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UPGRADING WIND AND STORAGE RESOURCES FOR INCREASED DEMAND-SIDE ENERGY GENERATION AND MARKET VALUE

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ABSTRACT

Energy generation from renewable sources promises to help bring sustainability to the electricity system. Wind turbines have been used to intercept wind flows while energy storage promises to help in reducing the effect of intermittency in renewables. While the net benefits of installing Distributed Energy Resources (DER) are diverse and locational, this work examines adding new wind turbines and battery storage to the existing wind turbines on a distribution network that has a typical daily peak load around 1000 kW and a base load around 500 kW. The DERs were deployed in different scales; first, to increase demand side generation of wind energy only and secondly, for stacked services. While the *NEPLAN 360* modelling tool was used for the technical analysis to assess the effect of the upgrade, an economic analysis was performed through the payback period on investment. The results suggest that – given the current market structure at this location – deploying more DERs just for increased demand-side generation, while technically achievable, is not economically feasible. The upgrading approaches profitability as the storage is deployed to provide more stacked services across the electricity grid – could be achieved with favourable market policies.

KEYWORDS: Ancillary services, Demand-side generation, DER upgrade, Energy storage, Market services, Wind energy

INTRODUCTION

Generating clean energy from wind and photovoltaics (PV) using Distributed Energy Resources (DER) has been identified as a possible way for developing a cleaner and sustainable energy system. While this sustainable way of energy generation is desirable, there are challenges with the intermittency of renewables. The use of energy storage and demand controls have been identified as possible solutions, [1] and [2]. A stable and reliable operation of the power system requires that energy demand be met with energy supply. While this balancing between energy demand and energy supply has been relatively easier with conventional generators, the intermittent nature of renewables brings complexities. Deploying DERs in promoting the generation of clean energy comes with opportunities as well as challenges. The opportunities include; cheap source of unlimited energy – Sun and wind, cleaner energy system, safe and secure energy system, less dependency on polluting fossil fuel, and storage helps in eliminating the constraints and curtailments of renewables [3], [4], and [5]. Whereas, the challenges include; the complexity brought by the intermittency of renewables, the location-dependent nature of the real benefits of DERs like storage [6], the dynamic nature of DER economics, and inconsistent integration policies. The differences in the quality of renewable resources at different locations; the differences in load profile, market structure; the differences in the architecture of the power grid, energy mix of the grid, the point on the grid where a DER is to be installed; all make the benefits derived from installing DER vary considerably from location to location. In this work, the benefits of upgrading on-site wind resources and energy storage on a distribution network are examined. The site has a typical daily peak load of 1000 kW and a base load of about 500 kW. The site is connected to the electricity grid via an 11kV substation. Currently, two 800KW wind turbines are installed. The wind turbines are grid-connected and could supply considerable excess power generation to the grid. To optimize demand-side generation and inform policies, the study examines how the DER at this site could be upgraded to include more wind turbines and battery storage. The storage is to improve self-consumption of demand-side generated energy while assisting the grid for value by offering ancillary services. The *NEPLAN 360* modelling tool is used for the technical analysis while the economics of the upgrade project is analysed on payback period of investment for different upgrade scales and services. To see where policy changes could bring more value for DER, the potential benefits of adding the storage is estimated across the electricity supply chain.

METHODS

Description of Distribution Network:

1

The distribution network has nine substations on-site connected to an alternating current electricity grid via an 11kV transformer. The typical base load through the day is about 500 kV while the peak load is around 1000 kV. The load profile is like that of a campus where the load typically rises gradually in the morning, peaks around afternoon, and gradually drops all through the night before picking up again in cycles in the following day. There are two customer-owned *Enercon E48* wind turbines on-site for demand-side generation, each rated 800KW. One of the turbines is directly connected to the grid. The outputs of the turbines are restricted to 670 kW for planning and application noise compliance. There are two arrays of rooftop photovoltaic (PV) on-site used for local heating only – these are not grid-connected and not included in analysis.

In the last calendar year, the total energy consumed on-site was 6,189,647 kWh; while 3,720,642 kWh of that energy was imported from the grid, 3,042,075 kWh was generated from the two wind turbines, a 28,710 kWh was generated from the PV arrays, and a total 601,780 kWh was exported back to the grid. This puts the annual displaced imported electricity by demand-side generation – all self-generation minus exports – at 2,469,005 kWh. There is a high voltage connection agreement that puts the Maximum Import Capacity of this site at 2,500 kW and the Maximum Export Capacity at 1,242 kW. The imported electricity price varies, typically £0.12/kWh. Electricity export price varies as well, typically £0.0525/kWh. The exported electricity price is usually lower than the imported electricity price, in a ratio of 3 to 7 typically. A line diagram depicts the initial configuration of the network, Fig. 1.
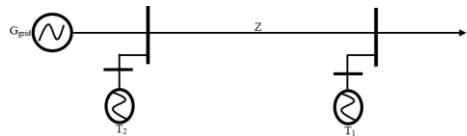

Figure 1: Initial Network Configuration

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

where L represents the total power consumed in aggregated system load, T_1 is the power from the first turbine, T_2 is the power from the second turbine, Z represents the power expended within system impedance, and G_{grid} is the power supply from the grid.

Now, in addition to the existing DER on-site, some wind turbines and behind-the-metre battery storage are introduced – through a *NEPLAN 360* model – to the distribution network to increase demand-side generation while using the storage to take up any excess wind turbine generation, Fig. 2. Using; the load profile for the last calendar year, wind generation data of the two existing turbines, a typical electricity export-import price, and hypothesized prices for DERs – informed by wide consultation of literature and industry; the result of upgrading the DERs are analysed from technical and economic perspectives to ascertain benefits, the likely practices, or policy changes that could help make demand-side energy generation feasible.
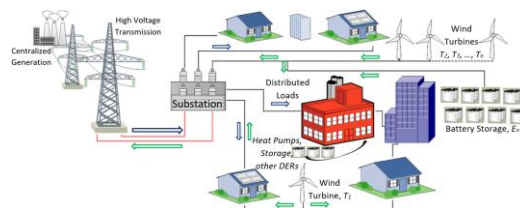

Figure 2: Layout of the Distribution Network

Selecting a Storage Technology:

The point where the storage is required is behind-the-meter on a distribution network, within end user premises. The storage will be primarily required to help maximize the use of demand-side generated energy from wind turbines while potentially serving the grid through ancillary services. The storage should be able to serve as a load and as a generator. An account of different energy storage options is given in [7] and [8]. Sodium ion and Lithium ion batteries are the suitable storage options here; they have wide operating temperature ranges below and above 0^0C, they can last for up to 15 years with good round-trip efficiencies above 85% and have long cycle life. Sodium is abundant; however, Lithium ion technology is more mature. Lithium ion batteries have tolerance for many discharge cycles, are not susceptible to memory effects, could be designed or cascaded for more power and energy supply, and are less prone to self-discharge.

Technical Power Flow Analysis:

Power flow analysis determines the effect of changes to the power network. After adding the new turbines and storage to the distribution network, a power flow analysis is carried out to ensure that the stability and the reliability of the network has not been compromised: Given that the net complex power into a bus i is given as;

$$S_i = P_i + jQ_i = (P_{Gi} - P_{Di}) + j(Q_{Gi} - Q_{Di}) \qquad (2)$$

while (P_D and Q_D) and (P_G and Q_G) are the real and the reactive power generated (P_G and Q_G) and demanded (P_D and Q_D) respectively, within the bus;

$$P_i = P_{Gi} - P_{Di}$$
$$Q_i = Q_{Gi} - Q_{Di} \text{ ; for } i = 1, 2, 3, ..., n;$$

with n being the total number of buses within that network; the current flow within the bus i is given as;

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

where Y_{ii} – also known as the *self-admittance* – is the ith node's driving-point admittance; given as a sum of all the admittances at the node, Y_{ik} – also known as the *mutual admittance* – is the transfer admittance between the ith and a kth node; given as the negative of the sum of all the admittances between the ith and the kth nodes, meanwhile $Y_{ik} = Y_{ki}$. The complex power into the bus i could be written as;

$$S_i = P_i + jQ_i = V_i I_i^* \text{ ; for } i = 1, 2, 3, ..., n \qquad (4)$$

where V_i is the voltage at the ith bus and I_i^* is the current flowing through the bus in complex conjugate;

$$\text{this implies, } S_i^* = P_i - jQ_i = V_i^* I_i; \text{ for } i = 1, 2, 3, ..., n$$
$$S_i^* = P_i - jQ_i = V_i^*(\sum_{k=1}^{n} Y_{ik} V_k); \text{ for } i = 1, 2, 3, ..., n \qquad (5)$$

Now, if the real and the imaginary sections of Equation (5) are compared, then

$$P_i = R_e\{V_i^* \sum_{k=1}^{n} Y_{ik} V_k\}; \quad Q_i = -I_m\{V_i^* \sum_{k=1}^{n} Y_{ik} V_k\}; \text{ for } i = 1, 2, 3, ..., n \qquad (6)$$

In polar form, $\boldsymbol{V_i} = V_i \llcorner \delta_i$; $\boldsymbol{V_i^*} = V_i \llcorner -\delta_i$; and $\boldsymbol{Y_{ik}} = Y_{ik} \llcorner \theta_{ik}$; where θ is the current-voltage phase and δ is the load angle. Substituting a polar form of V_i^*, Y_{ik}, and V_k to Equation (6); the *static load flow equations* can be expressed for the real and the reactive power respectively as;

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

The load flow equations are solved with a numerical solution – they are non-linear. A stable network indicates convergence of power flow run on the *NEPLAN 360*.

Storage Power Management:

As an upgrade to the DER at location, additional wind turbines with suitable size of storage are installed to maximise demand-side generation from the turbines and for dedicated energy export to the grid for utility and ancillary services. In Fig. 3, switch S_{w1} is operated according to the control described by Equations (7a) and (7b) while the switch S_{w2} – flips so that the storage E_n is recharged or discharged – is operated according to the control described by Equation (8).
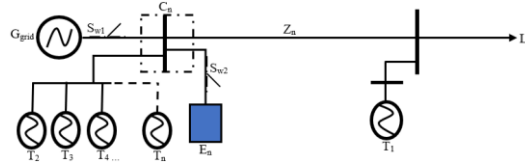

Figure 3: Addition of Storage and Turbines to Initial Network

$$S_{w1} = +ve, when \ L_n + Z_n > T_1 + T_2 + T_3 + \cdots + T_n + E_{n(min)} \qquad (7a)$$
$$S_{w1} = -ve, when \ L_n + Z_n < T_1 + T_2 + T_3 + \cdots + T_n + E_{n(min)} \qquad (7b)$$

where $E_{n(min)}$ is the implied energy discharge limit for aggregated storage, T_n is the energy feed from the nth additional turbine, L_n is the aggregated energy demand of load, and Z_n is the aggregated energy expended in system impedance.

$$E_{n(min)} \propto \left[(E_{n(SOC)}) \ AND \ (E_{n(Services)}) \ AND \ (Time_{Tariff}) \ AND \ (T_1) \ AND \ (T_2) \ AND \left(\sum_{3}^{n} T_n \right) \right]$$
$$S_{w2} \propto E_{n(min)} = 1 \ OR \ 0 \qquad (8)$$

3

where $E_{n(SOC)}$ is any specified state of charge of aggregated storage, $E_{n(services)}$ is the service demand on storage capacity, $Time_{Tariff}$ is the net instantaneous amount charged for electricity, T_1 is the energy feed from turbine number *1*, T_2 is the energy feed from turbine number *2*, and T_n is any additional energy feed from any *n*th additional turbine.

$$E_{n(\min)}(1)^+ = E_{n(\min)}(0)^+ \pm E_{n(\min)}(1)^-$$
$$E_{n(\min)}(2)^+ = E_{n(\min)}(1)^+ \pm E_{n(\min)}(2)^-$$

That is, $E_{n(\min)}(t)^+ = E_{n(\min)}(t-1)^+ \pm E_{n(\min)}(t)^-$; *for every storage charge-limit instance t = 1, 2, 3, ..., n*

A combined operation of switches S_{w1} and S_{w2} means that the storage will be charged from the power supplies from the wind turbines to a level that could permit it to be charged or discharged through the grid in response to signal to provide ancillary services; it is to be discharged to maximize the consumption of wind energy from the turbines and meet continuous instantaneous commitments of providing ancillary services to the grid. When not currently providing any ancillary services; the storage is charged with the turbine supplies only and discharged to serve local loads only; meanwhile, the storage is charged or discharged to a level that permits it to meet any ancillary services commitments; and when discharging to the grid, discharges within a predefined service commitment.

Economic Analysis

An economic analysis is carried out to ascertain the cost implications of adding storage and new wind turbine to the distribution network. The economic analysis is to indicate the economic feasibility of the upgrade project and suggest the likely payback period of investment on any additional DER. After looking at the charge-discharge requirement for storage from simulations and an applicable energy storage technology has been selected; a cost analysis is done to ascertain economic implications and inform on a cost-effective upgrade option, while also suggesting the likely policy changes that could promote demand-side energy generation through DERs.

The price of storage is hardly fixed – inconsistent prices are quoted in literature and industry. Moreover, performing a cost analysis using a quoted price at one time makes the analysis inaccurate at another time when the price has changed. Here, to avoid the errors inherent in price volatility of storage, the emphasis is on the science. Hypothetical price ranges – informed by the price ranges for Lithium ion battery and wind turbines from wide consultation of literature and industry – the likely price ranges of the storage at the current or future dates – are used in identifying the cost points at which installing the DERs becomes profitable. The economic analysis, while not claiming that installing any DER is currently profitable, is to identify that cost, resource, or market points at which the upgrade project becomes economically feasible. The analysis is to indicate how market conditions or policy changes could impact the profitability of the project. In the existing market, the export electricity price and the import electricity price vary but have consistent relations; the imported electricity price being often higher, usually in a ratio of 7 to 3.

Initially, the economic analysis is performed while the wind turbines and the storage are deployed only to increase self-consumption of demand-side generated energy. The selected prices of storage are assumed to be the cradle-to-grave cost, covering all costs from the capital cost to the cost through to end of life of storage. The cost of the Lithium ion battery is specified in terms of energy capacity, in £/kWh. The cost of the wind turbines is specified in terms of output power rating, in £/W – cost includes transformer, other accessory costs, and integration costs. The annual gain in using the self-generated energy in lieu of sending it to the grid is determined; this annual gain with the estimated lifespan cost of the DER is used in estimating the likely payback period of project, at different storage prices – wind turbine prices are considered relatively stable. The system is reset to, in addition to promoting the use of self-generated wind energy, commit certain percentage of the storage to providing ancillary services through *DS3/I-SEM* – while *I-SEM* is an existing wholesale market set up to allow electricity trading across borders, *DS3* was set up to promote the penetration of non-synchronous generation on the grid at this location, with service prices given in [9]. The storage is to commit to supplying total ancillary services of £10/MWh through the *DS3/I-SEM* for two-third of each year in a five-year contract, except when specified otherwise. A new investment analysis is performed.

To account for the full benefits of the DER upgrade – both currently realizable and potential – an estimate of the potential value of any additional storage is performed across the electricity supply chain. This analysis indicates those benefits that could further make the installation of storage profitable, given favourable electricity market conditions or policies.

MAIN RESULTS

The typical load profile, the energy generation profiles, and the storage charge-discharge characteristics on-site are depicted in Fig. 4(a). A suitable storage that could handle the discharge characteristics is required. While the power flow indicates

convergence; the load rises gradually from morning, reaches the peak around 1000 kW at noon, and slopes down at evening – depicting a typical campus load profile. While the wind turbines generate more energy – typically on a windy day, less energy demand is placed on the grid and the storage is set to charge and discharge to maximise wind energy from turbines. The energy mix of site with the two existing wind turbines – without any storage – is given in Fig. 4(b); here, all excess wind generation goes to the grid. Fig. 4(c), Fig. 4(d), Fig. 4(e), and Fig. 4(f) depicts the changes in energy mix after adding only storage (2Turbines+Storage), two turbines and 80% efficient storage (4Turbines+80%Storage), two turbines and 90% efficient storage (4Turbines+90%Storage), four turbine and >80% efficient storage (6Turbines+Storage), respectively.
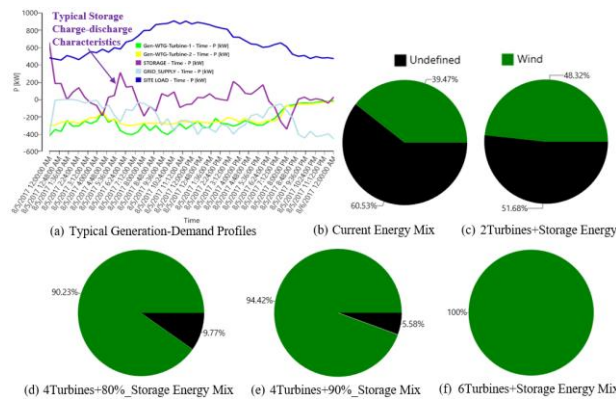

Figure 4: Generation-Demand Profile and Energy Mix Changes

As the number of turbines increases, the site approaches self-sufficiency in energy through demand-side generation; the gross annual gain and the percentage of wind energy consumption increases, Table 1. Whereas, the more efficient storage system helps to recover more of the wind energy, creating more market value – this shows the importance of selecting a storage technology having excellent round-trip efficiency as discussed in the method section. For the current study, a Lithium ion battery system with an efficiency of 85% is chosen, Table 1(b).

Table 1: Result for Increase in Wind Energy and Market Gain Using Different Storage Efficiencies				
(a) Using 90% Efficient Storage System				
Total Number of Wind Turbines	**Total Energy Recoverable (kWh)**	**Market Value of Recovered Energy (£)**	**Gross Annual Gain (£)**	**On-site Wind Energy Consumption (%)**
2	542,716.78	65,126.01	33,467.53	48.33
4	2,316,712.19	278,005.46	142,863.92	94.42
6	4,606,193.16	552,743.18	284,048.58	139.59
(b) Using 85% Efficient Storage System				
2	512,565.84	61,507.90	29,849.42	47.83
4	2,188,005.96	262,560.72	127,419.18	92.33
6	4,350,293.54	522,035.22	253,340.62	135.42
(c) Using 80% Efficient Storage System				
2	482,414.91	57,889.79	26,231.31	47.34
4	2,059,299.73	247,115.97	111,974.43	90.23
6	4,094,393.92	491,327.27	222,632.67	131.25

The payback period almost always exceeds the life spans of either the storage or the wind turbines when the storage is deployed only to increase demand-side generation of wind energy, Table 2. This is so for all the upgrade scales; for each of the increase in the number of installed wind turbines and the corresponding sizes of storage. This suggests that upgrading DER just to increase demand-side generation – while desirable for increased clean energy generation – is hardly economically feasible. The hypothesised costs of DER have been carefully selected to reflect the best of prices.

Table 3 presents a new picture where the storage also commits to providing some levels of ancillary services, in addition to helping to increase utilisation of wind energy. Here, the storage has been committed to provide ancillary service for two-third of the year for only five years within the DER life. The amount of gain derived now depends on the quantity of services rendered and for how long. The result suggests that installing the DERs for stacked services makes the upgrade project approach profitability, depending on market structure and cost.

Table 2: Payback Period on DER Investment at Different Costs

(a) +2MW/4MWh Storage				
Aggregated Li-ion Battery Cost; +No of Wind Turbine at Cost	**Total Equipment Upgrade Costs (£ Million)**	**Storage/Turbine Life Span (Years)**	**Gross Annual Gain (£)**	**Payback Period (Years)**
Storage only at £100/kWh	0.40	10-15/9-14 & 18-23*	29,849.42	13.4
Storage only at £180/kWh	0.72	10-15/9-14 & 18-23*	29,849.42	24.1
Storage only at £260/kWh	1.04	10-15/9-14 & 18-23*	29,849.42	34.8
(b) +2Turbines (Enercon E48 800KW) + 2MW/12MWh Storage				
Storage at £100/kWh; +2 Turbines at £1.7/W	3.92	10-15/20-25	127,419.18	30.8
Storage at £180/kWh; +2 Turbines at £1.7/W	4.88	10-15/20-25	127,419.18	38.3
Storage at £260/kWh; +2 Turbines at £1.7/W	5.84	10-15/20-25	127,419.18	45.8
(c) +4Turbines (Enercon E48 800KW) + 2MW/40MWh Storage				
Storage at £100/kWh; +4 Turbines at £1.7/W	9.44	10-15/20-25	253,340.62	37.3
Storage at £180/kWh; +4 Turbines at £1.7/W	12.64	10-15/20-25	253,340.62	49.9
Storage at £260/kWh; +4 Turbines at £1.7/W	15.84	10-15/20-25	253,340.62	62.5

* The existing wind turbines were installed in 2008 and 2017; their remaining lifetime is around 9-14 and 18-23 years respectively.

Table 3: Payback Period on DER Investment at Different Levels of Ancillary Service

(a) +2MW/4MWh Storage						
Aggregated Li-ion Battery Cost; +No of Wind Turbine at Cost	**10% Capacity for Ancillary Services (MWh per year)**	**10% Service; Payback Period (Years)**	**20% Capacity for Ancillary Services (MWh per year)**	**20% Service; Payback Period (Years)**	**95% Capacity for Ancillary Services (MWh per 30 days per year)**	**95% Service; Payback Period (Years)**
Storage only at £100/kWh	1,171.20	9.6	2,342.40	7.5	1,368.00	9.2
Storage only at £180/kWh	1,171.20	17.3	2,342.40	13.5	1,368.00	16.5
Storage only at £260/kWh	1,171.20	25.0	2,342.40	19.5	1,368.00	23.9
(b) +2Turbines (Enercon E48 800KW) + 2MW/12MWh Storage						
Storage at £100/kWh; +2 Turbines at £1.7/W	3,513.60	24.0	7,027.20	19.8	4,104.00	23.3
Storage at £180/kWh; +2 Turbines at £1.7/W	3,513.60	30.0	7,027.20	24.7	4,104.00	29.0
Storage at £260/kWh; +2 Turbines at £1.7/W	3,513.60	35.9	7,027.20	29.5	4,104.00	34.7
(c) +4Turbines (Enercon E48 800KW) + 2MW/40MWh Storage						
Storage at £100/kWh; +4 Turbines at £1.7/W	11,712.00	25.5	23,424.00	19.4	13,680.00	24.2
Storage at £180/kWh; +4 Turbines at £1.7/W	11,712.00	34.1	23,424.00	25.9	13,680.00	32.4
Storage at £260/kWh; +4 Turbines at £1.7/W	11,712.00	42.8	23,424.00	32.5	13,680.00	40.6

There are other potential benefits in storage application that could be realised with favourable market policies. As depicted in Fig. 5, some of the benefits include more ancillary services, backup power, green generation – realisable when price is placed on carbon, distribution and transmission deferrals – require proper electricity grid planning, and perhaps energy

arbitrage – with special prices for clean energy trading. For example, if the CO_2 factor of the grid supply is 0.2 $kgCO_2/kWh$ while a $200 kgCO_2/kWh$ is associated with manufacturing a Lithium ion battery, and a carbon tax of £80//tonneCO_2 exists; then green generation is £10.8, £60.8, and £73.8 per day for the 4MWh, the 12MWh, and the 40MWh batteries respectively; £326.4, £979.2, and £3,264.0 per day respectively through backup power – taking 80% of storage sizes for service, Fig. 5.
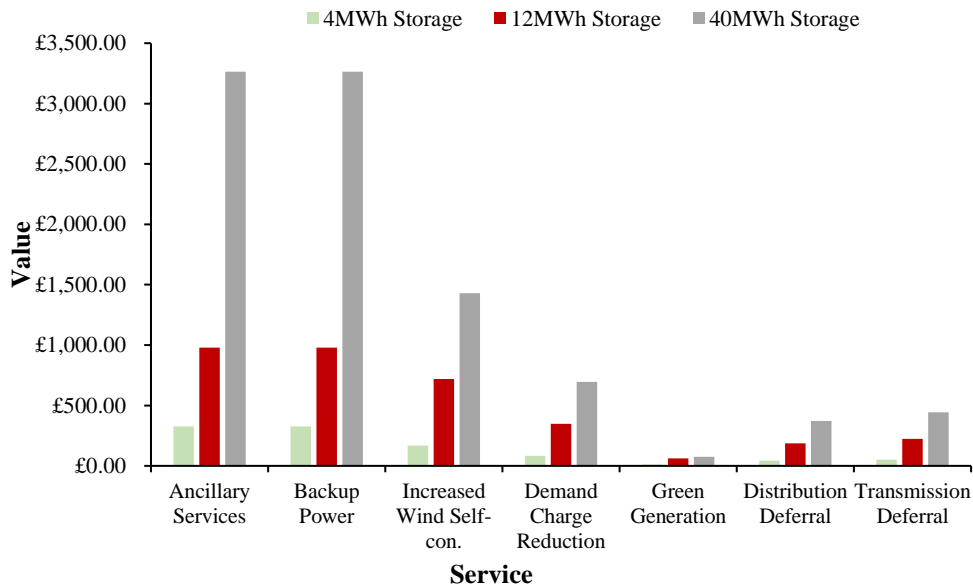

Figure 5: Potential Benefits for Different Storage Sizes across the Electricity Supply Chain

CONCLUSIONS AND POLICY IMPLICATIONS

Clean demand-side generation could be increased using more wind turbines while storage is used for increasing the local consumption of the clean energy. When the number of 800KW wind turbines on a 1000 kW-peak-load site on a distribution network was increased, with an addition of battery storage; the percentage of wind energy consumption on-site increased continuously until the site approached self-sufficiency in energy – around the point of six turbines using an above-80%-efficient storage system. While the upgrade project is technically feasible, the economics suggests that the upgrade only becomes profitable when the storage is deployed not just to increase demand-side generation of wind energy but also to provide other services across the electricity grid in stack, given equitable market prices and favourable integration policies.

ACKNOWLEDGEMENTS

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