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Evaluation of a battery energy storage system in hospitals for arbitrage and ancillary services

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ABSTRACT

The ambitious target of reaching net-zero greenhouse gas emissions by 2050 in the UK, which includes the decarbonisation of heat and electricity, means the increase of instantaneous power from non-dispatchable renewable energy sources (RESs). The intermittency of RESs will cause stability issues for the grid resulting from the mismatch between generation from RES and load demand. Battery energy storage systems (BESS) can match loads with generation and can provide flexibility to the grid. This study is proposing the health sector as a new flexibility services provider for the grid through BESS. The health sector has large loads that run throughout the year, and by managing this load it can provide flexibility to the grid. Four different scenarios have been evaluated for a range of behind-the-meter (BTM) BESS for a hospital in the UK to provide arbitrage and ancillary services considering the option of installing a photovoltaic (PV) system. It was found that BESS would not be economically viable through arbitrage alone since the payback period was always greater than the BESS lifetime. However, bundling services by participating in the ancillary services market resulted in payback periods as low as 3.10 years for some systems, and the net present value (NPV) could reach more than £5 million. This work provides evidence that the health sector can be a significant player in the transition to a renewables-led energy system, an exemplar for other sectors, and one of the solutions to recovery from the COVID19 pandemic.

1. Introduction

1.1. Context of the work

In 2019, the United Kingdom (UK) set a target of net-zero greenhouse gas emissions by 2050, which made it the first major economy to bind to this target legally [1]. On average in the first three quarters of 2020, renewable electricity contributed to 37.1% of the total electricity generation in the UK, and this contribution was 47.2% for the first quarter, 44.4% in the second quarter, and 40.2% in the third quarter of 2020 [2]. Northern Ireland (NI), as one of the four countries of the UK had a target to achieve 40% of its electricity from renewables in 2020, which was overachieved with 47.7% at the end of the third quarter in 2020 [3]. The major variable renewable energy sources (RESs) are wind and solar photovoltaic (PV). Wind meets 35% of total NI electricity demand, and the connected wind capacity is 1.30 GW which is divided into 1.155 GW (90.5% of total wind) connected to the distribution network (DN) and only 0.12 GW (9.5% of total wind) connected to the transmission network. Current connected solar PV capacity is 0.27 GW [4]. Wind and PV contribute to 92 % of the total RES capacity, both of which are non-dispatchable resources. As Fig. 1 shows, NI minimum system demand during the last three years (between 2018 and 2020) varied between 0.37 GW and 0.44 GW, and the maximum system demand for the same period varied between 1.52 GW and 1.65 GW, while wind generation maximum power varied between 0.99 GW and 1.01 GW [5]. As shown in Fig. 1, instantaneous wind power can exceed the total demand in NI. During 2020 wind power penetration reached 119% of NI demand.

NI as a part of the island of Ireland has the highest level of instantaneous system non-synchronous penetration (SNSP) of 70%, higher than any other electrically isolated grid in the world. SNSP is defined as the ratio of non-synchronous power generation (such as wind and PV) expressed as a percentage of total system demand [6]. SNSP will be increased to 90% in 2030 [7]. In the future, other power systems across the globe will need to manage their power systems with levels of SNSP similar to the Irish system, in order to meet their emission targets. Power

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systems that have similarity in the market size, the geographical scale, and the limitation of interconnection can found in other places like in Singapore, Tasmania and New Zealand, but none of them has that level of non-dispatchable generation compared to the Irish power system [8].

Despite this success, in 2020, up to the end of September 16% of the available wind generation was dispatched down; 8.8% as curtailments (due to power system limitations like inertia limits); 7.2% as network constraints (network limitations) [5]. Table 1 shows some statistics related to the demand and to wind energy in NI between 2018 and 2020. In 2020, with 16.04% dispatched-down wind energy for the first three quarters, this was the highest percentage of the lost energy when compared to the full period between 2018 and 2020. As a result, 355 GWh from wind energy was available but could not be used. Assuming an average retail tariff of 0.10 £/kWh, the loss is 35.5 M£ only for the first three quarters in 2020. Wind capacity was the same for the last three years (2018-2020), but in general, total system demand declined. The increased dispatch-down in 2020 is partly a result of the closure of a range of facilities during to the lockdown after the COVID19 outbreak [9].

To be able to achieve 90% SNSP target in 2030, to reach net-zero target in the UK by 2050, and to avoid more lost clean electricity, the NI power system requires more flexible demand. The existing sources of flexibility within the power system mainly come from ancillary and capacity services from large centralised, shareholder-owned assets. This work discusses how NI is an ideal place to incentivise new demand-side providers of flexibility services to the power system, mainly focusing on the health sector.

Hospitals within the public sector are one of the centres of attention for communities and can be leaders in the transition towards a lower CO_2 emission future. Public hospitals can have a widespread impact on the public by encouraging the deployment of new technologies [10]. Worldwide, 4.4% of greenhouse gases come from the health sector, and in the UK itself, 5.4% of the total emissions are from the health sector [11]. More than 33% of public sector emissions comes from the UK National Health Service (NHS), which stands for the highest share among other public sector parties [12]. According to the Climate Change Act, the UK had to reduce its CO_2 emissions by 34% in 2020 against the 1990 baseline [13]. NHS as part of the UK public sector, was part of the CO_2 reduction plan and succeeded in decreasing the CO_2 emissions by 19% between 2008 and 2018 [14]. In addition, the health sector will be able to gain another benefit from reducing its CO_2 footprint, which is the reduction of the greenhouse gases (GHG) that negatively affect human health, consequently, this will reduce its operational costs by reducing the hospital admissions related to respiratory issues.

The health sector in NI consumes 182 GWh annually and is considered the second largest electricity consumer after the water sector, with 2.3% of the total electricity consumption. Hospitals are considered one of the most energy-intensive facilities and contribute to the climate change issue [15], since patients are in continuous need of controlled ambient temperature (heating and cooling), in addition to the need for high standards of indoor air quality, the lighting of large areas, and the power needed for health equipment [16]. By flexing its large demand for power, the health sector has potential to help communities to mitigate the risk of climate change and its adverse effect on human health.

Table 1
NI wind capacity, wind generation, and annual wind dispatch-down for the period between 2018 and 2020.

Year	2018	2019	2020
1. Year Total Dispatch- Down (Constraints and Curtailments)	9.41%	10.68%	16.04% (End of September)
1.1 Constraints	4.02%	4.71%	7.22%
1.2 Curtailments	5.39%	5.97%	8.82%
2. Wind Installed Capacity (MW)	1,276	1,276	1,276
3. Wind Generation (GWh)	2,391	2,462	2,357 (End of November)
4. NI Total System Demand (GWh)	8,100	7,895	6,791 (End of November)

Some studies have addressed flexibility services provision in NI from batteries within the Social Housing sector to provide ancillary services [17], since NI has large scattered rural areas resulting in a long transmission and distribution networks. Since hospitals also have large loads connected to the DN, and 90.5% of the wind power which is responsible for more than one third of total NI demand is also connected to the same stringy and long DN, there is great potential for hospitals to be a new player as a flexibility provider for the power system, to reduce the curtailment of clean energy from RES and to be part of achieving net zero emissions reduction targets.

1.2. Literature review

Batteries are frequently found within the health sector as part of the electrical power system in hospitals, and they are mainly employed for two kinds of applications: hybrid systems and resilience. A BESS within a hybrid electrical systems are used for load and generation management, cost management, and CO_2 reduction. These hybrid systems can exist in on-grid systems and off-grid systems. Since on-grid hospitals are connected to the low voltage distribution network, and they can have distributed generation including RES, diesel generators (DG), and BESS, they can operate as microgrids (μGs) that have the ability to operate in grid-connected mode or islanded mode. The second application is for resilience of the electrical power supply in hospitals, providing a backup power source in case of grid failure. Resilience is very important in hospitals, since they are facilities with critical loads that can stand between life and death. BESS already exist within hospitals as a source of backup power or as starters for the backup DG. Some studies have which have addressed these applications of BESS in hospitals are examined here.

A hybrid system was proposed and techno-economically optimised

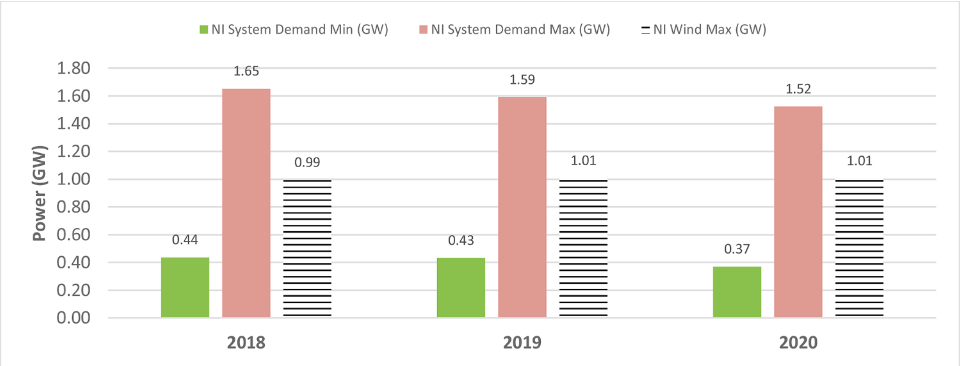

Fig. 1. NI electrical system demand Vs wind power between 2018 and the end of November 2020.

for a stand-alone district hospital consisting of PV, wind turbine and BESS [18]. Another stand-alone hybrid system consisting of PV, DG and BESS was economically optimised for a hospital by finding the lowest net present cost (NPC) [19]. A stand-alone hybrid μG hospital which included BESS and PV was analysed to optimise the cost of energy, the net present cost of the system and CO_2 emissions [20]. For a mobile off-grid hospital, a hybrid system consisting of PV, DG, and BESS is proposed to supply its electrical load instead of using DG alone, or DG with BESS [21]. The optimisation variables were weight minimisation, cost minimisation only, and both cost and weight minimisation. It was found that the lowest levelized cost of energy (LCOE) for medium and large off-grid hospitals is for a hybrid system that includes RES, BESS, and DG.

BESS can be combined with RES in grid-connected hospitals to take advantage of battery incentives and to have a viable investment with a short payback period [22]. Using BESS with RES, an additional profit and shorter payback period can be achieved in the future when CO_2 credit schemes are available, which incentivises the system for reduction in CO_2 emissions.

In grid-connected hospitals, BESS can do peak shaving and can cover the hospital loads in the case of grid connection loss [23]. A hybrid system comprising a PV system, battery, and fuel cell was assessed for a hospital as a grid-connected μG [24]. The battery bank is used to store excess generation from PV, and the stored energy could either be used as an emergency backup in case of grid fault or to be sold with a feed-in-tariff (FIT) revenue scheme to provide additional income.

The resilience of a microgrid (μG) in a public hospital was studied to ensure the electrical power supply for critical loads in surgery rooms and a drug store [25]. The hybrid system in the μG which consisted of PV system, Li-ion batteries, and DG was optimised for both resilience and economics. In normal grid operation, the imported energy was reduced and used to charge the batteries in cases where they have reached their minimum state of charge (SOC). A μG that includes a hospital was evaluated for resilience in islanded mode in the case of power outages and to offer economic benefits when connected to the grid [26]. Using distributed energy resources (DER) connected behind the meter which included BESS, PV, and DG, the μG in connected mode can make revenues by providing services to the grid or could provide behind the meter services directly.

Some grid-connected case studies considered using the BESS with a combined heat and power (CHP) system in hospitals without RES to reduce the operation cost of CHP using peak shaving, to increase energy reliability, and to allow flexible operation [27].

Most of the diesel engine starting failures are caused by batteries not being able to supply the needed power, which could cause life loss in hospitals [28]. Using a simple hybrid storage system consisting of supercapacitors and batteries, the reliability of genset starting system was significantly improved; the starting of the backup generators was ensured even with 10% SOC, and the battery degradation was reduced. In addition to the aforementioned study, the authors in [29] analysed the failure of backup diesel generators caused by the failure of starting batteries, and proposed an automatic parallel system between different backup generators' batteries: to eliminate the possibility of having a dead battery; to reduce the risk of grid outages that is increased by the high penetration of intermittent RESs; and to reduce the threat on human lives in the hospital caused by the loss of electrical power.

In [30], a hybrid microgrid (μG) that included a BESS was proposed and economically optimised to enhance the resilience of a hospital during unscheduled grid outage. In the economic optimisation there was no BESS, only WT and DG. In the resilience optimisation, the BESS is needed side by side with WT and DG which led to the increase of the total NPC, and the cost of energy (COE). The relationship of the battery price and the value of lost load were investigated with the resilience of a hospital in islanding mode [31]. The results showed that the expected decrease in the battery prices will improve the resilience of RES when combined with BESS in applications that need high reliability like hospitals in islanded mode. Hospitals as a critical and resilient facility within the public sector facilities can be a leader for the development of flexible demand in the transition to higher shares of RES, and can provide innovation and learning for BESS as a new energy technology in the public sector [32]. The integration of RES with flow batteries is considered to replace backup combustion generators that are used to provide emergency power, to enhance the security of supply, and to convert hospitals from energy sinks to healthy and reliable energy resources. A hybrid system of batteries, PV system, and diesel generator was designed, analysed, and optimised for cost and performance including grid outage for a μG hospital within a university campus [33]. Batteries with diesel generator were used for emergency power only. The batteries are mainly charged from the PV system.

An example of a hospital as a new player in the flexibility market was illustrated in [34], which was renumerated for providing balancing services (reserve) through demand-side response (DSR) supplied by backup generators but without using BESS. The hospital uses its own generators to cover its baseload, export excess capacity to the grid, and to avoid peak prices.

As can be seen, there are limited discussions addressing the use of the battery in hospitals for grid services. The nearest research to this application is [26], which was not specific to hospitals or the health sector, and the hospital was one of three facilities included in μG, which also included a school and governmental public office. The main aim behind the proposed μG which included BESS was that the hospital was awarded a grant to develop a μG in response of resiliency initiative. The three facilities had a history of grid outages during bad weather that can last up to three days. The study considered only one size for the BESS of (0.441 MW/0.441 MWh). In addition, it was not mentioned how the BESS was charged: whether from PV or the grid, and whether if it could charge from the grid in case it has reached its minimum SOC.

1.3. *Scope of this study*

This study focuses on BTM BESS in hospitals in the Belfast Health and Social Care Trust in Northern Ireland. Unlike many available studies that analysed BESS in hospitals, this study has the following main contributions:

- It addresses the gap in the literature of using the battery in a hospital for grid services, in addition to arbitrage, by participating in the Irish all-island ancillary services market to provide a frequency service and reserve services.
- It includes economic evaluation of a wide range of BESS capacities with value stacking.
- It calculates the savings after installing the BESS on half-hourly basis using different time of use prices.

This study will adopt an empirical approach that uses indicative pass-through tariff prices (based on the Irish all-island wholesale market) and actual ancillary services market economic data. It does not need any complex software to study the impact of adding a BTM BESS on the load profile for an actual hospital in NI. It also evaluates its benefits under different scenarios which considered the option of adding PV generation. This empirical approach can be used by other hospitals or similar facilities to evaluate the impact of integrating BESS. Finally, this study indicates how the health sector may be able to relieve financial stress by developing new income streams.

1.4. *Paper structure*

This paper is organised as follows: in Section 2, the methodology used in this study is discussed, including the available data, the BESS details, the operation algorithm, the proposed PV system, evaluation templates, and the economic assessment. In Section 3, the case study for an actual hospital in NI is illustrated. The results of the case study and the discussion are in Section 4. Finally, Section 5 presents the main conclusion of this work.

2. Methodology

In this section, the available data, the BESS, the PV system the evaluation templates, and the economic assessment are discussed.

2.1. Hospital load data

The hospital studied is the Belfast City Hospital (BCH) which is a university teaching hospital with a capacity of 900 beds. BCH provides acute services and other specialist services to people across NI, including renal transplants and a range of cancer services. The hospital's load data are available from its electrical meters as half-hourly power and energy readings. BCH imports 23 GWh annually from the distribution network. Fig. 2 shows the monthly load ranges for the whole year between 1st, December 2018 and 30th, November 2019. BCH maximum imported power was 5.468 MW on 23rd, August 2019 and minimum load was 1.134 MW which occurred on the 6th, November 2019.

The highest monthly consumption is in August with 2.20 GWh, and the lowest monthly consumption was in February with 1.67 GWh. July and August have the highest consumption among other months, due to the increase in the cooling demand during these two months, which resulted in longer operation of the chillers.

2.2. Battery energy storage system

2.2.1. Values of battery energy storage system

There has been a major cost reduction and improvement of reliability and performance of BESS through the last decade. However, monetisation of the value of the services that BESS can provide is still a challenge [35]. BESS has many characteristics that can create system value, including:

- BESS capacity is more effective in responding to ramping and regulation requests than conventional sources due to its fast response (less than a second).
- BESS can displace power peaking plants that have high costs and lower efficiency.
- The modularity of BESS allows the avoidance of high initial investment costs and can allow scaling in the future.

BESS is an important technology to facilitate the deployment of more RES, for example to solve the intermittency and variability issues associated with RES like PV and wind [36]. BESS can provide frequency services since it has a fast ramp rate that allows to reach its full power in less than one second from the beginning of an event (including the delay and the ramp times) [37], and some current BESS technology is able to provide ramp rates for full power reversal within 40 milliseconds (ms) [38]. Furthermore, BESS can be used for peak load shaving to reduce the maximum power drawn from the grid [39], can provide flexible and quality power, and can reduce the electricity bill for grid connected users by managing the operation of the BESS [40].

In our case study in Section 3, the focus is on using BESS for arbitrage and ancillary services. Arbitrage means to take advantage of the difference in electricity market prices at different times of the day, and by managing when to charge and discharge the BESS, reduce electricity costs. Ancillary services include frequency response and reserve services. Frequency response involves charging or discharging in response to frequency events when the power grid frequency is outside defined limits. Reserve is the available capacity that can synchronise and provide power to the power system within longer specified time limit.

2.2.2. Lithium-ion battery

Li-ion batteries are considered the most mature and widespread battery technology, especially for large scale applications from a couple of megawatt-hours to multiple of hundreds of megawatt-hours [41]. Li-ion batteries have dominated the residential and the large-scale markets due to: the recent fast decrease in the prices among other technologies, long operating life, and high efficiency [42]. Li-ion is preferred over lead-acid batteries for its deep discharge capability [26]. In addition, Li-ion ability to switch between charging and discharging mode quickly allows it to respond to frequency events when participating in ancillary services market [43]. Li-ion batteries are considered one of the best options for healthcare facilities due to their high number of cycles and high energy density [23]. Due to the distinguished specifications of the Li-ion batteries, they will be considered in the case study in Section 3.

2.2.3. BESS operation algorithm

Since in our case study, the BESS is used for arbitrage and ancillary services, the operation of BESS is divided into two modes of operation. The first mode defines BESS operation for arbitrage as follows:

A. To cover as much of the BCH load as possible during a defined period of high grid electricity prices. The highest price is for Winter Peak time which extends between 4 PM and 7 PM, starting from November to the end of February. The second highest price is Summer Day time that extends between 8 AM to 8:30 PM, starting from March to the end of October.

B. In the following situations, the BESS is not allowed to discharge, therefore, the BCH load will be covered from the grid:

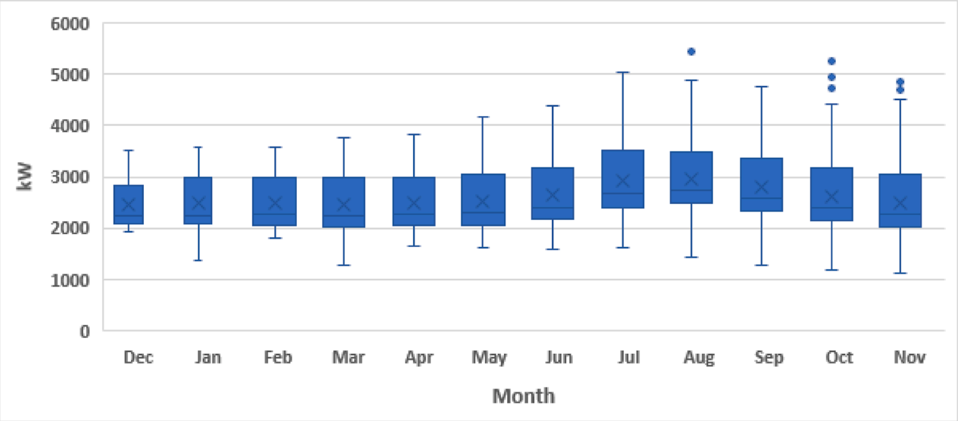

Fig. 2. BCH monthly load demand between December 2018 and the end of November 2019.

B.1. Outside the preset discharge times discussed in A.
B.2. During the lowest tariff (night tariff) between 10:30 PM and 8 AM.
B.3. If minimum SOC has been reached.

A. Any remaining energy and without exceeding the minimum SOC can be used to cover the BCH load after the times with the highest electricity prices and before the (Night) time.
B. If the required power from the BESS is higher than its converter rating, the BESS will utilise its maximum discharge power. Otherwise, the required power will be delivered.
C. BESS will be fully charged from the grid on a constant power during the Night price time. The charging period is distributed for a selectable number of intervals during the Night price time, and which is the lowest price, from 10:30 PM to 8:00 AM. The constant charging power for the selected charging time during Night price will allow a longer charging period with a low charging power, as a result, the load factor of BCH is increased since high charging power for short periods are avoided, and on the other hand, the battery aging caused by high charging currents is reduced. Fig. 3 summarises the arbitrage algorithm for the suggested BESS.

The island of Ireland had thirty-four low frequency events in the period between October 2018 and September 2019, and the frequency nadir reached as low as 49.4 Hz [17]. Furthermore, in NI, the power system inertia needed to allow an SNSP of 75% can be achieved through synthetic inertia provided by a 360 MW BESS [44]. Consequently, with the future target of 90 %SNSP by 2030, more synthetic inertia is needed, which could be supplied by BTM BESS. For that reason, the second mode of operation incorporates BESS operation in responding to ancillary services events (frequency and reserve). In such cases, the priority is for the event, and the BESS will start feeding its full power until either the event has been cleared by the system operator or the battery is fully discharged. In this part of the study, arbitrage can utilise the BESS energy capacity until the minimum SOC is reached; however, the minimum SOC was calculated to make the BESS able to provide ancillary services events for 30 min on full power before it is fully discharged.

Using this operation algorithm and since there is always demand from the BCH, the charge is limited to once at night, and when the BESS is allowed to discharge, it will start feeding BCH loads and continue to do that until it reaches the minimum SOC, or totally discharge if there is any ancillary services event. As a result, BESS will charge once a day and discharge once a day, which means 365 cycles per year. In [43], similarly to our case study, the BESS with a warranted life of 10 years and expected life of 15 years was constrained to one cycle per day. One cycle per day means one full charge and one full discharge daily in order to meet the warranty conditions that requires maintaining the annual throughput of 365 full cycles and with the ability to be fully discharged [45]. Our case study considered a BESS with 15 years lifetime and one cycle per day.

2.2.4. Lithium-ion battery system cost

The economic evaluation of the suggested system will require recent costs for BESS and PV. For that reason, a Li-on BESS and PV system costs were collected from local suppliers and can be shown in Table 2.

2.3. PV system

A PV system was designed using HelioScope online design tool to find the available PV capacity that can be installed at the BCH. Using 340-watt peak (Wp) modules, a 1,440 kWp PV system can be installed as carports and roof top system. The PV system design is shown in Fig. 4. The PV system will be able to supply (1,091,120 kWh) in the first year, and after the first year of operation, the PV system output will decrease linearly to reach at least 80% of its rated capacity after 25 years which is the expected PV system lifetime [46]. The estimated half-hourly generation profile of the PV system that was obtained using Helioscope will be used to study the impact of adding PV system to the BCH with a range of BESS capacities. The PV generation was always less than the total load, hence, there was no energy exported to the grid.

2.4. Evaluation templates

Current available tools are not able to capture the entire revenue streams that energy storage can supply [35]. BESS valuation models are needed to calculate the feasibility of the investment since BESS cannot participate in all services together. As a result, the authors considered building simple templates using **Microsoft Excel** to make the needed calculations for the case study in Section 3, and to evaluate the benefits from arbitrage and ancillary services. Consequently, two evaluation templates were built:

1. The first template is to simulate the effect of adding a BESS with a certain energy and power capacity to the load profile of the BCH and

Table 2
Selected BESS and PV costs to be used in the study.

Cost Parameter	BESS (£/kWh)	BESS (£/kW)	PV (£/kWp)
Selected Cost	400	150	1,100

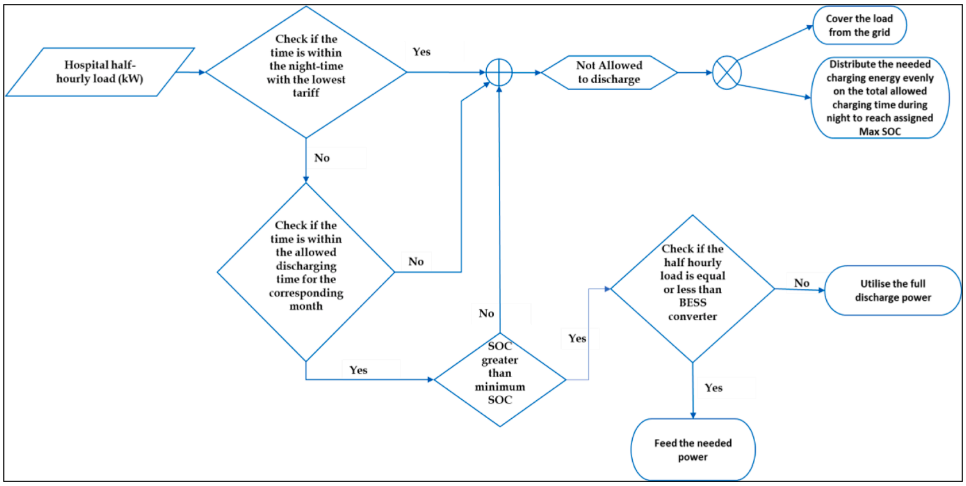

Fig. 3. Algorithm of BESS operation for arbitrage with an assigned charge/discharge time.

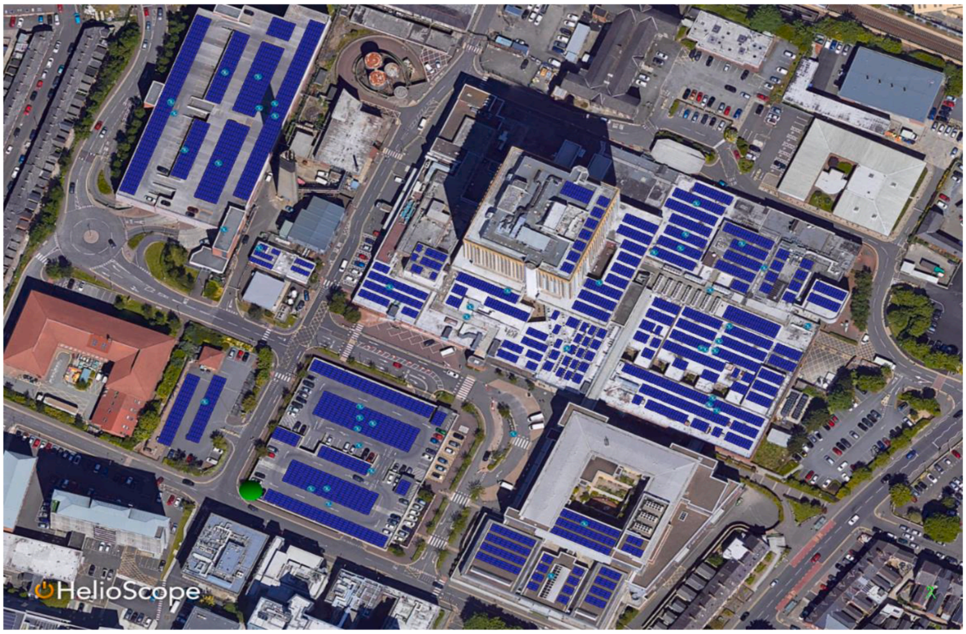

Fig. 4. Suggested PV system design for BCH.

generates the new corresponding load profile depending on the BESS parameters shown in Table 3. The first template allows to change the BESS parameters like: energy capacity, the converter power, the minimum allowed SOC, the charging efficiency (ζcharge), and the discharging efficiency (ζdischarge). A special function is available in the template, which is the ability to select the allowed charging times during the lowest tariffs at night, and the allowed discharge window, including the months and hours, which was discussed earlier in Section 2.2.3. The time selection for discharging times is important, since when combining BESS to PV system under different electricity prices during the day, the effect of: time of use price,battery storage cost, and electricity load data should be studied on the revenues [47].

2. A second template was formulated to study the distribution of the new load profile after adding BESS over different times of use. The second template is needed to study the increase and decrease in consumption for each electricity rate that varies during the same day, differs from weekdays to weekends, and differs from summer months to winter months. The new energy bill, and the savings are calculated on half-hourly basis. The total annual savings can be obtained precisely to study the feasibility for different BESS with different power and energy ratings.

Table 3
An example of BESS input parameters for the first calculation template.

Selected BESS Converter Power (kW)	1,000
Selected BESS Energy Capacity (kWh)	3,000
Minimum SOC (%)	30%
Initial SOC (%)	100%
ζcharge	93%
ζdischarge	93%
MAX allowed number of Half-hourly intervals to charge (from 10:30 PM to 8 AM = 19 intervals)	19.00
Winter Limited Discharging time from	16:00:00
to	20:30:00
Winter Months from	11
to	2
Summer Limited Discharging time from	08:00:00
to	20:30:00
Summer Months from	3
to	10

2.5. Economic assessment

2.5.1. Simple payback period

Payback period can be used as an important indicator to evaluate the PV and BESS [22]. In this paper, a range of BESS capacities will be evaluated (MW and MWh) in different scenarios, in addition to evaluating two different modes of operation, arbitrage and ancillary services. As a result, and for simplicity, the simple payback period (SPBP) was considered for the first economic evaluation and will give a first indication of applicable results, in order to exclude any SPBP outside the expected lifetime of the project. Furthermore, after limiting the applicable results, the analysis will be extended using Net Present Value (NPV) which will be discussed in Section 2.5.2. The simple payback period will be calculated using Eq. (1).

$$SPBP = \frac{C_{BESS} + C_{PV}}{AR_{Arbitrage} + AR_{Ancillary}} \tag{1}$$

C_{BESS} is the total capital cost of the BESS which includes the cost of the DC side (£/kWh) and the AC side (£/kW). C_{PV} is the total PV cost (£/kWp). $AR_{Arbitrage}$ is the annual revenue (£/year) from arbitrage using the selected BESS and includes the saving from the PV system if considered in the scenario. This revenue comes from the difference between the cost of the used energy during the lowest price time (Night time) to charge the BESS, and the energy was not imported from the grid and was met using the BESS during higher prices. The difference in prices between Winter Peak rate and Night rate during winter months can reach around 0.17 £/kWh, and in summer months, around 0.03 £/kWh. $AR_{Ancillary}$ is the annual revenues from participation in the ancillary services market in (£/MW/year) for the applicable services.

Some scenarios in the case study will not consider using the PV or participation in the ancillary services market; as a result, the related cost and revenue will be set to zero in Eq. (1).

2.5.2. Net present value

After limiting the considered scenarios in the case study by avoiding not applicable SPBP, a further economic analysis will be done using the NPV in order to calculate the total revenues for different BESS ratings during the total system lifetime.

The NPV will be calculated using Eqs. (2) and (3) as follows:

$$NPV(C_{BESS},N) = -C_{BESS} + \sum_{n=1}^{N} \frac{R_{BESS} - A_{OM}}{(1+i)^{n}} \tag{2}$$

$$R_{BESS} = AR_{Arbitrage} + AR_{Ancillary} \tag{3}$$

R_{BESS} as shown in Eq. (3) is the annual revenues reimbursed after the installation of the BESS from both arbitrage ($AR_{Arbitrage}$) and from the participation in the ancillary services market ($AR_{Ancillary}$), and which have been discussed earlier in Section 2.5.1. N is the considered number of years to study the NPV of the selected system and in our case, N will be 15 years as it is the expected lifetime of the selected BESS. Since NPV considers the time value of money, i is the discount rate and will be considered as 5%. For simplification, all the annual revenues from BESS will be the same throughout the system lifetime. A_{OM} is the operation and maintenance (O&M) cost for BESS. The O&M annual cost for BESS for similar projects can be found around 3.37% of the DC side cost (kWh cost) [48], or 4.12% from the capital investment [49]. To be more conservative and for simplicity, the annual O&M cost for the BESS will be considered 5% of its capital cost and will be the same annual amount during the BESS lifetime. In the NPV calculations and for simplicity, no loans were considered, and it is assumed that the BCH is able to buy the BESS in one payment at the beginning of the project.

3. Case study

The case study is for the BCH, which was introduced in Section 2.2. The Belfast Health and Social Care Trust (BHSCT) which is responsible for the health services in the Greater Belfast area, recently deployed BESS within some of their facilities. They are undertaking some trial projects in health centres and hospitals, for assessment for resilience, and to be used to manage PV systems. This case study will study how BESS could also potentially open new revenue streams for the BHSCT and encourage the deployment of more BESS within the health sector and helping to achieve the UK targets in emissions reduction.

3.1. BCH load profile data

The load profile of the BCH for the whole year between 1st December 2018 and 30th November 2019 will be used in the case study. In some scenarios which will be discussed in Section 3.3, when the PV system is considered, a new load profile is generated to be considered with the BESS. Since the available load profile is a half-hourly power data, the case study considered a constant power during the interval of a half an hour.

3.2. DS3 ancillary services market

DS3 (Delivering a Secure, Sustainable System) is the ancillary services market in the island of Ireland, and it was established to meet RES electricity target of 40% in 2020 [6]. Currently, an SNSP of 70% is allowed, and this will be increased gradually to meet the proposed 2030 target of 70% electricity energy consumption from RES. Within DS3, a subset of system services can be procured from new providers who are not related to the energy market dispatch [50]. This part of the market is known as Volume Capped Procurement. The subset of system services includes Fast Frequency Response, Primary Operating Reserve, Secondary Operating Reserve, Tertiary Operating Reserve 1, and Tertiary Operating Reserve 2. These services are described in Table 4.

The payments of the subset of services will be according to the payment rates published in [51]. In addition, a temporal scarcity scalar (TSS) is applicable to the same subset of services which can be defined as a factor that will be multiplied by the rates for each service (FFR, POR, SOR, TOR1, TOR2) when a certain SNSP level has been reached [52]. TSS can be considered 2.29 for FFR and 2.76 for (POR, SOR, TOR1, TOR2) for the whole year [53]. The payment for each service mentioned in Table 4 above can be calculated using Eq. (4) as follows:

Table 4
DS3 volume capped procurement services.

Service name	Acronym	Short description
Fast Frequency Response	FFR	MW responded to a frequency trigger between 2 and 10 seconds
Primary Operating Reserve	POR	MW responded to a frequency trigger between 5 and 15 seconds
Secondary Operating Reserve	SOR	MW responded to a frequency trigger between 15 to 90 seconds
Tertiary Operating Reserve 1	TOR1	MW responded to a frequency trigger between 90 seconds to 5 min
Tertiary Operating Reserve 2	TOR2	MW responded to a dispatch or control instruction between 5 and 20 min

$$\begin{gathered} Service\ Payment\ (\text{Â£}) = Available\ Capacity\ (MW)x \\ Payment\ Rate\ (\text{Â£}/MWh)xService\ TSS\ xDuration\ (hr) \end{gathered} \tag{4}$$

As described in Table 4, the service is considered as MW responded to a trigger or dispatched within a time frame. Consequently, using Eq. (4) and for simplicity, the revenues of BESS can be calculated and expressed per unit power MW. Based on previous the payment rates and the TSSs, the BESS is expected to earn £206,000 annually per MW from all services (FFR, POR, SOR, TOR1, TOR2), and if FFR is excluded the BESS can still earn £168,000 annually per MW [54].

3.3. Energy and power ratings for the battery system

The energy to power ratio (ETPR) is critical for the feasibility of the BESS. For example, an ETPR less than 0.5 has a cost higher than total revenues and is not suitable for energy-intensive services like ancillary services and arbitrage [35]. The suggested ETPR which are common within the industry standards are between 1 and 4. The large scale BESS must have a minimum SOC to be able to respond to grid for at least 30 min at full power [42,54].A factor of 1.5 MWh per MW is typical to fulfill the 30 min requirement [42] and BESS with 1.5 and 2.5 hours can provide more revenues from arbitrage [54] . The selected power range for the BESS that will be evaluated in arbitrage mode will increase from 1 MW to 5 MW in steps of 1 MW, and the maximum ETPR will be 4. The BESS power and energy range that will be evaluated for the ancillary services will exclude an ETPR of 1, and will include ETPR of 1.5, then ETPR from 2 to 4 in steps of 1.

3.4. Scenarios

In this case study, four scenarios were considered for arbitrage:

1. Scenario 1 (Sc. 1): Adding BESS to the base case (current situation).
2. Scenario 2 (Sc. 2): Adding BESS and PV to the base case.
3. Scenario 3 (Sc. 3): Adding BESS to the base case with limited discharge time.
4. Scenario 4 (Sc. 4): Adding BESS and PV to the base case with limited discharge time.

As illustrated earlier in Section 2.2.3, the BESS will be charged from the grid on a constant power for a selectable number of intervals during the Night price time, from 10:30 PM to 8:00 AM, and which will be applied for all scenarios (1-4).

For scenarios 2 and 4, the suggested PV system in Section 2.3 is considered. For scenario 1 and scenario 2, the discharge is allowed anytime outside the Night price until minimum SOC is reached. On the other hand, in scenarios 3 and 4 the BESS is allowed to discharge only during a selected discharge time, and this will cover the highest price time.

The payback period will also be considered for each scenario mentioned earlier with the additional revenues that will be accrued from the participation in the ancillary services market as follows:

1. TSS High: Participating in all services (FFR, POR, SOR, TOR1, TOR2) with the expected high annual revenue of £206,000 per MW.
2. TSS Low: Participating in reserve services without FFR (POR, SOR, TOR1, TOR2) with the expected low annual revenue of £168,000 annually per MW.

4. Results and discussion

4.1. Simple payback period results

After considering the mentioned scenarios in the previous section for arbitrage only, the SPBPs were calculated for the selected BESS power and energy ranges, and the results are shown in Fig. 5.

For Sc. 1, which was adding BESS to the BCH and was allowed to discharge whenever there is demand outside the Night tariff, the SPBPs varied between 68.21 years and 86.2 years. Sc. 1 is not applicable in real life since the BESS has an expected lifetime of 15 years. For Sc. 2, which considered adding a 1,440 kWp PV system to the BESS, the payback periods have decreased and ranged between 18.2 years and 43.21 years. The PV system has increased the annual revenues, but at the same time has increased the initial capital cost, and the SPBPs are still high since the lowest SPBP is 18.2 years. Sc. 3 involves limiting the discharge time of the BESS to cover BCH load during the times with the highest prices. The SPBPs results varied between 34.01 and 43.51, which is less than SPBPs for Sc. 1, but are still not applicable in real life for the expected lifetime of the BESS. Finally, in Sc. 4, which added PV to the BESS and controlled the discharge time to cover the highest prices, the SPBPs ranged between 17.25 years and 33.12 years which is not applicable. The lowest SPBP is 17.25 years which represents the lowest SPBP among these scenarios, but it is still higher than the BESS lifetime.

Since in all scenarios, the lowest payback period is greater than the expected BESS lifetime of 15 years, the results showed that using BESS for arbitrage only is not feasible for any BESS rating, and this is because the revenue is low to cover the initial cost of the BESS, and which is the same for the scenarios that includes PV system with its additional cost.

After considering the revenues from **TSS Low** ancillary services in addition to arbitrage, the new SPBPs are illustrated in Fig. 6. In Sc.1, the SPBPs varied between 4.24 and 9.04 years. The significance of participating in the DS3 ancillary services market is starkly illustrated when comparing the new SPBP with the old SPBP for Sc. 1, which varied between 68.21 years and 86.2 years. Furthermore, in Sc. 2, the SPBP varied between 5.36 and 10.95 years. For Sc. 3, and which achieved the lowest range of SPBP for the BESS for arbitrage and **TSS low**, the SPBP ranged between 4.03 and 8.40 years. And finally, in Sc. 4 the SPBP varied between 5.13 and 10.09 years. After considering **TSS Low** ancillary services, the longest SPBP is 10.95 years in Sc. 2 for 1 MW/4 MWh BESS which is still acceptable for a BESS project with 15 years lifetime. The shortest SPB period is 4.03 years which is for Sc. 3 for all BESS with an ETPR of 1.5.

The SPBPs after considering revenues from **TSS High,** and which are the highest possible revenues in the DS3 market, are shown in Fig. 7. In Sc. 1, when considering **TSS High**, the SPB period ranged between 3.49 and 7.56 years. For Sc. 2, the SPBPs varied between 4.50 and 9.73 years. In Sc.3 and which has the lowest SPBP range for the BESS for arbitrage and **TSS High**, and the lowest among any other scenario, the SPBS varied between 3.35 and 7.11. Finally, in Sc. 4 the SPBPs ranged between 4.33 and 9.05. The lowest SPBP for all scenarios is with **TSS High** since the highest available revenues are considered from DS3 ancillary services market. After considering **TSS High** ancillary services, the highest SPBP was 9.73 years in Sc. 2 for 1 MW/4 MWh BESS, and again is still acceptable for a BESS project with 15 years lifetime. The lowest SPBP is 3.35 years which is in Sc. 3 for all BESS with an ETPR of 1.5.

In purely monetary terms, the results indicate that the BESS will not be an economically viable investment if it is used solely for arbitrage, and must be considered for participation in the ancillary services market, to stack revenues and to be able to recover the high initial investment. Scenario 3 has always the lowest SPBP with the TSS when compared to other scenarios, and which shows the importance of managing the discharging and charging time of the BESS to be able to obtain the maximum difference in the charging and discharging electricity prices. In addition, Sc. 2 and Sc. 4 show that combining the PV system with the BESS has always increased the SPBP, which indicates that the revenues from participating in the ancillary services market is much higher than the revenues from the PV system. The investment in

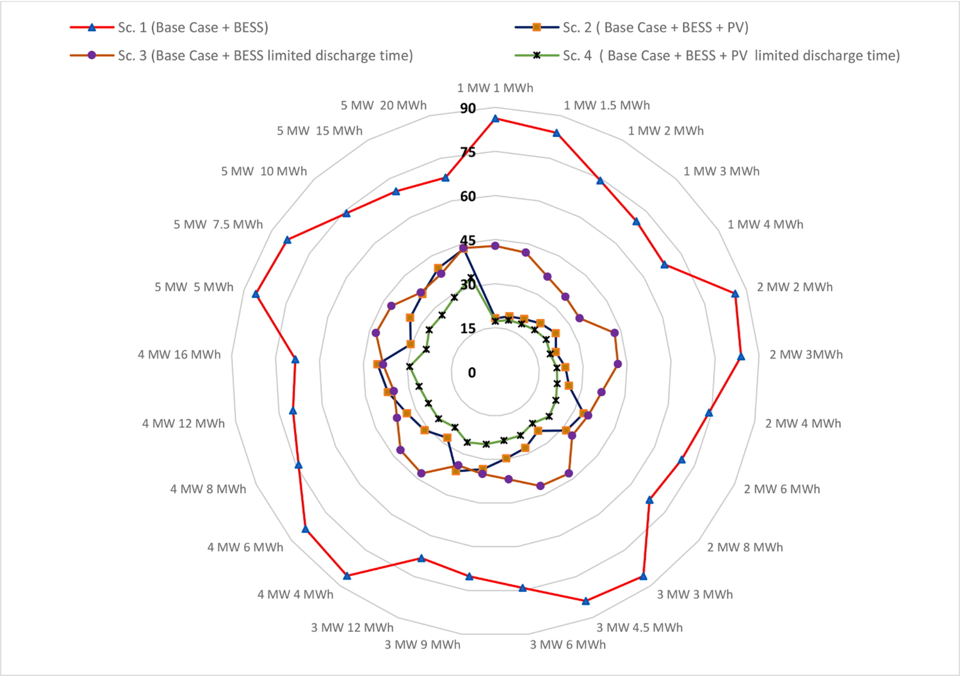

Fig. 5. SPBP for arbitrage only for all scenarios (1 to 4) for the selected range of BESS.

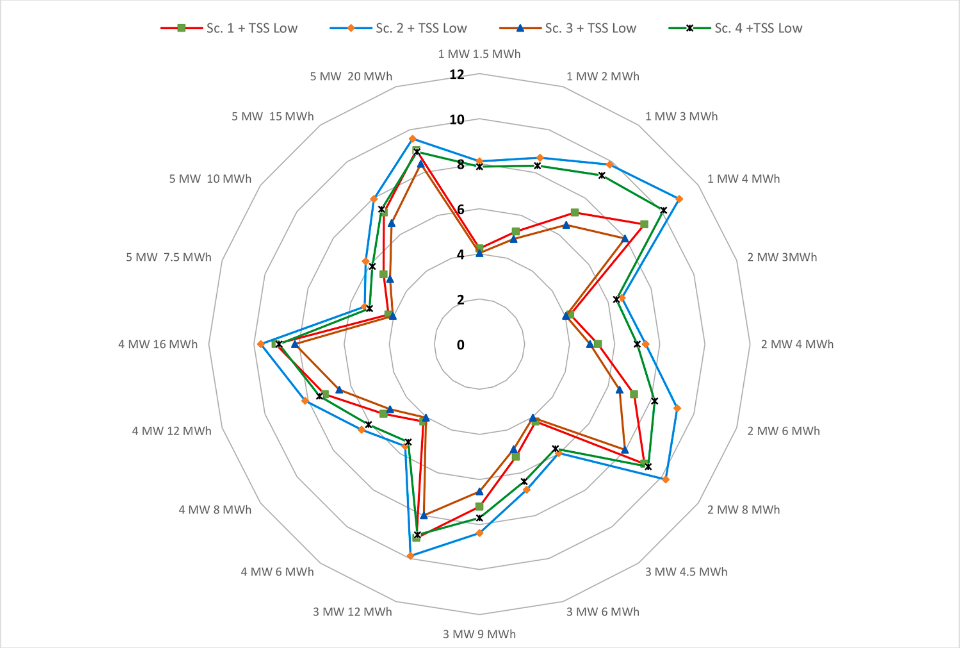

Fig. 6. SPBP for arbitrage with TSS Low for all scenarios (1 to 4) for the selected range of BESS.

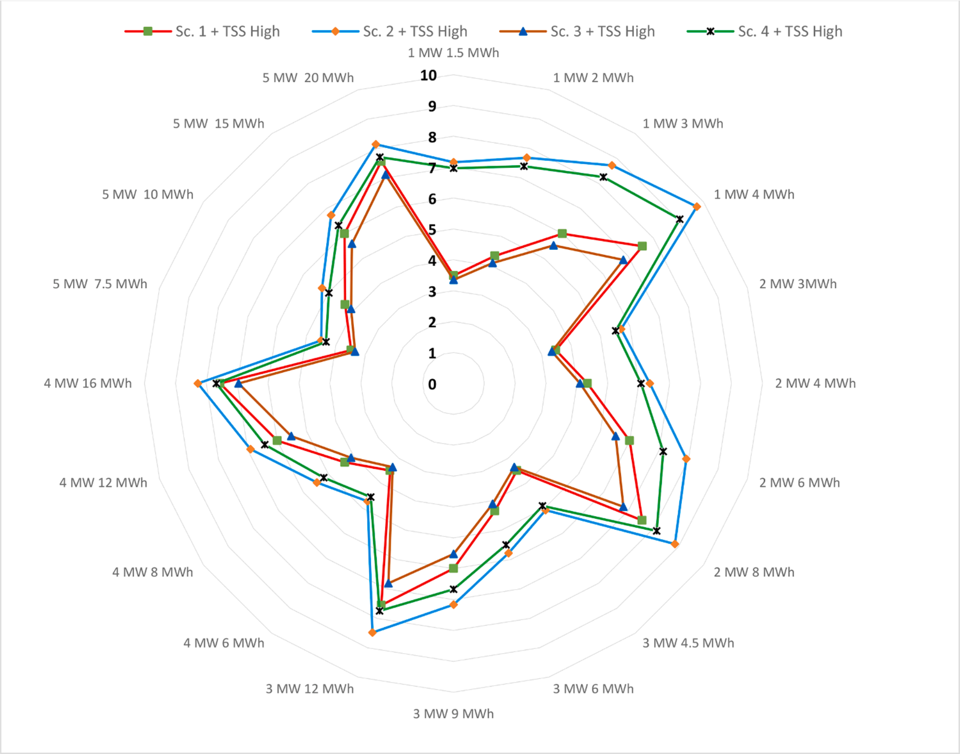

Fig. 7. SPBP for arbitrage with **TSS High** for all scenarios (1 to 4) for the selected range of BESS.

the PV system will cost around 1.6 M£, and the expected annual revenues from PV are £ 111,000. On the other hand, a 1 MW/ 1.5 MWh BESS system will cost £750,000 but will reimburse £168,000 annually from the DS3 ancillary services market. As a result, investing in the DS3 market by installing BESS will be more profitable than investing in the PV.

The lowest SPBP can be achieved from Sc. 3 with **TSS High** which limits the BESS discharge time and participates in all available services in DS3 ancillary services market, in addition to arbitrage. On the other hand, to be more conservative and to avoid high expectation, it is suggested to expect the revenues from arbitrage with **TSS Low** not **TSS High**, and this will likely reflect the nearest scenario to real life for the BCH case study. Consequently, a further economic evaluation will be illustrated in Section 4.2 to compare NPV for the full selected BESS range with Sc. 3 for arbitrage and **TSS Low** only, for ETPR from 1 to 4, and to limit the minimum SOC to be able to provide ancillary services as required for 30 min on full power before it is fully discharged.

4.2. Net present value results

In order to help in making the decision in which BESS rating to invest, a revenue comparison was made between different batteries through the system lifetime of 15 years. The information from the SPBP alone will not give us the best investment choice, since different investments can have the same SPBP but different NPV. For example, when looking at Fig. 8 which shows the new results for the SPBP for Sc. 3 for arbitrage and **TSS Low** with the full range of ETPR, all BESSs with an ETPR 1 have the same SPBP of 3.10 years. The same thing happened with an ETPR of 1.5 that resulted in 4.03 years SPBP, and with an ETPR of 2 the SPBP was 4.86 years. The BESS with ETPRs of values of 2 and 3 have almost the same SPBPs with a slight difference in small fraction of one year. The comparison should be extended using the NPV for each BESS. NPV reflects the time value of money, thus, the discounted value of future revenues compared to the present time.

The NPV results for the full BESS range with Sc. 3 for arbitrage and **TSS Low** is illustrated in Fig. 9. The NPV results showed that all BESSs with an ETPR of 4 have negative values and which means that it is less attractive as an investment, since the annual earnings will not cover the capital investment with the annual costs of O&M. The highest NPV is always for an ETPR of 1 for all BESS power ratings. This is because the main revenue from the BESS comes from the participation in the DS3 ancillary service market which pays for the available power capacity, therefore, all BESS with the same power rating will get the same revenue from DS3. On the other hand, when investing in larger energy capacity for the same power rating, this will significantly increase the total cost of the BESS, since the most expensive share of the BESS cost is the DC side (kWh) not the AC side (kW), and the additional revenue will come from arbitrage which is very low compared to the DS3 revenues. The NPV for the BESS with the same power rating varies from the highest NPV with an ETPR of 1 to the lowest with a negative NPV for an ETPR of 4.

The highest NPV is for a 5 MW/5 MWh BESS with a value of £5,018,894. The lowest positive NPV was for a 1 MW/ 3 MWh BESS with a £168,432. The choice of the investment should be taken for any BESS with an ETPR of 1. The revenue increases with the increase of the BESS power. The limitations will be the maximum allowed power by the system operator to participate in the ancillary services market, and the budget of the investment.

5. Conclusion

In this study, a range of BTM BESS are evaluated using empirical load and market data in a range of scenarios for a hospital in NI for arbitrage, and to provide ancillary services. Electricity costs were calculated considering an electricity tariff derived from wholesale market data that varies during the same day, differs from weekdays to weekends, and differs from summer months to winter months. It was found that BESS is not economically viable for arbitrage only since the payback period is always higher than the expected system lifetime of 15 years. The viability of the BESS project can be substantially improved by stacking the arbitrage revenues with a subset of ancillary services within the DS3 ancillary services market. When income from the DS3 ancillary services market is included in the revenue stack, the SPBP can be as low as 3.35 years, and the maximum SPBP was 10.95 years which is still less than system expected lifetime.

The shortest SPBP was for Sc. 3 in which BESS is without PV, the BESS discharge time was controlled to cover the highest electricity prices and a dedicated minimum SOC was kept for the participation in the DS3 ancillary services market. Sc. 3 was furtherly economically evaluated using the NPV, and the results showed that BESS with ETPR of 4 has a negative NPV and should be avoided as an investment. The best ETPR which reimburse the highest revenues during the BESS lifetime is 1, and the positive NPV can vary between £168,432 for a 1 MW/ 3 MWh BESS and £5,018,894 for a 5 MW/5 MWH BESS. The choice of which BESS capacity to invest in is dependent on the system operator's limitation on the maximum total capacity allowed to participate in the ancillary services market and is limited by the available budget. Since the revenue that comes from arbitrage is relatively low, the amount of energy that was dedicated for the arbitrage can be diverted to provide resilience for the hospital, for example by providing backup power for critical loads in case of power outage.

This paper suggests a new revenue stream for the health sector from participating in the ancillary services market using BESS, that could allow the health sector to play a significant role in the transition towards net-zero future in 2050 since it provides part of the needed ancillary services needed by the power system to accommodate higher levels of SNSP.

Due to COVID19 pandemic, the health sector faces economic challenges, including government cuts to public sector budgets. The job losses associated with the Covid 19 pandemic may lead to loss of

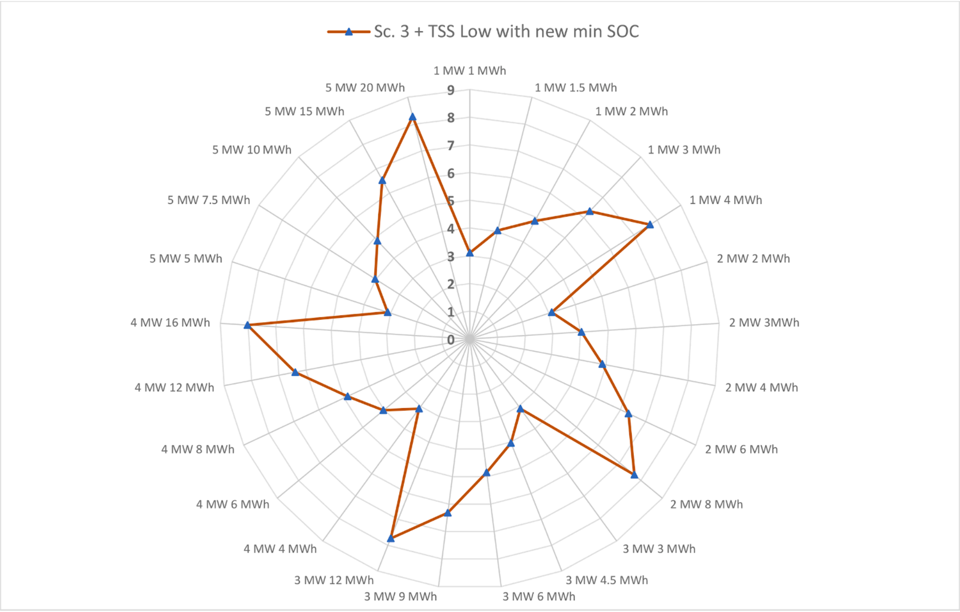

Fig. 8. New SPBP for Scenario 3 for arbitrage with TSS Low for the full selected range of BESS with ETPR from 1 to 4.

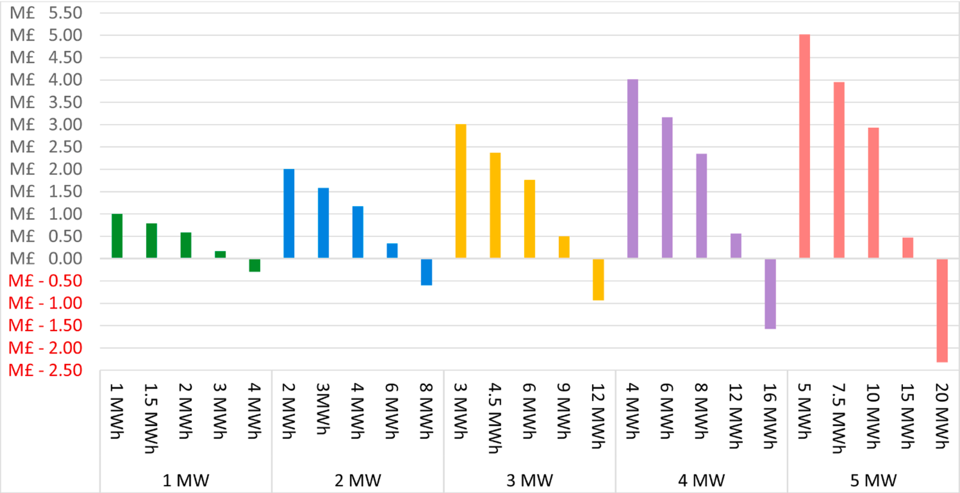

Fig. 9. NPV for Scenario 3 for arbitrage with TSS Low for the full selected range of BESS with ETPR from 1 to 4.

national health insurance revenues and less income for the health sector [55]. Accessing the full BESS value stack could increase resilience and help BHSCT to meet targets for net zero, while the potential income for the health sector from a new revenue stream could help to relieve the pressure on funding from the government after COVID19 outbreak and increase both the environmental and economic sustainability of the health sector.

CRediT authorship contribution statement

Motasem Bani Mustafa: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Patrick Keatley:** Conceptualization, Resources, Data curation, Writing – review & editing, Supervision. **Ye Huang:** Conceptualization, Writing – review & editing, Supervision. **Osaru Agbonaye:** Writing – review & editing. **Oluwasola O. Ademulegun:** Writing – review & editing. **Neil Hewitt:** Conceptualization, Project administration, Funding acquisition.

Declaration of competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] E. and I.S. Department for Business, The Climate Change Act 2008 (2050 Target Amendment) Order 2019, 2019. https://www.legislation.gov.uk/ukdsi/2019/9780111187654 (accessed January 29, 2021).

[2] E. & I.S. Department for Business, Energy Trends December 2020, 2020. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/946748/Energy_Trends_December_2020.pdf (accessed January 30, 2021).

[3] Department for the Economy, Electricity Consumption and Renewable Generation in Northern Ireland-Year Ending September 2020, 2020 https://www.economy-ni.gov.uk/sites/default/files/publications/economy/Issue-17-electricity-consumption-and-renewable-generation-northern-ireland-october-2019-to-september-2020.pdf (accessed January 30, 2021).

[4] Northern Ireland Electricity Networks, Renewable Generation Status Q2 2020, 2020. https://www.nienetworks.co.uk/connections/generation-connections/generation-useful-resources (accessed January 31, 2021).

[5] EIRGRID Group, System and Renewable Summary Report, 2020. https://www.eirgridgroup.com/how-the-grid-works/renewables/ (accessed February 1, 2021).

[6] EIRGRID Group, DS3 Programme, 2020. https://www.eirgridgroup.com/how-the-grid-works/ds3-programme/ (accessed February 1, 2021).

[7] EIRGRID Group, Strategic Incentives 2020 Proposals Consultation, 2020. https://www.eirgridgroup.com/site-files/library/EirGrid/Strategic-Incentives-2020-Proposals.pdf (accessed February 1, 2021).

[8] F. Gaffney, J.P. Deane, B.P.Ó. Gallachóir, Reconciling high renewable electricity ambitions with market economics and system operation: lessons from Ireland's power system, Energy Strateg. Rev. 26 (2019), 100381, https://doi.org/10.1016/j.esr.2019.100381.

[9] The Irish Times, Electricity Demand Falls Less in Republic than in UK, Eirgrid Says, 2020. https://www.irishtimes.com/business/energy-and-resources/electricity-demand-falls-less-in-republic-than-in-uk-eirgrid-says-1.4257643 (accessed February 1, 2021).

[10] H.S. Boudet, Public perceptions of and responses to new energy technologies, Nat. Energy. 4 (2019) 446–455, https://doi.org/10.1038/s41560-019-0399-x.

[11] NHS, NHS England-Greener NHS Campaign to Tackle Climate 'Health Emergency,', 2020. https://www.england.nhs.uk/2020/01/greener-nhs-campaign-to-tackle-climate-health-emergency/ (accessed January 19, 2021).

[12] NHS-Sustainability Development Unit (SDU), Core Carbon Footprint of NHS Trusts and Foundation Trusts – Carbon Emissions Per Metre Squared of Occupied Floor Area, 2019 https://digital.nhs.uk/data-and-information/national-indicator-library/core-carbon-footprint-of-nhs-trusts-and-foundation-trusts-carbon-emissions-per-metre-squared-of-occupied-floor-area-iap00519 (accessed January 22, 2021).

[13] HM Government, Carbon Plan, 211AD. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/47621/1358-the-carbon-plan.pdf (accessed January 22, 2021).

[14] J. Wise, NHS makes good progress on sustainability, report shows, BMJ 362 (2018), https://doi.org/10.1136/bmj.k4032.

[15] World Health Organization and Health Care Without Harm, Healthy Hospitals Healthy Planet Healthy People From Who-From Health Care Without Harm, 2009. http://www.who.int/world-health-day/ (accessed January 19, 2021).

[16] M. Santamouris, E. Dascalaki, C. Balaras, A. Argiriou, A. Gaglia, Energy performance and energy conservation in health care buildings in hellas, Energy Convers. Manag. 35 (1994) 293–305, https://doi.org/10.1016/0196-8904(94)90062-0.

[17] O. Agbonaye, P. Keatley, Y. Huang, M. Bani-Mustafa, O.O. Ademulegun, N. Hewitt, Value of demand flexibility for providing ancillary services: a case for social housing in the Irish DS3 market, Util. Policy. 67 (2020), 101130, https://doi.org/10.1016/j.jup.2020.101130.

[18] A.A. Mas'ud, An optimal sizing algorithm for a hybrid renewable energy system, Int. J. Renew. Energy Res. 7 (2017) 1595–1602. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85043469001&partnerID=40&md5=d805863be554d4f60abc57fcd8ecc388.

[19] R. Dufo-López, E. Pérez-Cebollada, J.L. Bernal-Agustín, I. Martínez-Ruiz, Optimisation of energy supply at off-grid healthcare facilities using Monte Carlo simulation, Energy Convers. Manag. 113 (2016) 321–330, https://doi.org/10.1016/j.enconman.2016.01.057.

[20] D.M. Alotaibi, M. Akrami, M. Dibaj, A.A. Javadi, Smart energy solution for an optimised sustainable hospital in the green city of NEOM, Sustain. Energy Technol. Assess. 35 (2019) 32–40, https://doi.org/10.1016/j.seta.2019.05.017.

[21] I.R. Cristóbal-Monreal, R. Dufo-López, Optimisation of photovoltaic-diesel-battery stand-alone systems minimising system weight, Energy Convers. Manag. 119 (2016) 279–288, https://doi.org/10.1016/j.enconman.2016.04.050.

[22] J. Zhang, H. Cho, R. Luck, P.J. Mago, Integrated photovoltaic and battery energy storage (PV-BES) systems: an analysis of existing financial incentive policies in the US, Appl. Energy. 212 (2018) 895–908, https://doi.org/10.1016/j.apenergy.2017.12.091.

[23] A. Franco, M. Shaker, D. Kalubi, S. Hostettler, A review of sustainable energy access and technologies for healthcare facilities in the Global South, Sustain. Energy Technol. Assessments. 22 (2017) 92–105, https://doi.org/10.1016/j.seta.2017.02.022.

[24] N.M. Isa, H.S. Das, C.W. Tan, A.H.M. Yatim, K.Y. Lau, A techno-economic assessment of a combined heat and power photovoltaic/fuel cell/battery energy system in Malaysia hospital, Energy (2016), https://doi.org/10.1016/j.energy.2016.06.056.

[25] A. Lagrange, M. de Simón-Martín, A. González-Martínez, S. Bracco, E. Rosales-Asensio, Sustainable microgrids with energy storage as a means to increase power resilience in critical facilities: an application to a hospital, Int. J. Electr. Power Energy Syst. 119 (2020), https://doi.org/10.1016/j.ijepes.2020.105865.

[26] P. Balducci, K. Mongird, D. Wu, D. Wang, V. Fotedar, R. Dahowski, An evaluation of the economic and resilience benefits of a microgrid in Northampton, Massachusetts, Energies 13 (2020), https://doi.org/10.3390/en13184802.

[27] A. Gimelli, F. Mottola, M. Muccillo, D. Proto, A. Amoresano, A. Andreotti, G. Langella, Optimal configuration of modular cogeneration plants integrated by a battery energy storage system providing peak shaving service, Appl. Energy. 242 (2019) 974–993, https://doi.org/10.1016/j.apenergy.2019.03.084.

[28] C. Boccaletti, S. Elia, E.F. Salas M, M. Pasquali, High reliability storage systems for genset cranking, J. Energy Storage. 29 (2020), https://doi.org/10.1016/j.est.2020.101336.

[29] A. D`Orazio, S. Elia, E. Santini, M. Tobia, Succor system and failure indication for the starter batteries of emergency gensets, Period. Polytech. Electr. Eng. Comput. Sci. 64 (2020) 412–421, https://doi.org/10.3311/PPee.15274.

[30] J. Liu, L. Jian, W. Wang, Z. Qiu, J. Zhang, P. Dastbaz, The role of energy storage systems in resilience enhancement of health care centers with critical loads, J. Energy Storage. 33 (2021), https://doi.org/10.1016/j.est.2020.102086.

[31] S. Tsianikas, J. Zhou, I.I.I. Birnie D.P., D.W. Coit, Economic trends and comparisons for optimizing grid-outage resilient photovoltaic and battery systems, Appl. Energy. 256 (2019), https://doi.org/10.1016/j.apenergy.2019.113892.

[32] N. Gurieff, D. Green, I. Koskinen, M. Lipson, M. Baldry, A. Maddocks, C. Menictas, J. Noack, B. Moghtaderi, E. Doroodchi, Healthy power: reimagining hospitals as sustainable energy hubs, Sustain 12 (2020) 1–17, https://doi.org/10.3390/su12208554.

[33] İ. Çetinbaş, B. Tamyürek, M. Demirtaş, Design, analysis and optimization of a hybrid microgrid system using HOMER software: Eskişehir osmangazi university example, Int. J. Renew. Energy Dev. 8 (2019) 65–79, https://doi.org/10.14710/ijred.8.1.65-79.

[34] E. Proffitt, Case studies of demand side response and storage schemes. Profit. from Demand Side Flex. Storage, 2nd ed., The Major Energy Users' Council in association with National Grid, UK, 2017, pp. 55–57.

[35] P.J. Balducci, M.J.E. Alam, T.D. Hardy, D. Wu, Assigning value to energy storage systems at multiple points in an electrical grid, Energy Environ. Sci. 11 (2018) 1926–1944, https://doi.org/10.1039/c8ee00569a.

[36] S. Shivashankar, S. Mekhilef, H. Mokhlis, M. Karimi, Mitigating methods of power fluctuation of photovoltaic (PV) sources - a review, Renew. Sustain. Energy Rev. 59 (2016) 1170–1184, https://doi.org/10.1016/j.rser.2016.01.059.

[37] P.V Brogan, R.J. Best, D.J. Morrow, K. McKinley, M.L. Kubik, Effect of BESS response on frequency and RoCoF during underfrequency transients, IEEE Trans. Power Syst. 34 (2019) 575–583, https://doi.org/10.1109/TPWRS.2018.2862147.

[38] T. Feehally, A.J. Forsyth, R. Todd, M.P. Foster, D. Gladwin, D.A. Stone, D. Strickland, Battery energy storage systems for the electricity grid: UK research facilities, in: IET Conf. Publ., 2016, https://doi.org/10.1049/cp.2016.0257.

[39] L. Bolívar Jaramillo, A. Weidlich, Optimal microgrid scheduling with peak load reduction involving an electrolyzer and flexible loads, Appl. Energy. 169 (2016) 857–865, https://doi.org/10.1016/j.apenergy.2016.02.096.

[40] G. Carpinelli, F. Mottola, D. Proto, A. Russo, A multi-objective approach for microgrid scheduling, IEEE Trans. Smart Grid. 8 (2017) 2109–2118, https://doi.org/10.1109/TSG.2016.2516256.

[41] IRENA, Utility-Scale Batteries-Innovation Landscape Brief, 2019. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Utility-scale-batteries_2019.pdf (accessed January 20, 2021).

[42] J. Figgener, P. Stenzel, K.-P. Kairies, J. Linßen, D. Haberschusz, O. Wessels, G. Angenendt, M. Robinius, D. Stolten, D.U. Sauer, The development of stationary battery storage systems in Germany – a market review, J. Energy Storage. 29 (2020), https://doi.org/10.1016/j.est.2019.101153.

[43] The University of Queensland, The Business Case for Behind-The-Meter Energy Storage-Q1 Performance of UQ's 1.1MW Tesla battery, 2020. https://sustainability.uq.edu.au/files/11868/EPBQtyRptq12020.pdf (accessed September 21, 2020).

[44] EIRGRID/SONI, RoCoF Alternative & Complementary Solutions Project Phase 2 Study Report, n.d. https://www.eirgridgroup.com/site-files/library/EirGrid/RoCoF-Alternative-Solutions-Project-Phase-2-Report-Final.pdf (accessed February 18, 2021).

[45] Tesla, Powerpack - Commercial & Utility Energy Storage Solutions, (n.d.). https://www.tesla.com/en_GB/powerpack (accessed January 20, 2021).

[46] Trina Solar, TSM-PD14 TalMax Datasheet, (n.d.). https://static.trinasolar.com/sites/default/files/PS-M-0328 Datasheet_Tallmax_2018_B_0.pdf (accessed February 11, 2021).

[47] A. Sani Hassan, L. Cipcigan, N. Jenkins, Optimal battery storage operation for PV systems with tariff incentives, Appl. Energy. 203 (2017) 422–441, https://doi.org/10.1016/j.apenergy.2017.06.043.

[48] Lazard, Lazard's Levelized Cost of Storage Analysis, 2019. https://www.lazard.com/media/451087/lazards-levelized-cost-of-storage-version-50-vf.pdf (accessed September 22, 2020).

[49] E. & I.S. Department for Business, Storage Cost and Technical Assumptions for BEIS, 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/910261/storage-costs-technical-assumptions-2018.pdf (accessed September 22, 2020).

[50] EIRGRID/SONI, Consultation on DS3 System Services Contracts for Regulated Arrangements -DS3 System Services Implementation Project, 2017.

[51] SONI, DS3 System Services-Statement of Payments, 2018 https://www.soni.ltd.uk/media/documents/DS3-SS-Statement-of-Payments-2018-19.pdf (accessed July 7, 2021).

[52] SONI, DS3 System Services Agreement, 2018. http://195.80.65.90/site-files/library/EirGrid/NI-DS3-System-Services_Regulated-Arrangements_final.pdf (accessed February 12, 2021).

[53] EIRGRID/SONI, Temporal Scarcity Scalar values for use in Volume Capped Arrangements, 2019. http://www.eirgridgroup.com/site-files/library/EirGrid/Temporal-Scarcity-Scalar-values-for-Volume-Capped-Arrangements.pdf (accessed February 12, 2021).

[54] P.V Brogan, R. Best, J. Morrow, R. Duncan, M. Kubik, Stacking battery energy storage revenues with enhanced service provision, IET Smart Grid 3 (2020) 520–529, https://doi.org/10.1049/iet-stg.2018.0255.

[55] D. Cutler, How Will COVID-19 Affect the Health Care Economy, 1 (2020) e200419–e200419. https://doi.org/10.1001/jamahealthforum.2020.0419.