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Energy Storage on a Distribution Network for Self-Consumption of Wind Energy and Market Value

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Abstract: Wind energy could be generated and captured with a storage device within the customer premises for local utilization and for the provision of various services across the electricity supply chain. To assess the benefits of adding a storage device to an electricity distribution network that has two wind turbines with a base load of 500 kW and a typical peak load under 1500 kW, a 2 MW/4 MWh storage is installed. To observe the effects of adding the storage device to the network, a technical analysis is performed using the NEPLAN 360 modelling tool while an economic analysis is carried out by estimating the likely payback period on investment. A storage potential benefit analysis suggests how changes in integration policies could affect the utility of adding the storage device. With the addition of the storage device, self-consumption of wind energy increased by almost 10%. The profitability of the project increased when the device is also deployed to provide stacked services across the electricity supply chain. Policies that permit the integration of devices into the grid could increase the profitability of storage projects.

Keywords: distributed energy resources; economics of storage; energy storage; self-consumption of wind; storage services; wind energy

1. Introduction

The need for low-carbon energy systems in achieving energy sustainability has encouraged the adoption of different techniques for increasing cleaner energy generation and utilization through distributed energy resources (DER). For instance, in the UK where a net-zero emission target has been set [1] and in Northern Ireland where an increasing level of system non-synchronous penetration (SNSP) is to be achieved on the electricity grid [2], it is desirable to generate clean energy from renewables like wind turbines. The variable nature of the renewables reduces their effectiveness where the stability and reliability of the electricity grid is to be maintained. To address the challenges in the variability of the renewables for a resilient grid, some solutions have been proposed, namely demand-side energy management and the use of energy storage devices [3,4].

Integrating renewables and energy storage devices into the grid comes with challenges and opportunities. The opportunities include optimal power management and economic benefits [5], better utilization of relatively cheap renewable resources [6], increased consumption of the energy produced from renewable sources [6], less pollution from energy production activities, and reduction of the curtailments and constraints of renewables [7]. The storage could also be deployed for stacked services in multi-use purposes [8,9].

The challenges in the integration include the complex nature of the real benefits of storage, the locational nature of the values for renewables and storage [10], the dynamics of storage economics, and certain inconsistencies in policies that could discourage innovation. The peculiarities in the characteristics of the aggregate power system within a region (the structure of the grid, the fuel mix of the grid, the load profile of attached loads to the grid, the point on the grid where DER are to be located, the availability of different energy sources, and the electricity market at the location) make the value derivable from installing DER rather unique, typically varying from location to location [10].

In [11], the market designs for and the characteristics of different ancillary services are described with emphasis on the increasing role of DER in providing the ancillary services that have historically been provided by conventional synchronous generators. The procurement schemes and the emerging ancillary services that may be offered by the distributed resources are also described. The roles that DER may play in decarbonization within the distribution network through the provision of ancillary services have been described in [12]. In [13], a multi-source energy storage model that consists of a conventional energy storage, multi-energy flow resources, and a demand response resource, at the demand and the supply sides, has been described for achieving economic self-management of energy through an intelligent control management method. The integrated distributed energy system was deployed to deal with the variability in loads and renewable supply. In [14], an energy management system that maximizes renewable energy utilization while providing certain ancillary services using a heat pump and a thermal energy storage system has been reported to help achieve cost saving, reduction of purchased energy imbalance from the grid, more reliable use of the heat pump, and a more stable surrounding temperature.

This work investigates the use of an energy storage device for increasing self-consumption of wind energy and providing market services within a distribution network having features given in [15,16]. It is well known that energy storage techniques could be used to capture renewable energy for later use. However, there is a knowledge gap in ascertaining the real value of deploying the storage at the specific locations having a unique network, market, and policy characteristics. Moreover, as reported in [17], it is often uneconomical to deploy storage devices at high investment costs when the other possible storage application revenues are not considered. The work explores the other value streams that could make deploying the storage device more profitable at the distribution network. The addition of the storage device is modelled and technically analyzed using the NEPLAN 360 software while the economic feasibility of the storage project is assessed by estimating the likely payback period on investment.

The local network is a campus site where the base load is 500 kW while the typical peak load is below 1500 kW. The distribution network has two behind-the-meter (BTM) wind turbines which are connected to an alternating current electricity grid through an 11 kV substation. Currently, any excess energy production from the turbines is fed to the grid at a price fixed by the utility. Instead of feeding the excess locally generated wind energy to the grid, the work examines installing a 2 MW/4 MWh storage device to capture the excess energy—to increase self-consumption of wind energy while also using some capacity of the storage device for providing certain ancillary services to the grid. As reported in [18], wind turbines could be deployed to provide grid services; in this work, only the storage device is deployed for the grid services. To see how changes in policies could impact the profitability of the project, a potential benefit analysis for adding the device is undertaken using an existing market structure.

2. Materials and Methods

2.1. Description of Distribution Network

To investigate how the energy storage device could be used to increase local consumption of wind energy and provide certain ancillary services, a model of the distribution network is created using the NEPLAN 360 software. There are 10 substations that feed different loads on-site. There are two grid-connected wind turbines running on-site.

The site is connected to the electricity grid via an 11 kV feeder. From a typical one-year data of the site, a total energy of 3,720,642 kWh was imported from the grid. A total energy of 3,042,075 kWh was generated from the wind turbines; whereas 601,780 kWh—representing about 20% of the total energy generated from wind—was exported to the grid. The total annual energy consumption within the same one-year period was 6,189,647 kWh. The load profile depicts a campus site where the base load is 500 kW and the typical peak load is less than 1500 kW, Figure 1.

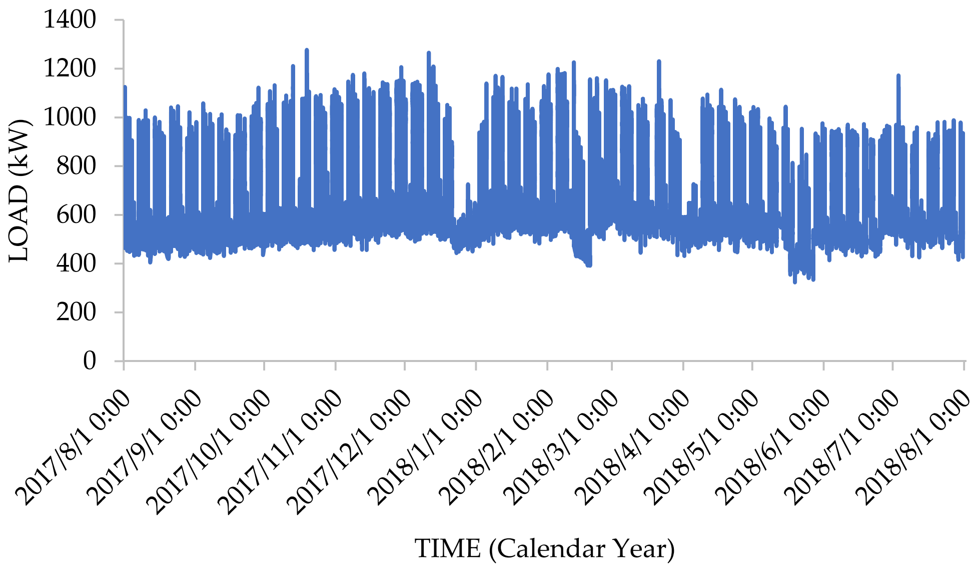

Figure 1. One-year (365 days) load profile of site.

A high voltage connection agreement puts the maximum energy that may be exported from the site to the grid (the maximum export capacity) at 1242 kW; the maximum energy that may be imported from the grid to the site (the maximum import capacity) is 2500 kW.

The line diagram of Figure 2 and Equation (1) both describe the initial configuration of the distribution network.

$$T_2 \pm G_{grid} = T_1 + Z + L \tag{1}$$

where L denotes the total power consumed in the aggregated system load, Z represents the total power expended in system impedances, T_1 represents the power supplied from the turbine number one, G_{grid} represents the energy from the power grid, and T_2 represents the power supplied from turbine number two.

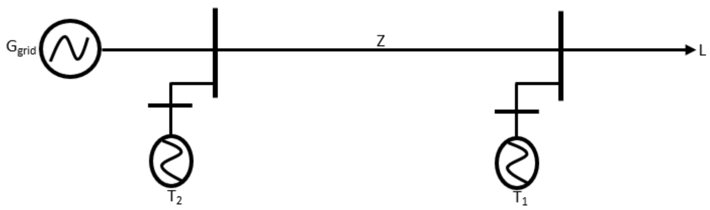

Figure 2. Line diagram of distribution network.

The BTM energy storage device is installed to capture any excess energy generation from the wind turbines T_1 and T_2. The network elements of the site are depicted in Figure 3.

Meanwhile, the loads in the local network are constantly linked to the grid for continuous power supply irrespective of the power output of the wind turbines. Rather than feeding the excess wind energy from the turbines to the grid, a storage device is installed on the network to take up the excess wind energy for later consumption on-site.

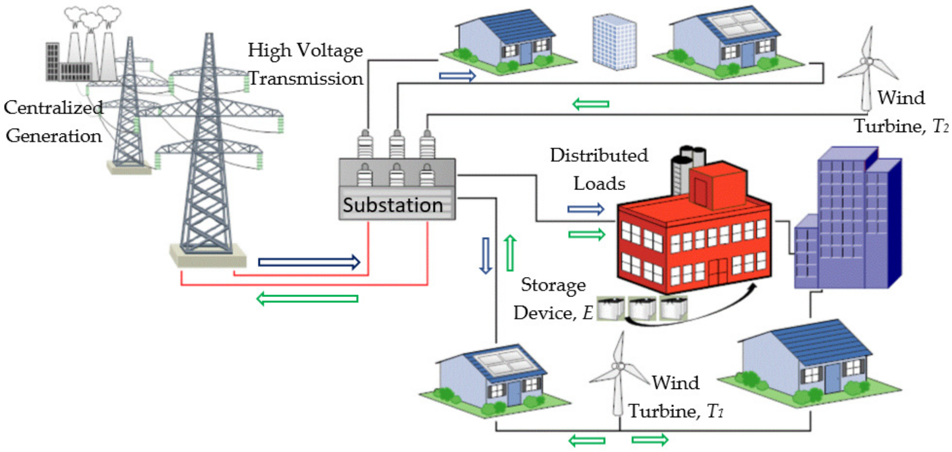

Figure 3. Arrangement of network elements.

The data of the aggregate power produced from the turbines and data of the maximum power demanded for the one-year period are used as the typical energy profiles of the site. During this period, the base load swung around 500 kW and the peak demand was 1376 kW. The generation profiles of the wind turbines, the local load profile, and the total exported electricity data are used to estimate a suitable storage portfolio that could help achieve the objectives of maximizing self-consumption of wind energy and providing market services. In other words, the power profiles of site within the same period (the power demand, the power generation, and the electricity import-export profiles) are used in ascertaining a suitable storage device—a storage technology that could meet the charge-discharge characteristics required. A cost analysis is carried out on some of the applicable storage technologies.

2.2. Storage Technologies

It is usually possible to find more than one suitable storage device for any storage project. The final device selection could be made based on any specific storage, utility, or user requirements. The account of the characteristics of different storage technologies, including the storage that may be suitable in a BTM application, are given in [19,20]. The technical characteristics of the different energy storage technologies and applications are presented in [21,22]. Some storage technologies possess interesting characteristics. Take batteries for example: they are modular—they could be combined in modules to form small, medium, and large power banks. Such modularity of batteries and some other storage devices makes them rather suitable in BTM and customer-premise storage applications. Moreover, the battery could be sized to meet the exact user requirements, optimizing the use of resources. The other factors that are considered in selecting the storage device for the BTM application include power requirement, charge–discharge requirement, duration of service required, operating temperature, space and location requirements, maintenance needs, maturity of the storage technology, and cost.

Some of the established storage options are considered for the project and a few of the most suitable technologies meeting the desired needs are selected for economic analysis; for example, flywheel storage and a lithium ion (Li-ion) battery are considered.

2.3. Power Flow Analysis for Determining the Effect of Storage

To observe how the installation of the storage device will affect the distribution network, a power flow analysis is undertaken. The network is considered operationally stable before the installation of the device. After installing the storage device, the network is observed to verify that installing the device has not compromised the stability and reliability of the distribution network.

Given that the real and the reactive power flowing into a bus i of a network is P and Q respectively, the *static load flow equations* used for network analysis could be expressed as:

$$P_i = V_i \sum_{k=1}^{n} V_k Y_{ik} \cos(\theta_{ik} + \delta_k - \delta_i) \tag{2a}$$

$$Q_i = -V_i \sum_{k=1}^{n} V_k Y_{ik} \sin(\theta_{ik} + \delta_k - \delta_i) \tag{2b}$$

where V_k is the voltage at bus k, Y_{ik} is the mutual admittance between the ith node and a kth node, n is the number of buses within the network, θ represents the phase angle between current and voltage, δ represents the load angle, and V_i represents the bus voltage.

Appendix A contains a derivation of the load flow equations. The non-linear static load flow equations are solved numerically. The NEPLAN 360 modeller has a library of numerical solutions for technical power flow analysis. The modeller takes the network elements and their electrical parameters as inputs, uses a numerical method to analyse the power network, and outputs the electrical signals (current, voltage, power) at the network nodes and within the elements. It also indicates whether the numerical model converges or not and indicates where any excess power flows occur. With a model of the distribution network created, running a power flow reveals the changes to the network as a result of installing the storage device.

2.4. Power Management of Storage

The diagram of Figure 4 describes the final configuration of the distribution network.

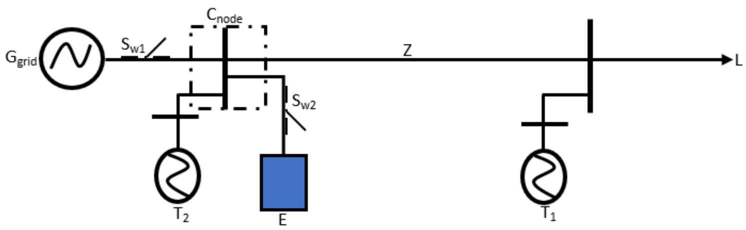

Figure 4. Adding storage to distribution network.

The switch S_{w1} links the distribution network to the grid. Equation (3a,b) describe how the switch S_{w1} is to be operated.

$$S_{w1} = 1, \; when \; L + Z > T_1 + T_2 + E_{(min)} \tag{3a}$$

$$S_{w1} = 0, \; when \; L + Z < T_1 + T_2 + E_{(min)} \tag{3b}$$

where L denotes the energy demand by system load, Z represents the total energy expended in the system impedance, T_1 represents the energy feed from the turbine number one, T_2 represents the energy feed from the turbine number two, $E_{(min)}$ represents the implied device discharge limit, and S_{w1} represents switch one.

The switch S_{w2} determines the time that the storage device E is to be charged or discharged; it is operated according to a control rule set at the C_{node}. Equations (4) and (5) describe the operation of the switch S_{w2} and the control at the C_{node}.

$$E_{(min)} \propto \left[(E_{SOC}) \; AND \; (E_{Services}) \; AND \; \left(Time_{Tariff}\right) AND \; (T_1) \; AND \; (T_2) \right] \tag{4}$$

$$S_{w2} \; \propto \; E_{(min)} = 1 \; OR \; 0 \tag{5}$$

where T_2 represents the energy feed from the turbine number two, T_1 represents the energy feed from the turbine number one, $Time_{Tariff}$ is the instantaneous price of electricity, $E_{services}$ is the aggregate ancillary service demand on the storage device, E_{SOC} is any specified charging state of the device,

$E_{(min)}$ represents the implied device discharge limit, "*AND*" is a summing logic, S_{w2} represent switch two and "*OR*" is also a logical expression.

$$E_{(min)}(1)^{+} = E_{(min)}(0)^{+} \pm E_{(min)}(1)^{-}$$

$$E_{(min)}(2)^{+} = E_{(min)}(1)^{+} \pm E_{(min)}(2)^{-}$$

that is,

$$E_{(min)}(t)^{+} = E_{(min)}(t-1)^{+} \pm E_{(min)}(t)^{-}$$

for any discharge-limit instances $t = 1, 2, 3, \ldots, n$.

Switches S_{w1} and S_{w2} operate to ensure that the storage device is charged with a power supply from the wind turbines only. The switches ensure that the device is discharged to maximize self-consumption of the on-site-generated wind energy while also securing certain capacity of the device for the provision of any commitment to ancillary services.

2.5. Assessing the Benefit of Storage

A feature assessment of some storage technologies discussed in [19–22] is undertaken to identify some of the storage options that could meet the defined objectives of maximizing self-consumption of wind energy and providing ancillary services. A cost analysis is carried out on the identified devices. The profitability of adding the storage device is determined by taking the likely storage cost ranges, storage efficiencies, storage capacity, the electricity market, and the potential additional storage services as key parameters.

2.5.1. Benefits of Self-Consumption of Wind Energy

A benefit analysis is carried out to ascertain the gains in installing the storage device for increasing the self-consumption of wind energy. The costs of energy storage systems are not fixed. Because of the dynamic nature of storage economics, in estimating the cost of storage, hypothesised prices are used to reduce the effect of random errors that could arise from the use of a static price quote. Using a price quote given at a time for an analysis invalidates any result from the analysis in a new economic setting. Taking into cognizance the high likelihood of changes in the prices of some of the storage technologies and with a broad study of the inconsistencies in price quotes from literature and industry—for example, consider the different prices specified for the same storage technology plus notes on cost inconsistencies in [14,19,22–32]—the most likely cost range for each of the storage technologies is heuristically selected for analysis.

While the analysis is not claiming that any storage option is currently economical under the existing market arrangement, the analysis aims to identify the cost point at which the storage becomes economically feasible with respect to the distribution network and to reveal where changes in market conditions or storage costs could impact the profitability of the storage project. The cost range also makes it possible to apply the results of the analysis within any reasonable future changes to the economics of storage.

Using an existing market system, the benefits of installing the storage device for increasing self-consumption of wind energy is analysed. In the market, the price of import electricity and the price of export electricity are in the ratio of 7 to 3 typically, the price of import electricity being often higher: when the import electricity price is at £7/kWh, the exported electricity price will be around £3/kWh. The prices could vary in different economic settings but have consistent relations—based on the historical analysis of the site export-import payment data and in [33].

The benefit through self-consumption of wind energy is based on the difference between the import and export electricity prices; the prices are fixed within days but could change when the utility decides to review rates to reflect new economics. The total recoverable energy is obtained by multiplying the captured (used to be exported) energy by the storage efficiency. The market value of the recovered energy is obtained by multiplying the total recoverable energy by the market price. The gross annual gain is the difference between the market value of the recovered energy at the import electricity price and the market value of the exported energy at the export electricity price.

2.5.2. Benefits through Market Services

In another case, in addition to helping to increase self-consumption of wind energy, certain capacity of the storage device is committed to providing some services to the electricity grid through DS3/ISEM [34–36]—"Delivering a Secure, Sustainable Electricity System" (DS3) is a programme developed to increase the penetration of renewables like wind on the power network, whereas the Integrated Single Electricity Market (ISEM) is a cross-border electricity market that allows the interconnection of grids for wholesale electricity trading.

The values from the actual provision of the ancillary services are not included because the actual provision of the services is usually within very short times [18] and the exact amount of the services provided may not be pre-determinable since the services are demanded by the electricity grid only during special operating conditions, maintaining the stability of the grid. The values accounted for here are only for the service "commitment," and not for the actual performance: the value derivable from connecting the storage device to the grid and making certain capacities available for charging or discharging in supporting the grid during operational emergencies.

The services that the storage devices could provide are selected and aggregated from the DS3 service suite given in [36]. The service suite helps in maintaining the stability and reliability of the grid as non-synchronous power sources increase with the integration of the variable renewables. The service products are required to guarantee a qualitative performance of the grid. The products are described by the transmission network operators—EirGrid and the System Operator for Northern Ireland (SONI) in [37,38]—with rates defined for specified times in [39]. The suite of services that a typical storage device could provide is summarised in Table 1 [40–42].

Table 1. Storage eligible DS3 service suite with base rates in £/MWh (2019–2020).

Products	Abbreviation	Storage Eligible	Payment Rate (£/MWh)
Fast Frequency Response	FFR	Yes	1.98
Primary Operating Reserve	POR	Yes	2.97
Ramping Margin 1	RM1	Yes	0.11
Ramping Margin 3	RM3	Yes	0.16
Ramping Margin 8	RM8	Yes	0.15
Replacement Reserve (De-Synchronised)	RRD	Yes	0.51
Replacement Reserve (Synchronised)	RRS	Yes	0.23
Secondary Operating Reserve	SOR	Yes	1.80
Tertiary Operating Reserve 1	TOR1	Yes	1.42

While ancillary services were traditionally provided by equipment connected to the transmission network; in certain instances the services could be provided through devices connected to the distribution network—this will usually depend on locational service needs, existing interconnection policies, and requires planning and coordination of network operations. The storage device could be restricted within certain limits in providing the services [42,43].

For this case of presenting the device for both maximizing self-consumption of wind energy and committing to providing certain ancillary services in stack, a new economic analysis is performed. The new analysis is to reveal how the commitment of the device to providing stacked market services impacts the profitability of the storage project. The total DS3 service provided is the summation of the storage eligible DS3 service suite of Table 1—at the aggregated standard rate of £10.47/MWh.

At the first instance 20% of the storage capacity is committed within less than 2% of total lifespan of the storage device, for the estimation of Gain 1 and the payback Period 1. The same storage capacity is committed for 25% of the device lifespan at the second instance, for the estimation of the Gain 2 and the payback Period 2. The ancillary service gain is a product of the committed capacity and the aggregated value, £10.47/MWh. The new annual gains are estimated as the sum of the gain from self-consumption of wind energy and the gain from the provision of ancillary services. It is assumed that committing the storage device to providing the ancillary services comes at zero or insignificant extra cost.

2.5.3. Potential Benefit across Electricity Supply Chain

This section examines the value of the storage device installed on the described distribution network in general, not only the device deployed to capture the wind energy produced by BTM turbines. To account for the full range of values that could be derived from any typical installation, a potential benefit analysis is carried out for the entire stack of services that the storage device could potentially offer across the electricity supply chain.

In accounting for the potential storage benefits, with assumptions where required, the following approximate daily storage service values are estimated:

- DS3 services: the total suite of the DS3 service that the storage device commits to is £10/MWh, the size of the device deployed is 2 MW/4 MWh, 40% of the device capacity has been committed to providing the services, the storage system has 85% roundtrip efficiency—the storage has minimal energy losses while charging and discharging.
- Increased wind self-consumption: the size of the storage device is 2 MW/4 MWh, the device is 85% efficient (roundtrip), the site data—containing the import and the export electricity prices, the energy exports from the wind turbines, the energy generated by the turbines, and the total load energy required—are used in calculating the gross annual gain from self-consumption of wind energy. The daily potential gain is estimated by dividing the gross annual gain by the number of days in a year.
- Time-of-use-bill-management: the size of the storage device is 2 MW/4 MWh; the device is 85% efficient (roundtrip), the site data are used in calculating the mean daily import; using the Power NI—an electricity supplier—Economy 7 (2-Rate) meter plan [44], a third of the total electricity required is set to be imported at a low rate period (at nights) while the remaining electricity is imported at a high rate period (during the day).
- Demand response of load shifting: the size of the storage device is 2 MW/4 MWh; the device is 85% efficient (roundtrip), the site data are used in calculating the mean daily import; using the SSE Airtricity (an electricity supplier) KeyPad Powershift meter plan, a third of the total electricity required for the day is imported within the "low" rate period—between 1:00 and 9:00 [45,46] while the remaining electricity is imported at the "normal" rate period during the day.

Some of the storage services highlighted are mutually exclusive; for example, while the storage device has been deployed for increasing self-consumption of wind energy and providing certain levels of ancillary services, the device may no longer be fully utilisable for time-of-use-bill-management at the same time. While inadequate policies may not allow some storage benefits to be realizable now, the potential benefit analysis is to indicate storage-utilisation possibilities and reveal the changes in policies that could monetise additional storage values at the distribution network.

Other potential storage values could be estimated for specific sites within the distribution network. Meanwhile, any given application could require using a storage device with specific characteristics.

3. Results and Discussion

While the on-site loads are supplied with the power generation from the wind turbines and the grid, the installed storage device takes up any excess wind energy generation from the turbines as the load flow converges while the network elements operate within safe limits, illustrated for a typical windy day in Figure 5.

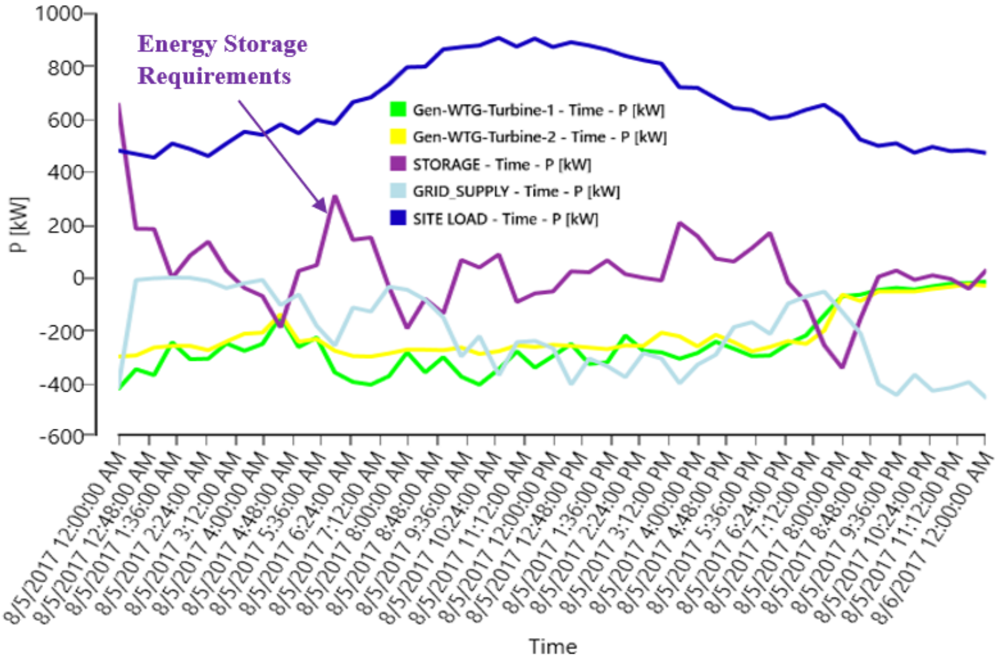

Figure 5. Energy profiles for an illustrative day.

The energy profile reveals the charge-discharge characteristics, suggesting an applicable storage device, Figure 5. Between midnight (00:00) and evening (18:00), the aggregate power from the two wind turbines was close to 600 kW—a typically windy day. With the load demand rising from the base point at 500 kW, the loads are served from the turbines (with the excess wind generation and low demand at this time) and the storage device is discharged to meet the additional demand until at around 4:30 when the energy generation from the turbines increases, the load demands being fully served and the excess wind energy charging the device through to around 5:40. As the load demand increases through the day, more energy is imported from the grid to supplement the energy generation from the turbines while the storage device is kept at a state of charge. At about 20:00, the wind energy generation drops; the battery is discharged as much as possible while the deficit in energy supply is met by the grid—the import from the grid moving close to 400 kW.

The profile indicates that the deployed storage device could be subject to daily multiple rounds of discharge cycles to achieve a maximum self-consumption of wind energy. This suggests that the deployed storage device should have the capability for several rounds of deep discharge.

Within the one-year period under consideration, while a 3,720,642 kWh of energy at a market value of £4,464,777.04 (3,720,642 kWh × £0.12/kWh) was imported from the grid, a total energy of 601,780 kWh at a market value of £31,593.45 (601,780 kWh × £0.0525/kWh) was exported to the grid. The total recoverable energy is obtained by multiplying the captured (used to be exported) energy (601,780 kWh) by the storage efficiency. The market value of the recovered energy has been obtained by multiplying the total recoverable energy by the market price of £0.12/kWh—the import and the export electricity prices are approximated from the historical analysis of the export and the import payments data. In [33], a similar price relation between the export electricity price and the import electricity price for grid-connected wind turbines on the foregoing distribution network may be seen. The gross annual gain shows the difference in market value at the import electricity price of £0.12/kWh and at the export electricity price of £0.0525/kWh, Table 2.

Table 2. Effect of storage efficiency on total recoverable energy.

Efficiency of Storage System (%)	Total Recoverable Energy (kWh)	Market Value of Recovered Energy at £0.12/kWh (£)	Gross Annual Gain at £(0.12–0.0525)/kWh (£)	Self-consumption of Wind Energy (%)
95	571,691.00	68,602.92	37,009.47	48.89
90	541,602.00	64,992.24	33,398.79	48.40
85	511,513.00	61,381.56	29,788.11	47.91
80	481,424.00	57,770.88	26,177.43	47.42
75	451,335.00	54,160.20	22,566.75	46.93
70	421,246.00	50,549.52	18,956.07	46.45

The quantity of the recoverable energy is more when using a storage a device of higher efficiency—as less of the excess wind energy is wasted through the charge-discharge cycles with the higher efficiency storage system; for example, while a total energy of 571,691.00 kWh is recoverable when using a 95% efficient storage system, only a 421,246.00 kWh of energy is recoverable when using a 70% efficient storage system. In the existing market in which the import electricity price is £0.12/kWh and the export electricity price is £0.0525/kWh—taken as typical prices—the gross annual gain and the percentage of energy serving the loads from the storage device are more while using the high-efficiency storage system, Table 2. The result of Table 2 suggests that, to derive more gain from deploying a storage device for increasing self-consumption of the locally generated wind energy, a storage technology having a higher efficiency should be used.

Another important storage characteristic that should be considered is the operating temperature of the storage device in respect of its environment. For example, some battery performances may degrade while operating outside recommended temperature ranges. The mean annual temperatures at this site over centuries have ranged from 8.5 °C to 10.0 °C, with a record extreme maximum temperature at 32.3 °C and minimum temperature at −9.0 °C [47,48]. The storage technologies selected can operate well within the site temperature range.

In other words, the storage technologies selected have typical roundtrip efficiencies above 65%, could meet the charge-discharge characteristics required, are mature or demonstrated technologies, have reasonable cost trends, have operating temperature features that make them appropriate at the site, are applicable at the point of the distribution network, and could serve both as load and as generator. Of the considered storage technologies, flywheel storage, a lithium ion battery, sodium ion (Na-ion) battery, and a zinc-bromine (Zn-Br) flow battery are found to meet the storage requirements [19–22].

Considering the changes to the energy mix of the site: with the storage, no on-site generated wind energy is supplied to the grid—the storage captures the excess wind energy for self-consumption on-site. As depicted in Figure 6, the percentage of the wind energy in the energy mix at the location moved from 39.47% in Figure 6a to 48.32% in Figure 6b—an almost 10% increase in self-consumption of wind energy. The other part of the energy mix came from a grid supply with an average energy mix containing about 55% of the total energy generation coming from fossil fuel sources [15].

In analysing the value derived from deploying the storage device for self-consumption of wind energy: the total storage capacity cost is a total system cost—covering any cost associated with the acquisition, installation, and usage of the storage (including fixed cost, variable cost, capital cost, initial cost, maintenance cost, and any complementary costs). The cost ranges are heuristic test-case selections. The cost options help to see where the profitability of the storage project lies for different storage cost parameters that could typify varying market conditions, using a payback period estimation within the life span of the storage device.

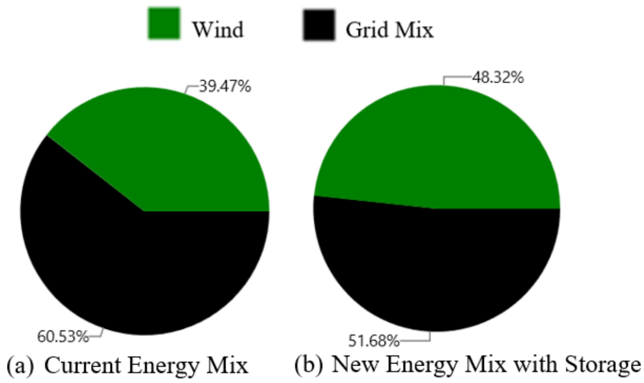

Figure 6. Energy mix of site.

Each of the storage technologies has been assigned a nominal storage efficiency; the values are the overall roundtrip efficiencies of the whole system of storage. The typical lifespan of a flywheel storage is taken to be above 20 years, the lithium ion and the sodium ion batteries are taken to have lifespans between 10 to 15 years, and the zinc-bromine flow battery is considered to have a lifespan of between 5 to 10 years [19,22]. The lifespans of the storage technologies are included to show where the technologies could make economic sense around the hypothesised prices. The payback period is the ratio of the cost of the total storage system to the gross annual gain of storage, Table 3.

Table 3. Deployment of storage device to store excess wind energy only.

Selected Energy Storage Technologies and Costs (£/kW; £/kWh)	Total Storage Capacity Cost (£ Million)	Nominated Storage Efficiency (%)	Life Span (Years)	Gross Annual Gain (£)	Payback Period (Years)
Flywheel at £120/kW; at £80/kWh	0.56	90	20+	33,398.79	16.8
Flywheel at £1880/kW; at £1715/kWh	10.62	90	20+	33,398.79	318.0
Li-ion Battery at £110/kW, at £70/kWh	0.50	85	10–15	29,788.11	16.8
Li-ion Battery at £1580/kW, at £1510/kWh	9.20	85	10–15	29,788.11	308.8
Na-ion Battery at £90/kW, at £60/kWh	0.42	80	10–15	26,177.43	16.0
Na-ion Battery at £1200/kW, at £1100/kWh	6.80	80	10–15	26,177.43	259.8
* Zn-Br Flow Battery at £105/kW, at £65/kWh	0.47	75	5–10	22,566.75	20.8
* Zn-Br Flow Battery at £1150/kW, at £800/kWh	5.50	75	5–10	22,566.75	243.7

* As most power equipment usually last for over 40 years, it is customary to evaluate new equipment within a minimum of 10-year frame. Zn-Br Flow battery may not last for up to 10 years.

The results of Table 3 suggest that with the current market conditions, the deployment of the 2 MW/4 MWh energy storage device for self-consumption of wind energy could become economically feasible at the storage cost around £500,000. Given that the storage technologies have similar costs, flywheel storage promises higher return on investment because of its longer lifespan, inherent almost-unlimited cycles, and ruggedness in responding effectively to providing specialised electricity grid services. However, its considerable self-discharge rate could make it a less desirable choice for deferred self-consumption of stored energy [22]. A lithium-ion battery could be a better option for being a more mature technology, being less susceptible to self-discharge, being able to withstand several rounds of deep discharging, and like most batteries, being able to respond in time to providing grid services [19].

While the results of Table 3 are for the case where the storage device has been deployed only for increasing self-consumption of wind energy, Table 4 depicts the result of deploying the device for providing certain DS3 market services in addition to increasing self-consumption of wind energy.

Table 4. Deployment of storage for self-consumption of wind energy and ancillary services.

Selected Energy Storage Technologies and Costs (£/kW; £/kWh)	Ancillary Services Duration/ Lifespan (%)	New Annual Gain 1 (£)	New Payback Period 1 (Years)	Ancillary Services Duration/ Lifespan (%)	New Payback Period 2 (Years)
Flywheel at £120/kW; at £80/kWh	0.42	36,150.31	15.5	25	2.8
Flywheel at £1880/kW; at £1715/kWh	0.42	36,150.31	293.8	25	53.9
Li-ion Battery at £110/kW, at £70/kWh	0.56–0.83	32,126.90	15.6	25	3.9
Li-ion Battery at £1580/kW, at £1510/kWh	0.56–0.83	32,126.90	286.4	25	72.3
Na-ion Battery at £90/kW, at £60/kWh	0.56–0.83	28,048.42	15.0	25	3.5
Na-ion Battery at £1200/kW, at £1100/kWh	0.56–0.83	28,048.42	242.4	25	57.7
Zn-Br Flow Battery at £105/kW, at £65/kWh	0.83–1.7	23,970.04	19.6	25	6.3
Zn-Br Flow Battery at £1150/kW, at £800/kWh	0.83–1.7	23,970.04	229.5	25	74.2

With the storage deployed for the multipurpose of increasing self-consumption of wind energy and providing the ancillary services, the results indicate a shorter payback period on investment, suggesting increased profitability. The total DS3 service provided has been taken from the storage eligible DS3 service suite of Table 1. The storage capacity is committed within less than 2% of total lifespan of the storage device at the first instance: this estimates the new annual Gain 1 and the new payback Period 1. The same capacity is committed for 25% of the device total lifespan at the second instance: estimates a new Gain 2 and the new payback Period 2, Table 4. The new annual gain is the sum of the gain from self-consumption of wind energy and the gain from the provision of ancillary services.

The payback periods are shorter when the storage device is committed for longer duration. This suggests that, when deploying a storage device at the distribution network, it could be more profitable to commit the device to providing ancillary services to an extent permissible and that does not pose a risk to the security of other investments serving the grid.

Another picture is depicted in Figure 7, where the daily potential value that the deployed energy storage system could offer to stakeholders across the electricity supply chain has been estimated using the approximate data described in Section 2.5.3. While some of the potential values such as demand charge reduction and increased wind self-consumption are concrete, others—such as transmission and distribution deferrals—could be conceptual and often require favourable integration policies and proper grid planning or coordination to become realizable.

Certain incentives could be available for generating and using more clean energy on-site; for example, the revenue stream from the Renewable Obligation Certificate (ROC) that was in place to promote renewable energy in Northern Ireland [33]. Similarly, some mechanisms that reduce investment risks; for example, the power purchase agreements (PPA) could serve to guarantee the market for the storage services. The ROC and the PPA arrangements are typical market and integration policies that could impact the value of any energy storage project.

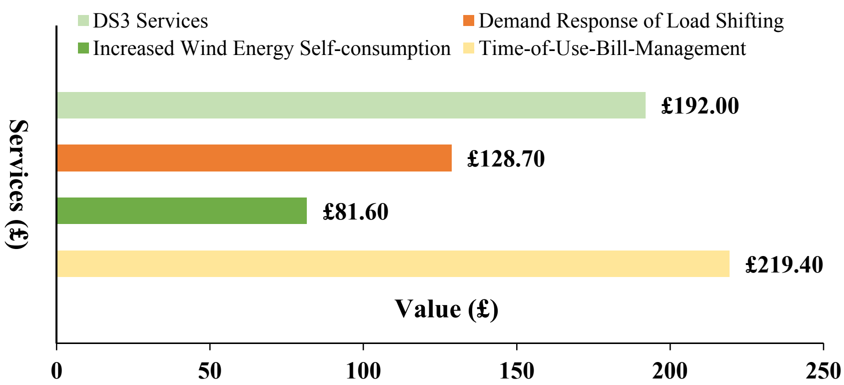

Figure 7. Potential daily revenue of storage across electricity supply chain.

Meanwhile, beyond the distribution network, some other storage benefits which are also typically very site-specific could be derived while using the storage device for capturing or saving energy for later use. To mention a few: to manage the output of mass wind turbines where a network congestion would have disallowed any further grid-integration of turbines, a storage device could be installed for managed connection. The storage device could also be installed at the higher voltage ends of the electricity network for energy arbitrage; for example, for bulk energy trading during periods of high price volatility through the Irish ISEM intra-day market [35].

Lastly, a country-wide analysis could be performed to see how storage systems could be deployed to support renewables and bring optimal benefits to the customer, to the grid, and to the utility; maximizing renewable energy generation in achieving key sustainability targets.

4. Conclusions

Energy generation from wind turbines connected to the distribution network could contribute to the effort of decarbonizing electricity systems. With storage devices, more of the on-site generated wind energy could be captured for later energy consumption. For grid-connected systems, where the market and integration policies permit it, the storage device could—in addition to providing customer services—be committed to providing DS3 services of active and reactive power, ramping margins, and reserves. When a 2 MW/4 MWh storage device was deployed at a distribution network having two 800 KW BTM wind turbines, a typical peak load under 1500 kW and a base load around 500 kW, the percentage of self-consumption of wind energy rose from 39.47% to 48.32%. Deploying the device for providing other market services in addition to helping to achieve increased self-consumption of wind energy makes the storage project more profitable—suggesting a mechanism through which the storage system could be deployed to contribute to the on-going effort of maximizing the utilization of clean energy for sustainable development. The profitability of the storage system deployed at the distribution network is dependent on the aggregate storage cost, the integration policies at the location, and the ability to deploy the device for stacked services. Through favourable integration and environmentally cautious policies, energy storage could provide customer and ancillary services within the electricity supply chain.

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Appendix A

Static Load Flow Equations:

Given that the net complex power flowing into a bus i of a network is:

$$S_i = P_i + jQ_i = (P_{Gi} - P_{Di}) + j(Q_{Gi} - Q_{Di}) \quad \text{(A1)}$$

where P_D and Q_D are the real power demand and the reactive power demand respectively while P_G and Q_G are the real power generation and the reactive power generation within the bus respectively,

$$P_i = P_{Gi} - P_{Di}$$

$$Q_i = Q_{Gi} - Q_{Di}, \text{ for } i = 1, 2, 3, \ldots, n$$

If n represents the number of buses within the network, the flow of current through the bus i is:

$$I_i = \sum_{k=1}^{n} Y_{ik} V_k, \text{ for } i = 1, 2, 3, \ldots, n; \quad \text{(A2)}$$

where V_k is the voltage at bus k, Y_{ik} is the mutual admittance—the admittance between the ith and the kth nodes; is the negative of the total admittances existing between the ith and kth nodes, whereas,

$$Y_{ik} = Y_{ki}$$

Similarly, the complex power flowing into a bus i is given as:

$$S_i = P_i + jQ_i = V_i I_i^* \text{ ; for } i = 1, 2, 3, \ldots, n \quad \text{(A3)}$$

with I_i^* representing a complex conjugate of the current flow within the ith bus, and V_i representing the bus voltage,

$$\begin{gathered} S_i^* = P_i - jQ_i = V_i^* I_i; \text{ for } i = 1, 2, 3, \ldots, n; \\ S_i^* = P_i - jQ_i = V_i^* \left(\textstyle\sum_{k=1}^{n} Y_{ik} V_k \right); \text{ for } i = 1, 2, 3, \ldots, n \end{gathered} \quad \text{(A4)}$$

Now, if the real and the imaginary sections of Equation (A4) are correlated,

$$P_i = R_e\left\{ V_i^* \sum_{k=1}^{n} Y_{ik} V_k \right\}; \; Q_i = -I_m\left\{ V_i^* \sum_{k=1}^{n} Y_{ik} V_k \right\}; \text{ for } i = 1, 2, 3, \ldots, n \quad \text{(A5)}$$

In polar form, $V_i = V_i \delta_i$; $V_i^* = V_i - \delta_i$ and $Y_{ik} = Y_{ik} \theta_{ik}$; while θ represents the phase angle between current and voltage, δ represents the load angle.

Substituting the polar expressions for V_i^*, Y_{ik}, and V_k in Equation (A5); the real power and the reactive power components of the *static load flow equation* are respectively,

$$P_i = V_i \sum_{k=1}^{n} V_k Y_{ik} \cos(\theta_{ik} + \delta_k - \delta_i)$$

$$Q_i = -V_i \sum_{k=1}^{n} V_k Y_{ik} \sin(\theta_{ik} + \delta_k - \delta_i)$$

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