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Techno-Economic Analysis of a Flywheel Energy Storage System performing a Dynamic Frequency Response Service

Andrew J. Hutchinson
Department of Electrical and Electronic Engineering
University of Sheffield
Sheffield, United Kingdom
ahutchinson1@sheffield.ac.uk

Daniel T. Gladwin
Department of Electrical and Electronic Engineering
University of Sheffield
Sheffield, United Kingdom
d.gladwin@sheffield.ac.uk

***Abstract*—Frequency response services are an increasingly essential service to the stability of the UK electrical distribution system. Due to this, it is a prime target for deployment of energy storage systems. This market is currently dominated by conventional Battery Energy Storage Systems (BESSs) due to their maturity as a technology and favorable technical characteristics. Flywheel Energy Storage Systems (FESSs) are not commonly deployed for this service due to their generally high power/energy ratio and traditionally high manufacturing costs, however, the ongoing development of new FESSs with a wide range of technical characteristics and reduced costs presents an opportunity for re-evaluation. Here we show the results of a techno-economic study that identifies an appropriate target power/energy ratio range and necessary target cost (£/kW) for a FESS to be a viable option for providing frequency response services. The study subsequently discusses the techno-economic effects of hybridization of the system with BESS technology providing the framework for further analysis. The results of this study provide potential flywheel manufacturers with the information necessary to develop commercial systems for this application.**

Keywords—flywheel, energy storage, grid storage, simulation

I. INTRODUCTION

Flywheels have been proposed and modelled in a variety of applications to varying degrees of success. [1] and [2] both provide detailed overviews of the current state of Flywheel Energy Storage (FES) research, applications and pilot projects. The key benefit of FES is its high-power density, however, recent entrants to the market have included flywheels that focus on high energy density with a low power/energy ratio, leaving opportunities for flywheels to offer a wider range of services.

National Grid ESO, the UK's system operator, offers a range of services that could be provided by Energy Storage. Firm Frequency Response (FFR) is an umbrella term representing both dynamic and non-dynamic responses to changes in frequency and many of these services are suitable for short term storage. This paper will focus on DFR (Dynamic Frequency Response).

DFR is a service that requires initial delivery from a knee point of +/- 0.015Hz change before full delivery at +/- 0.5Hz which operates post fault to rebalance the system. Figure 1 shows the performance requirements for providing DFR in the UK whilst Fig 2 shows a 5C 1MW Flywheel Energy Storage System (FESS) providing this service. The C-Rate is defined as the rate (in hours) at which an energy store can be fully discharged (for example, a 1C 1MWh energy store will discharge fully delivering 1MW for 1 hour) and is a useful variable to analyze the power/energy ratio of storage systems.

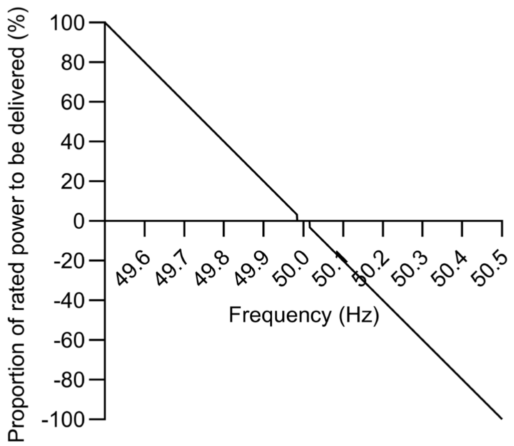

Fig. 1. Response envelope for the UK DFR services showing dead-band between 49.985Hz and 50.015Hz

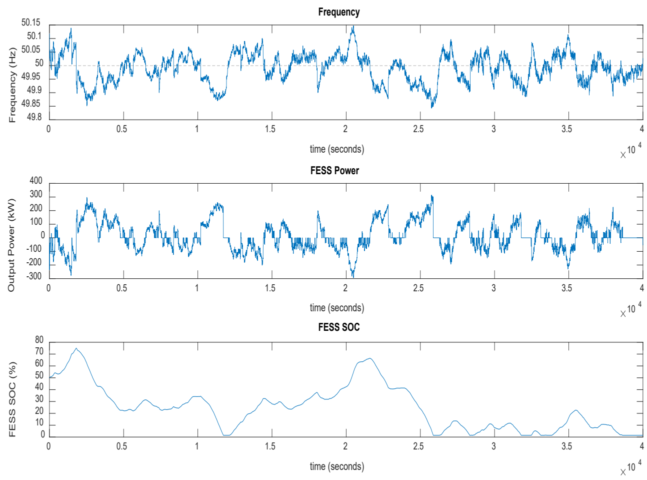

Fig. 2. Frequency, output power and state of charge (SOC) for a 5C 1MW FESS delivering a DFR service.

Frequency regulation in both central grid and microgrid applications has been discussed in many previous studies [3][4][5][6]. The study presented in [6] discusses a FESS installation in New England, USA, along with performance data from the site. A key finding from this test site was the excessive cycling required from the installation with the data

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collected equating to approximately 125,000 full charge/discharge cycles across the operational lifetime. An equivalent electrochemical storage system would have to be replaced multiple times due to is significantly lower cycle lifetime compared to a FESS. A useful area of research would be to develop an economic framework for determining the relative benefits of different storage types within this application.

This paper discusses the techno-economic assessment of both an independent flywheel system and a hybrid FESS/BESS system when performing DFR services on the main UK electrical grid providing novel results on the technical effectiveness of these systems to meet the required performance criteria and the required target capital cost (TCC) to produce a system economically viable for operation in this market.

II. Methodology

The energy storage systems have been modelled using MATLAB/Simulink building upon previous works [7][8] to simulate their performance for providing the DFR service as shown in Fig 1. Both storage systems were modelled using the bucket principle [9] whereby the storage system is viewed as a bucket with energy being move in/out on a second by second basis. Losses in the systems are accounted for and spinning losses in the flywheel are included. The system was simulated operating over a whole year with frequency data taken from the real-life frequency recordings of National Grid ESO in 2019 [10]. This is raw data that already accounts for any existing grid-balancing services procured by National Grid ESO.

Net Present Value (NPV) is a metric which seeks to represent the value of an investment by comparing the current value of cash inflow with the present value of cash outflow [11]. NPV is calculated using a generic formula (1) and offers a standardised method for comparing profitability of an installation which is used widely across different research areas [12]. The return on investment required is controlled by changing the discount rate d, and in the majority of literature reviewed this has been set as 10% for higher risk investment opportunities such as energy storage development [10][11].

C_{inflow} is calculated from an availability payment of £6.03 for each 60-minute period that the system is available more than 95% of the time. In real-world operation you are paid for the agreed contract and expected to deliver 95% of the time while declaring any failures to deliver which could lead to loss of contract.

For the purposes of this study and to allow for comparative analysis, payments are only made for periods where the availability exceeds 95% however current service agreements do not allow for this level of granularity in service assessment. This value was calculated as an average of the availability payments in £/hr/MW recorded by National Grid [15] in 2019. N is the lifetime of the system, $C_{investment}$ is the total capital cost of the system and n is the current year of calculation increasing in increments of 1 from $n=1$ to N. A lifespan of 20 years is the target in this study and d is set to 10%.

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

Table I details different FESSs that are either currently in development or deployed in existing installations and their relevant performance characteristics. Evidently, there is a wide range of technical parameters available for flywheel installations, and this work seeks to identify how these would perform providing DFR services on the UK grid. It will also consider what the target Total Capital Cost (TCC) in £/kW would be to achieve a positive NPV for this scenario.

A thorough study on the life cycle costs of a variety of energy storage systems was conducted in [16] providing a good foundation for cost-comparison studies in this field. It suggests that the average TCC for a FESS was £742/kW (€867/kW) as of 2015. This value is likely to have reduced in the intervening 6 years through technological and manufacturing advancements.

FESS configurations have been assessed by keeping the power rating constant and changing the C-Rate. In the first (FESS-only) analysis the system was matched as a 1MW service with a 1MW FESS with the C-Rate being varied to represent changing energy capacity. The simulations consisted of running a DFR service 24/7 across the year utilizing frequency data from 2019. The C-Rates chosen have been based upon the configurations identified in Table I ranging from 0.25C to 20C and Table II shows a summary of the different configurations used in the analysis.

The second analysis was carried out on hybrid systems, assessing different sizes of Battery Energy Storage System (BESS) combined with a 0.2MWh/1MW/5C FESS. FESS analysis

TABLE I
EXISTING FLYWHEEL MANUFACTURERS AND THE CHARACTERISTICS OF THE PRODUCTS OFFERED

Manufacturer	Technical Specification		
	kWh Rating	*kW Rating*	*C-Rate*
Adaptive	12	250	20
	12	500	40
Energisto	50	50	1
	1000	200	0.2
Vycon	0.5	125	250
Levisys	10	40	4
Amber	32	8	0.25
OXTO	7.5	60	8
Omnes	200	50	4

TABLE II
CONFIGURATIONS OF FESS ANALYZED CONSIDERED IN FESS-ONLY DFR STUDY

		Technical Specification		
		kWh Rating	*kW Rating*	*C-Rate*
FESS Configuration	**A**	4000	1000	0.25
	B	1000	1000	1
	C	400	1000	2.5
	D	200	1000	5
	E	100	1000	10
	F	66	1000	15
	G	50	1000	20

III. FESS-Only Analysis

A. Performance Analysis

The main performance metric for the system is to remain available for response services at least 95% of the time. If the system has no stored energy (0% SOC) then it is not available for export, if it has reached capacity for energy stored (100% SOC) then it is not available for import. Total availability is calculated using equation (2).

$$Availability = \frac{\sum Seconds\ where\ demand\ is\ met}{Total\ number\ of\ operational\ seconds} \quad (2)$$

Fig. 3 shows that for 2019 the 95% target is achieved across all months for configurations A and B whilst failing to reach this for 3 out of 12 months for configuration C. Configuration D maintains an average availability of more than 90% across the year but all higher C-Rated systems fall below the 90% mark meaning they would be less desirable for the DFR service.

Another parameter for assessing the effectiveness of DFR services is the total amount of energy imported and exported from the system as it ties directly to how often the system is responding to the request signal. Fig 4 illustrates how the changing C-rate affects the performance of the system for this metric along with average availability. Configuration A will provide the best performance in this regard, with a steady decrease in energy throughput as the C-Rate is increased (due to their decreasing energy capacity) and this therefore has a large impact on the economic viability of the systems.

From the C-Rate analysis conducted, the range of viable C-Rates for a power-matched system is between 0.25 and 2.5C. However, in terms of imported/exported energy it offers a relatively small benefit in decreasing the C-Rate beyond 1. This also applies to the average availability across the year, with this metric going from 100% average availability for a 0.25C system to 99.18% for a 1C system. The only other system with an average availability above 95% is configuration C which recorded a 95.74% average availability across the year.

Table III shows the results of further performance monitoring tests. There is a clear increase in the number of cycles per year as the C-Rate is increased and with life cycle estimates for existing Flywheels ranging from 100,000 to 500,000+ [17], flywheels at the lower end of this estimate may struggle to provide sufficient lifetime at higher C-Rates.

B. NPV Analysis

The total capital cost ($C_{investment}$ in equation (2)) of the system in £/kW was varied between £200/kW and £900/kW and the performance of the system was simulated keeping the availability payment constant across the specified configurations. The subsequent C_{inflow} value for each configuration and TCC point was used to calculate the overall NPV with the results of this shown in Fig. 5. This figure demonstrates how the NPV changes with variations in TCC and can be used to identify at what price point each system becomes economically viable for providing this service.

A 15C FESS only achieves positive NPV at a target price of below £250/kW whereas a 20C FESS would have to reach a target TCC of lower than £200/kW to achieve a positive NPV. This is not a realistic aim considering the current

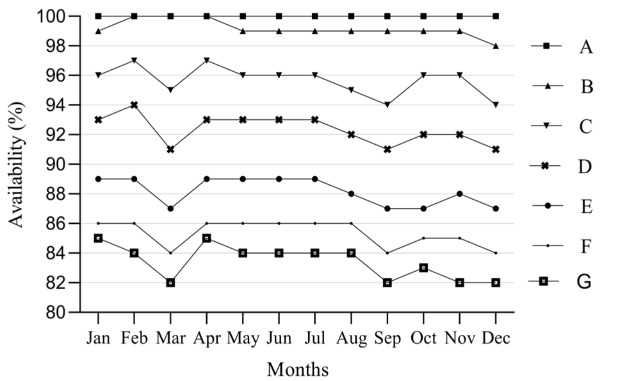

Fig. 3. Availability across the year for varying configurations specified in Table II.

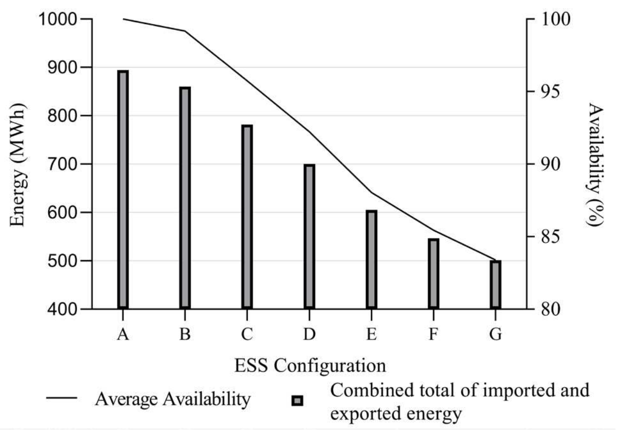

Fig. 4. Availability and energy throughput for varying C-Rates of a 1MW FESS

TABLE III
SELECTED PERFORMANCE STATISTICS FROM FESS-ONLY STUDY

Configuration	Performance Statistics			
	Average SOC	*Cycles per Year*	*Average Import Power (kW)*	*Average Export Power (kW)*
A	77	742	-49.5	52.6
B	61	1322	-46.8	51.5
C	54	2341	-42.4	46.9
D	52	3828	-38.0	42.1
E	51	6292	-32.8	36.4
F	50	8373	-29.7	32.8
G	50	10138	-27.2	30.1

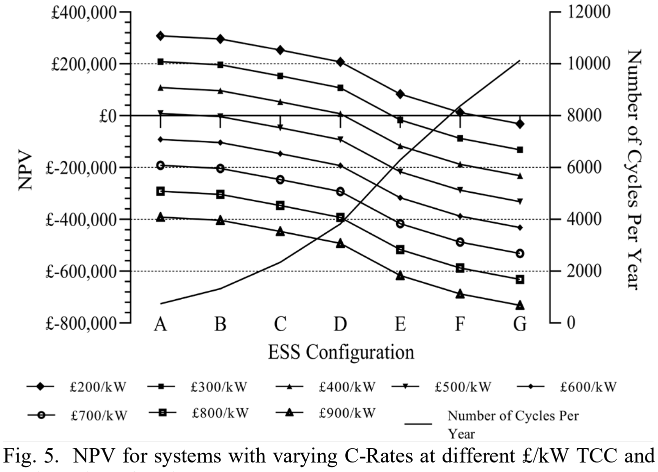

Fig. 5. NPV for systems with varying C-Rates at different £/kW TCC and total number of cycles per year

average £/kW value of £867/kW [16] and therefore these can be discounted from consideration.

At the lower end of the C-Rate scale, the 0.25C and 1C systems both cross the threshold into positive NPV at a similar value in the £550/kW region. This is likely to be achievable as further advancements in flywheel technology are made. More strenuous targets would be the £400/kW threshold for a 5C system which would require more significant advancements to be made.

There is a sizeable decrease in the economic prospects from configuration E to G, and this is mainly due to the rapidly increasing number of cycles leading to a potential for the system not achieving a 20-year lifespan.

The total cycle limit has been set at 100,000 to represent the lowest commonly referred value within the literature and a higher NPV could be achieved for the higher C-Rate systems if this limit were to be increased. From the data collected, once the number of permissible cycles is increased past 200,000 there is no further change in NPV as all systems achieve the specified lifespan of 20 years.

Whilst the 0.25C and 1C FESS both produce promising results with a good technical and economic performance, it is unlikely that these configurations will reach a cost value sufficiently low enough to displace the current market dominance of BESSs. This therefore leaves a likely target range of 2.5-5C aiming for no more than £400/kW to provide a financially viable FESS-only DFR service.

IV. Hybrid Analysis

For this analysis, configuration D performing a 1MW service was hybridized with varying sizes of BESS. Table IV shows the configurations assessed in this section. Consideration has been given to both maintaining the FESS size and introducing additional BESS (configurations I and J) and also partially replacing the FESS capacity with BESS (configurations K, L and M).

The TCC for the FESS was set as £407/kW to baseline the NPV at £0 for this system and a sensitivity analysis performed to see how the NPV changed in relation to this baseline. The cost of the BESS introduced has been taken from the average value determined in [16] of £471/kWh. Any necessary increases in power conversion systems, installation and ancillary services have been accounted for in the costs.

TABLE IV
CONFIGURATIONS OF FESS AND BESS CONSIDERED IN HYBRID DFR STUDY

		Technical Specification					
		FESS			BESS		
		kWh Rating	*kW Rating*	*C-Rate*	*kWh Rating*	*kW Rating*	*C-Rate*
System Configuration	**H**	200	1000	5	-	-	-
	I	200	1000	5	50	50	1
	J	200	1000	5	100	100	1
	K	190	950	5	50	50	1
	L	180	900	5	100	100	1
	M	160	800	5	200	200	1

The cycle capacity for the BESS has been specified as 10,000 as a commonly agreed value within literature. For the purposes of this study, it has been determined that the effect of a cycle for batteries (which is the result of electrochemical ageing) and for flywheels (the result of mechanical ageing) can be compared on a like-for-like basis due to the literature providing good guidelines on what the maximum allowable number of cycles is for each technology is regardless of method of ageing.

The controls for this system consist of the FESS acting like a filter for the requests by attempting to provide the service by itself, with the battery only operating when the flywheel cannot meet the service requests. Fig. 6 shows an overview of the control methodology for the hybrid system and Fig. 7 shows the system performing a DFR service.

A. Hybrid Performance Analysis

The scale of performance increase when introducing a hybrid system is minimal. Whilst there is an increase in both metrics shown in Fig. 8, in both cases it is a relatively small performance boost. The increase in availability is brought about by the increased energy capacity available as soon as the BESS is introduced which in turn leads to an increased overall energy throughput.

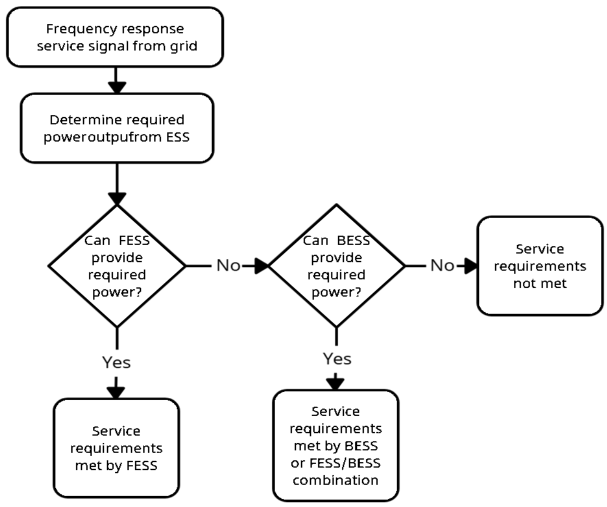

Fig. 6. Hybrid control methodology

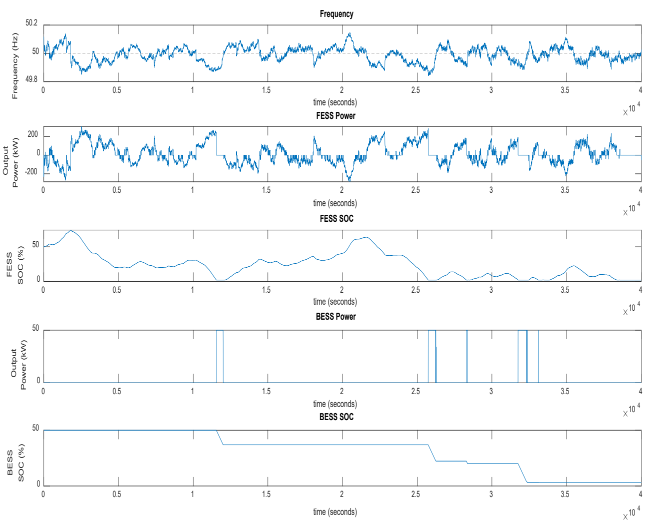

Fig. 7. Frequency, output power (FESS), state of charge (FESS), output power (BESS) and state of charge (FESS) for a 5C 1MW FESS and 1C 0.1MW BESS delivering a DFR service.

Configuration M provides the best overall performance closely followed by configuration J with them achieving average availabilities of 94.08% and 93.98% respectively and increases in total energy throughput of 6.41% and 9.66% respectively. This illustrates how small increases in average availability can represent significant increases in energy throughput.

The remaining performance characteristics are shown in Table V and show a similar pattern of minimal performance benefits from the introduction of a hybrid system.

As the FESS size is reduced, the number of cycles it is exposed to increases, with configuration M expected to complete 89,900 cycles over 20 years. It is clear that further reductions in FESS size beyond that specified in configuration M would likely result in a cycle limit of 100,000 being reached before the specified 20-year lifetime and hence having a potentially significant impact on economic viability.

The number of BESS cycles for all configurations leads to a 20-year cycle expectancy of between 8580 (Configuration J) and 9560 (Configuration M). As with the FES, this is close to the specified cycle limit before system replacement would be required and another significant impact on economic viability. This should be a key consideration when sizing ESS for frequency response services and the balance between the two different ESS mediums cycle capacities that make up the hybrid system should be carefully managed.

B. Hybrid NPV Analysis

When additional BES is introduced to configuration D the overall NPV change is negative as shown in Fig. 9. Referring back to Fig. 8, it is evident that there are only small performance increases achieved through adding a BESS.

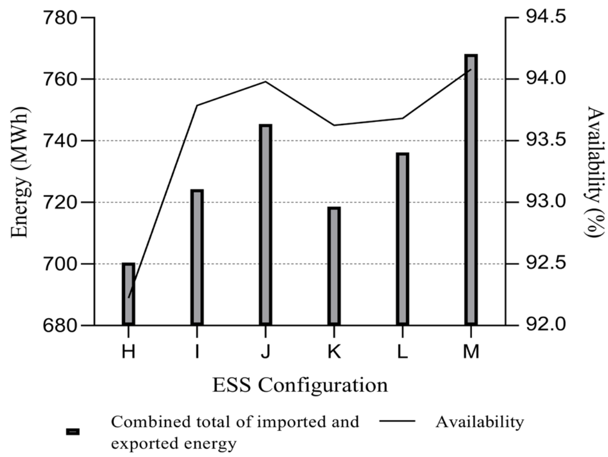

Fig. 8. Performance characteristics for different hybrid configurations

The availability compared to configuration H increases by just 0.57% in configuration I and 0.76% in configuration J which does not increase the availability payments by a sufficient amount to offset the additional cost of installing a BESS.

Comparatively, when sections of the FESS capacity are replaced with BESS there is a notable positive change in NPV. By replacing 5% of the total capacity with BESS there is an overall NPV change of +£14,634 (Configuration K). However, as a higher proportion of BESS is introduced the benefit gets lower and ultimately the NPV change goes negative once again. This is due to the performance of the system already reaching a peak whereby any further replacement of FESS with BESS does not provide a sufficient improvement in performance to outweigh the increasing cost. For example, the TCC increases by £3,153 between

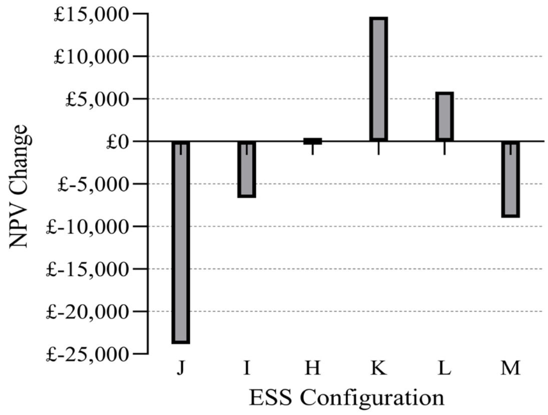

Fig. 9. NPV change for different hybrid configurations baselined to configuration H.

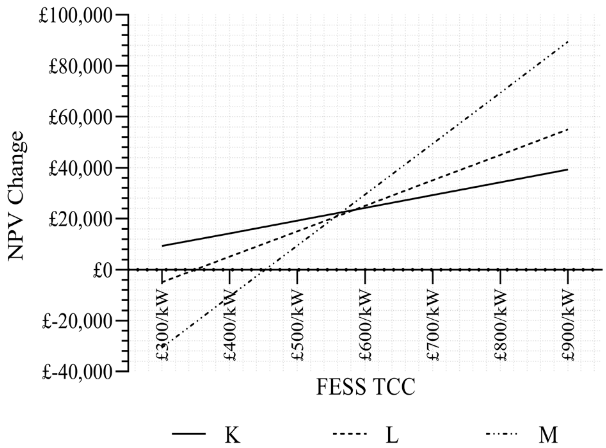

Fig. 10. NPV change for different FESS TCCs

TABLE V
SELECTED PERFORMANCE STATISTICS FROM HYBRID STUDY

	Performance Characteristics					
Configuration	***Average SOC Flywheel***	***Average SOC Battery***	***FESS Cycles***	***BESS Cycles***	***Average Import Power (kW)***	***Average Export Power (kW)***
H	51.82	-	3828	-	-38.0	42.1
I	49.29	47.61	3829	434	-39.4	43.4
J	49.29	48.38	3829	429	-40.6	44.6
K	49.27	47.55	3973	458	-39.1	43.1
L	49.25	48.32	4130	477	-40.1	44.0
M	49.20	48.57	4495	478	-42.1	45.7

configuration K and L whilst the average availability shows only a marginal increase from 93.625% to 93.682%.

Fig. 10 shows how changing the TCC of the FESS changes the impact that hybridization has on overall NPV. At the upper end of the FESS cost scale, there is a greater benefit to be had from introducing a higher proportion of BES such as in configuration M, whilst this higher proportion of BES becomes a disadvantage causing a negative NPV change as the FESS TCC reaches £400/kW. The crossover point at which it becomes detrimental to replace greater amounts of the FESS with BESS is when the FESS TCC reaches £583.86.

Conversely, when the FESS cost reaches the lower end of the scale, replacing a small proportion of it with BES can lead to a positive NPV change although overall the lower FESS:BESS ratio is less sensitive to changes in FESS TCC.

V. CONCLUSION

In [18] the average TCC for a FES installation is given as £749/kW (€867/kW). IRENA (International Renewable Energy Agency) predicts that the cost of installing a FESS will fall by approximately 35% through 2030 leading to an estimate of £486/kW by that time. Based on the results of the study undertaken in this paper, that value would need to reach £400/kW or lower before the flywheels in the sub-5C region became economically viable for DFR, representing over a 50% reduction over the coming years.

Of the flywheel configurations studied, C-Rates up to 5C present an adequate performance capability in terms of average availability across the operational period. When considering higher C-Rates it is likely that supplemental energy storage with a higher energy capacity would be required to provide an acceptable service.

The lower energy capacity of flywheels can be rectified by using them in tandem with more energy-centric forms of storage such as batteries. There is a small but noticeable increase in system performance when combining the two energy storage mediums and a positive NPV change in certain scenarios is achievable. The value of a hybrid ESS system is however highly dependent on the ratio of cost between the two energy storage mediums and the balance in cycle numbers relevant to the cycle capacity of the different systems.

VI. REFERENCES

[1] M. E. Amiryar and K. R. Pullen, "A review of flywheel energy storage system technologies and their applications," *Appl. Sci.*, vol. 7, no. 3, 2017, doi: 10.3390/app7030286.

[2] A. A. K. Arani, H. Karami, G. B. Gharehpetian, and M. S. A. Hejazi, "Review of Flywheel Energy Storage Systems structures and applications in power systems and microgrids," *Renew. Sustain. Energy Rev.*, vol. 69, no. September 2015, pp. 9–18, 2017, doi: 10.1016/j.rser.2016.11.166.

[3] N. Hamsic *et al.*, "Increasing renewable energy penetration in isolated grids using a Flywheel Energy Storage System," *POWERENG 2007 - Int. Conf. Power Eng. - Energy Electr. Drives Proc.*, pp. 195–200, 2007, doi: 10.1109/POWERENG.2007.4380112.

[4] R. Takahashi and J. Tamura, "Frequency control of isolated power system with wind farm by using flywheel energy storage system," *Proc. 2008 Int. Conf. Electr. Mach. ICEM'08*, 2008, doi: 10.1109/ICELMACH.2008.4800025.

[5] A. A. Roya, F. Ghardashi, D. Kabiri, A. Sheykholeslami, and H. Haeri, "Voltage and frequency control in smart distribution systems in presence of DER using flywheel energy storage system," *IET Conf. Publ.*, vol. 2013, no. 615 CP, pp. 10–13, 2013, doi: 10.1049/cp.2013.1172.

[6] M. L. Lazarewicz and T. M. Ryan, "Integration of flywheel-based energy storage for frequency regulation in deregulated markets," *IEEE PES Gen. Meet. PES 2010*, pp. 4–9, 2010, doi: 10.1109/PES.2010.5589748.

[7] A. Hutchinson and D. T. Gladwin, "ScienceDirect Optimization of a Wind Power site through utilization of Flywheel Energy Storage Technology," vol. 00, 2019.

[8] A. J. Hutchinson and D. T. Gladwin, "Sensitivity analysis of a wind farm with integrated flywheel energy storage," *Proc. IEEE Int. Conf. Ind. Technol.*, vol. 2020-Febru, pp. 549–553, 2020, doi: 10.1109/ICIT45562.2020.9067176.

[9] T. Simpkins and C. O. Donnell, "Optimizing Battery Sizing and Dispatching To Maximize Economic Return," *Battcon Station. Batter. Conf.*, no. May, pp. 1–14, 2017, [Online]. Available: www.battcon.com.

[10] National Grid ESO, "Historic Frequency Data," 2021. https://www.nationalgrideso.com/balancing-services/frequency-response-services/historic-frequency-data (accessed Feb. 14, 2021).

[11] X. Yan, C. Gu, F. Li, and Q. Ai, "Cost-benefit Comparison of Different Techniques for Addressing Wind Curtailment," *Energy Procedia*, vol. 142, pp. 1759–1764, 2017, doi: 10.1016/j.egypro.2017.12.560.

[12] C. Diyoke, M. Aneke, M. Wang, and C. Wu, "Techno-economic analysis of wind power integrated with both compressed air energy storage (CAES) and biomass gasification energy storage (BGES) for power generation," *RSC Adv.*, vol. 8, no. 39, pp. 22004–22022, 2018, doi: 10.1039/c8ra03128b.

[13] IEA, "Projected Costs of Generating Electricity," p. 215, 2015, [Online]. Available: https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf.

[14] S. Schoenung, "Energy storage systems cost update: a study for the DOE energy storage systems Program," *Sandia Natl. Lab. DE-AC04-94AL85000*, no. January, pp. 1–30, 2011, doi: SAND2011-2730.

[15] National Grid ESO, "Firm Frequency Response (FFR) Post Tender Reports," 2021. https://data.nationalgrideso.com/ancillary-services/firm-frequency-response-post-tender-reports (accessed Mar. 09, 2021).

[16] B. Zakeri and S. Syri, "Electrical energy storage systems: A comparative life cycle cost analysis," *Renew. Sustain. Energy Rev.*, vol. 42, pp. 569–596, 2015, doi: 10.1016/j.rser.2014.10.011.

[17] F. Goris and E. L. Severson, "A review of flywheel energy storage systems for grid application," *Proc. IECON 2018 - 44th Annu. Conf. IEEE Ind. Electron. Soc.*, vol. 1, pp. 1633–1639, 2018, doi: 10.1109/IECON.2018.8591842.

[18] IRENA, *Electricity storage and renewables: Costs and markets to 2030*, no. October. 2017.