleian, Assessment of energy storage for transmission-constrained wind, Appl. Energy 124 (2014) 377–388, [Online]. Available: http://dx.doi.org/10.1016/j.apenergy.2014.03.006.

[9] Z. Zhou, C. Wang, Output power curtailment control of variable-speed variable-pitch wind turbine generators, in: Asia-Pacific Power and Energy Engineering Conference, APPEEC, Vol. 2015-March, IEEE, 2014, no. March.

[10] H.H. Abdeltawab, Y.A.R.I. Mohamed, Robust energy management of a hybrid wind and flywheel energy storage system considering flywheel power losses minimization and grid-code constraints, IEEE Trans. Ind. Electron. 63 (7) (2016) 4242–4254.

[11] Renewables Now, UK sees new wind generation record of 19.6gw, 2022, [Online]. Available: https://renewablesnow.com/news/uk-sees-new-wind-generation-record-of-196-gw-771716/.

[12] Western Power Distribution, Network capacity map, 2022, [Online]. Available: https://www.westernpower.co.uk/our-network/network-capacity-map/.

[13] Department for Levelling Up Housing and Communities, Government to launch consultation on local support on onshore wind, 2022, [Online]. Available: https://www.gov.uk/government/news/government-to-launch-consultation-on-local-support-on-onshore-wind.

[14] A. Allegretti, H. Horton, Sunak set to end ban on new onshore windfarms, 2022, [Online]. Available: https://www.theguardian.com/environment/2022/dec/06/sunak-set-end-ban-new-onshore-windfarms-england-tory-rebellion.

[15] M. Andoni, V. Robu, W.G. Früh, D. Flynn, Game-theoretic modeling of curtailment rules and network investments with distributed generation, Appl. Energy 201 (2017) 174–187, [Online]. Available: http://dx.doi.org/10.1016/j.apenergy.2017.05.035.

[16] M. Jenkins, I. Kockar, Impact of P2P trading on distributed generation curtailment in constrained distribution networks, 2020.

[17] K.L. Anaya, M.G. Pollitt, Going smarter in the connection of distributed generation, 2017, pp. 608–617.

[18] C. Marantes, Low Carbon Networks Fund Full Submission - Flexible Plug and Play Low Carbon Networks, Vol. 44, Tech. Rep., LCN Fund, 2013, pp. 1–53.

[19] N. Huang, Q. Chen, G. Cai, D. Xu, L. Zhang, W. Zhao, Fault diagnosis of bearing in wind turbine gearbox under actual operating conditions driven by limited data with noise labels, IEEE Trans. Instrum. Meas. 70 (2021).

[20] S. Karimi, P. Musilek, A.M. Knight, Dynamic thermal rating of transmission lines: A review, Renew. Sustain. Energy Rev. 91 (March) (2018) 600–612, [Online]. Available: https://doi.org/10.1016/j.rser.2018.04.001.

[21] J. Teh, C.M. Lai, Reliability impacts of the dynamic thermal rating and battery energy storage systems on wind-integrated power networks, Sustain. Energy Grids Netw. 20 (2019) 100268, [Online]. Available: https://doi.org/10.1016/j.segan.2019.100268.

[22] J. Teh, I. Cotton, Reliability impact of dynamic thermal rating system in wind power integrated network, IEEE Trans. Reliab. 65 (2) (2016) 1081–1089.

[23] C.M. Lai, J. Teh, Network topology optimisation based on dynamic thermal rating and battery storage systems for improved wind penetration and reliability, Appl. Energy 305 (May 2021) (2022) 117837, [Online]. Available: https://doi.org/10.1016/j.apenergy.2021.117837.

[24] M.K. Metwaly, J. Teh, Probabilistic peak demand matching by battery energy storage alongside dynamic thermal ratings and demand response for enhanced network reliability, IEEE Access 8 (2020) 181547–181559.

[25] Drax Power, Getting Britain ready for the next generation of energy projects. [Online]. Available: https://www.drax.com/power-generation/getting-britain-ready-for-the-next-generation-of-energy-projects/.

[26] Z. Zhou, C. Wang, Output power curtailment control of variable-speed variable-pitch wind turbine generators, in: Asia-Pacific Power and Energy Engineering Conference, APPEEC, Vol. 2015-March, IEEE, 2014, no. March.

[27] M. Khalid, A.V. Savkin, Minimization and control of battery energy storage for wind power smoothing: Aggregated, distributed and semi-distributed storage, Renew. Energy 64 (2014) 105–112, [Online]. Available: http://dx.doi.org/10.1016/j.renene.2013.09.043.

[28] R. Sebastián, R. Peña Alzola, Flywheel energy storage systems: Review and simulation for an isolated wind power system, Renew. Sustain. Energy Rev. 16 (9) (2012) 6803–6813.

[29] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, F.D. Bianchi, Energy management of flywheel-based energy storage device for wind power smoothing, Appl. Energy 110 (2013) 207–219.

[30] M. Gholami, O. Shahryari, N. Rezaei, H. Bevrani, Optimum storage sizing in a hybrid wind-battery energy system considering power fluctuation characteristics, J. Energy Storage 52 (PA) (2022) 104634, [Online]. Available: https://doi.org/10.1016/j.est.2022.104634.

[31] A.J. Hutchinson, D.T. Gladwin, Sensitivity analysis of a wind farm with integrated flywheel energy storage, in: Proceedings of the IEEE International Conference on Industrial Technology, Vol. 2020-Febru, 2020, pp. 549–553.

[32] F. Goris, E.L. Severson, A review of flywheel energy storage systems for grid application, in: Proceedings: IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Vol. 1, IEEE, 2018, pp. 1633–1639.

[33] B. Zakeri, S. Syri, Electrical energy storage systems: A comparative life cycle cost analysis, Renew. Sustain. Energy Rev. 42 (2015) 569–596, [Online]. Available: http://dx.doi.org/10.1016/j.rser.2014.10.011.

[34] M.E. Amiryar, K.R. Pullen, A review of flywheel energy storage system technologies and their applications, Appl. Sci. 7 (3) (2017).

[35] M.A. Awadallah, B. Venkatesh, Energy storage in flywheels: An overview, Can. J. Electr. Comput. Eng. 38 (2) (2015) 183–193.

[36] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, R. Villafáfila-Robles, A review of energy storage technologies for wind power applications, Renew. Sustain. Energy Rev. 16 (4) (2012) 2154–2171.

[37] C.K. Das, O. Bass, G. Kothapalli, T.S. Mahmoud, D. Habibi, Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality, Renew. Sustain. Energy Rev. 91 (November 2016) (2018) 1205–1230, [Online]. Available: https://doi.org/10.1016/j.rser.2018.03.068.

[38] R. Takahashi, J. Tamura, Frequency control of isolated power system with wind farm by using flywheel energy storage system, in: Proceedings of the 2008 International Conference on Electrical Machines, ICEM'08, 2008, pp. 8–13.

[39] R. Sebastián, R. Peña Alzola, Flywheel energy storage systems: Review and simulation for an isolated wind power system, Renew. Sustain. Energy Rev. 16 (9) (2012) 6803–6813.

[40] S. Ould Amrouche, D. Rekioua, T. Rekioua, S. Bacha, Overview of energy storage in renewable energy systems, Int. J. Hydrogen Energy 41 (45) (2016) 20914–20927.

[41] J. Tan, X. Wang, T. Wang, Y. Zhang, Alleviation of oscillations power of wind farm using flywheel energy storage, in: IEEE Power and Energy Society General Meeting, Vol. 2014-Octob, IEEE, 2014, pp. 1–5, no. October.

[42] L. Wang, J.Y. Yu, Y.T. Chen, Dynamic stability improvement of an integrated offshore wind and marine-current farm using a flywheel energy-storage system, IET Renew. Power Gener. 5 (5) (2011) 387–396.

[43] H. Lee, B.Y. Shin, S. Han, S. Jung, B. Park, G. Jang, Compensation for the power fluctuation of the large scale wind farm using hybrid energy storage applications, IEEE Trans. Appl. Supercond. 22 (3) (2012) 5701904.

[44] G.S.M. Mousavi, F. Faraji, A. Majazi, K. Al-Haddad, A comprehensive review of flywheel energy storage system technology, Renew. Sustain. Energy Rev. 67 (2017) 477–490, [Online]. Available: http://dx.doi.org/10.1016/j.rser.2016.09.060.

[45] S. Akhavan Shams, R. Ahmadi, Dynamic optimization of solar-wind hybrid system connected to electrical battery or hydrogen as an energy storage system, Int. J. Energy Res. 45 (7) (2021) 10630–10654.

[46] S. Cupples, A. Abtahi, S.A. Raziei, Modeling, optimizing and financial analysis of hybrid renewable energy systems coupled with energy storage, in: 2021 16th International Conference on Ecological Vehicles and Renewable Energies, EVER 2021, IEEE, 2021, pp. 1–7.

[47] P. Alikhani, A. Mrad, H. Louie, L.B. Tjernberg, On the reliability and life cycle cost analyses of small-scale standalone solar systems in rural areas, in: 2021 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2021, 2021.

[48] L. Barelli, G. Bidini, D.A. Ciupageanu, D. Pelosi, Integrating hybrid energy storage system on a wind generator to enhance grid safety and stability: A levelized cost of electricity analysis, J. Energy Storage 34 (November 2020) (2021) 102050, [Online]. Available: https://doi.org/10.1016/j.est.2020.102050.

[49] J. Atherton, R. Sharma, J. Salgado, Techno-economic analysis of energy storage systems for application in wind farms, Energy 135 (2017) 540–552, [Online]. Available: http://dx.doi.org/10.1016/j.energy.2017.06.151.

[50] C. Spataru, Y.C. Kok, M. Barrett, T. Sweetnam, Techno-economic assessment for optimal energy storage mix, Energy Procedia 83 (2015) 515–524, [Online]. Available: http://dx.doi.org/10.1016/j.egypro.2015.12.171.

[51] L. Ren, Y. Tang, J. Shi, J. Dou, S. Zhou, T. Jin, Techno-economic evaluation of hybrid energy storage technologies for a solar-wind generation system, Phys. C 484 (1037) (2013) 272–275, [Online]. Available: http://dx.doi.org/10.1016/j.physc.2012.02.048.

[52] M. Khalid, A.V. Savkin, Minimization and control of battery energy storage for wind power smoothing: Aggregated, distributed and semi-distributed storage, Renew. Energy 64 (2014) 105–112, [Online]. Available: http://dx.doi.org/10.1016/j.renene.2013.09.043.

[53] S. Schoenung, W. Hassenzahl, Long- vs . Short-term energy storage technologies analysis a life-cycle cost study a study for the DOE energy storage systems program, Power Qual. SAND2011-2 (August) (2003) 84, [Online]. Available: http://infoserve.sandia.gov/sand{_}doc/2003/032783.pdf.

[54] M. Bahloul, S.K. Khadem, An analytical approach for techno-economic evaluation of hybrid energy storage system for grid services, J. Energy Storage 31 (2020).

[55] B. Lian, A. Sims, D. Yu, C. Wang, R.W. Dunn, Optimizing LiFePO4 battery energy storage systems for frequency response in the UK system, IEEE Trans. Sustain. Energy 8 (1) (2017) 385–394.

[56] S. Bhattacharjee, P.K. Nayak, PV-pumped energy storage option for convalescing performance of hydroelectric station under declining precipitation trend, Renew. Energy 135 (2019) 288–302, [Online]. Available: https://doi.org/10.1016/j.renene.2018.12.021.

[57] BEIS, Consultation on proposals regarding the planning system for electricity storage, 2019, [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment{_}data/file/770703/electricity-storage-planning-consultation.pdf.

[58] A. Pino, F.J.P. Lucena, J.G. MacHo, Economic analysis for solar energy integration in a microbrewery, in: SEST 2019 - 2nd International Conference on Smart Energy Systems and Technologies, 2019.

[59] C.S. Lai, G. Locatelli, A. Pimm, X. Li, L.L. Lai, Levelized cost of electricity considering electrochemical energy storage cycle-life degradations, Energy Procedia 158 (2019) 3308–3313, [Online]. Available: https://doi.org/10.1016/j.egypro.2019.01.975.

[60] V. Efthymiou, C. Yianni, G. Georghiou, Economic viability of battery energy storage for the provision of frequency regulation service, J. Power Technol. 98 (5) (2018) 403.

[61] S. Koohi-Fayegh, M.A. Rosen, A review of energy storage types, applications and recent developments, J. Energy Storage 27 (November 2019) (2020) 101047, [Online]. Available: https://doi.org/10.1016/j.est.2019.101047.

[62] H. Chen, T.N. Cong, W. Yang, C. Tan, Y. Li, Y. Ding, Progress in electrical energy storage system: A critical review, Prog. Nat. Sci. 19 (3) (2009) 291–312, [Online]. Available: http://dx.doi.org/10.1016/j.pnsc.2008.07.014.

[63] R. Carnegie, D. Gotham, D. Nderitu, P.V. Preckel, Utility Scale Energy Storage Systems, Tech. Rep., Purdue, 2013, [Online]. Available: https://www.purdue.edu/discoverypark/sufg/docs/publications/SUFGEnergyStorageReport.pdf.

[64] F. Meishner, D.U. Sauer, Wayside energy recovery systems in DC urban railway grids, ETransportation 1 (2019) 100001, [Online]. Available: https://doi.org/10.1016/j.etran.2019.04.001.

[65] A. Hutchinson, D.T. Gladwin, Optimisation of a wind power site through utilisation of flywheel energy storage technology, in: Energy Reports, Vol. 6, Elsevier Ltd, 2020, pp. 259–265.

[66] Wind Technik Nord, Wind technik nord 250 kw turbine, 2013, p. 4, [Online]. Available: http://www.rm-energy.co.uk/wp-content/uploads/2013/04/RME{_}WTN250{_}brochure{_}final.pdf.

[67] CarbonBrief, Analysis: Record-low price for UK offshore wind is four times cheaper than gas. [Online]. Available: https://www.carbonbrief.org/analysis-record-low-price-for-uk-offshore-wind-is-four-times-cheaper-than-gas/.

[68] IEA, Informing energy sector transformations, 2017, [Online]. Available: www.iea.org/etp/tracking.