Economic conditions for the provision of a seasonal energy storage service in the UK

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***Abstract*—The provision of a seasonal energy storage service in Great Britain has been identified as a priority for creating a viable environment for the deployment of long-duration energy storage technologies. Many prominent technologies are well positioned to deliver such a service but there has been minimal research conducted into how to ensure that this is economically viable. This first-of-its-kind study analyses how a seasonal energy storage service could be structured, and the effect of different economic parameters on the viability of different technologies being deployed to deliver it. It is shown that of the most prominent storage technologies, Compressed Air Energy Storage, Gravity Energy Storage and Pumped Hydro Storage are the best positioned for delivering a seasonal energy storage service within current techno-economic parameters. For a 3-month storage period, the lowest service fee determined for viable economic performance is £1,350/MWh for a Compressed Air system whilst for a 1-month storage period both Pumped Hydro and Compressed Air systems would require a service fee below £500/MWh.**

I. INTRODUCTION

Seasonal energy storage (SES) has been extensively discussed in the UK but with few firm proposals for implementation. It has been suggested that more than 10TWh of SES, and greater than 100TWh for inter-year storage will be required to replace natural gas for power system balancing [1]. The UK government has set several carbon emission-related targets in recent years, with the most prominent of these being reaching net zero by 2050 [2].

The current electricity generation mix in the UK still retains a prominent mix of carbon-intensive generation, where gas accounted for 32% of overall electricity generated in 2023 [3]. This factor combined with high levels of wind curtailment shows the growing need to store excess renewable energy for usage in the future, rather than paying for this energy to be curtailed [4].

This paper looks at the currently proposed strategies for the deployment and operation of SES in the UK and provides an overview of five technologies that can operate in the required timescales. The initial results of an economic analysis are then presented, investigating the feasibility of a proposed seasonal storage service that would time-shift electricity generation by timescales greater than 1 month. This study provides the methodology and foundational results for more complex investigations taking into account further variables and deployment strategies.

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A. Existing Policy

The majority of literature regarding SES focuses on the technical aspects of its deployment or highlights the requirements for its introduction, with no research yet conducted on how providing an SES service could be achieved.

This paper concentrates on reviewing the currently published policy for SES in the UK to provide context for the future requirements of such a service as well as providing some context around the current outlook for the deployment of SES.

The work in [5] describes many of the issues facing the electricity network in Great Britain. It highlights that the wind and solar resources are unevenly distributed throughout the network, potentially causing further transmission congestion. Crucially, it describes the current issues facing SES, namely that they are capital-intensive (requiring very high initial investment costs) and lack of long-term contracted revenue streams. The question of how these revenue streams can be developed in the form of seasonal storage services is the basis of the work in this study.

The report in [6] discusses the fact that existing markets are unlikely to be able to support the scale of SES that will be required for a net zero grid. It highlights that the resolution of this issue is critical to ensuring that large-scale storage is deployed within the required time frame.

Finally, the lack of clarity in existing and future markets for SES is highlighted in the responses to the government call for evidence on long-duration electricity storage [7]. Once again, the key barriers to the deployment of this technology are stated as a lack of market signals and revenue certainty, along with the high upfront capital costs and long lead times. Additionally, the lack of a market for this category of storage that can monetize the specific benefits it can bring is highlighted.

TABLE I
AVERAGE VALUES FOR THREE KEY SES CHARACTERISTICS ACROSS STUDIED LITERATURE

	CAES	H_2ES	PHS	TES	GES
RTE (%)	65	40	75	38	80
Lifetime (Years)	29	18	53	19	30
Self-Discharge (%/day)	0.5	0.01	0.01	0.35	0

From the literature reviewed, there is significant interest from all major stakeholders to identify possible ways to provide revenue and market certainty for SES. This study will look at how this could be addressed through the proposal of a SES service, and the economic parameters that would be required to make such a service viable to asset owners.

B. Novel Contribution

This paper provides details on the first research conducted into the feasibility of SES being deployed to provide an inter-month storage service in the U.K. The novel methodology presented here will form the basis of complex further studies and provides foundational results that show for the first time the economic conditions that would facilitate deploying SES for this application.

C. Technology Overview

This paper covers five storage technologies capable of providing the durations of storage required by SES. These consist of Hydrogen Energy Storage (H_2ES), Thermal Energy Storage (TES), Compressed Air Energy Storage (CAES), Pumped Hydro Storage (PHS) and Gravity Energy Storage (GES).

A literature review was conducted on the three technical characteristics considered most relevant to storing energy for durations over 1 month, namely round trip efficiency (RTE, %), operational lifetime, and self-discharge rate per day (%). The results of this literature review are shown in Figure 1 which illustrates the significant variation in stated characteristics for these technologies. The average values across the literature reviewed are shown in Table I.

In terms of the lifetime of the system, PHS significantly exceeds the lifetime of the other energy storage technologies with a minimum stated lifetime of 30 years. There is significant variation in the stated lifetime for all of the SES technologies, most of all TES which ranges between 5 and 40 year lifetimes.

GES is quoted throughout literature as having no self-discharge, something which sets it apart from the other SES technologies. However, both PHS and H_2ES are subject to very small self-discharge rates compared to that of TES and CAES, which are both quoted as having a high self-discharge rate of up to 1% a day.

Finally, in terms of round-trip efficiency PHS, GES and CAES all peak at similar values. However, CAES is also sometimes described in literature as having a relatively low efficiency. The SES with the highest degree of commonality across the literature is GES which ranges between 75% and 85%. Both H_2ES and TES are described as having low efficiencies.

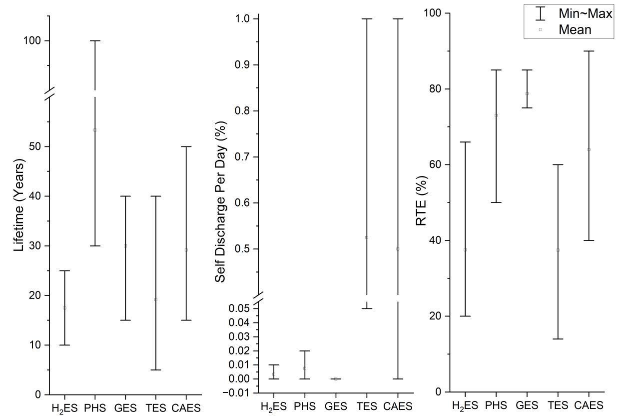

Fig. 1. Range of values for stated characteristics within literature a) Lifetime in years b) Self-discharge per day (%) c) Round trip efficiency (%) [8][9][10][11][12][13][14]

II. SEASONAL ENERGY STORAGE AS A SERVICE

It is clear from the literature review and government policy recommendations that a SES service is likely to be required and developed in the near future. However, the key question that arises is how to design such a service so that it remains attractive and profitable to asset owners.

There are many markets available to energy storage asset owners, from arbitrage to frequency response. These markets represent a certain level of revenue that asset owners would be unable to access if they were contracted to store energy for longer durations. One approach to determining the economic conditions of providing SES is to analyse the 'lost revenue' of not engaging in these markets. However, this approach would only reflect a snapshot of the time in which the analysis was performed, and as markets change this could result in a service that becomes too expensive to the system operator, or not lucrative enough to the asset owner. Between February 2023 and January 2024 the average revenue for a BESS operating in the UK markets was £46,414/MW/year [15]. This value is on a per MW basis, so could represent any size of BESS installation. This value is useful as an indicator of whether the proposed service fee would generate too low or too high levels of revenue compared to the existing battery market.

The study in this paper looks at the economic criteria from a different perspective. Based on current and predicted prices for the five energy storage technologies discussed previously, this work analyses what level of payment would be required for different durations of seasonal storage to provide a positive economic outlook for the deployment of these technologies.

A. Methodology

The costing information (specifically investment cost in £/MWh and O&M costs in £/kW) for this study are taken from [16] with values detailed in Table II. The average exchange rate for 2022 is used to convert from USD to GBP [17].

For this initial study, 2022 values were utilised to illustrate the present scenarios for the deployment of SES. This provides

TABLE II
COSTING VALUES USED IN THIS STUDY [16]

	CAES	H_2ES	TES	PSH	GES
Investment Cost ($/kWh)	112	295	215	221	266
O&M Costs ($/kW)	9.82	16.89	24.15	15.59	17.77

the baseline for future studies utilising the 2030 values detailed in the same report. This study only considers 1,000MW (10,000MWh) installations. This is done with the view that any installation that is chosen to provide an SES service should be able to provide a significant contribution to the total system demand. However, the calculation tool developed as part of this work does provide the option for analysing 100MW systems and this will form a part of future analysis.

Additionally, in this study, it is assumed that the SES installation cannot participate in any other grid services whilst participating in the SES service.

Yearly gross profit is calculated using Equation 1 where S_f is the service fee in £/MWh, E_c is the energy storage capacity in MWh, η is the round trip efficiency, t_st is the storage duration in days and U_f is the utilisation factor. The cost of recharging the system to correct for self-discharge is given in Equation 2 where L_d is the % of capacity lost to self-discharge each day and C_en is the cost of purchasing energy to charge the system. The ongoing yearly operation costs are calculated using Equation 3 where $C_\mathrm{O\&M}$ is the yearly O&M costs per kW and P_c is the rated power of the ESS in kW. Finally, the yearly gross profit is calculated using Equation 4.

$$C_{revenue} = S_f E_c (\frac{365}{t_s}) 0.5 \eta U_f \tag{1}$$

$$C_{recharge} = \frac{L_d t_s E_c C_{en}}{0.5\eta} \tag{2}$$

$$C_{costs} = (C_{O\&M} P_c) \tag{3}$$

$$C_{profit} = C_{revenue} - C_{recharge} - C_{costs} \tag{4}$$

In these calculations, the round trip efficiency value is multiplied by 0.5 as only the discharged power is considered within this equation, and it is assumed that when the SES is charged up as part of the service it charges to full capacity as part of the service fee.

In this study, it is assumed that any energy lost through self-discharge is replaced by purchasing additional energy to recharge. In practice this would be part of a cost-benefit analysis to buy energy to recharge at its cheapest point, however for this study a constant value of the average day-ahead price of £99.80/MWh between February 2023 and January 2024 has been utilised [18]. Future studies will analyse the effect of optimal trading on the economics of this service. The values for self-discharge and efficiency are taken from the average values in the literature previously discussed in Table I. It is expected that the installation would be contracted to discharge the energy continuously at a C-Rate determined by the grid operator. For example, the installation would be informed at the time of discharge of the C-Rate they should discharge at, but the end result would always be the full dissipation of energy stored within the asset.

The utilisation factor represents the ratio of time that the SES is operating the service, where a U_f value of 1 would represent the system operating the service constantly with no downtime between subsequent storage periods. For this study, this value has been set to 0.9 to represent short periods of downtime between periods of delivery.

The two key variables which represent the design of the service are the storage duration (t_s) and the service fee (S_f). The service fee is varied between £100-£5,000/MWh to provide context for the required service value that would create a positive economic use case for SES. The storage duration can be varied to illustrate the effect that different durations beyond 1 month have on the financial viability of the system.

This value for yearly gross profit is then used to determine the payback period for each technology with respect to the lifetimes previously discussed in Table I. The payback period achieved is compared with the predicted lifetime of the system across the range of service fees.

B. Results

In this section, analysis is performed on several variables to provide a baseline assessment of the suitability of different SES technologies for the provision of a SES service.

Firstly, the estimated yearly revenue (from Equation 1) for each system is calculated, as shown in Figure 2. This initial assessment is conducted using a storage duration of 3 months (t_st = 90). The service fee was varied between £500/MWh and £4,000/MWh to illustrate the range of values over which each technology becomes economically viable.

Of the five technologies studied, TES is the least economically viable. At the highest service fee analysed it generates the lowest revenue of the five technologies studied. This is due to the poor round-trip efficiency and high self-discharge rate.

Conversely, CAES, GES and PSH all perform similarly with little variation in results between the three technologies. GES performs the best of all the technologies studied in this regard, a result of having no self-discharge and a high round trip efficiency. Interestingly, despite CAES having a relatively high self-discharge rate the fact that it has a good round-trip efficiency means it still provides a high level of revenue.

Table III shows the level of service fee that would be required for each technology to achieve the levels of revenue currently achieved by battery energy storage in the UK. For all technologies to be able to be deployed at the average level, the service fee would need to be set to approximately £2,050/MWh. However, a service fee of £1,600/MWh would allow PSH, GES and CAES to be competitive in this regard.

Any service designed for SES will need to take into account the balance between ensuring that multiple technologies can participate, whilst also ensuring that the value of the service is not excessively high and over-valued. Based on the results so

TABLE III
SERVICE FEE (£/MWH) REQUIRED FOR DIFFERENT SES TECHNOLOGIES TO MATCH AVERAGE BATTERY REVENUES FROM 2023

	CAES	H_2ES	TES	PSH	GES
Service Fee (£/MWh)	1600	1850	2050	1500	1450

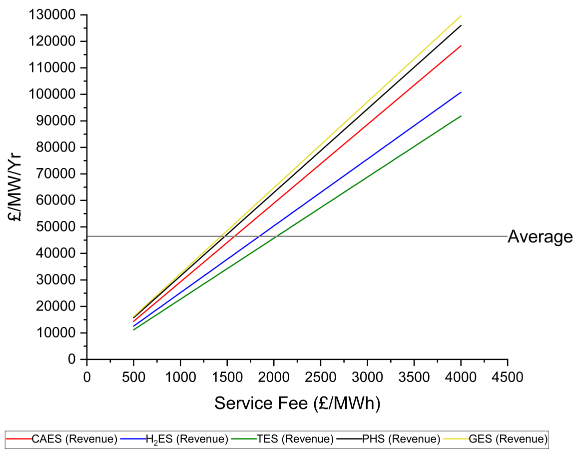

Fig. 2. Estimated yearly revenue (when t_{st} = 90) for different SES technologies and a power rating of 1000MW, with average battery revenue for 2023 included for reference

far, a service fee of £2,050 would likely result in a competitive market.

Two service durations will be analysed in this section, a 1-month duration and 3-month duration. This can have a significant impact on the viability of different technologies due to varying self-discharge rates, and this section highlights the challenges associated with longer service durations.

The payback period for varying service fees and a 1-month storage duration is shown in Figure 3. With a 1-month storage duration the payback period for all systems is positive, with all of them falling below their stated lifetime at less than £1,900/MWh service fee. The CAES system performs the best, starting at less than a 25 year payback period and falling rapidly as the service fee is increased. The H_2ES system is the worst performing, although it still performs well overall. These results suggest that if a service was designed for 1-month durations then deployment in this application would be viable for the whole range of technologies studied.

For a 3-month service duration however, the results are less positive. Figure 4 shows the payback period in this scenario, where it can be seen that the CAES system is now the only technology that achieves a payback period of less than 14 years. The service fee required for each technology to pay back the investment within their stated lifetime from literature is shown in Table IV. For both the TES and H_2ES systems they will not reach pay back their investment at a service fee within the range studied. The CAES and PHS systems both pay back within the stated lifetime for service fees lower than £1,450/MWh whilst for GES this value is £2,600/MWh. The common factor for these three technologies is that they have

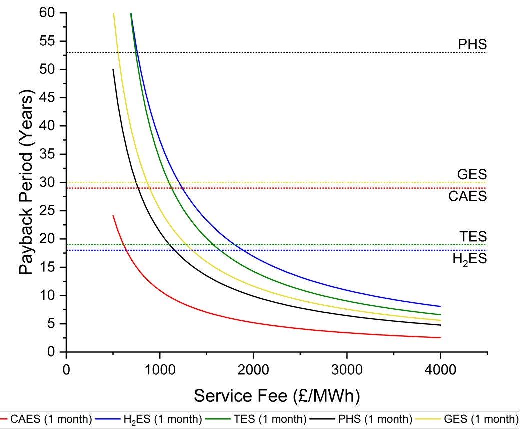

Fig. 3. Payback period for varying service fees when storage duration is 1 month with reference lines for approximate technology lifetime from literature

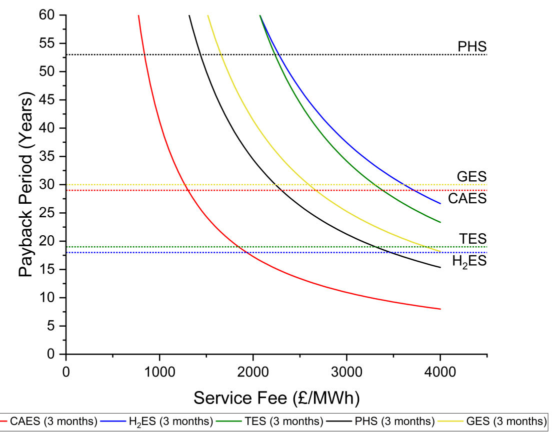

Fig. 4. Payback period for varying service fees when storage duration is 3 months with reference lines for approximate technology lifetime from literature

longer predicted lifetimes than TES and H_2ES systems.

Overall, it is likely that for a SES service to be a viable application for all technologies the storage duration would need to be as low as possible. However, this does contrast against the objectives for seasonal storage services to store energy for longer periods of time. From the analysis provided in this initial study, CAES, GES and PHS are the most relevant candidates for deployment in this application.

Finally, Figure 5 shows the payback period for 100MW

TABLE IV
SERVICE FEE (£/MWH) REQUIRED FOR DIFFERENT SES TECHNOLOGIES TO PAY BACK INVESTMENT WITHIN THEIR AVERAGE LIFETIME FROM LITERATURE FOR VARYING STORAGE DURATIONS

	CAES	H_2ES	TES	PSH	GES
1 Month	<500	1900	1600	<500	900
3 Months	1350	>4000	>4000	1450	2600

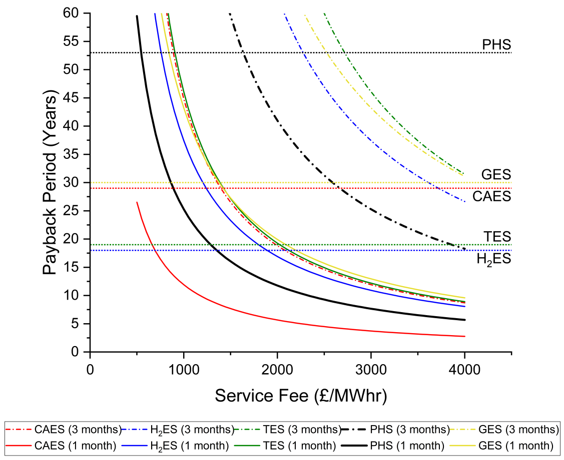

Fig. 5. Payback period for 100MW systems with varying service fees and storage durations with reference lines for approximate technology lifetime from literature

systems, rather than the 1000MW systems discussed throughout this study. For all technologies and storage durations, the payback period is longer than that of a 1000MW system, and the service fee at which they pay back within their stated lifetime is increased. This highlights the fact that for this application, larger systems are more viable whereas for a smaller system, the decreased investment costs are outweighed by reduced revenue. This provides an indication for the potential of further work exploring the different scales of installation and the economic conditions required for them to be viable.

III. Conclusion

This paper has presented the initial results of a study to determine the economic parameters required to establish a SES service that would be viable for delivery by a range of long-duration storage technologies.

Overall, the preliminary results show that CAES, GES and PHS systems are the most likely technologies to be viable for deployment to deliver such a service. The technical characteristics that restrict the suitability of the technologies has been established, namely the fact that systems with high self-discharge rates, low efficiency and high O&M costs will struggle to be competitive for this service. This provides key information on the aspects that require further research and development to improve these systems.

For a 1-month service, both CAES and PSH will pay back the investment within their stated lifetime at service fees below £500/MWh, whilst the highest service fee required is H_2ES at £1,900/MWh. For a 3-month service, CAES achieves the lowest service fee at £1,350/MWh, with both H_2ES and TES requiring service fees in excess of £4,000/MWh.

Future work will expand upon the foundations built in this study, specifically looking at expanded sensitivity analysis on technical characteristics, and an exploration of the effect of using 2030 predicted capital costs on the economic outlook. It will also explore the different conditions required when smaller-scale installations are considered and the benefits of targeted trading to restore energy lost through self-discharge.

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