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Stacking Battery Energy Storage Revenues with Enhanced Service Provision

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Abstract: Battery energy storage systems offer many desirable services from peak demand lopping/valley filling to fast power response services. These services can be scheduled so they enhance each other, in this manner the inverter size is effectively leveraged with battery capacity. A variable cost for under frequency service provision will be required to incentivise this type of operation and various options are explored in the paper.

It is demonstrated that battery energy storage systems may struggle for profitability under certain service payments; however, returns can be maximised through revenue stacking. In this paper enhanced service provision results in increased power system service provision and returns from energy arbitrage. A 10 year and a 2-year dataset, containing information on the the Irish power system, are used to investigate potential per MW revenue from a BESS with a 1.5 and 2.5-hour battery.

Three statistically derived, engineering based, power system service scalar multipliers are investigated and compared to the scalar being introduced on the Irish system. It is demonstrated that flexible service payments can be increased by more than 10% while receiving arbitrage payments. The seasonal variation in BESS revenue is investigated and observed to be mitigated or exacerbated by service scalars.

1. Introduction

Many governments have set ambitious renewable energy targets that will stress national and international power systems, forcing them to work in unanticipated ways [1]. While reducing carbon dioxide emissions is highly desirable, it will require power system operators to explore new methods of operating [2]. On most liberalised power systems, renewable energy investment and deployment was encouraged with incentives, whereby private companies owned and operated the power generators. The same method is being employed for power system services in Great Britain [3] and Ireland [4]; these services should allow the power system to operate securely during times of low inertia, due to high renewable infeed or low demand. It is vital that incentives are intelligently structured to ensure desirable operation [5], provide sufficient returns [6] and not allow for rapacious exploitation [7].

Battery energy storage systems are becoming more common on power systems at the tens of MW range. These units have served as a proof of concept and proof of scale for battery energy storage systems (BESS) systems. During their operation they have demonstrated conventional and enhanced power system services [8]. While these systems have demonstrated their value in the research field, for mass deployment BESS will need to be profitable.

While not widely adopted, BESS have shown significant economic and engineering value on small, islanded grids [9]. In [10] batteries are shown to balance variation in wind generation while meeting 60% to 80% of load. In these circumstances BESS are financially viable, as the electricity price is high, the anticipated payback in [10] is 4.5 years. A challenge for deployment on islands is the development of BESS controls and operational requirements. Considerable effort has been spent on developing requirements and remunerations for BESS on the Irish system [4]; this network has a scale between an island and a continental grid. Similar effort is occurring in the UK [11] and other systems.

The next stage of BESS development is beginning, with hundreds of MW being deployed on power systems and at single sites. It is suggested in [12] that the 100 MW/129MWh battery installed in Southern Australia by Neoen and Tesla could have a RoI of 3-years. A major selling point of BESS is in the fast frequency response area, where they deliver power to the system within hundreds of milliseconds to seconds following a fault, as required in Great Britain [3] and Ireland [4]. If the frequency response time is reduced, then potentially BESS could be eligible for a rate of change of frequency (RoCoF) or inertia service [13]; similar to the synchronous inertia service (SIR) described in [4]. These types of services should allow significant expansions of renewable energy resources and prevent incidents like the 2016 blackout in South Australia.

The Irish power system is of engineering interest as it is a large, islanded power system with substantial renewable energy infeed [14]. The renewable energy typically comes from wind powered, doubly fed induction generators, these do not inherently provide inertia or other frequency services. Ireland can also import a significant amount of power over high voltage direct current (HVDC) interconnectors, with further expansion planned. In Ireland HVDC has been employed for static reserve and frequency droop services, but it also does not provide inertia.

The displacement of synchronous generation, by nonsynchronous sources, threatens higher RoCoF and lower
frequency nadirs during generation load imbalances. If RoCoF and frequency thresholds are compromised, then substantial disruption of supply is threatened. BESS have particular promise on low inertia systems as they can have a greater per unit effect.

On the Irish system, the amount of power from sources that do not provide inertia is quantified with the metric ‘system non-synchronous penetration’ (SNSP) [15], this is the ratio of non-synchronous generation to demand. SNSP is used to maintain acceptable system security by limiting wind and HVDC non-synchronous infeed.

From the start of 2018 system SNSP has been limited to 65% but is scheduled to increase to 75% by 2020; this will help meet the goal of 40% of electricity generation from renewable energy by 2020. At present Ireland is utilising the SNSP metric as the basis of a temporal scarcity scalar [5] that adjusts certain power system service payments. It is argued in this paper that SNSP is not the best metric to reflect power system inertia or service availability.

Ireland has introduced a Fast Frequency Response (FFR) service [4]; which is similar to, but should not be confused with, the Firm Frequency Response being introduced by National Grid in Great Britain [3]. The SNSP based temporal scarcity scalar will be applied to both the FFR service and the more conventional frequency services detailed in Table 1. The specifics of the scalar design have varied significantly over the years, primarily from recommendations by the DS3 working group and industry. The work presented in this paper informs this development.

Temporal scarcity scalars, based on statistical methods, are proposed in this paper and investigated with a two-year dataset. These scalars:
- levelized BESS returns across the year
- provided a better guarantee of BESS returns
- reduce potential exploitation of incentive schemes
- reduced potential for service market manipulation
- have a better engineering justification
- incentivises investment in battery capacity

Based on a 10-year dataset, a revenue/cost analysis for a BESS operating on the Irish system is made in Section 2. This benchmarks requirements for the financial viability of BESS. Simple changes to service scalars in Ireland [16] moved BESS from financially inviable to lucrative. Ireland had been similar to other power systems where BESS were found to be inviable [6].

Enhanced service provision is investigated in Section 3, whereby a BESS can deliver a service in excess of its maximum output. This occurs when the BESS is charging and is a case of the battery leveraging the size of the inverter, through load relief and power response. Power system parameters are investigated for their financial and engineering suitability when scheduling an enhanced response.

Four power system service scalars are presented in Section 4, one of these is in operation on the Irish system, the other three are proposed by the authors. In Section 5 various control strategies are applied to a hypothetical BESS, with per MW returns are stated, this is based on a 2-year dataset. It is demonstrated that BESS can simultaneously participate in energy arbitrage and enhanced power system service provision, as in [17]. In Section 6 seasonal variability is investigated, services are observed to either exacerbated or reduced monthly variation in BESS revenue.

### 2. Estimating BESS Cost and Revenue

It is vital that BESS assets are profitable, otherwise companies may abandon their investment. Such an occurrence would damage future investment prospects for BESS and remove a valuable protection and control asset. One method of ensuring sustainable service provision from BESS is to increase profitability; another method is to reduce costs. This investigation begins by benchmarking BESS costs and anticipated revenue streams, establishing thresholds for BESS profitability.

#### 2.1. BESS Cost

An estimated cost breakdown of installing a 4 MW/16 MWh BESS is provided in [18]. An estimate for a 4 MW/2 MWh BESS can be made as battery costs were provided. The low and high cost estimates for a 4 MW, half hour, system then becomes, $1.3M to $7.4M (€1.1M to €6.0M or £961k - £5.2M) per MW. The significant variation in price arises from battery cost becoming less dominant and inverter and grid connection costs becoming more dominant. If the BESS is to provide a 10% return on investment per year, then revenues of $130k to $740k (€110k to €600k or £96.1k - £520k) per MW per year would be required. If a 10% return on investment per year is required for profitability, then BESS could struggle [6], [8].

#### 2.2. BESS Service Revenue in the UK

In 2016 National Grid put out a tender for 200 MW of BESS, of which 201 MW were accepted. The enhanced frequency response (EFR) service requires a 30-minute battery, meaning a minimum of 100.5 MWh of storage should be installed. The total payments to BESS operators will be £75M (€66M, $92M) over 4 years, or €95k (£83.8k, $116k) per MW per year.

### Table 1 New Power System services introduced on the Irish Power System in October 2018. Note that these payments do not include the application of scalars and that the Unit of Payment is MW × Availability (hours).

| Service Name                      | Abbreviation | Unit of Payment | MW Delivered Between | Revenue [€/MW per Year] |
|-----------------------------------|--------------|-----------------|----------------------|-------------------------|
| Fast Frequency Response           | FFR          | MWh             | 2 and 10 seconds     | 18,057                  |
| Primary Operating Reserve         | POR          | MWh             | 5 and 15 seconds     | 27,087                  |
| Secondary Operating Reserve       | SOR          | MWh             | 15 and 90 seconds    | 16,392                  |
| Tertiary Operating Reserve 1      | SOR          | MWh             | 90 and 300 seconds   | 12,974                  |
| Tertiary Operating Reserve 2      | TOR1/2       | MWh             | 5 and 20 minutes     | 10,344                  |

Total 18,057 66,797
Table 2: SNSP intervals over an “average wind year”, as defined in [ref]

| SNSP Level | Hours/Year | % of Year |
|------------|------------|-----------|
| <50%       | 4369       | 48        |
| 50 to 60%  | 1265       | 14        |
| 60 to 70%  | 1309       | 15        |
| >70%       | 1993       | 23        |

Table 3: Application of temporal scarcity scalar to power system service payments [ref]

| SNSP Level | POR-TOR2 | FFR |
|------------|----------|-----|
| <50%       | 1        | 0   |
| 50 to 60%  | 1        | 1   |
| 60 to 70%  | 4.7      | 4.7 |
| >70%       | 6.3      | 6.3 |
| Yearly Average | 2.77 | 2.29 |

A return of €95k per MW per year is 13.6% less than €110k per MW per year that would be required to pay for the low-cost battery in [18]; and this ignores operation and maintenance costs. This general observation supports the conclusion in [6] that BESS may struggle for profitability. The value of this service was determined through a tender process, so companies should have confidence that they can meet the service requirements at the agreed price.

There are a number of reasons why companies may have made unprofitable tenders, such as large companies being willing to operate in a loss leading capacity to establish themselves in a new market, seeing this as a research and development opportunity or wishing to smoother smaller competitors. Some companies may be able to install BESS at a lower than expected cost if they have access to sites with existing infrastructure or manufacture BESS. Finally, companies may have identified additional, and potentially novel, revenue streams whereby they can effectively game service or arbitrage revenue.

2.3. BESS Frequency Response Revenue in Ireland

The Irish power system operators are introducing new power system services, some of which are primarily intended for BESS. The new services are detailed in [4] and summarized in Table 1. Under normal circumstances power system services would return €85k (€74 or $104k) per MW per year. However, BESS revenues are increased from below the levels in Great Britain to significantly above, with the application of scalars.

The FFR service was introduced in October 2018 [5]. At present the performance scalar requires a response in less than 2 seconds. The remuneration increases to a maximum of times 3, if a response within 0.15 seconds or less is demonstrated. The increase in revenue reflects the increase in the value of service; as described in [4] and quantified in [13]. These scalars are determined by the performance of the BESS asset and are called “product scalars” in [5].

Most frequency services are paid for at a fixed rate and based on availability; however, Ireland’s transmission system operators (TSOs) have decided to apply temporal scarcity scalars. These scalars were open ended when they went live in September 2018, with the potential of significant fluctuation in service payments. In May 2019 the design of the scalar was varied, capping and normalising payments [16]. This update is desirable for industry and consumers, it is also in line with the motivation of this research.

The scarcity scalar was originally based on the specific value of SNSP; however, after further consultation this was adjusted to “an average wind year rather than operational SNSP” [16]. The details of the “average wind year” are presented in Table 2. The temporal scarcity scalar, as applied to FFR and POR-TOR2, are presented in Table 3, along with average service multipliers over the year.

Previous to the introduction of the new temporal scarcity scalars in May 2019, BESS returns in the region of €67k to €173k per MW per year might have been anticipated (Table 1, with a product scalar of 3 for FFR). Under the new service payments BESS operators could expect €185k to €226k per MW per year.

The TSOs in Northern Ireland and the Republic of Ireland have demonstrated how flexible service payments and incentive structures can be. They have demonstrated how small changes can significantly change the financial viability of a BESS – by applying scalars to POR-TOR2. They have also demonstrated how appropriate measures can limit service payment over and under payment – through the use of the average wind year and volume capping. Finally, the TSOs have introduced 6-year contracts to protect investors [5].

2.4. Potential Revenue from Arbitrage

It is expected that all BESS devices will wish to provide the power system services described in Table 1. To meet these criteria a minimum of a 23-minute battery is required. In reality 30-minute batteries will be favoured, providing room for energy management, degradation and minimum state of charge. Unfortunately, this will mean the inverter will remain idle most of the time. The authors would like to encourage investors to increase the size of the battery by providing an economic justification for energy arbitrage. This type of operation should also benefit public relations as most people believe batteries charge when renewable energy is abundant and provide power when it is not. Also, arbitrage puts downward pressure on spikes in energy price.

The energy market on the Irish power system is unified under the Single Electricity Market Operator (SEMO). This public body is required to make market data available for scrutiny and is the primary source of the data used in this section [19].

Various techniques can be employed to determine maximum theoretical revenue from an energy storage device. The techniques can employ perfect foresight, whereby a control scheme knows future prices, or a control that must anticipate future prices, more realistic. Furthermore, arbitrage is intended as a self-cannibalising market; therefore, the effect of trading on market price should be considered when conducting a thorough
economic investigation. In this case, 300 MW of BESS, each with a full 2-hour charge/discharge each day, would have a market participation factor of approximately 1.7%, as average demand is approximately 3 GW.

Typically, arbitrage will reduce the difference between maximum and minimum energy cost. While it can be anticipated that arbitrage will lower maximum daily price, BESS services may lower the cost of low demand electricity. This effect can arise through reduced renewable energy curtailment.

This investigation is intended to provide generous estimates for arbitrage returns. This high benchmark is set for the purposes of determining the maximum possible financial viability of BESS arbitrage and for comparison with control strategies investigated in Section 4.

In [20] a least square method was employed to identify maximum arbitrage earnings, this was constrained optimisation based on BESS power and capacity. In this paper a further constraint was desired, namely a minimum trading value. This value would likely vary between storage technologies and would be dictated by I/O losses, operation and maintenance costs etc. In this section a minimum trading price of €10 per MWh is used.

An iterative technique was employed that incremental placed a single trade, this involved a charge and discharge at two 30-minute trading periods. Once a trade was complete the power, state of charge (SOC) and revenue vectors were updated between the trades. A charge/discharge can take place within a region not containing a maximum SOC; similarly, a discharge/charge can only take place in regions where the SOC is above zero. If a lucrative trade is blocked, due to state of charge, it is because a more lucrative trade has been placed and an alternative trade must be sought. This technique scanned the data, found the most lucrative trade (possibly spanning years), placed this single trade and updated the power, SOC and revenue vectors. Further trades were placed until the trade value dropped below the pre-set threshold. This exhaustive search approach was implemented using the Python package Numpy and is available on GitHub [21].

Displayed in Fig. 2 is an estimate of the maximum yearly returns from energy arbitrage with a 1 MW BESS

![Fig. 2. Maximum potential returns from a storage device operating on the Irish system over 10 years.](image1)

For such a scheme to be implemented TSOs need to allow the BESS to vary participation in frequency services, similar to synchronous generators. Service participation would then vary to track service payment, with Irelands service scalars presented in Table 2 and 3. In this paper the Irish temporal scarcity scalar is investigated alongside temporal scarcity scalars that reflect daily variation in generation, power system inertia and synchronous generator output.
Stacking revenue from energy arbitrage and enhanced service provision is predicated on the observation that times of low inertia, due to renewable generation or low demand, correlate with low electricity prices (and vice versa). Shown in Fig. 4 is variation in the system marginal price (SMP) with total synchronized capacity (an indicator of inertia) and renewable energy output (lowering inertia). High inertia typically occurs during peak demand, when frequency services are typically less valuable. It is during this time that BESS would stop providing frequency services and instead export energy, gain revenue and provide a peak lopping service.

Low inertia typically occurs due to high wind penetration and low demand [11] (typical during the night) during this time the BESS would charge with cheap energy and be available to provide an enhanced FFR service, due to power import (as in Fig. 3). This indicates that through the provision of an enhanced FFR service, earnings would also be made through energy arbitrage.

### 3.1. Correlations with Wholesale Price

If a BESS is to derive revenue from arbitrage and enhanced service provision, then there must be a correlation between SMP and the power system conditions that determine the temporal scaling factor of the service. The correlations between SMP, synchronous generation and renewable generation can be observed in Fig. 4. It can be noted that increasing synchronous plant tends to increase SMP while displacing synchronized plant with renewable generation tends to decrease the electricity price, as might be expected.

Presented in Table 4 is linear regression data that quantifies the correlation between SMP and the stated power system metric. These metrics can be used to incentivise a variety of desirable power system services; the engineering rational for identifying these is briefly discussed in this section.

The regression analysis was carried out on a dataset containing the power system metrics stated in Table 4, column $\bar{x}$. The dataset was created from half hour generator outputs and generator information, both of which are publicly available [19]. The dataset covers ten years from January 2008 to December 2017.

A simple first order linear regression was carried out, using (1). Higher order polynomials were not employed as the gradient of the regression is the most important factor. Also presented in Table 4 is the regression squared ($R^2$) value which is used as a measure of the error in (1); with 100% being complete correlation and 0% no correlation.

$$\bar{SMP} = A \times \bar{x} + C + \epsilon$$

(1)

Total generation and synchronized generation can be observed to have a reasonable $R^2$ correlation with SMP, 19.1% and 20.5% respectively. The gradients of these lines are also similar, 0.019 and 0.020, and suggest that every additional GW of generation increases SMP by approximately €20. This correlation study suggests that synchronous generation has slightly more effect on SMP than total generation, which includes renewable generation and HVDC imports. The correlation between SMP and generation can be extrapolated from Fig. 5 and daily generation variation; this metric has the same profile as average generation per hour, averaged over the year. Synchronous generation was chosen as a basis for one of the temporal scalars, given its strong correlation with SMP, high gradient and the desire to reduce emissions.
Synchronized generator total capacity is the total name plate capacity of all synchronized units and gives an indication of generator inertia. While the total synchronized capacity shows less correlation with SMP ($R^2 = 10.1\%$), it has a similar effect on SMP ($A = 0.016$). The lower correlation with SMP can be understood from Fig. 5, as it appears plant is kept online overnight, and part loaded, most likely due to operational constraints [22]. It is worth noting from Fig. 5 that the profile of daily synchronized capacity would tend towards the profile of daily generation if they were not constrained on. If optimal output is supported with BESS services, then the BESS could avail of cheaper electricity, increasing arbitrage returns.

SNSP is employed as a temporal scarcity scalar for the FFR service in Ireland. The results in Table 4 demonstrate that there is very little correlation between SMP and SNSP ($R^2 = 4.0\%$). SNSP is primarily driven by wind energy (an $R^2$ correlation with SMP of 1.4%) and HVDC imports which should have a reasonable correlation with SMP. While the correlation between SMP and SNSP is weak the gradient of correlation (-0.060) indicates that SMP is on average €3.6 lower when SNSP is at 60%, compared to 0%. This price differential is low on average but provides higher returns in granular studies in Section 5.

The daily variation values in Table 4 are calculated by subtracting the 24-hour moving average from the half hour value for total generation, synchronous generation and total synchronized capacity. This method removes seasonal offset variation and exposes daily variation in the stated values. If a TSO wanted to encourage a BESS to actively participate in daily system dynamics, then a temporal scarcity scalar based on this method could be employed. It can be observed from Table 4 that daily generation variation has some of the strongest correlations with SMP and therefore could provide the highest returns for an enhanced service. This correlation can be directly observed in Fig. 5. This metric is used as the basis of a temporal scarcity scalar as it should have applications on other networks.

Other correlations with SMP are presented in Table 4 for the interested reader, but the response of a BESS to all these correlations is largely the same. A BESS that charges while SMP is low will avail of cheap energy and be able to provide an enhanced under frequency response. A BESS that discharges when SMP is high will have a diminished under frequency response, but the response should be less valuable.

4. Optimal Enhanced Power System Services

In this section four temporal scarcity scalars are investigated, these vary the FFR service payments depending on its perceived value. This incentivises enhanced service provision through the import of power.

The temporal scarcity scalars are based on SNSP, variation in daily generation, power system inertia and synchronous generation. Data covering 2015 and 2016 were used as total wind generation during these years was remarkably similar. The SNSP scalar was fitted to an average wind year, as described in [16].

The scalars developed by the authors use statistical methods, they have a minimum value of 0, a maximum of 2 and average to 1 over a year. As noted in Section 2 and Table 3, the SNSP scalar averages to 2.77 for the POR-TOR2 services and 2.29 for the FFR service. The proposed scalars were brought into alignment with the SNSP scalar utilising equations 2 and 3, where $f_{CDF}(t)$ is the cumulative distribution functions presented in Fig.6b-d.

\[
(POR - TOR2)_{SCLR} = 1 + 1.77 \times f_{CDF}(t)
\]

\[
FFR_{SCLR} = 2.29 \times f_{CDF}(t)
\]

The POR-TOR2 service, as described in (2), has a minimum service scalar of 1 and a maximum scalar of 4.54. The FFR service scalar varies between a minimum service scalar of 0 and a maximum of 4.58. This can be compared to the maximum SNSP scalar of 6.3 in Table 3. Smaller extremes in payment reduce the potential revenue from enhanced operation, but likewise protect the consumer.

4.1. SNSP Temporal Scarcity Scalar

The SNSP temporal scarcity scalar, as described in [5] and implemented on the Irish system, is tested in this paper. Presented in Fig. 6a is the cumulative distribution of SNSP on the Irish system over 2015 and 2016. The deviation from a normal distribution is notable. SNSP from wind generation alone largely follows a standard deviation curve, only effected by wind curtailment. The deviation from a normal distribution arises from the use of the HVDC interconnectors.

Plotted on the secondary axis is the temporal scarcity scalar described in [5] and fitted to the “average wind year” [16]. The step changes in POR-TOR2 and FFR service payment are dictated by the amount to time spent in that region, as described in Table 2. Before the introduction of the average wind year concept, anticipated revenues for FFR services could have increased from 0% in the years 2016 and 2017 to 196% based on targets for 2020. Thankfully the introduction of the statistical methods in [16] have protected BESS operators and consumers.

4.2. Daily Synchronous Generation Variation Temporal Scarcity Scalar

Displayed in Fig. 6b is the cumulative distribution function of daily variation in generator output. This temporal scarcity scalar is designed to provide increased service revenues when generation is at a daily minimum. In this case enhanced service provision directly encourages a peak lopping and valley filling service.

It can be noted that the cumulative distribution function in Fig. 6b deviates significantly from a normal distribution. The data does not fit a normal distribution as human behaviour and consumption characteristics are not statistically smoothed over a single day, as can be observed in Fig. 5. A normal distribution emerges in Fig. 6c and 6d as daily consumption is smoothed with yearly variation.

The daily variation scarcity function was derived from two straight lines, fitted to the data, as presented in Fig. 6b. Limits of 0 and 2 were placed and the functions
adjusted to return an average value of 1 over the year. In this case the scarcity scalar averages to 100.08%.

This temporal scarcity scalar could be better suited to power systems with less seasonal load variation than the UK and Ireland or power systems suffering from transmission congestion or generation shortfall.

4.3. Inertia Based Temporal Scarcity Scalar

Displayed in Fig. 6c is a cumulative frequency plot of nameplate capacity of synchronised generation on the Irish system during 2015/16. While the nameplate capacity is not exactly proportional to inertia, it nevertheless provides a strong indication of synchronous inertia. This approximation is particularly well suited to Ireland where most generation is from CCGT plant with OCGT and coal plant making up most of the rest. CCGT and coal plant were observed to have similar inertial responses [23].

Several simple observations can be made from Fig. 6c, the average amount of synchronised generation on the Irish power system was 4,110 MW. The lowest value was 2,300 MW and the maximum was 6,497 MW. The power system is most vulnerable when synchronised capacity is lowest, due to the shortfall in inertia and frequency services.

A line of best fit was derived from the cumulative distribution function; this function was manipulated to create the temporal scarcity equation displayed and plotted on Fig. 6c. The equation can be used to calculate an interval by interval value for the inertia temporal scarcity scalar. The scarcity scalar averages to 100.06%. The scarcity function can be updated to maintain an average value of unity.

4.4. Synchronous Generation Scarcity Scalar

Displayed in Fig. 6d is a cumulative frequency plot of synchronised generator output on the Irish system during 2015 and 2016. The cumulative distribution function was used to derive a line of best fit, this was tuned such that it averaged to 100.07%; again this figure can be updated.

Average synchronised generation is observed to be 3,002 MW, with a minimum of 1,220 MW and a maximum of 5,901 MW. The average capacity factor is therefore 73.0%, varying between 53.0% and 90.8%. These figures indicate that there is significant potential for taking plant offline and lowering customer costs, at the expense of synchronous inertia. With an increased wind penetration, the capacity factor will likely drop further if existing synchronous inertia restrictions [22] are not relaxed and lost services replaced.
Increasing capacity, making arbitrage less self-evident generation would be.

Synchronising provision.

Boxing is significant expansion on the half hour batteries currently employed.

Table 5 Annual arbitrage returns and increases in service payments for BESS operating with varying operating charge/discharge parameters and optimisation factors

| Battery Size [hr] | Max Charge [%] | Max Discharge [%] | Control Scheme | Arbitrage Returns [€/(MW-year)] | SNSP Scalar [%] | Daily Var. Scalar [%] | Inertia Scalar [%] | Synch. Gen. Scalar [%] |
|------------------|----------------|-------------------|----------------|---------------------------------|----------------|----------------------|---------------------|------------------------|
| 1.5              | 100            | 100               | Max. Arbitrage | 43,174                          | 103.3          | 107.9                | 102.8               | 105.3                  |
| 1.5              | 50             | 100               | SMP            | 39,675                          | 102.9          | 108.1                | 102.9               | 105.2                  |
| 1.5              | 50             | 100               | SNSP           | 32,128                          | 104.8          | 105.2                | 102.1               | 104.5                  |
| 1.5              | 50             | 100               | Daily Var. in Gen. | 34,200                        | 101.8          | 109.2                | 103.7               | 105.5                  |
| 1.5              | 50             | 100               | Sync. Inertia  | 33,864                          | 102.2          | 108.7                | 103.9               | 105.3                  |
| 1.5              | 50             | 100               | Sync. Gen.     | 36,547                          | 103.6          | 108.7                | 103.5               | 106.0                  |
| 2.5              | 100            | 100               | Max. Arbitrage | 58,909                          | 105.2          | 112.9                | 104.7               | 108.5                  |
| 2.5              | 50             | 100               | SMP            | 51,997                          | 104.2          | 112.5                | 104.7               | 107.9                  |
| 2.5              | 50             | 100               | SNSP           | 39,855                          | 106.8          | 108.2                | 103.4               | 106.7                  |
| 2.5              | 50             | 100               | Daily Var. in Gen. | 46,349                        | 102.6          | 114.1                | 105.7               | 108.2                  |
| 2.5              | 50             | 100               | Sync. Inertia  | 45,875                          | 103.1          | 113.6                | 106.1               | 108.1                  |
| 2.5              | 50             | 100               | Sync. Gen.     | 48,114                          | 104.9          | 113.4                | 105.4               | 108.7                  |

*Optimised arbitrage returns, with perfect foresight; as described in Section 2D

The economic implications of increasing capacity factor, by desynchronising generators, can be understood from Table 4. Each additional MW of synchronous capacity tends to increase SMP by €0.016 per MWh, while each MW of synchronous generation increases SMP by €0.020. If 1 MW of BESS import can underwrite the desynchronisation of multiple MW of plant, then the cost of importing energy may drop, making arbitrage less self-cannibalising.

5. Revenue from Enhanced Service Provision

The potential of enhanced service provision to increase service and arbitrage revenue is investigated on a 1.5 and 2.5-hour BESS. This study is carried out on the FFR service, as described in Table 2 and 3, similar, but less dramatic, results would be expected for the POR-TOR2 service. The aim in this section is to investigate the ability of BESS to participate in enhanced service provision. Expected annual and monthly revenue are examined in Section 6.

In this investigation the full 1.5 and 2.5 hours of charging and discharging are employed. It is assumed that a further set aside would be required for service provision. On the Irish and Great Britain systems 30-minutes of operation is sufficient, therefore a 2- and 3-hour battery would be required. Further, losses arising from input/output and operation and maintenance are not considered, simply trading value and service provision.

The BESS was charged and discharged based on data from the forthcoming day, much of which could be determined from day ahead scheduled generation. Participation in the balancing market, also described in [5], could raise additional funds and result in charge/discharge profiles similar to those realised in this study. The method utilised in this section should give a more realistic indication of potential revenues. It was found that between 67.7% and 84.5% of maximum potential arbitrage is realised through enhanced service provision, this is in agreement with [17].

Consideration is not given to the downward pressure on maximum SMP, when energy is sold. Consideration is also not given to the downward pressure on SMP when importing energy and providing an enhanced power system response. While it is likely that arbitrage earnings would reduce for BESS operators, it is likely that the combined effect would further reduce customer cost. For a thorough discussion of market effects see [20].

In this investigation the BESS discharges when SMP is at its highest value during the day. Highest SMP almost always occurs between 16:00 and 20:00, as indicated in Fig. 5, due to demand characteristics; very occasionally a generation shortfall can cause substantial short term increases in SMP. A maximum discharge rate was permitted, discharging at 100% allows the BESS to achieve maximum SMP revenue. During this time no under frequency response will be available and no FFR revenue will be received; but the FFR should be least necessary and least remunerated when SMP is high.

A maximum charge rate of 50% was set and was intended to extend enhanced service provision over a longer period. It can be noted from Fig. 5 that SMP is low for 6 to 8 hours during the night when demand is low. Consequently, a long charge at low SMP has little effect on arbitrage returns. It is during this long charge time (3 to 5 hours) that the BESS can provide an enhanced under frequency response.

The 1.5 and 2.5-hour batteries were chosen as they have the potential to provide substantial arbitrage returns (Fig. 2), they can deliver the enhanced response over an appreciable amount of time and they would encourage a significant expansion on the half hour batteries currently incentivised in Great Britain and Ireland.

The arbitrage and scalar returns for a 1.5-hour and 2.5-hour battery are presented in Table 3. Six control strategies are presented, two are based on maximising energy arbitrage, the other four are based on the temporal scarcity scalars discussed in Section 4.

5.1. Operating the BESS for SMP Returns

The BESS was first controlled with SMP, this provides a benchmark for arbitrage returns using energy cost as a control factor. As noted in Section 3, simply carrying out energy arbitrage should achieve significant participation in most temporal scarcity scalars, thereby providing a secondary benchmark. Financial returns from SMP were
investigated with the perfect foresight charging algorithm discussed in Section 2.4 and with the day ahead charge/discharge algorithm used to maximise service participation but using SMP as a figure to optimise.

Maximum Arbitrage in Table 3 is derived using the method outlined in Section 2.4, however the minimum trading value was reduced to €5. This lower figure permitted more energy trading to occur, which resulted in more enhanced service provision. It can be noted from Table 3 that Maximum Arbitrage control resulted in very reliable participation in most temporal scarcity scalars.

The SMP based control scheme, employing the day ahead algorithm, achieved consistent service participation. A reduction in arbitrage returns can be noted, where yearly income drops from €43.2k per year to €39.7k per year, a fall of 8.1% compared to the Maximum Arbitrage case on a 1.5-hour battery.

Interestingly arbitrage returns dropped by 11.7% on the 2.5-hour battery; demonstrating that sophistication of the charge/discharge algorithm needs to increase with battery size to realise greater returns. While the arbitrage effectiveness of the SMP based control drops with battery size, this control strategy still provides higher arbitrage returns than enhanced power system service provision. When comparing SMP control to Maximum Arbitrage, a reduction in power system service participation can be noted when moving from a 1.5 to a 2.5-hour battery. This would indicate that greater performance could be achieved.

Table 3 demonstrates that a BESS operated for arbitrage revenue will inadvertently provide a consistent enhanced power system service. This result demonstrates the correlation between SMP and the power system measurements discussed in Section 3.1. The fact that arbitrage and power system service participation are so closely linked will mean BESS operators will need to determine if a small increase in service participation justifies a reduction in arbitrage revenues.

5.2. SNSP Based Temporal Scarcity Scalar

While SNSP provides an appreciable arbitrage return, earnings are reduced by between 19.0% and 23.4% compared to SMP control. This result can be understood as SNSP, especially when it is relatively small, does not correlate particularly well with SMP (Table 4). SNSP does rise during the night, which will incentivise low cost charging, but it does not correlate with SMP to the same extent as the other control factors investigated (Table 4).

Enhanced power system service returns from SNSP based control did successfully increase FFR service returns by 4.8% and 6.8%. For a baseline FFR payment of €18-54k per MW per year and an average scalar increase of 2.29 (Table 3), revenue would be increased by between €1.98k and €8.41k per MW per year. This revenue will not cover the drop in SMP revenue as SNSP control increased service participation by 2.9% and 4.2%.

It can be noted that SNSP control provided the lowest arbitrage returns for all temporal scarcity scalars. Demonstrating that SNSP is a poor multipurpose temporal scarcity metric.

5.3. Daily Synchronous Generation Variation Scalar

This scalar correlates strongly with SMP and has a high magnitude variation, as observed in Fig. 5 and Table 4. Consequently, daily variation in synchronous generation provides a reasonable arbitrage return. Compared to SMP control, arbitrage returns dropped by 13.9% (€5.5k per year) and 10.9% (€5.6k per year) for the 1.5 and 2.5-hour batteries.

The daily variation in synchronous generation control scheme increased participation in the service by between 9.2% and 14.1%, for a 1.5-hour and a 2.5-hour battery respectively. This would result in a service revenue increase of between €3.8k per year and €17.4k per year, in the worst and best-case scenarios. This result would demonstrate that active participation in this service makes financial sense, if SMP control did not inadvertently achieve such a high participation in the service. It is likely improved control schemes could increase arbitrage returns making active enhanced service provision more profitable.

Operating the BESS to maximise returns from this scalar results in substantial participation in the inertia and synchronous generation temporal scarcity scalars. While the direct engineering justification for this temporal scarcity scalar may be low (on the Irish and Great Britain systems), the indirect engineering justification may be high. This observation, coupled with significant arbitrage revenue, makes this metric worthy of consideration as the basis of a temporal scarcity scalar.

5.4. Synchronous Generation Nameplate Capacity Based Temporal Scarcity Scalar

Synchronous inertia-based control provided relatively low arbitrage returns and relatively poor enhanced service provision. The poor arbitrage returns can be understood from the correlation in Table 4 and Fig. 5. It is evident from Fig. 5 that variation in synchronous inertia is much less pronounced than generation variation or SMP variation, this will limit returns. The low variability is a result of thermal plant being constrained on due to operation requirements and grid codes [22], but this could change.

It is intended that BESS derived FFR services will provide a safeguard during times of low inertia; allowing plant to be taken offline and lowering SMP. This action will move the results derived from this synchronous inertia service towards those observed for the synchronous generation scalar, which provided good SMP returns.

A synchronous inertia (or power system inertia) derived temporal scarcity scalar has the greatest engineering justification. Unfortunately, the historic returns indicate that there is very little arbitrage or enhanced service revenue justification for engaging in it. However, this may change as synchronous inertia becomes decoupled from operating conditions and operational constraints.

5.5. Synchronous Generation Based Temporal Scarcity Scalar

Operating the BESS in opposition to changes in absolute synchronous generator output resulted in the
highest arbitrage returns after SMP operation. Arbitrage earnings were reduced by between 7.9% and 7.5% for a 1.5 and a 2.5-hour battery respectively. This control function also achieves reasonable participation in its temporal scarcity scalar, increasing FFR revenues by between 6.0% and 8.7%. These result in yearly increases in earnings of between €2.5k and €10.8k.

The financial justification for enhanced service provision, under these operating parameters, only apply to BESS achieving higher performance scalars. This observation is similar to that for generation variation; however, the potential loss of arbitrage earnings is lower, meaning experimentation has a lower penalty.

A major advantage of this scarcity scalar is that it, unlike a synchronous inertia scalar, is less liable to system operator manipulation (and potential allegation of malpractice). Synchronous generator output makes up the balance between customer demand and non-synchronous infeed; both of which are largely out of operator control until operating parameters are infringed. This operating parameter should also converge with the synchronous inertia parameter, as mentioned. This operating parameter also achieved high participation in the SNSP scalar, this should encourage Ireland’s TSOs as it is used as a basis for their temporal scarcity scalar.

6. Complementary Seasonal Revenues from Arbitrage and Power System Services

The anticipated per MW yearly returns for a 2.5-hour BESS are presented in Table 6. In this case the full 2.5-hours of battery are charged/discharged, so a further 30 minutes of set aside may be required for service provision. In this section the times three performance scalar is applied to the FFR service, so the value stated is a maximum and would likely reduce. The deviation from the results in Table 5 arise as a single window of operation was used (24-hours). It can be noted that the annual difference in revenues in Table 6 is less than 7.5% and a BESS investor could expect returns of €360-400k per MW per year. This value would make a BESS an attractive investment under the conditions described in Section 2.

A substantial increase in power system service revenue arose from the updates in [16]; whereby the FFR service increased by 2.29 and POR-TOR2 by 2.77, as specified in Tables 1-3. These high returns are effectively guaranteed, but capped, with the application of the “average wind year” [16]. The volume capped application process, specified in [5], also protects customers.

The significant increase in service payments has diminished the significance of arbitrage earnings. When the service payments are averaged to one, arbitrage earnings make up approximately 25% of revenue, rather than 12%. However, observations made before the change in service payment still hold. Seasonal BESS income variation could place stress on BESS operators and not incentivise optimal operation.

6.1. SNSP Temporal Scarcity Scalar

The anticipated returns from service provision and arbitrage for a BESS operating on the Irish power system are shown in Fig. 7a. It can be noted that the vast majority of earnings come from services. A substantial variation in monthly income can be observed, with winter revenue (high load) double summer earnings. The profile of Fig. 7a can be contrasted with the profile of Fig. 7c, which more closely follows proposals from National Grid in [11].

The variation in revenue arises from the demand and wind generation characteristics on the Irish system. In short SNSP is on average higher during the winter, increasing service payments, and the variation between minimum and maximum SMP is largest, driving arbitrage revenues. In general, the minimum SMP remains relatively constant throughout the year, while the maximum SMP can more than double between summer and winter.

Demand is highest during the winter months, due to people being indoors, heating and lighting (with air conditioning not being significant during the summer). The high demand increases energy price and incentivises the import of power over HVDC interconnectors, raising SNSP. Ireland also experiences higher wind speeds during the winter and consequently SNSP is increased. Therefore, both energy arbitrage and power system services are compensated to a higher degree during the winter.

6.2. Generation Offset Scarcity Scalar

This scalar provided the most consistent power system service returns across the year, as can be observed in Fig. 7b. This result is expected as this scalar averages to unity over any 24 hour period. A small increase in service payments can be noted from October through March, driven by enhanced service provision when demand variation is highest. Arbitrage returns during high demand months are higher, increasing the small annual variation.

The lack of monthly variation belies the high degree of daily generation that occurs with this scarcity scalar. This scalar most directly incentivises BESS to engage in peak lopping and valley filling services. This type of operation would benefit networks with transmission constriction and generation shortfall. This scalar may be better suited to larger power systems, with annual load profiles that differ from Great Britain and Ireland.

6.3. Synchronous Inertia Scarcity Scalar

This scalar has the strongest engineering justification and is most in line with the proposals of National Grid in [11]. National Grid have specifically identified summer, minimum demand nights as being a time of greatest vulnerability. Consequently, BESS operating
under this scarcity scalar, would receive greatest compensation during the low demand summer months, as can be noted from Fig. 7c. In this study December and January appear as outliers against the general trend, an indication of the extent of non-synchronous infeed.

It can be noted that arbitrage goes some way to smoothing the fluctuations in service revenue during the year. Before the introduction of the service multipliers (of 2.29 and 2.77 in Table 3) arbitrage achieved more smoothing. This effect would emerge again if service payments were normalised or if the full three times product scalar was not obtained by the qualifying BESS.

One problematic issue with this scalar is that synchronous generation is often constrained on due to operational requirements. This type of power system manipulation is common place and necessary. Unfortunately, if this type of control affects power system service payments, then allegations of market manipulation are likely to arise.

6.4. Synchronous Inertia Scarcity Scalar

This scalar, along with generation offset, achieved the most consistent BESS returns across the course of the year, as can be observed in Fig. 7d. In the authors opinion this is the scarcity scalar that has the best balance of an engineering justification, reducing synchronous generation, a balanced BESS return and freedom from market manipulation.

While synchronous generation does not directly reflect power system inertia, it has a strong correlation with it. The advantage of this scalar is that it neither incentivises or disincentivises a network operator from balancing synchronous generation between multiple generators. Meanwhile synchronous generation is dictated by demand characteristics and wind generation that are largely out of network operator’s control. While HVDC activity could affect this scalar, it should have a major effect.

Arbitrage was observed to smooth monthly BESS revenue returns before and after the changes in service payments detailed in [16]. Consequently, it is felt that this power system service scalar should provide consistent returns, from service provision, enhanced service and arbitrage, as network conditions evolve rapidly.

7. Conclusion
This paper demonstrated that BESS in Great Britain may struggle for financial viability. BESS in Ireland were in a worse position until service revenues were increased by factors of 2.29 and 2.77. Service payments at this rate are however volume capped and it is likely that these revenues will drop as the technology matures. This paper explored both potential revenues from energy arbitrage and the ability to achieve enhanced service provision through charge scheduling. It is hoped that these results may incentivise BESS with a larger battery, that actively participate in the energy market as well as the service market.

This paper has investigated the potential per MW per year returns for BESS, operating on the Irish system. It would appear that a 1.5 hour and 2.5 hour battery could increase their annual income by between €32k and €52k per MW through energy arbitrage alone, as displayed in Table 5. This remuneration could be valuable when financial viability is marginal.

Power system scalars, like those being introduced in Ireland [5, 12c], were investigated; specifically temporal scarcity scalars. It was found that enhanced service provision could increase the value of these services by 4.8% to 14.1% (Table 5), depending on the scalar. It was also noted that engaging in arbitrage inadvertently resulted in significant enhanced service provision.

The synchronous generator output temporal scarcity scalar is favoured by the authors. While this scalar has a weaker engineering justification than an inertia based one, it has several desirable incentives. This scalar is less liable to manipulation and encourages the convergence of synchronous generator output from synchronous inertia, lowering SMP. This scalar also provided high arbitrage returns, allowing BESS operators to engage in enhanced service provision with limited financial impact. This scalar, in conjunction with arbitrage, also provided levelized returns during the year.

The research was extended to investigate seasonal variations in both arbitrage and service payments. Arbitrage returns were observed to consistently vary by a factor of 2.5 between June (low demand) and November (high demand). This seasonal variation in income was exacerbated by the SNSP based temporal scarcity scalar, being introduced in Ireland, increased payments by almost a factor of 2. Seasonal variation in service payment was inverted with an inertial temporal scarcity scalar. Seasonal variation was virtually nullified with the use of the synchronous generation derived scarcity scalars.

This enhanced power system service provision investigation has demonstrated that BESS inverter capacity can be leveraged (during times of scarcity) with battery capacity. It is demonstrated that participation in enhanced service provision will typically result in arbitrage earnings, and vice-versa. It is desirable that appropriate temporal scarcity scalars are chosen by TSOs, to encourage optimal BESS operation and well bounded service payments.

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