



A social cost benefit analysis of grid-scale electrical energy storage projects: A case study



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HIGHLIGHTS

- A Monte Carlo simulation is paired with the social cost benefit analysis.
- Battery lifespans may be shorter than the lifespan of a conventional upgrades.
- Only a subset of locational and system-wide benefits is captured simultaneously.
- Future cost decline drives the social welfare of grid-scale storage investments.

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ABSTRACT

This study explores and quantifies the social costs and benefits of grid-scale electrical energy storage (EES) projects in Great Britain. The case study for this paper is the Smarter Network Storage project, a 6 MW/10 MWh lithium battery placed at the Leighton Buzzard Primary substation to meet growing local peak demand requirements. This study analyses both the locational and system-wide benefits to grid-scale EES, determines the realistic combination of those social benefits, and juxtaposes them against the social costs across the useful lifecycle of the battery to determine the techno-economic performance. Risk and uncertainty from the benefit streams, cost elements, battery lifespan, and discount rate are incorporated into a Monte Carlo simulation. Using this framework, society can be guided to cost-effectively invest in EES as a grid modernization asset to facilitate the transition to a reliable, affordable, and clean power system.

1. Introduction

Electrical energy storage (EES) can support the transition toward a low-carbon economy (decarbonisation) by helping to integrate higher levels of variable renewable resources, by allowing for a more resilient, reliable, and flexible electricity grid and promoting greater production of energy where it is consumed, among others [1]. In addition to decarbonisation, EES promotes lower generation costs by increasing the utilisation of installed resources and encouraging greater penetration rates of lower cost, carbon-free resources [2]. EES plays an important role supporting distributed generation and distribution planning processes for future power systems. Different jurisdictions are evaluating the value of EES (and other Distributed Energy Resources) for planning purposes related to the next generation of electric distribution utilities [3–5].

The global electrical energy storage market is expanding rapidly

with over 50 GW expected by 2026 of utility-connected energy storage and distributed energy storage systems.¹ In the United States alone, deployment is expected to be over 35 GW by 2025 [6]. This upward trend is mainly explained by favourable policy environments and the declining cost of EES, especially batteries [7]. Market structures that support its deployment are also observed (i.e. California Public Utility Commission – CPUC and the goal is to install 1.3 GW of EES by 2020) [8]. The declining costs of EES combined with cost optimisation models show an increase in the number of applications and use-cases of storage technologies [9,10]. There are different types of EES technologies with specific technical characteristics (i.e. response time, number of cycles, discharge time, storage duration), that make them more or less suitable for a different range of EES applications (i.e. peak shaving, voltage control, frequency regulation) [11,12]. Depending on the market, EES technologies and their applications can be subject to different regulatory context and policies [13–15]. Even though there are a large

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¹ See: <https://www.navigantresearch.com/newsroom/global-annual-power-capacity-additions-for-utility-scale-and-distributed-energy-storage-to-exceed-50-gw-by-2026>.

number of EES technologies, not all of them are exposed to the same level of development. This reflects the different size of capital and/or operational costs among them. In fact many of them are still in a research or development stage. While pumped hydro storage is among the most mature and cheapest storage technologies for short-term and long-term storage [16], battery storage is the one with the most commercial interest and growth potential [17].

EES can be used for multiple applications and can therefore generate different revenues streams whose value depends on the type of technology² [18] and the place where the EES facility is located, at generation sites, on the transmission or distribution grid or behind the end consumer's meter [19]. Different studies have evaluated the cost and benefits of EES however few of them take into account the multi-product nature in agreement with the diverse EES revenues streams and the uncertainty component. Idlbi et al. [20], estimate the net benefits of battery storage systems – BSS (connected at medium voltages (MV)) in the provision of reactive power versus other options such as conventional reinforcement. They suggest that BSS for voltage compliance is more economically viable than the grid reinforcement option but less viable than power curtailment. However this viability can increase if we take into account the multi-product nature of BSS, which is not limited to reactive power support only, and the fact that battery costs show a downward trend, which is making EES more competitive. Gunter and Marinopoulos [21], estimate and evaluate the contribution of grid connected EES to frequency regulation and peak limiting (for demand charge reduction) in the eastern United States (PJM served area) and California (CAISO served area). Results from their cost benefit analysis (CBA) and sensitivity analysis suggest that EES deployment is economically viable even with market structures less beneficial than the current ones. However, the large profitability of EES in California may be explained by the subsidies applied to the development of EES (i.e. Self-Generation Incentive Program – SGIP³). Shcherbakova et al. [23] evaluate the economics of two different battery energy storage technologies (Sodium-Sulfur and Lithium-ion) for energy arbitrage in the South Korean electricity market. They find that none of these storage technology is economically viable based on the current market conditions. They also recognise that the inclusion of other potential financial benefits in ancillary services (e.g. frequency regulation) and other applications may reverse this result. Wade et al. [24] evaluate benefits of battery storage (focused on a specific trial operated by EDF Energy Networks in Great Britain) connected to the distribution network. The benefits of the storage system are evaluated based on the response of multiple events requiring voltage control and power flow management. The authors find that the introduction of EES embedded in the distribution network has a positive impact on the tasks associated to these two variables.

Other studies concentrate on the analysis of the costs and benefits of EES and renewable energy integration (i.e. storage and renewables) using specific optimisation models. Sardi et al. [25] evaluate the cost and benefits of connecting community energy storage in the distribution system with solar PV generation. A comprehensive set of EES benefits and some specific costs were identified. The authors suggest that the proposed strategy helps to find the optimal location of the EES that maximises the total net present value (NPV). Han et al. [26], propose an optimisation model for integrating grid-connected microgrids with solar PV and EES. A cost benefit analysis is used in order to establish a generation planning model of a micro-grid that maximises the net profits.

Among the studies that are more related to this study are Perez et al. [27], Newbery [28] and SNS [29]. These studies are also focused on the evaluation of net benefits of a particular case study (Smarter Network Storage project). However, our paper is the one that includes the most comprehensive list of EES benefits and costs. This paper in comparison with others, incorporates risks and uncertainty of net benefits, costs and battery lifespan (using Monte Carlo simulation). In addition, rather than modelling EES from a business case perspective or in a future-state of the power system dominated by renewables and distributed generation, this study uniquely evaluates a specific energy storage project from society's perspective (social welfare) in order to cost-effectively guide investment in EES projects and discuss policy implications and electricity market reforms for achieving a low carbon network. Accurately valuing EES projects helps inform system operators, distribution network operators, generators, suppliers, regulators, and policy-makers to make decisions to efficiently allocate resources to modernize the electricity grid.

This paper seeks to examine the empirical trials from the Smarter Network Storage (SNS) project through the lens of a social cost benefit analysis to evaluate publicly sanctioned investments in grid-scale EES in Great Britain. The social cost benefit analysis framework answers the fundamental question of whether or not society is better off after making the investment in grid-scale EES. The uncertain benefit and cost streams are evaluated through a Monte Carlo simulation and then arranged through a discounted cash flow to provide a net present social value of the investment. SNS represents the first commercially-deployed, multi-purpose grid-scale battery in Great Britain, and it has been selected as the case study for this research because its empirical results from years of trials are well documented.

The paper is organised in the following manner. Section two provides the background and a brief description of our case study: the Smarter Network Storage project. Section three discusses the Cost Benefit Analysis method. Section four identifies and quantifies the social costs. Section five identifies and estimates the different social benefits and related revenues streams. Section six discusses the results by combining the analysis of the costs and benefits and the implications of the net present value results. Section seven lays out the conclusion and offers insights into policy recommendations for enhancing the value of EES through electricity market reforms.

2. About the case study: Background of the Smarter Network Storage project

2.1. Smart Network Storage project background

In order to facilitate the low carbon transition of the power system, the Office of Gas and Electricity Markets Authority (OFGEM) established the Low Carbon Network Fund, a £100 million per annum (p.a.) fund – which ran for 5 years from April 2010 to March 2015 - to support clean energy demonstration projects sponsored by Distribution Network Operators (DNOs).⁴ One such DNO, UK Power Networks (UKPN) established the Smarter Network Storage project in 2013 to showcase how EES could be used as an alternative to traditional network reinforcements, enable future growth of distributed energy resources, and a low carbon electricity system. The Smarter Network Storage project deployed a lithium-ion battery with 6 megawatts (MW) and 10 megawatt-hours (MWh) of power and energy, respectively, at the Leighton Buzzard Primary substation to offset the need for an additional sub-transmission line to alleviate capacity constraints.

² Classification based on the way how energy is stored.

³ In the latest budget allocation (which comes from authorised revenue collection), energy storage technologies get 80% of funds and generation technologies the remaining 20%. Total authorised regulatory revenue collection to the end of 2019 amounts to circa US\$ 501 million. Different incentives rates applied for energy storage (US\$/Wh) depending on the type of system (large-scale storage, small residential storage) and the Step (from 1 to 5), [22].

⁴ For more information: Office of Gas and Electricity Markets authority. "Low Carbon Networks Fund." Available at: <https://www.ofgem.gov.uk/electricity/distribution-networks/network-innovation/low-carbon-networks-fund>.

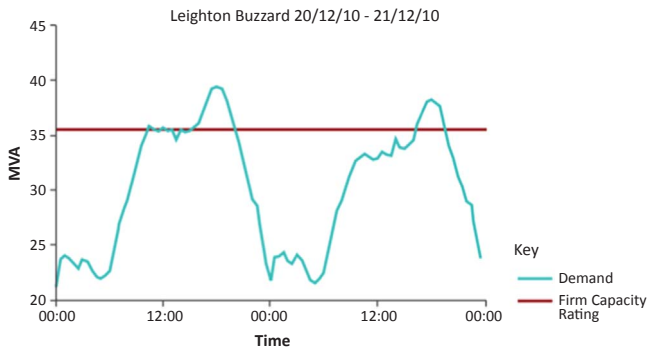


Fig. 1. Load profile during two high demand days at Leighton Buzzard.

2.2. The capacity problem

Electricity supply in Great Britain is composed of four key sectors: generation, transmission, distribution, and suppliers. Within this electricity supply chain is the Leighton Buzzard Primary substation, an asset owned by UKPN and a bottleneck for providing reliable power to customers in the distribution network. Leighton Buzzard is a town located in Bedfordshire, England and has a population of approximately 37,000 people. The current Leighton Buzzard primary substation design includes a 33/11 kV substation and two 33 kV circuits, each with a rated thermal capacity of 35.4 MVA. Due to cold snaps in the winter, UKPN experiences its peak demand for electricity in the winter insofar that the local peak demand surpasses the 35.4 MVA capacity limit. Fig. 1 [30], p. 15) illustrates this capacity problem dating back to December 2010.

To alleviate the current capacity constraints, the Leighton Buzzard substation is able to re-route 2 MVA of electricity supply. This transfer capacity from neighbouring sections of the distribution network has successfully resolved the peak demand problem in Leighton Buzzard in the short-term; however, it is costly and does not avert the larger issue of growing peak demand over the long-term. Thus, UKPN sought to investigate two potential long-term solutions to the capacity constraint.

2.3. The two options for network reinforcement

The first option is the conventional approach that DNOs like UKPN would historically choose using a least-regret investment criteria. This option includes building new distribution infrastructure to support the growing electricity needs: an additional 33 kV circuit connecting to the 132/33 kV Sundon Grid and a third 38 MVA transformer located at the Leighton Buzzard substation. This reinforcement would provide an additional 35.4MVA in firm capacity at Leighton Buzzard, which is significantly above predicted capacity requirements for the medium-to-long term [30].

The second option is often referred to as a Non-Wires Alternative (NWA) investment because it need not require the expansion of the wires on the electricity grid. Rather, UKPN could build an EES device at the site of the substation to alleviate the capacity constraints. The EES would discharge electricity during times of peak demand to alleviate stress on the electricity grid, and then charge during times of low demand. The EES would be configured and dispatched in a manner to offset the need for the conventional upgrade.⁵

Fig. 2 [30], p. 15) compares the two options for network reinforcement. On the one hand, UKPN could build a third circuit (illustrated by the hashed line) between the 132/33 kV Sundon grid and the 33/11 kV Leighton Buzzard substation. On the other hand, UKPN could build an EES device (illustrated by the green schematic) to offset the

⁵ Power-to-gas, power-to-heat, compressed air energy storage (CAES), thermal energy storage, sodium-ion, flow batteries, etc. were not assessed by UKPN, hence have been excluded from the scope of this study.

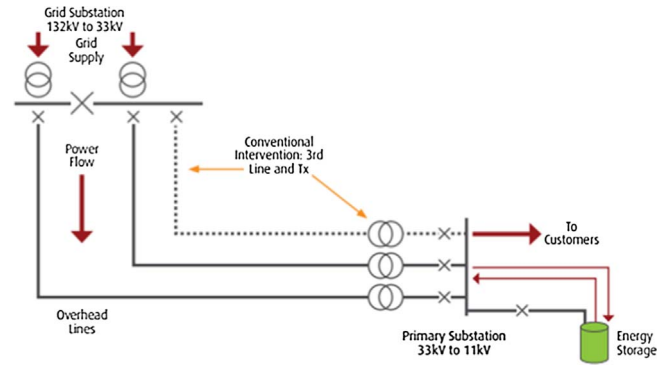


Fig. 2. Comparing the two options for network reinforcement.

need for the conventional upgrade.

Using financing from the Low Carbon Network Fund, UKPN opted to choose the latter solution and build the EES device in 2013, called the Smarter Network Storage project. The EES device for the Smarter Network Storage project was a lithium-ion battery (developed from a lithium-manganese blend) of the size 6 MW/7.5MVA/10 MWh.⁶

In addition to deferring the upgrade for capacity, the Smarter Network Storage project sought to realise additional benefits from building a battery by participating in the wholesale power markets and providing location-specific and system-wide services. Due to the unbundling regulations in the UK for DNOs, the Smarter Network Storage project is owned by UKPN⁷ but it is operated by Smartest Energy and its aggregator is Kiwi Power. Since 2013, UKPN has recorded empirical results from testing and trialling the battery, as it performs in reality while interconnected to the grid. Using the empirical trial runs, this paper seeks to evaluate the decision to invest in EES from a societal perspective using social cost benefit analysis.

3. The social cost benefit analysis method

The social cost benefit analysis framework is an effective tool for evaluating the publicly sponsored investment in Smarter Network Storage. A full social cost benefit analysis should be able to address the impact of an EES project on economic efficiency and equity [32].

Galal et al. [33] identify three main agents in society: consumers, private producers and government. When applying their framework to the electricity supply chain, the agents in society include OFGEM, National Grid, UKPN, consumers, suppliers, and developers. Within electricity markets, deploying a battery would provide different revenue streams for each agent, hence requiring a different business model subject to the individual agent’s value proposition. However, the social cost benefit analysis takes a more holistic perspective looking across the various agents of the energy supply chain, incorporating market-based value streams and non-market shadow prices. This tailored social cost benefit analysis framework is illustrated in Eqs. (1) and (2).

Eq. (1): Social cost benefit analysis

$$\Delta SW_t = \sum_i (V_t^i) + \sum_j (\lambda_t^j) - \sum_k (C_t^k) \tag{1}$$

ΔSW_t = The annual change in the social welfare before and after the investment in the battery

V_t = The annual market-based value to society

⁶ MW is a measurement of the real power capacity of the battery. Mega Volt-Ampere (MVA) is a measurement of the apparent power capacity, which includes both real and reactive power capacity. MWh is a measurement of the energy capacity of the battery.

⁷ Non-distribution business activities, such as income generation from storage projects, are limited by de minimis restrictions specified in the distribution licence. These restrictions mean that turnover from and investment in non-distribution activities must not exceed 2.5% of DNO business revenue or licensee’s share capital respectively [31].

λ_t = The annual non-market based value to society determined by shadow prices
 C_t = The annual costs incurred by society
 i = i^{th} annual market based value
 j = j^{th} annual non-market based value
 k = k^{th} annual cost.

Eq. (2): Net present value analysis

$$NPV = \sum_{t=0}^T \left[\frac{1}{(1+r)^t} * \Delta SW_t \right] \quad (2)$$

NPV = The Net Present Value of the project
 r_t = the discount rate, determined by the weighted average cost of capital at time (t)
 t = the number of years.

The use of the sigma notation is critical to the social cost benefit analysis because the time dimension for the benefit and cost streams extend through the useful life of the battery project. The useful life is defined as the period between the beginning of construction to the end of decommissioning the project. This enables the coupling of a social cost benefit analysis with a useful lifecycle assessment to evaluate the techno-economic performance of the battery. In addition to the useful lifecycle assessment, the social cost benefit analysis will require the use of discounted annual cash flows to determine the net present value of both the benefits and costs.

Moreover, note the removal of all transfer payments from one agent to another within society. Transfer payments are the exchange of financial claims in which there is no net value generated to society. The need to remove transfer payments induces a more critical examination of project cash flows which rely on taxation, subsidies, duties, and improvements in the cost of financing because these mechanisms may merely involve the transfer of resources from one agent to another within society. In Section 4, certain benefit streams are also omitted from the analysis because they can be classified as transfer payments.

For the useful lifecycle assessment of the social cost and benefit streams, the discount rate is determined by the pre-tax weighted average cost of capital (WACC).⁸ The pre-tax WACC removes the impact of taxation from the financial analysis (consistent with the view on transfer payments) and values the risk and uncertainty associated with the EES project. SNS [29] established the cost of equity at 7.2%, the cost of debt at 3.8%, and the debt-equity ratio at 62%; therefore, the pre-tax WACC in real £ terms is 5.09%. For this analysis, the discount rate was varied between 3.0% (the social discount rate) and 7.2% (the cost of equity). All values in this report are presented as £2013, unless otherwise noted.

The social cost benefit analysis framework in this study is adapted from Galal et al. [33]. It includes the use of a counterfactual (opportunity cost) such that the calculated NPV guides investments in EES relative to other solutions. Using the Kaldor-Hicks compensation principle, the investment in the Smarter Network Storage project would be deemed worthwhile to society if $NPV > 0$. Such a result would warrant that the investment was net-beneficial to society [34]. On the other hand, if $NPV < 0$, this would signify that the investment was net-costly to society.

3.1. Incorporating risk and uncertainty with Monte Carlo simulations

Incorporating risk and uncertainty enhances the project appraisal and policy assessment because the social benefits and costs are not deterministic values but rather subject to variation under different

future scenarios. In the case of evaluating the Smarter Network Storage project, the variables are stochastic and vary significantly due to uncertainty in future reforms of the electricity market and policy settings, etc.

A Monte Carlo simulation is a computer-based technique that uses statistical sampling and probability distribution functions to simulate the effects of uncertain variables [35]. Monte Carlo simulations should be paired with a social cost benefit analysis because it is meaningful to attach statistical distributions to model the uncertainty. The Monte Carlo simulation is executed for 10,000 multi-dimensional trials and applies a normal distribution (Eq. (3): Normal Distribution for Assessing Social Benefits) to each of the eight benefit streams, to each of the six costs elements, and incorporates the potential variation in the lifespan of the battery and the discount rate.

Eq. (3): Normal distribution for assessing social benefits

$$f(x|\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (3)$$

μ = the expected value of the benefit
 σ = the standard deviation of the benefit value
 x = the simulated outcome of the benefit value.

4. Identification and estimation of the social costs

Typically, the social costs vary by type of EES technology, the power and energy capacity, and the use-case. This section establishes a clear and consistent framework for capturing all the useful lifecycle costs of EES and then applies it to the Smarter Network Storage project. The costs are bifurcated into capital expenditures and operating expenditures. Our use of the lifecycle cost analysis captures capital and operating maintenance costs of storage systems. Some maintenance costs are a function of the cycling of storage and are embedded into the Monte Carlo cost and degradation simulations. The cost of financing (taxes, accelerated depreciation, tax shields, duties, etc.) the battery is removed from the analysis because it is not a social cost.

4.1. Capital expenditures

The capital expenditures of a lithium ion battery pertain to the battery cells, the battery pack, the balance of system, the soft costs, and the engineering, procurement and construction (EPC). The following discussion parses out the intricacies of the costs of EES devices and normalizes the costs to the size of 6 MW/10 MWh for the Smarter Network Storage project.

4.1.1. Battery cells and pack

The battery cells and packs are at the core of the battery energy storage system (BESS). The Smarter Network storage project acknowledges that the main cost driver of the cells and packs is the power-to-energy ratio of the storage device. Therefore, costs of these components are often reported as £/kWh. It is estimated that an identical battery with the size of 6 MW/6 MWh would have 60–65% of the total capital expenditure of the 6 MW/10 MWh battery [36].

The Smarter Network Storage project includes 192 Samsung SDI lithium-manganese battery cells connected in series per pack. These packs were then placed into 264 trays per rack, with 22 racks connected to each 500 kW of the storage management system. Each switchgear (string management system) includes 12 trays, composed of 22 battery string, and the entire battery system is accompanied with an 11 kV switch room. For a 6 MW battery, the result is a total of 50,688 Samsung SDI battery cells that are integrated into battery packs. Additional battery configurations and technical specifications are provided by the project developers and vendors [37,38].

⁸ Pre-tax WACC = (Pre-tax cost of equity * percentage of equity) + (pre-tax cost of debt * percentage of debt).

4.1.2. The balance of system

The balance of system for the BESS includes just the hardware costs for the equipment to support the functionality of the battery cells and packs. The balance of system costs include the rectifier and the bi-directional inverter because the battery operates in direct current (DC) but charges from and discharges to the grid, which operates on alternating current (AC). The balance of system costs include power conversion systems, enclosures, containerization, safety equipment, system packaging, and any other system operating technologies. The balance of system costs are often reported in £/kW because the equipment is designed to support the maximum power output of the battery.

4.1.3. Soft costs & engineering procurement and construction (EPC)

The soft costs include the customer acquisition, customer analytics, industry education, permitting fees, supply chain costs, and installation labour. As evidenced by other more mature technologies such as photovoltaics, soft costs can decline rapidly as standardization reduces the permitting fees, labour-hours, and supply chain costs. As the EES industry matures, the soft costs will likely follow an asymptotic cost decline curve.

The engineering, procurement, and constructions (EPC) costs largely included civil engineering, procurement of land for use, and logistics for construction of the site. The need to construct an entire building to house the BESS became the driver for the EPC costs. For the Smarter Network Storage project, a building equivalent to the size of three tennis courts was constructed to safely and securely operate the 240 tonnes of equipment.

4.2. Operating expenditures

The BESS has annual operating expenditures that include system upkeep and electricity purchasing. Upkeep costs include inspection & maintenance, spare parts, facilities costs, insurance, management & administration, control systems, and risk management & energy trading. Regardless of the utilisation of the BESS, these upkeep costs are relatively similar year-over-year in real £ terms (see Appendix B).

The BESS has electricity purchasing costs that include tariffs and charges to interconnect to the electricity grid and provide wholesale power services. These costs include the wholesale energy price during charging of the battery, low voltage auxiliary consumption, balancing services use of system charges, residual cash flow and reallocation cash flow, contract for differences operational levy, and daily service fees. These costs are directly a function of the utilisation and type of balancing service provided by the BESS; thus, they will fluctuate year-over-year as the performance and dispatch of the battery and the wholesale energy price change over its lifespan.

Operating costs that have been omitted from this analysis include the DNO fixed charge, the DNO capacity charge, and tolling because they are transfer payments. The DNO fixed charge and capacity charge are transfer fees incurred by every grid-interconnected device to the distribution system of UKPN. In the same vein, tolling is a transfer fee that the UKPN levies on Smartest Energy (the battery operator) and Kiwi Power (the battery aggregator) to operate its equipment (in accordance with the unbundling rules for DNOs).

4.3. Degradation costs

Degradation costs are a function of the utilisation and age of the BESS. The algorithm of the degradation model includes cycle frequency, length, and characterization; therefore, providing different wholesale market services may exhibit a unique degradation of the battery. The results from the degradation analysis unveiled that the battery has a Coulombic efficiency of 0.999954 when cycling between 0 and 68% of its depth of discharge [27]. This would result in approximately a 4.6% degradation of the battery cells and pack per 1000 cycles. When the battery reaches 75% of its rated nominal energy capacity, the battery is

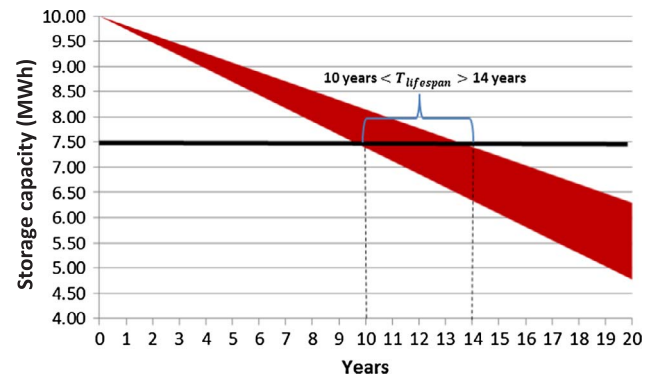


Fig. 3. Energy storage degradation.

determined to have reached its full lifespan and needs to be decommissioned, justified by the growth of the battery’s internal resistance and subsequent heat loss [27].

In addition to degradation from the utilisation of the battery, there is also degradation from its age after the manufacturing date. This wear-and-tear affects the energy capacity of the battery cells, packs, and balance of system. SNS [29] calculated that the annual energy capacity degradation per annum was 0.5%. Eq. (4) calculates the energy capacity degradation of the battery and Eq. (5) calculates the lifespan of the battery.

Eq. (4): Energy storage capacity degradation

$$EC_t = EC_0 - \sum_{t=0}^{T_{lifespan}} \left[\left(\eta * \frac{4.6\%}{1000} \right) + \check{D}C_t \right] \quad (4)$$

Eq. (5): Battery energy storage system lifetime

$$T_{lifespan} \text{ occurs when } 0.75 * EC_t = EC_0 \quad (5)$$

EC_t = the energy storage capacity (MWh) at time (t)

EC_0 = the energy storage capacity (MWh) at the initial time of the manufacturing date

η = the number of cycles

$\check{D}C_t$ = the annual degradation of the energy capacity of the BESS, independent of cycling

$T_{lifespan}$ = the lifetime of the EES project (years).

Fig. 3 illustrates the degradation of the Smarter Network Storage project over time. Depending on the utilisation of the battery and the annual wear and tear on the system components, the lifespan of the battery ranges from 10 to 14 years. This lifespan is critical to the social cost-benefit assessment of the battery, and the range is incorporated into the Monte Carlo simulations for the social cost benefit analysis to account for the variability and uncertainty in future dispatch and scheduling of the battery.

Not only does the energy storage capacity degrade with time and utilisation, but the roundtrip efficiency of the battery degrades as well. At the beginning of life, the AC-AC roundtrip efficiency⁹ of the battery is 87% [39], which is largely a function of the BESS and the AC/DC converter. The Smarter Network Storage battery is estimated to experience annual efficiency degradation from the cells, pack, and the balance of system of 1% per annum and 1% per 1000 cycles [29]; meanwhile, the AC/DC converter experiences slower rates of degradation [40]. The efficiency degradation is critical to assessing the operating costs of the battery because these energy losses require the battery

⁹ AC-AC roundtrip efficiency is the ratio of the energy put into the battery during charging (MWh) and the energy that can be retrieved when the battery is discharging (MWh). It includes losses pertaining to inverting and rectifying power between AC and DC.

to draw more electricity from the grid to provide equal output services; thereby, resulting in higher operating costs.

Eq. (6): Electrical energy efficiency degradation of the BESS

$$\epsilon_t = \epsilon_0 - \sum_{t=0}^{T_{\text{lifespan}}} \left[\left(\eta * \frac{1.0\%}{1000} \right) + \dot{D}E_t \right] \quad (6)$$

ϵ_t = the roundtrip electrical efficiency (%) of the BESS at time (t)
 ϵ_0 = the roundtrip electrical efficiency (%) of the BESS at the initial time of the manufacturing date
 $\dot{D}E_t$ = the annual degradation of roundtrip electrical efficiency of the BESS, independent of cycling.

The BESS also draws power from the grid to operate its auxiliary equipment to monitor the state of charge of the battery, power communication signals with the grid and grid operator, and power the telemetry equipment with the battery operator. This “parasitic load” is 29.2 kW and reduces the rated power output of the BESS [39]. A machine learning approach has been shown to facilitate battery state-of-health diagnosis and prognosis, potentially extending battery lifespans in the future [41].

4.4. Social costs results

The social costs of the Smarter Network Storage project vary over time as the industry exhibits economies of scale and the learning curve. Therefore, the costs have been dissected between the costs likely incurred by the Smarter Network Storage project in 2013 and the projected cost decline for identical battery installations deployed between 2017 and 2020. In agreement with a range of studies [19,42–46], the total social costs in 2013 are £10.70 million and drop to between £8.31 and £6.51 million before the end of the decade. Fig. 4 shows the breakdown of each cost component in £/kWh and how the costs are projected to decline over time. The battery cells and balance of system are the two largest cost drivers of current social costs; however, these two components are also expected to witness the greatest cost decline in the near future.

For the Monte Carlo simulation, the future costs are presented as a uniform distribution function to reflect that dynamic changes in the costs of the BESS. While most studies provide the 1st and Nth cost of BESS, the approach used in this analysis does not overlook that the real cost of BESS during the transition of the electricity grid can be anywhere between the 1st and Nth cost.

5. Identification and estimation of the social benefits

5.1. The multiple services provided by electrical energy Storage

EES can provide multiple services to multiple markets. A comprehensive literature review of studies [4,5,14,15,23,19,47–49] was undertaken to collect the universe of benefits from EES projects. These locational and system-wide benefits are then organized by their beneficiary, including National Grid, OFGEM, UKPN, Developers, Customers, and the Wider Society. The categories that are underlined in Appendix D are classified as true social benefit streams from the Smarter Network Storage project.

The Smarter Network Storage project was the first grid-scale storage project in Great Britain to demonstrate the simultaneity of some of these multiple services. However, it is not possible for an EES device to provide all of these aforementioned services simultaneously. Some of these services would double count the benefits of an EES project or the participation in one service would disqualify the EES from participating in another service. The Smarter Network Storage trials verified that certain value streams cannot be bundled together or do not provide net benefits to society. These value streams have henceforth been removed

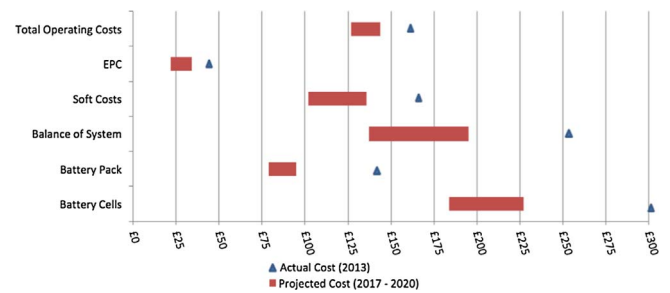


Fig. 4. The social costs of the smarter network storage project (£/kWh).

from the calculation of the true social benefits of the battery project. These services are: Enhanced Frequency Response (EFR), Short term operating Reserve (STOR), Triad Avoidance, Capacity Markets and Reliability & Resiliency. Appendix E provides a short description of these services. Therefore, only a handful of benefits can truly be stacked together in the social cost benefit analysis. These are described in what follows.

5.1.1. Primary frequency response

The system frequency, 50 Hz at equilibrium in Great Britain, measures the balance between that supply and demand. If the frequency falls out of the range of 49.5–50.5 Hz, there may be damage to the power electronics interconnected to the grid. The Smarter Network Storage project participated in providing static firm frequency response rather than dynamic firm frequency response because it was more cost-effective during the trial period.

During the trial period, the battery was available for over 7000 h per annum (p.a.) and utilised by National Grid for this service during two separate events. National Grid compensates frequency response providers with an availability payment when the unit is committed to providing frequency response and a utilisation payment for when the unit is dispatched for frequency response. In agreement with National Grid [50] and Perez et al. [27], the estimated availability payment is £8/MW/h and the utilisation payment is £24/MW/h, and the Monte Carlo simulation used a market price fluctuating $\pm 25\%$ for the availability payment and the utilisation payment, each. Frequency response is the largest revenue stream from wholesale power services, making it a critical feature of the social benefits for grid-scale EES projects.

5.1.2. Arbitrage

During the course of a day, the wholesale energy market price may fluctuate considerably. The wholesale energy market price, which is assumed to vary between £30/MWh and £50/MWh [29].

EES is able to take advantage of the diurnal price fluctuation by charging the battery during times of low prices and discharging during times of high prices, when the EES is not providing other critical grid services. The Smarter Network Storage project participates in arbitrage for approximately 150 h of discharge p.a. [29], and the Monte Carlo simulation incorporates a $\pm 15\%$ price fluctuation at the time of buying and selling electricity, each. The results show that the revenues from arbitrage are significant but not enough to justify a grid-scale EES project on their own.

5.1.3. Distribution deferral

The Smarter Network Storage project was designed to defer the need to upgrade the capacity of the sub-transmission line connecting the Sundon Grid to the Leighton Buzzard primary substation. Therefore, there is value in avoiding the cost necessary to upgrade the distribution circuit and this can be directly valued using the counterfactual: the cost of the conventional distribution upgrade.

The estimated cost for the conventional upgrade would be £6.2 million [29]. However, building a sub-transmission line would provide an additional capacity of 35.4 MVA and have an expected life of

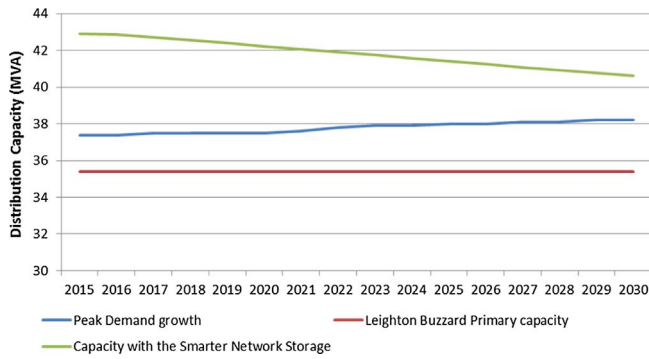


Fig. 5. Load growth forecast for the Leighton Buzzard Primary Substation [The Leighton Buzzard Primary capacity and the Peak Demand growth are provided by data from SNS [30]. The capacity of the Smarter Network Storage project has been calculated using the degradation analysis presented in Section 3.].

40 years; whereas, the Smarter Network Storage project only provides 7.5 MVA and has an expected life of 10–14 years. In order to determine the true benefit of distribution deferral, it is critical to determine the length (in years) of that deferral. Fig. 5 shows peak demand growth juxtaposed with capacity increases from the Smarter Network Storage project. It is concluded that the Smarter Network Storage provides sufficient capacity to accommodate peak demand growth on the circuit throughout its lifespan (despite degradation accounting for the decreasing Smarter Network Storage capacity over time).

With the battery providing sufficient additional capacity in the near future, the value of distribution deferral is predicated on the lifespan of the battery. The benefit is captured through the avoided cost of the conventional upgrade, which is represented as an annuity of cash flows. The annual cash flows are calculated using the discounted cash flow model illustrated in Eq. (7) with the discount rate equal to the WACC (which had a confidence interval between 3.0% and 7.2%), the present value of £6.2 million, and $t = 40$ years. The present value of that cash flow over the lifespan of the battery (10–14 years) is the value of the distribution deferral, and it is determined that this value is significant in the social cost benefit analysis.

Eq. (7): Discounted cash flow model for an annuity

$$PV = C * \left[1 - \frac{1}{(1+r)^t} \right] / r \quad (7)$$

PV = the present value of the distribution deferral

C = the annual cash flow of the investment

r = the discount rate

t = the number of years.

5.1.4. Network support

Network support is defined as the portfolio of benefits pertaining to reactive power support (kVAR), power quality, voltage control, and energy loss reduction in the distribution system. Demonstration results from the Smarter Network Storage project proved that it can provide these non-market services to the DNO, thereby providing a tangible benefit of system cost-savings. Therefore, these benefits are calculated through the use of shadow prices to value these non-market benefits.

SNS [51] calculated that the value of network support for the Smarter Network Storage project in 2030 would be approximately £48/kW-yr. For the Monte Carlo simulation, this value is determined to be an upper bound for today's value of network support, with the expected value and lower bound at -15% and -30% , respectively. The results show that network support from batteries provides a relatively valuable service to society.

5.1.5. Security of supply

Security of supply (peak shaving) ensures the reliability of adequately supplying electricity to the customer [52]. Each peak shaving event is characterised by the duration of the event and the maximum power (MVA) needed to reduce the demand to appropriate levels. This value is distinctly different from the distribution deferral because it monetizes the wholesale energy market-based benefits associated with peak shaving.

During the trial period, the annual amount of peak shaving required was 97 h spread across 45 days. During this time, the maximum power required for peak shaving was 5.7 MVA and the annual energy requirement for peak shaving was 141.6 MVAh [53]. The revenue calculation from peak shaving is equivalent to that of arbitrage; the only difference being that peak shaving is an involuntary form of arbitrage. Therefore, EES charges at £30/MWh and discharges at £50/MWh and the Monte Carlo simulation incorporates a $\pm 15\%$ price fluctuation in each.

The Great Britain local electricity price to a customer includes long-run transmission and distribution system costs, but it does not have locational transmission congestion costs and transmission losses [54]. Therefore, local peak shaving is not necessarily coincident with system-wide peak shaving, especially for a heavily congested Leighton Buzzard substation. UKPN valued security of supply with identical variance in energy market prices to arbitrage.

5.1.6. Reduced distributed generation curtailments

Distributed generation (DG) is the generation of electricity at or close to the point of consumption and has become increasingly prevalent due to declining prices, customer choice, and backup power. The power grid in Great Britain was designed for uni-directional power flows from centralised generation; however, the advent of DG may create bi-directional power flows on the power grid today. These $N - 1$ conditions are exacerbated during times of high DG production and low electricity demand, hence DG can be curtailed.

EES can increase the capacity to host DG and reduce DG curtailment, thereby creating a social benefit because the EES can effectively stabilize the power system by maintaining a balance of supply and demand in real-time [55–57]. Both the battery and the conventional upgrade may be able to reduce distributed generation curtailment by increasing the hosting capacity of the distribution circuit; however, only the battery enables bi-directional power flows by absorbing excess DG, such that this social benefit is additional beyond the conventional upgrade.

In Great Britain, DG is largely driven by wind and solar, which have a capacity factor of 30% and 11.16%, respectively [58]. Within UKPN's Eastern Power Network (which includes Leighton Buzzard), the curtailment for DG wind and solar is roughly 6% [59]. It has been calculated that grid-scale EES could reduce this curtailment by half [60]. The product of reduced curtailment (MWh) and the wholesale energy market price of £40/MWh [29] determine the value of the reduced curtailment. Given the large uncertainty surrounding future DG capacity, the Monte Carlo simulations incorporate variability in DG growth, ranging from 5% to 15% per annum, a wholesale energy market price fluctuating $\pm 15\%$, and initial DG installed capacity between 4 and 8 MW.

5.1.7. Carbon abatement

A carbon price is a price applied to carbon pollution to encourage polluters to reduce the amount of greenhouse gas they emit into the atmosphere. To meet its greenhouse gas emissions reduction goals of 80% from 1990 levels by 2050, Great Britain currently uses the European Union Emissions Trading Scheme and Carbon Price Floor. However, the social cost of carbon is used for this project appraisal because it quantifies the damage costs incurred by society from carbon emissions. The social cost of carbon is determined by the Department of the Energy and Climate Change [61],¹⁰ and prices are converted to £2013 in Fig. 6.

¹⁰ DECC was the predecessor central government department to the Department of Business, Energy, and Industrial Strategy (BEIS).

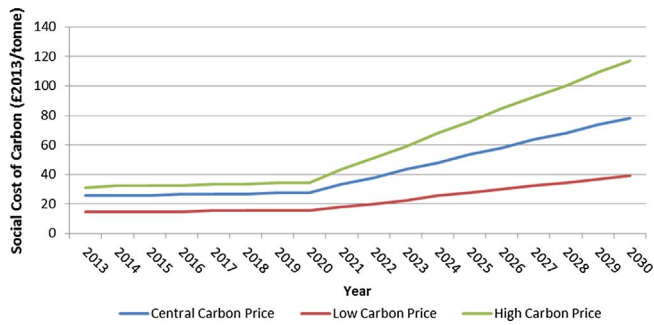


Fig. 6. Social cost of carbon prices.

The social cost of carbon is the shadow price for the value of each tonne of carbon dioxide that is abated by the Smarter Network Storage project. It is estimated that this Project abated 1.7 kilo tonnes of carbon dioxide per annum [62]; therefore, the product between the quantity of carbon abated and the social cost of carbon is equal to the value of this benefit stream. For the social cost benefit analysis, this avoided cost of emitting more carbon into the atmosphere is algebraically represented as a benefit of the Smarter Network Storage project. The Monte Carlo simulations incorporate the variability in the social cost of carbon.

5.1.8. Terminal value of the asset

At the end of the battery life, there still exists some terminal value of the assets, including the balance of plant and the civil works. Although a secondary market may exist for the battery cells and packs (which have degraded to the end of their useful life for the application at the Leighton Buzzard substation), such a market is not robust enough for this analysis. The balance of plant and civil construction may have a life that is longer than the cells and packs and have a terminal value that is calculable. If the developers of the Smarter Network Storage project were to replace the battery cells and packs, they may not need to replace the entire balance of plant; therefore, there is direct value attributed to these assets.

Furthermore, the civil works of the Project was designed to incorporate an 8 MW/17 MWh battery and included a lease for the land for 99 years [63], creating an *option value* at the end of the original battery's life. At the end of the project life, UK Power Networks has the option to install a new battery, develop another alternative solution, or energy efficiency and distributed generation may cause peak demand to fall below the original capacity of the distribution circuit insofar that no upgrade is required any longer. Battery augmentation and repowering would extend the lifespan of the BESS, while maintaining high asset utilisation rates. The *option value* is especially beneficial during the uncertainty of Great Britain's clean energy transition because it increases the choices and flexibility for future solutions.

The terminal value of these assets is calculated using a straight-line depreciation of 18% per annum [29]. The Monte Carlo simulation incorporates the variability in the life of the assets (10–14 years) and a depreciation of $\pm 5\%$.

5.2. Optimizing multiple services

In order to successfully and realistically provide multiple services for multiple stakeholders, the Smarter Network Storage project developed a Smart Optimization and Control System (SOCS) to optimize revenues from its dispatch and scheduling. The SOCS is comprised of a Forecasting Optimization Software System (FOSS) to forecast demand and remunerative markets, which is the critical first step in optimizing the set of services and revenues generated by the battery because grid services need to be tendered for weeks-to-months in advance. From the forecasts, the BESS then calculates a multiple linear regression model to optimize future battery dispatch in the multiple service markets [64]. Neural networks and machine learning could further optimize battery performance and dispatch to account for both battery and grid state-of-health [41]. The BESS is

Table 1
The value of cost streams.

Social cost category	Cost (2013)	Projected cost (2017–2020)
Battery Cells	£3,010,000	£2,270,000–£1,840,000
Battery Pack	£1,420,000	£950,000–£790,000
Balance of System	£2,520,000	£1,944,800–£1,368,000
Soft Costs	£1,700,000	£1,360,200–£1,020,000
EPC	£450,000	£335,700–£221,400
Operating Costs	£1,607,380	£1,437,617–£1,267,852
Total Social Cost	£10,707,380	£8,297,316–£6,507,252

configured to maximize social value with inputs from FOSS and subject to the constraints of the state of charge and security of supply.

Eq. (8): Objective function to optimize multiple services

$$\text{Max} \left\{ \sum_{t=0}^{T_{\text{lifespan}}} [(M_t^S * \pi_t^S) + (M_t^D * \pi_t^D)] \right\} \quad (8)$$

M_t^S = the scheduling for a market service for time (t)

π_t^S = the profit for the scheduling of that market service at time (t)

M_t^D = is the dispatch for a market service for time (t)

π_t^D = the profit for the dispatch of that market service at time (t).

The constraints to this optimization of the multiple services are two-fold:

- State of Charge.** State of charge is the measure of the immediate capabilities of the battery and is analogous to a “fuel gauge” for the battery [65]. The battery must be at the required level of charge to provide a distinct service to the grid. Participating in one service may preclude the ability for EES to provide another service because the EES will not be in the required state of charge. Therefore, the state of charge has been included as a constraint when valuing the beneficial services from the Smarter Network Storage project.
- Security of Supply.** The Smarter Network Storage project was designed to offset the need for conventional distribution reinforcement by reducing the peak demand on the existing grid infrastructure. Therefore, the dispatch and scheduling of the project must always prioritize the security of local supply above all other services in order to maintain the reliability on the grid. The EES shall not be dispatched for any other service that may conflict with its ability to provide security of supply, and this constraint is also accounted for when valuing the Project's beneficial services.

6. Social cost benefit analysis results

6.1. Total social costs of the Smarter Network Storage project

The social costs from Section 3 have been calculated for 2013 and projected for 2017 to 2020. The present values of the useful lifecycle costs are presented in Table 1. At any point between 2017 and 2020, the probability of realizing these costs is considered equally likely, thus these values present the bounds for the uniform distribution in the Monte Carlo simulation.

6.2. Total social benefits of the Smarter Network Storage project

This section discusses the assumptions and calculations of the social benefits (see Appendix A and Appendix C for further details on the assumptions and calculations). The present values of the useful lifecycle assessment are presented in Table 2. The values are presented with a 95% confidence interval (consistent with the parameters for the normal distribution used for the Monte Carlo simulations) to incorporate empirical market data and real-world risk and uncertainty.

Table 2
The value of the benefit streams.

The social benefit streams from SNS	Value with 95% confidence interval
Primary Frequency Response	£1,554,608–£3,878,579
Arbitrage	£272,313–£552,914
Distribution Deferral	£2,546,250–£4,019,613
Network Support	£1,152,840–£2,533,917
Security of Supply	£176,096–£357,551
Reduced Distributed Generation Curtailment	£67,256–£529,299
Carbon Abatement	£191,556–£851,255
Terminal Value of Asset	£293,980–£485,022
Total Social Benefit	£6,254,899–£13,208,151

6.3. Techno-economic results of the Smarter Network Storage project

The eight benefits streams, six cost elements, the time horizon, and the discount rate were all incorporated into the Monte Carlo simulations to determine the NPV of the Smarter Network Storage project. For Figs. 7 and 8, the x-axis is the NPV result and the y-axis is the frequency of that NPV result from the Monte Carlo simulations. As evidenced by the difference in the two results, lowering the capital costs through economies of scale is the quintessential driver to improving the NPV of grid-scale EES projects.

Fig. 7 shows by way of comparison that, for similar projects installed with the 2013 costs (i.e. with only the benefits, lifetime and discount rate subject to uncertainty), the expected value would be –£1,484,420 and the median would be –£1,469,634. The standard deviation was £1595,258. Furthermore, the results show that of the 10,000 trials, 1% had a positive NPV and 99% had a negative NPV.

These results prove that, in 2013, the social costs outweighed the benefits. Such an investment would not have not likely passed the Kaldor-Hicks criterion, due to then high capital costs of the battery technology. The simulation also shows that a positive NPV would only happen under a limited number of extremely positive outcomes.

Fig. 8 shows that, if the project was installed any time between 2017 and 2020, the expected value would be £1,833,887 and the median would be £1,840,840. The standard deviation was £1643,244. Furthermore, the results show that of the 10,000 trials, > 99% had a positive NPV and < 1% had a negative NPV.

These results prove that, for projects to be installed between 2017 and 2020, the social benefits outweigh the costs. The investment in a grid-scale EES project would likely satisfy the Kaldor-Hicks criterion, even with sub-par market prices and shadow prices or a higher discount rate. Sustained investment and production-cost efficiency contributed to a techno-economic performance improvement of approximately £3.3 million between 2013 and 2017–2020.

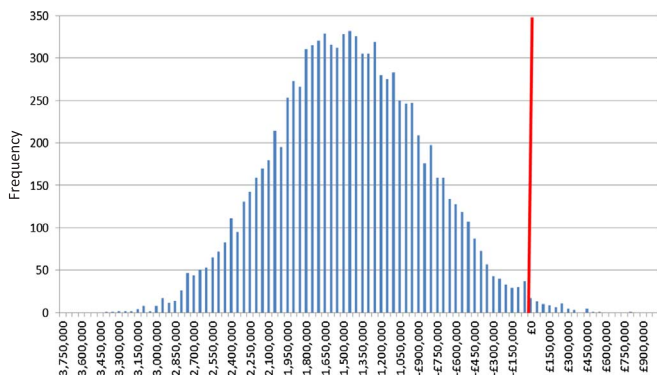


Fig. 7. NPV of identical smarter network storage projects installed in 2013.

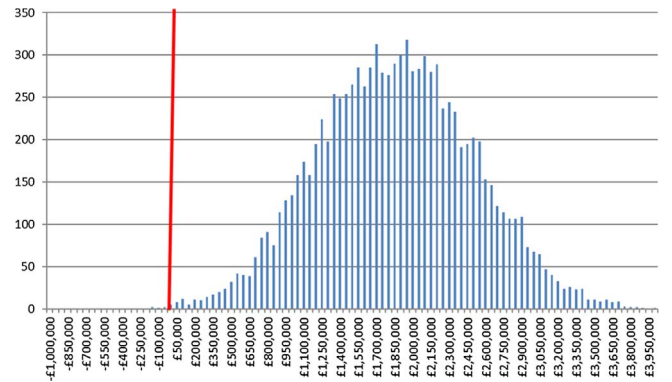


Fig. 8. NPV of identical smarter network storage projects installed between 2017 and 2020.

6.4. Key insights and implications from the techno-economic analysis

The social welfare generated from EES projects has improved over time and the results show that grid-scale EES can support the electricity grid's transition to a low carbon, reliable, and affordable network. The following discussion offers multi-faceted policies to support EES projects with the objective to improve their NPV and support the future electricity grid.

Electricity Market Reforms. EES can provide grid services ranging from power quality and load shifting to bulk power management. To maximize the utilisation of the EES asset, reforms to the electricity market must unlock the potential for EES to provide more simultaneous benefits, such as the capacity market and upward and downward reserves in the ancillary service market. Furthermore, the current ancillary service market compensates suppliers based on power capacity (£/MW/h) rather than energy capacity (£/MWh). For the Smarter Network Storage project, 10MWh was required for local security of supply, and the added benefits of building a larger energy capacity are not fully appreciated in the ancillary service market to offset the added costs. This disconnect between cost drivers, reliability drivers, and revenue drivers suggests a need for further electricity market reforms. Demand response can provide grid services [66,67]; however, a single battery often cannot participate in demand response markets unless they are aggregated together to reach larger capacity levels. Electricity market reforms are necessary to value EES for both power and energy to align with flexible sizing characteristics of EES project investments. Moreover, electricity market reforms are critical to turning non-market based benefits - such as carbon abatement, network support, and the option value to incrementally increase system capacity - into market-based benefits which align private incentives to invest in EES with their public benefits.

Research, Development, and Deployment. The cost decline of EES has been the main driver for the improved NPV of grid-scale EES projects exhibited over time. Operating costs can be lowered by preventing interconnection costs from being applied twice to the battery because the battery is currently classified as a generator and consumer. Soft costs can be lowered through greater standardization of the installation and permitting process. Hard costs can be lowered through greater research and development of battery cells, packs, and the balance of system. Degradation costs can be lowered through a larger database of empirical data that improves battery degradation forecasting, modelling, and mitigation.

Investment Risk Mitigation Strategy. Of the plethora of EES project benefits, frequency response (both firm frequency response and enhanced frequency response) is the critical revenue stream to warrant new EES investment. Long-term contracts and price certainty for frequency response services should be a policy focal point to reduce the risk and uncertainty in EES investment returns. The Smarter Network Storage project was the first EES in Great Britain to trial many market services simultaneously, and this diversification of revenue streams can become a risk mitigation strategy to attract future investment in the technology.

Optimal Locational Benefits. The economics of EES projects relies heavily on both system-wide and locational benefits. Many ancillary services are compensated on system-wide levels (frequency response, triads, carbon abatement, reactive power support, etc.); however, as the future electricity grid becomes more distributed and decentralized, the location-specific benefits will become increasingly important. Locational benefits (distribution network upgrade deferral and DG curtailment) were critical contributions to the overall success of the Smarter Network Storage project. Optimally siting future grid-scale EES projects in ideal locations can turn projects from a negative NPV to a positive NPV. Analysis of the capacity of the local distribution system to absorb more renewable energy/more demand will help identify the optimal locations to deploy future EES projects.

7. Conclusions

The social cost benefit analysis provides a strong framework to assess whether the regulatory regime should encourage more investment in grid-scale EES. We commend this approach to regulators and those assessing the public benefit of grid scale EES. Our approach draws attention to the fact that positive (or negative) private NPVs for such storage projects may not be accurately reflecting their true costs and benefits from the point of view of society.

This framework accounts for both the market and non-market benefits from the perspective of society and juxtaposes them with the social costs, thereby capturing insights into economic development, equity, and efficiency. Transfer payments between agents within society are removed from the analysis to provide a project appraisal that truly represents the net value to society. Through the Kaldor-Hicks criterion, a positive NPV of the grid-scale EES investment improves the state of society overall.

It is also concluded that a Monte Carlo simulation should be paired with the social cost benefit analysis when incorporating the risk and uncertainty of future benefit and cost streams of grid-scale EES. Rather than providing deterministic values, stochastic modelling incorporates the many real-world variables that affect the net present value of a project. For a stochastic sensitivity analysis, Monte Carlo simulations are helpful because statistical distributions can be applied to the benefit and cost streams.

The benefit streams from the Smarter Network Storage project are only a subset of the universe of possible benefits emanating from grid-scale EES. Although the Smarter Network Storage project was the first battery in Great Britain to trial multiple market services, some services were not able to be paired together or were not truly social benefits. Key benefit streams of grid-scale EES projects, such as Capacity Markets, STOR, and Triad Avoidance, were concluded to be either not

social benefits or uneconomical to perform.

Within the social benefit analysis, it is critical to include energy capacity and electrical efficiency degradation. The degradation determines the lifespan of the project, which directly impacts the value of distribution deferral and the terminal value of the asset and indirectly affects the other six benefit streams. Claiming the value of distribution deferral is equivalent to the cost of the conventional distribution upgrade would overstate the true value because the Smarter Network Project is a 10 to 14-year investment; whereas, the conventional distribution upgrade is a 40-year investment. Thus, the value of distribution deferral should be calculated as a fraction of the cost of the conventional distribution upgrade, subject to the timespan of the deferral.

The results of the social cost benefit analysis show that an EES project installed in 2013 likely had a negative NPV, but an identical project installed between 2017 and 2020 likely will have a positive NPV. The social welfare generated from EES continues to increase via project cost decline, performance and lifespan improvement, optimizing locational benefits, supportive long-term financial contracts, and favourably reforming electricity markets for grid-scale EES technologies.

Project costs can be lowered through streamlined interconnection processes to reduce permitting and installation costs as well as prevent interconnection costs from being applied twice to the battery for generation and consumption. Electricity market reforms can maximize the utilisation of EES through the provision of potential ancillary services, such as enhanced frequency response and coupling those services simultaneously with the capacity market. Properly compensating EES by energy capacity payments and for non-market based services, such as carbon abatement and network support, can diversify revenue streams and reduce the risk in EES project investment. Ultimately, the analysis shows how society can cost-effectively invest in EES as a grid modernization asset to facilitate the transition to a reliable, affordable, and clean power system.

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Appendix A. Assumptions table

Variable	Determined values	Ref.	Confidence interval
<i>Financial assumptions</i>			
Discount Rate	5.09%	[29]	3.8–7.2%
Electricity Wholesale Price	£40/MWh	[29]	± 15%
Depreciation	18%	[29]	± 5%
<i>Performance assumptions</i>			
Energy Capacity	10 MWh	[29]	
Power Capacity	6 MW	[29]	
Efficiency	87%	[39]	
Lifespan	12 years (one cycle per day)	[27,29]	± 2 years
<i>Technical variables</i>			
Wind Capacity Factor	30%	[58]	
Solar Capacity Factor	11.16%	[58]	

Appendix B. Operating costs table

Variable	Assumed values	Ref.	Confidence interval
<i>Operating costs</i>			
Inspection & Maintenance	£10,000 p.a.	[29]	
Spare Parts	£5000 p.a.	[29]	
Facilities Cost	£40,000 p.a.	[29]	
Insurance	£5000 p.a.	[29]	
Management/Administration	£15,000 p.a.	[29]	
Self-discharge Losses	£18 p.a.	[29]	
Control Systems and Risk Management	£10,000 p.a.	[29]	
Electricity Purchasing	Charging at £40/MWh	[29]	Market price varies \pm 15%

Appendix C. Benefits calculations table

Variable	Assumed values	Ref.	Confidence interval
<i>Benefits calculations</i>			
Frequency Response	Holding payment £8.00/MW/h	[50]	\pm 25%
	Utilisation payment £24.00/MW/h	[50]	\pm 25%
Arbitrage	Buy at £30/MWh	[29]	\pm 15%
	Sell at £50/MWh	[29]	\pm 15%
Distribution Deferral	Value of the counterfactual is £6.2 million	[29]	Deferral lasted 10–14 years
Network Support	£48/kW-yr	[51]	The expected value is $-$ 15%. The lower bound is $-$ 30%.
Security of Supply	Buy at £30/MWh	[29]	\pm 15%
	Sell at £50/MWh	[29]	\pm 15%
Increased Distributed Generation	Wholesale market price at £40/MWh	[29]	DG capacity 4–8 MW Growth rate 5–15% p.a. Market Price varies \pm 15%
Carbon Abatement	1.7 kilo tonnes of CO ₂ abated p.a.	[61,62]	Price of carbon determined by DECC [61]
Terminal Value Of asset	Depreciation is 18%	[29]	\pm 5%
	Lifespan is 12 years	[27,29]	\pm 2 years

Appendix D. The universe of social benefits from electrical energy storage

Category	Definition
<i>Bulk power system (National Grid, OFGEM, Developers)</i>	
Enhanced Frequency Response	The response to system frequency signals in less than 1 s to restore electricity supply–demand equilibrium
<u>Primary Frequency Response</u>	The response to system frequency signals at 10 s from the frequency signal to restore electricity supply–demand equilibrium
Secondary Frequency Response	The response to system frequency signals at 30 s from the frequency signal to restore electricity supply–demand equilibrium
Frequency Control by Demand Management	The response to system frequency signals by modulating demand in order to restore electricity supply–demand equilibrium
High Frequency Response	The response to system frequency signals by reducing generation output or consuming more power to restore supply–demand equilibrium
Fast Reserve ^a	Generation capacity that serves load at a ramp rate of 25 MW within 2 min of an unexpected contingency event, such as an unplanned generation outage
Short term operating Reserve (STOR) ^a	Generation capacity that serves load within 20 min of an unexpected contingency event, such as an unplanned generation outage
Triad Avoidance (Transmission Deferral) ^c	National Grid recovers the cost of the transmission system through demand charges for the three half hours in a year with the most transmission congestion, known as triads
Transmission Congestion & Loss	The reduction in congestion and loss on the transmission network to improve the efficiency of locational marginal prices at the nodal level

<u>Energy Arbitrage (Trading)</u>	The purchase of wholesale electricity when the price of energy is low and sale of wholesale electricity when the prices are high
Capacity Market	Generation capacity to provide the necessary reserve margin for system resource adequacy
<i>Distribution system (UKPN, Ofgem)</i>	
<u>Distribution Deferral^d</u>	Delaying, reducing the size of, or entirely avoiding utility investments in distribution system upgrades necessary to meet projected load growth on specific regions of the grid
<u>Network Support^b</u>	The portfolio of services including reactive power support, power quality, voltage control, and reduction of distribution losses. These services make the distribution system more cost-efficient to operate and upkeep
<u>Security of Supply</u>	Dispatching stored energy to the grid during peak conditions to reduce the stress of capacity constraints on the distribution system (i.e. peak shaving)
<u>Terminal Value of the Asset</u>	The end of life asset value that can be extracted and utilised to provide options and flexibility to distribution network operators
<i>Customer service and bill savings (Suppliers)</i>	
Reliability (Avoided Outage Costs) ^d	The measure of the grid's ability to serve the load of all its customers at the level of its intended purpose. Islanding sections of the grid or providing uninterruptable backup power supply are forms of local reliability
Resiliency (Black Start) ^d	In the event of a grid outage, black start generation assets are needed to restore operation to larger power stations in order to bring the regional grid back online. Energy Storage has black start capabilities to reduce the duration of the customer outage
<u>Reduced Distributed Generation Curtailment</u>	Minimizing the curtailment of electricity generated from behind-the-meter wind and solar systems to increase the capacity factor of distributed generation
Time-of-Use (TOU) Bill Management ^d	Customer bill reduction by minimizing electricity purchases during peak electricity-consumption hours and shifting these purchases to periods of lower rates
<i>External (Society)</i>	
<u>Carbon Abatement</u>	The reduction of carbon emissions from the power sector and its adhering social costs pertaining to climate change
Environmental Benefits (Water, Land, Criteria Pollutants)	The reduction in environmental costs such as water usage, land use, and emissions of other criteria pollutants
Fuel Price Volatility	The avoided risk and uncertainty from the volatile market price of commodities such as coal, oil, and natural gas
Physical and Cyber Security	The reinforcement in system security and distribution system architecture to reduce the vulnerability from physical and cyber threats to the electricity grid

^a 66.^b 49.^c 67.^d 44.

Appendix E. List of additional ancillary services not included in the cost benefit analysis

- a. **Enhanced Frequency Response.** EES can effectively provide frequency response because it pairs an energy neutral technology with an energy neutral service. National Grid established this new market to provide response to frequency signals within 1 s. However, the Smarter Network Storage project did not qualify for this service due to technical constraints.
- b. **Short term operating Reserve (STOR).** The Smarter Network Storage project qualified for providing STOR services and received payments for availability and utilisation; however, the revenue from these payments is less than the marginal costs to provide the service insofar that it is uneconomical for the battery project to provide this service moving forward [70].
- c. **Triad Avoidance.** National Grid recovers its transmission costs through Transmission Use of System (TUoS) payments, determined by the amount of electricity consumed by each user during triads. If the Smarter Network Storage project avoids a triad, other agents of society would be forced to pay more during the triad so that National Grid can make its specified return on its transmission investments. Therefore, triad payments are predominantly manifestations of transfer payments and are not included as a social benefit.
- d. **Capacity Markets.** The capacity market is designed to ensure sufficient, reliable capacity is available on the bulk power system by providing guaranteed contractual payments to encourage investment in new and existing generation capacity [71]. Avoided generation costs are a social benefit by using firm capacity from EES to reduce the need to procure generation capacity. EES can participate in the capacity market [72]; however, it would limit its ability to provide other 2 services such as arbitrage, local security of supply, and Triad avoidance. The Smarter Network Storage project participated in local security of supply rather than the capacity market.
- e. **Reliability & Resiliency.** Reliability and resiliency are valuable benefits that can be calculated using an algorithm for value of lost load (VOLL), system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), and customers experiencing multiple interruptions (CEMI). There is no specific indication that the Smarter Network Storage project would have provided additional reliability and resiliency benefits beyond the conventional upgrade; therefore, this value is deemed negligible.

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