Towards A Sustainable Electricity Grid: Market and Policy for Demand-Side Storage and Wind Resources

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TOWARDS A SUSTAINABLE ELECTRICITY GRID: MARKET AND POLICY FOR DEMAND-SIDE STORAGE AND WIND RESOURCES
--Manuscript Draft--

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Abstract:	While the net benefit of installing Distributed Energy Resources (DER) is largely locational, this work examines the system value in adding wind turbines and battery storage to a Northern Irish electricity distribution network. The DER were deployed in modules: first, for increased self-consumption of wind energy and secondly, for additional services. The results suggest that, given the current market structure, deploying the DER solely for increased self-consumption, while technically achievable, is not economically feasible. The upgrading approaches profitability and sustainability as the storage is deployed for stacked market services – and could be achieved through suitable market policies.

Response to Reviewers:	Response to Reviewers GENERAL NOTE: The Authors acknowledge the constructive review of the work by the Reviewers. Kindly see the responses to each comment in blue texts here. The changes to the manuscript are indicated with the texts in blue ink within the manuscript. Reviewer 1: The article is well written and structured. Results are well discussed and relevant for the journal. I only would propose some minor changes. Please introduce a Nomenclature section with symbols and abbreviations. This would make it easier to follow the text. RESPONSE: A list of variables, parameters, and connotations is now provided within section 1. Figure 6: Introduce a horizontal line for P=0, that makes it easier to identify positive or negative values. RESPONSE: The Fig. 6 has been modified accordingly, section 4. Table 1: Could you give some references for the cost data you are using for turbine and batteries? RESPONSE: References for cost of storage were given to include references 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, and 66. Another reference has been added: reference 67; kindly see subsection 3.1 (3rd paragraph) and subsection 3.2 (3rd paragraph) for the reasons why the references for the cost of storage are this many. For the cost of turbine: reference 69 has now been included, under the subsection 3.2 (4th paragraph) and Table 1 under section 4. Reviewer 2: This paper provides empirical investigation, estimation and assessment of the issue of

the technical feasibility and economic feasibility of installing a particular DER, precisely adding wind turbines and battery storage to a Northern Irish electricity distribution network.

The model, analysis and results seem empirically standard.

The engineering description of the project is detailed, but the economic analysis is generic and not quantitatively well specified.

The only economic reference found is the following:

"The project only approaches profitability when the resources are deployed not just to increase wind energy but for the storage to also provide services to the electricity grid in a value stack, achievable with fair market plans and favourable integration policies".

I do not know what are in Dollars (or Pounds) terms a "fair market plans", what are "favorable policies"?

RESPONSE: The "favourable policies" are those policies that would encourage investment into DER. The "fair (equitable) market plans" are the equitable market plans that would ensure that the deployment of the DER maximizes benefits across the entire electricity supply chain; summarised under section 5 as follows:

Tariffs which enable provision of DS3 services as part of the revenue stack

Tariffs designed for sites with connected renewable generation

Tariff for Time-of-use-electricity-bill-management

Tariff for Demand response for load shifting and peak shaving

The policies were discussed under subsections 2.1 (2.1.1 especially) and 2.3; the market designs were described under subsection 2.2.

I do not know what use to make of the following:

"The imported electricity price varies, typically £0.12/kWh. Electricity export price varies as well, typically £0.0525/kWh."

What does it mean "typically"? If I were a Regulator, could I really impose a burden on the tax/subsidy system based on "typical" prices?

RESPONSE: A specific value has not been used for the cost of storage: this is because of the findings for the cost of storage in references 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, and 67; more explanations are given under subsection 3.2 (3rd paragraph) and section 4 (3rd paragraph).

The relationship between the import and the export electricity prices was not properly stated: the reader should know that there is a consistent relation between the two prices – even when the two prices change. Please see subsection 3.2 (2nd paragraph).

About the Regulator, because the campus is a large consumer/independent buyer, this is a directly negotiated energy contract, rather than a tariff (although some elements of the price – like network charges – are regulated).

Highlights

- We describe the important roles storage and wind resources could play in achieving sustainability of the electricity grid
- The metrics for sustainability for Northern Irish grid are described with respect to the UK Net Zero target
- The policies and the equitable market arrangements needed for supporting demand-side resources are described
- Wind turbines and storage are deployed on a Northern Irish electricity distribution network as case study
- The deployment approaches profitability and sustainability as the storage is deployed for stacked services through more equitable market policies

TOWARDS A SUSTAINABLE ELECTRICITY GRID: MARKET AND POLICY FOR DEMAND-SIDE STORAGE AND WIND RESOURCES

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ABSTRACT

While the net benefit of installing Distributed Energy Resources (DER) is largely locational, this work examines the system value in adding wind turbines and battery storage to a Northern Irish electricity distribution network. The DER – turbines and storage – were deployed in modules: first, for increased self-consumption of wind energy and secondly, for additional services. The results suggest that, given the current market structure, deploying the DER solely for increased self-consumption, while technically achievable, is not economically feasible. The upgrading approaches profitability and sustainability as the storage is deployed for stacked market services – and could be achieved through suitable market policies.

KEYWORDS: Electricity grid sustainability, Equitable energy market, Wind energy storage

1. INTRODUCTION

Using wind turbines driven by wind flows and solar photovoltaic (PV) that intercepts solar rays have been identified as means of generating clean energy and achieving sustainability. While having clean, safe, and sustainable energy systems is desirable, the variability of renewables has brought new challenges. To maintain the stability and reliability of the electricity grid, the supply of energy must be met with energy demand. To address some of the challenges, smart controls and energy storage have been proposed [1] and [2]. Hence, deploying Distributed Energy Resources (DER) – for cleaner energy generation – offers opportunities as well as manageable challenges. Some of the opportunities include optimal management of scarce energy-utility resources through demand controls [3], relatively cheap source of power, less emissions from energy production [4], security of supply, better utilization of natural resources in renewables, and storage for less constraints and curtailments of renewables [5].The possibility of changing the energy mix of the grid by shifting to the generation sources of lower CO_2 emissions using DER has been described in [6]. In [7] and [8], the possibility of deploying a storage device for multi-usage functions has been discussed. The challenges include complexities arising from integrating variable renewables; the location-dependent nature of the benefit of deploying DER [9]; the dynamic nature of DER economics; inconsistent integration policies; valuation, market, and policy barriers [10] [11].

The policy and market drivers for the development of integrated energy systems for sustainable electricity supply in Italy has been described in comparison with similar developments in the UK in [12]. The role of market-oriented regulations in promoting wind energy and distributed generation in Brazil are detailed in [13]. A challenge of funding incentives for renewables and how regulators could address the challenge through policy change in network tariff plans are enumerated in [14]. As the transitioning to a low-carbon energy system includes the multi-facet objective of ensuring a reliable and low-cost electricity to consumers, the flexible resources that could instantaneously respond during the times of electricity scarcity or surplus offer value – often, a missing value [15]. In [16], taking a system perspective, the importance of choosing a strategy that uses an energy market including capacity constraints for assessing the benefit of demand response at residential sites is discussed. As the electricity grid evolves with the quest of transitioning the grid to a sustainable energy system, new roles are also emerging – throughout the electricity supply chain – for major stakeholders [17].

Meanwhile, the diversity in the architecture and composition of the electricity grid – the arrangement of network elements, the characteristics and the status of the network elements, the constituent energy mix, and the load profile; the point on the grid where a DER is to be located; the differences in the qualities of the renewable energy sources available at different locations; the alternative energy sources; differences in market structures, and different emission goals at different national boundaries: all make the benefit derivable from installing the DER location dependent – changing from point to point, from network to network, and from one electricity grid to another.

Nomenclature

Abbreviations:

DER   Distributed Energy Resources

PV   Photovoltaic

NI   Northern Ireland

SNSP   System Non-Synchronous Penetration

UR   Utility Regulator for Northern Ireland

ISEM   Integrated Single Electricity Market

BEIS   Department for Business, Energy & Industrial Strategy

SONI   System Operator for Northern Ireland

NIE   Northern Ireland Electricity

GHG   Greenhouse gas

DS3   Delivering a Secure, Sustainable Electricity System

NIRO   Northern Ireland Renewables Obligation

ROC   Renewable Obligation Certificate

BTM   Behind-the-meter

PPA   Power Purchase Agreement

Parameters and Connotations:

S_{w1}	Switch number 1
S_{w2}	Switch number 2
E_n	Storage device
$+ve$	Positive
$-ve$	Negative
$\propto$	Direct proportionality
AND	Logical *AND*
OR	Logical *OR*
1	Switch on
0	Switch off
$\sum_x^n T_n$	Sum T from x to n
$(1)^+$	Value just after instance 1
$(0)^+$	Value just at a current instance 0
$(1)^-$	Value just before instance 1
$\llcorner$	Polar angle
kWh	Unit of energy in kilowatt-hour
MWh	Unit of energy in megawatt-hour
W	Unit of power in watt
kW	Unit of power in kilowatt
MW	Unit of power in megawatt
kV	Unit of voltage in kilovolt
CO_2	Carbon IV Oxide
£	British pound
£/kWh	Price of electricity in British pounds per kilowatt-hour
+	Add/Addition
-	Subtraction

%	Percent
η	Efficiency
Enercon E48	Enercon E48 wind turbine
NEPLAN 360	NEPLAN 360 modelling software

Variables:

E_{rec}	total energy recoverable from storage
W_T	total energy supplied to storage device from turbines
$E_{n(eff)}$	round-trip efficiency of aggregated storage system
$Time_{Tariff1}$	amount charged for electricity import
$G_{self(wind)}$	gain through self-consumption of wind energy
$E_{n(min)}$	energy discharge limit for aggregated storage
T_n	energy feed from the nth additional turbine
L_n	aggregated energy demand of load
Z_n	aggregated energy expended in system impedance
$E_{n(SOC)}$	state of charge of aggregated storage
$E_{n(Market)}$	market demand on storage capacity
$Time_{Tariff2}$	net instantaneous amount charged for electricity
T_1	energy feed from turbine number 1
T_2	energy feed from turbine number 2
T_n	energy feed from an nth turbine
$G_{DS3(Market)}$	gain through DS3 service market
$E_{n(min)}$	percentage of energy storage committed within specified energy discharge limit for storage
E_S	aggregated storage size
$P_{£/DS3}$	sum of the market prices for all DS3 services a storage is committed to provide
E_{energy}	total electricity to be imported
$E_{n(use)}$	electricity to be used by aggregated load
$E_{n(eff)}$	round-trip efficiency of aggregated storage system
$Tariff_{Day}$	amount charged for electricity during the day
$Tariff_{Night}$	amount charged for electricity at night
$Tariff_{Peak}$	amount charged for electricity during peak period
$Tariff_{Off-Peak}$	amount charged for electricity during off-peak period
S_{ch1}	standing charges required to maintain a tariff plan
G_{TU}	gain through time-of-use-electricity-bill management
S_i	complex power through node i
S_i^*	complex conjugate of power through node i
P_D	the real power demanded
Q_D	reactive power demanded
P_G	real power generated
Q_G	reactive power generated
P_i	real power through bus i
Q_i	reactive power through bus i
Y_{ii}	self-admittance within bus i
Y_{ik}	mutual admittance between buses i and k
I_i	current flow within bus i
I_i^*	complex conjugate of the current flowing through bus i
V_i	voltage at an ith bus
V_i^*	complex conjugate of the voltage at an ith bus
V_k	voltage at a kth bus
R_e	real
I_m	imaginary
θ	phase angle between current and voltage
δ	load angle
P_i	real power into a bus i
Q_i	reactive power into a bus i

In this work, the metrics for achieving sustainability of the Northern Ireland (NI) electricity grid and markets are described with the benefits of upscaling the wind and the storage resources on the distribution network used as a case study. The metrics, the market assessments, and the benefit analysis are designed to inform policies towards achieving sustainability of the NI electricity grid. The site in the case study currently has two grid-connected wind turbines and load substations connected to the distribution network through an 11kV transformer. The load profile swings between 500 kW and 1500 kW. Currently, part of the power supplied from the wind turbines is fed to serve the local loads while any excess generation goes to the grid at a price determined by the utility. The study examines how more turbines could be installed to increase the wind energy generation on-site while deploying battery storage in modules: managing the variable supply from the turbines, increasing self-consumption of the site-generated wind energy, and increasing profitability by using the storage device for providing more market services to the grid through suitable market arrangements. The technical analysis that determines the impact of the DER upscaling on the distribution network is done with the *NEPLAN 360* modelling tool while the economic analysis is performed through an estimation of the payback period on investment. To ascertain how changes in market conditions and policies could impact the upscaling project, a use-case analysis – where the device is deployed to provide new market services in addition to helping to increase self-consumption of wind energy – is performed.

2. METHODOLOGY

2.1. Metrics for NI Electricity Grid Sustainability:

Sustainability for the NI electricity grid is defined as generating, transmitting, and distributing electricity through any Net Zero emission means with a stable and reliable grid at the lowest cost possible to consumers. With Net Zero legislation passed in the UK [18], the desirability for increasing levels of System Non-Synchronous Penetration (SNSP) on the NI electricity grid [19] and other multinational targets: the best available sources of clean energy must be harnessed in achieving the Net Zero target while ensuring that the stability and reliability of the electricity grid is kept intact, and the electricity is supplied at reasonable cost and at affordable prices to the electricity users. Hence, the key metrics for achieving sustainability for the NI electricity grid include an equitable electricity market structure, a stable and reliable electricity grid, and Net Zero emission from the electricity production processes.

2.1.1. *Equitable Markets Through Electricity Regulation:*

Because of the importance of an affordable and reliable electricity supply to national development, regulations and market controls have been used as tools for creating efficiency and competition in a rather monopolistic electricity-production process. The electricity regulations in the US [20], in Australia [21], in Germany [22], and in the UK [23] are few examples. The Utility Regulator (UR) is the body responsible for regulating electricity in NI [24] – working to protect the interest of consumers.

The NI and the Republic of Ireland, in line with the EU energy framework, participate in a cross-border market that permits bulk electricity trading through the Integrated Single Electricity Market (ISEM) [25]. Energy policy is part of the responsibilities of the Department for Business, Energy & Industrial Strategy (BEIS) in the UK while the Department for the Economy (DfE) – operating under the Northern Ireland Assembly – leads the policies relating to the security of energy supply, the development of energy infrastructure, and promoting innovative techniques for energy efficiency in NI [26]. With the establishment of the regulating and policy-making bodies, inputs from industrial partners, the system and network operators (System Operator for Northern Ireland (SONI) and Northern Ireland Electricity (NIE) Networks), and inputs from evidence-based research: market structures could be re-designed to meet the latest emission targets with respect to key sustainability metrics.

2.1.1.1. *Low Electricity Price:*

In working to achieve the sustainability of the electricity grid, new methods of generating and distributing electricity could mean new electricity tariffs. Making the NI electricity grid a Net Zero emission system could mean additional cost, especially when the variability of certain renewables like wind must be managed for grid resilience. While the use of clean energy resources for electricity generation may not always imply an increase in electricity tariffs, an increase in tariff should reflect only the additional costs of using the cleaner energy sources so that the cost of using the electricity is bearable to the consumer until the clean energy technology becomes mainstream. Incentivised tariffs are provided to ensure this; for example, the feed-in tariff for promoting solar energy in Germany [27] and other countries [28]. To the user of electricity in NI, having electricity produced from Net Zero emission sources, having the electricity supplied through a stable and reliable grid, and always having the electricity at an affordable rate is electricity sustainability – as depicted within the area of the intersection of the circles in Fig. 1.
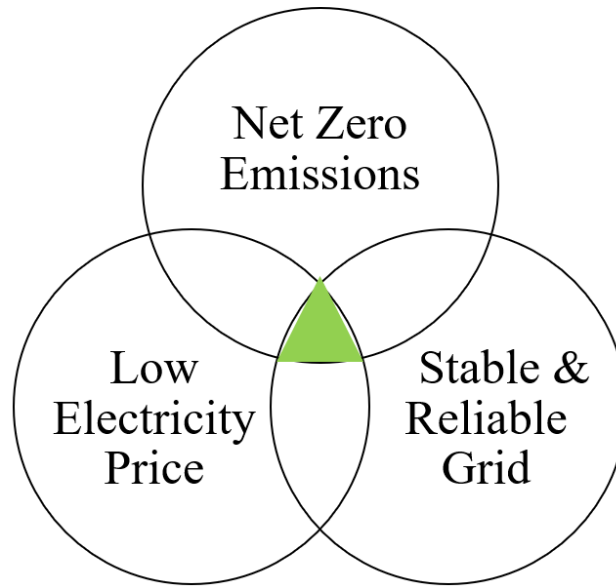
Fig. 1: Sustainability of Electricity Grid to the Electricity Consumer

2.1.1.2. Low Electricity Cost:

The system and network operators are crucial to achieving the sustainability of the electricity grid. The adopted energy techniques of achieving the sustainability of the grid should be achieved at least costs – this is to ensure that the cost of producing the electricity is recoverable even while making a profit. Any market regulation or policies should ensure that the cost of operating the grid is recovered and the utilities have fair profit margin. To the electricity grid operator in NI, having electricity produced from Net Zero emission sources, having the electricity supplied through a stable and reliable grid, and always supplying the electricity at a reasonable profit margin rate represents electricity sustainability, also depicted within the area of the intersection of the circles, Fig. 2.
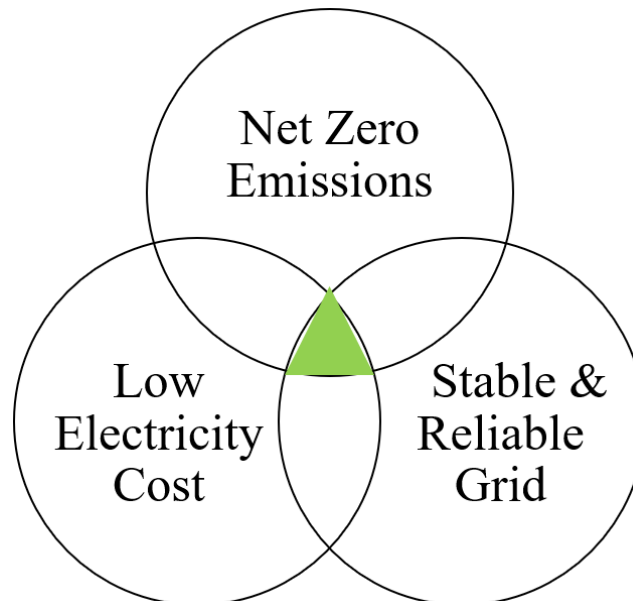

Fig. 2: Sustainability of Electricity Grid to the Utility

2.1.2. Net Zero Emissions:

To address the challenges of climate change that is a result of the emission of greenhouse gas (GHG) [29], countries – including the UK – are targeting achieving Net Zero emissions within few decades. The UK Net Zero emission target was set in 2019 [18]. With the Net Zero legislation passed, Net Zero should be an integral part of all government policy [30]. A Net Zero target means that all the anthropogenic emissions are removed while methods of GHG capture are deployed to remove other GHGs. The anthropogenic activities that cause emission of GHG include generating electricity by burning fossil fuels. While generating electricity from the combustion of fossil fuels is long established, the current challenges of

climate change calls for new policies that are favourable to the development of renewable energy resources. The use of renewable energy resources will not only help in tackling climate change but could also bring about new economic opportunities; for instance, an annual average turnover of around £1 billion and 5,900 full time equivalent jobs came directly from low carbon and renewable energy activities in NI in each of the years 2016 to 2018 [31]. With the Net Zero emission target set in the UK, all possible methods of harnessing clean energy must be developed – tapping into the natural resources for creating clean energy following the most natural processes. Several thousand wind turbines have been deployed successfully for clean energy in NI and other parts of the UK [32]. NI aimed to achieve a 40% electricity consumption from renewable sources by the year 2020 [33]. By December 2018, 41.1% of the total electricity consumption in NI was generated from renewable energy sources [34] – indicating the achievement of the 2020 target, months earlier than the set-date. The mechanisms that helped to achieve the set target include the "Delivering a Secure, Sustainable Electricity System" (DS3) programme developed to increase the level of SNSP [35], the ISEM [25], the supports of the system and network operators, and the Northern Ireland Renewables Obligation (NIRO) scheme for Renewable Obligation Certificates (ROCs) – NIRO was designed to incentivise the generation of clean energy [36] [37] – the mechanisms permitted more renewables to be connected to the grid equitably.

To achieve a higher percentage of electricity consumption from renewables, the market or policies that promoted the renewables should be upheld, re-introduced where they have been stopped, and additional ones created where necessary – in consultation with all key stakeholders, for a truly sustainable NI electricity grid. The policies should ensure better cooperation between network operators and improved customer-utility partnerships – these are key to achieving the Net Zero emissions target – as every effort must be directed towards supporting every clean resources or techniques available from the different sections of the electricity grid; for example, demand-side energy generation from wind turbines and solar PVs, controllable loads for demand response, demand-side energy storage for services across the grid, and other DER.

As suggested in Fig. 1 and Fig. 2, a stable and reliable electricity grid running at a minimal cost and offering affordable electricity should produce the electricity through Net Zero emissions processes to achieve sustainability of the NI grid.

2.1.3. Stable and Reliable Electricity Grid Amidst Variability of Renewables:

In NI, wind energy represents a larger percentage of the grid-integrated renewables [32]. The wind turbines run with wind flow; the energy outputs from the turbines hence vary from time to time. Meanwhile, a basic requirement for a stable and reliable electricity grid is always that energy demand be met with energy supply – the variability of the renewables hence poses a threat to grid stability. To maintain the stability of the grid sometimes energy outputs from renewables are curtailed; at times, renewable generators are subjected to constraints [38]. The transmission system operator – SONI – aims to increase the level of the SNSP possible on the grid [19] – this is to allow more of the variable non-dispatchable renewables like wind turbines to be connected to the grid while maintaining the grid stability at the same time – this is important to achieving the Net Zero emissions target. The operator created the DS3 market that allows stakeholders to make commitments to providing the grid with ancillary services, mainly services for reactive and active power, ramping margins, and operating reserves [39] – [45]. Making provision for the additional services – with a certain amount earmarked for the DS3 service commitments [46] – helps to guarantee a qualitative operation of the grid. The equipment that could be linked to the electricity grid in providing the services include conventional generators, battery storage, and wind turbines [41].

To achieve the Net Zero emissions target, transport and the heating processes may have to be electrified; this will put more pressure on the demand for electricity. Meanwhile, there is an opportunity to leverage advanced smart energy storage techniques for managing customer-premises renewables, the distribution network, and loads – through demand response, peak shaving, load shifting, network congestion management, behind-the-meter (BTM) services, and other locational auxiliary services; for example, Lithium ion battery storage which is less susceptible to self-discharge, tolerant to many rounds of deep discharge cycles, and modular could be combined into different sizes for BTM applications [47] – [50]. When adding DER to the electricity network, a technical power flow analysis (equations for the numerical solutions are given in Appendix A) needs to be performed to ensure that the stability of the grid has not been compromised.

2.2. Market Plans for Demand-side Storage Used with Wind Turbine:

2.2.1. Storage for Increased Self-consumption of Wind Energy:

In addition to the existing DER on the distribution network, some wind turbines and BTM battery storage are introduced – using a *NEPLAN 360* modelling tool – to increase demand-side generation while using the battery to take up any excess wind turbine generation, Fig. 3.
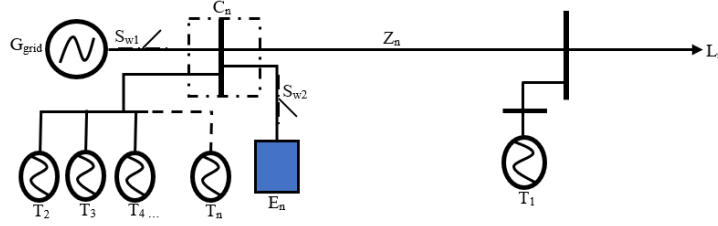
Fig. 3: Storage and Turbines on A Distribution Network

The total energy recoverable from storage, E_{rec}, is given as:

$$E_{rec} = W_T \times E_{n(eff)} \tag{1}$$

Where W_T is the total energy supplied to the storage device from the turbines, $E_{n(eff)}$ is the round-trip efficiency of the aggregated storage system, and $Time_{Tariff1}$ is the amount charged for electricity import; the gain through self-consumption of wind energy is given as:

$$G_{self(wind)} = E_{rec} \times \left(Time_{Tariff1}\right) \tag{2}$$

2.2.2. Storage for Self-consumption of Wind Energy and DS3 Market Services:

In Fig. 3, switch S_{w1} is operated according to the control described by Equations (3a) and (3b) while the switch S_{w2} – operates so that the storage device E_n is recharged or discharged – operated according to the control described by Equation (4).

$$S_{w1} = +ve, when\ L_n + Z_n > T_1 + T_2 + T_3 + \cdots + T_n + E_{n(min)} \tag{3a}$$
$$S_{w1} = -ve, when\ L_n + Z_n < T_1 + T_2 + T_3 + \cdots + T_n + E_{n(min)} \tag{3b}$$

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.

$$E_{n(min)} \propto \left[\left(E_{n(SOC)}\right) AND \left(E_{n(Market)}\right) AND \left(Time_{Tariff2}\right) AND (T_1) AND (T_2) AND \left(\sum_{3}^{n} T_n\right)\right]$$
$$S_{w2} \propto E_{n(min)} = 1\ OR\ 0 \tag{4}$$

where $E_{n(SOC)}$ is any specified state of charge of aggregated storage, $E_{n(Market)}$ is the market demand on storage capacity, $Time_{Tariff2}$ 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 nth 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 device 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 a signal to provide DS3 market services: it is to be discharged to maximize the consumption of wind energy from the turbines and meet continuous instantaneous commitments of providing the market services to the grid. When not currently providing any services, the device is charged with the turbine supplies only and discharged to serve local loads only. Meanwhile, the device is charged or discharged to a level that permits it to meet any market service commitments; and when discharging to the grid, discharges within the predefined service commitment.

$$G_{DS3(Market)} = \frac{1}{2} \times E_{n(min)} \times E_S \times P_{£/DS3} \tag{5}$$

While $G_{DS3(Market)}$ is the gain through the DS3 service market, $E_{n(min)}$ is the percentage of energy storage committed within the specified energy discharge limit for storage, E_S is the aggregated storage size, and $P_{£/DS3}$ is the sum of the market prices for all the DS3 services the storage has been committed to provide.

In providing certain DS3 services, a storage device could be required to supply or demand energy – discharge or charge: the device must have the capacity to instantaneously either discharge or charge within any period of service commitment.

2.2.3. Storage for Time-of-Use-Bill-Management and Energy Arbitrage:

Tariffs are designed for the different times of a day such that there is a lower tariff during typical periods of high supply from renewables and low electricity demands – typically at night; and a higher tariff is set for the period of less supply from renewables and high electricity demands, as often experienced during the day. The low tariff for the times of high renewables should cover the cost of running the electricity grid while encouraging customers to connect loads to take up the cheap supply. The higher tariff should be high enough to cover the cost of running the grid during the day and yet affordable to customers. By deploying a storage device, customers could maximise their electricity consumption during the night – at the times of the lower tariff – while minimising their electricity consumption during the day.

$$E_{energy} = E_{n(use)}\left[1 + \left(1 - E_{n(eff)}\right)^1 + \left(1 - E_{n(eff)}\right)^2 + \cdots + \left(1 - E_{n(eff)}\right)^n\right]; \text{ for } n = 3, 4, 5, \ldots, \infty \quad (6)$$

While E_{energy} is the total electricity to be imported, $E_{n(use)}$ is the electricity to be used by the aggregated load, and $E_{n(eff)}$ is the round-trip efficiency of the aggregated storage system, $Tariff_{Day}$ is the amount charged for electricity during the day, $Tariff_{Night}$ is the amount charged for electricity at night, and S_{ch1} is any standing charges required to maintain the tariff plan; the gain through the time-of-use-electricity-bill management G_{TU} is given as:

$$G_{TU} = \left[\left(E_{energy} \times Tariff_{Day}\right) - \left(E_{energy} \times Tariff_{Night}\right) - S_{ch1}\right] \quad (7)$$

The gain in purchasing electricity at the lower rate periods could contribute to the payback of the investment on storage. An example of a tariff plan that could be used by domestic consumers for the time-of-use-electricity-bill management is the *Power NI (an NI electricity supplier) Economy 7* (2-Rate) plan [51] or the *SSE Airtricity (another* electricity supplier in NI) *KeyPad Powershift* plan [52] [53].

To create the same opportunity for every customer, each electricity supplier should have a similar tariff plan. The energy arbitrage and demand response tariffs for storage could be designed like the time-of-use-electricity-bill-management tariffs where the storage device could typically take up electricity at the instantaneous times of lower charging rate and sell the electricity back to the grid at the period of higher rate for profit.

2.2.4. *Storage for Demand Response of Load Shifting:*

Designing higher tariff for peak electricity demand periods could shift avoidable loads to the off-peak periods for efficient management of electricity network resources. The equation for the total electricity to be imported is given in equation (6), with symbols retaining their usual meanings. The gain through demand response of load shifting, G_{DR}, is given as:

$$G_{DR} = \left[\left(E_{energy} \times Tariff_{Peak}\right) - \left(E_{energy} \times Tariff_{Off-Peak}\right) - S_{ch1}\right] \quad (8)$$

where E_{energy} is the total electricity to be imported, $Tariff_{Peak}$ is the amount charged for electricity during the peak periods, $Tariff_{Off-Peak}$ is the amount charged for electricity during off-peak periods and S_{ch1} is any standing charges required to maintain the tariff plan.

Similarly, the gain in purchasing electricity at the off-peak tariff periods could contribute to the payback of the investment on storage. An example of a tariff plan that could be used for the demand response of load shifting is the *SSE Airtricity KeyPad Powershift* plan [52] [53]. An application of the tariff-based load shifting for domestic heat pump is described in [54].

Meanwhile, some of the use-cases of storage in the market plans are mutually exclusive: a storage device may not be deployed to participate in all the electricity plans at the same time; for example, the device that has been deployed for increasing self-consumption of wind energy and participate in providing certain levels of DS3 services may not be deployed for time-of-use-electricity-bill management at the same time.

2.3. Incentive for Renewable Energy Generation:

Policies that make additional revenue streams available for renewable energy projects could be introduced to encourage investment in renewables. While renewables may not be the most cost-effective energy solutions, incentives and favourable integration policies help to minimise investment cost and risks; for example, the ROCs scheme [36]. Here, incentives for renewables are not considered in estimating project profitability – incentives are usually given within only a given period. Nevertheless, the mechanisms that support the integration of renewables are important: the risk mitigation instruments – such as the Power Purchase Agreement (PPA) strategies [55]; and basing the DS3 payments on service commitment and capping the services that a unit may provide for a fair play [45] [46] – should be sustained.

3. CASE STUDY

3.1. *Battery Storage and Wind Turbines on A Distribution Network:*

A campus distribution network is connected to an alternating current electricity grid via an 11kV transformer. The typical base load through the day is 500 kW while the peak load is under 1500 kW, Fig. 4. The campus 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 grid-connected BTM *Enercon E48* wind turbines on-site for demand-side energy generation, each rated 800KW. 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 to serve local load only – these are not grid-connected and not included in analysis.
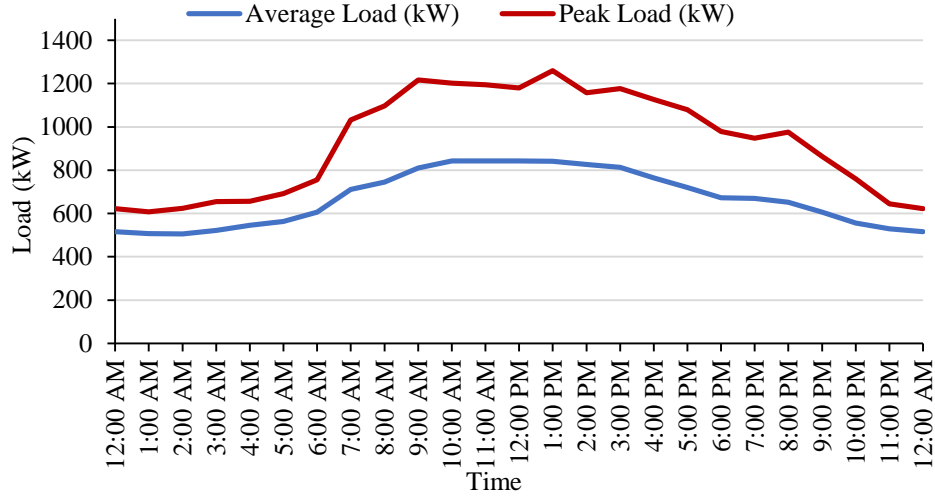
Fig. 4: Average Load Profile for a Calendar Year

In a 365-day 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, 601,780 kWh was exported to the grid – representing about 20% of the turbine-generated energy. A total energy of 28,710 kWh was generated from the PV arrays; this puts the annual imported electricity displaced 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 1242 kW. In addition to the existing DER on-site, more BTM wind turbines and battery storage are introduced in the *NEPLAN 360* model of the distribution network to increase demand-side generation while using the storage device to take up any excess wind turbine generation, Fig. 5.
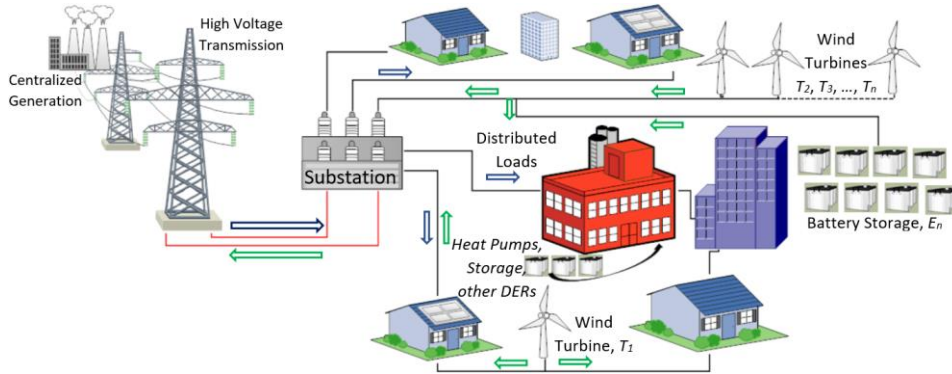

Fig. 5: Elements of the Distribution Network

Using the load profile for the calendar year, wind generation data of the two existing turbines, a typical commercial electricity export-import price, and hypothesized prices for storage – informed by wide consultation of literature and industry [47], [50], [56] – [67]; the result of upgrading the DER are analysed to ascertain the upgrade benefits and the policy changes that could help to make the demand-side energy generation feasible.

3.2. *Economic Considerations:*

The economic implication of upscaling the DER is performed to ascertain the cost-effectiveness of the project. A benefit analysis is used indicate the cost implication of adding any additional wind turbine and storage device to the distribution network. The analysis is to reveal the likely payback period on investment. Looking at the charge-discharge characteristics of the storage required, a device selection is made; a suitable size of the device is installed to optimize the energy of any additional wind turbines. With the technical analysis done to confirm network stability, the profitability of the DER upgrade is then determined: first, when the DER are deployed only for increasing self-consumption of wind energy and when, in addition to helping to achieve the increased self-consumption of the wind energy, the DER are also committed to providing certain services across the electricity supply chain. In other words, the storage is primarily deployed for increasing self-consumption of wind energy. Additional revenue streams could be created for the storage device: by also deploying certain capacity of the storage device for the provision of DS3 services, using the device for time-of-use-bill-management, or using it for demand response load shifting.

9

Under typical existing commercial tariffs in NI, the import electricity price and the export electricity price are in the ratio of 7 to 3 typically, with the import electricity price being higher: the prices can vary but usually have this consistent relationship. For instance, the subsisting value while taking data for this work was £0.12/kWh for the import electricity price and £0.0525/kWh for the export electricity price. The consistent relations between the import and the export electricity prices are evident from the historical analysis of the site data and similar relation is noticeable in [68].

The price of storage is not fixed – inconsistent prices are quoted in literature and industry [56] – [67]. Moreover, performing a cost analysis using a quoted price at one time makes the analysis inaccurate at another time when the price has changed. The likely price ranges for Lithium ion battery at the current or future dates are used in identifying the cost points at which installing the DER becomes profitable. The economic analysis, while not claiming that installing any DER is currently profitable under existing market parameters, is to identify the cost, resource, or market points at which the upgrade project becomes economically feasible. The analysis ultimately indicates how market conditions or policy changes could impact the profitability of the project.

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 the storage are aggregated costs, covering all costs from the capital cost through to the end of life costs 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 price indices and trends of wind turbine are given in [69]; here, the cost of the wind turbines is taken as £1.7/W. The annual gain in using the self-generated energy instead of sending it to the grid is determined; the gain, with the estimated lifespan cost of the DER, is used in estimating the likely payback period of the project. The system is reset to, in addition to promoting the use of self-generated wind energy, commit certain percentage of the storage device to providing ancillary services through the DS3 market set up to promote the penetration of non-synchronous generation on the electricity grid, with service prices given in [40]. The device is to commit to supplying a total DS3 service of £10.47/MWh. The device capacities are committed in different proportions: 10% capacity for short period, 20% capacity for short period – in less than 0.2% of the device lifespan, and 20% capacity for longer period – within 25% of the device lifespan. An investment analysis is performed in each case.

As noted in subsection 2.2.4, the device may not perform all functions at the same time: here, the storage is analysed for using the device for increasing self-consumption of wind energy and providing certain DS3 services as a typical use-case – exemplifying the likely market conditions that could improve investment in clean energy for sustainability by increasing the profitability of demand-side wind and storage projects.

4. RESULTS AND DISCUSSION

The typical load profile, the energy generation profiles, and the storage charge-discharge characteristics on-site are depicted in Fig. 6. A suitable storage device that could handle the discharge characteristics is required. While the power flow indicates convergence – suggesting a stable network – the load rises gradually in the 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 device is set to charge and discharge to maximise wind energy from the wind turbines.

The energy mix of the site with the two existing wind turbines – without any storage – is given in Fig. 7(a): here, all excess wind generation goes to the grid. Fig. 7(b), Fig. 7(c), Fig. 7(d), and Fig. 7(e) depict the changes to the energy mix after adding only storage, two turbines and 80% efficient storage, two turbines and 90% efficient storage, and after adding four turbines and 85% efficient storage, respectively.
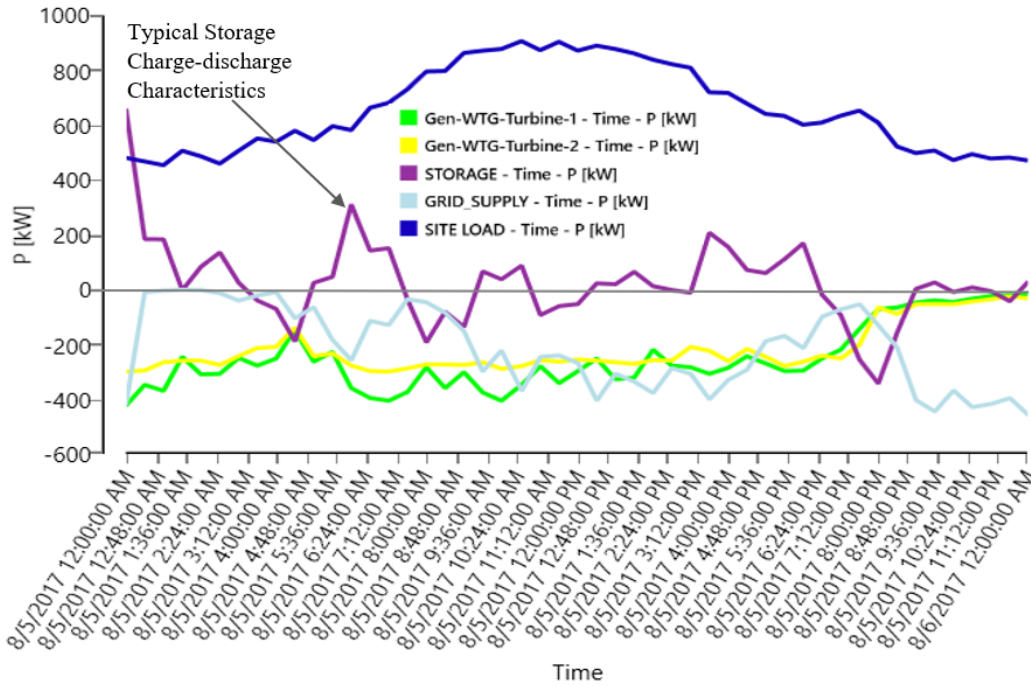
Fig. 6: Generation-Demand Profile for an Illustrative Day

(a) Current Energy Mix

(b) 2Turbines+ 85% η Storage

(c) 4Turbines+ 80% η Storage

(d) 4Turbines+ 90% η Storage
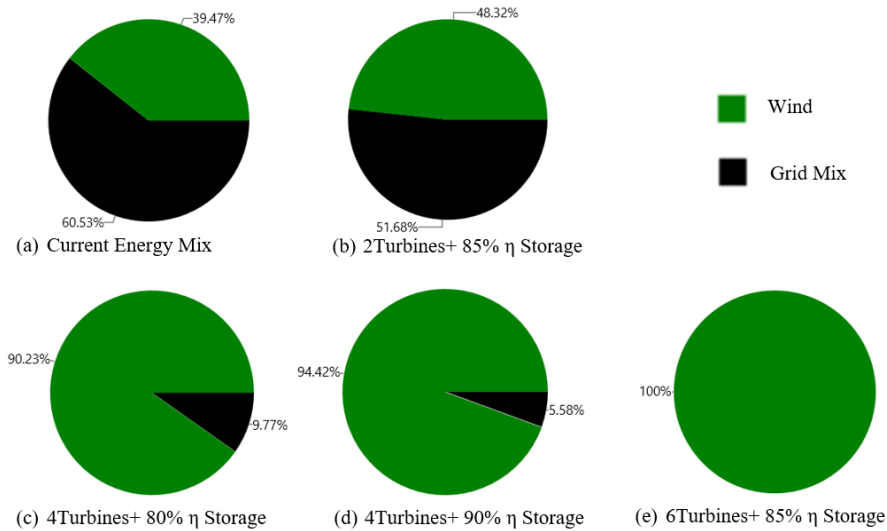
(e) 6Turbines+ 85% η Storage

Fig. 7: Changes to Energy Mix for Sustainability

As the number of the installed turbines increases, the site approaches self-sufficiency in electricity through demand-side generation and the gross annual gain and the percentage of wind energy consumption increases (more details in Table B.1 of Appendix B). 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 an excellent round-trip efficiency. For the current study, a Lithium ion battery system with a round-trip efficiency of 85% is chosen, Table B.1(b). The cost range of storage has been chosen as test cases. The lifespan of the battery is between 10 to 15 years while the wind turbine could last for 25 years [68] [69]. The payback period is the ratio of the total equipment cost to the gross annual gain.

The payback period almost always exceeds the life spans of either the storage device or the turbines when the device is deployed only to increase demand-side generation of wind energy, Table 1 – more details are given in Table B.2 of Appendix B. This is the case for virtually 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 solely to increase consumption of demand-side generation, while desirable for increased clean energy, is not economically feasible with the current market conditions. The hypothesised cost ranges of the DER have been carefully selected to reflect the best of prices.

Table 1: Deploying DER for Self-consumption of Wind Energy and Levels of DS3 Services

Application of DER: Storage Cost Between £100/kWh and £260/kWh [67] and Turbine Cost at £1.7/W [69]	Maximum Payback Period (Years)	Minimum Payback Period (Years)
(a) Only + 2MW/4MWh Battery		
Self-consumption of Wind Energy Only	34.9	13.4
+10% Capacity to Service (MWh per year)	24.7	9.5
+20% Capacity to Service for Duration 1 (MWh per year)	19.1	7.4
+20% Capacity to Service for Duration 2 (MWh within 12.5 years)	8.2	3.1
(b) +2 Turbines (Enercon_E48 800KW) + 2MW/12MWh Battery		
Self-consumption of Wind Energy Only	45.9	30.8
+10% Capacity to Service (MWh per year)	35.6	23.9
+20% Capacity to Service for Duration 1 (MWh per year)	29.1	19.5
+20% Capacity to Service for Duration 2 (MWh within 12.5 years)	13.9	9.3
(c) +4 Turbines (Enercon_E48 800KW) + 2MW/40MWh Battery		
Self-consumption of Wind Energy Only	62.5	37.3
+10% Capacity to Service (MWh per year)	42.1	25.1
+20% Capacity to Service for Duration 1 (MWh per year)	31.8	18.9
+20% Capacity to Service for Duration 2 (MWh within 12.5 years)	12.9	7.7

In another storage use-case scenario, the storage device is committed to providing some levels of DS3 market services, in addition to helping to increase self-consumption of wind energy. Here, the device has been committed to providing the service in three cases: 10% capacity for short period, 20% capacity for short period – within less than 0.2% period of the device lifespan, and 20% capacity for longer period – 25% period of the device lifespan. The results suggest that committing the storage device for longer durations could drastically reduce the payback period on investment, increasing the profitability of the project (Table 1 – more details in Table C.1 of Appendix C). The amount of gain derived now depends on the quantity of services rendered and for how long. The result suggests that installing the DER for stacked market services makes the DER upgrade project approach profitability, depending on market structure and DER costs.

There are potential market values for the demand-side resources that could be realised with the described market plans when supported with enabling policies: the additional value streams could come from the time-of-use-electricity-bill-management market, the demand response market, and perhaps, energy arbitrage in wholesale markets. The storage device could also be used as backup power and the deployment could benefit from incentive programmes like the NIRO scheme for renewable energy generation. The other utility services that the DER could offer include congestion relief, as well as distribution and transmission network deferrals; however, these would require changes to electricity grid planning processes.

5. CONCLUSIONS AND POLICY IMPLICATIONS

Clean demand-side energy generation could be increased using wind turbines with battery storage deployed to increase the self-consumption of locally generated wind energy. When additional wind turbines and battery storage were added in scales to the existing two 800KW wind turbines of a below-1500kW-peak-load distribution network, the percentage of self-consumption of wind energy on-site increased continuously until the site achieved self-sufficiency in energy – around the point of having six turbines while using an above-80% efficient storage system. While deploying the resources for the increased demand-side energy generation is technically feasible, the economics suggests that the upscaling project only approaches profitability when the resources are deployed not just to increase wind energy but for the storage to also provide services to the electricity grid in a value stack, achievable with more equitable market structures and favourable integration policies: policies that would encourage investment into DER and the market structures that would ensure that the deployment of the DER maximizes benefits across the entire electricity supply chain.

These markets and policies, while aiming to help achieve the Net Zero emissions target in NI by supporting renewables, should be designed to be fair to the customer and the utility – the market tariffs would be designed to cover the cost of running the electricity grid with reasonable profit at each of the tariff periods and to be financially rewarding enough to attract investment into the demand response market plans. Among the important tariff plans that should be made available to the customer within the distribution network are:

- ✓ Tariffs which enable provision of DS3 services as part of the revenue stack
- ✓ Tariffs designed for sites with connected renewable generation
- ✓ Tariff for Time-of-use-electricity-bill-management
- ✓ Tariff for Demand response for load shifting and peak shaving

The market tariffs should be open to every customer to participate in – the electricity suppliers would include all the tariff plans in their tariff suite to encourage the deployment of the DER across the electricity grid while allowing the customers to have fair returns on investment in demand-side units. The network operator could place caps on the services that may be provided by units as the safe operation and stability of the electricity grid demands while consistently expanding and planning the grid to accommodate more renewables towards achieving the Net Zero emissions target. With improved coordination of network operations, the points on the network where units may be connected to provide services to the grid should be made known to eligible customers – the network operator could proactively identify such locations on the electricity grid where the demand-side units could connect to provide the DS3 and demand response services to the grid.

The incentives that have served to promote clean energy generation from wind and the solar energy resources could be re-introduced to kick-start attaining the required levels of electricity consumption from renewables. While decarbonization could come with cost, the cost should be shared among all electricity stakeholders: in re-designing and modifying the electricity tariffs, inputs from the customers and the network operators, the major stakeholders, should be considered to achieve fair play for sustainability of the electricity grid.

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REFERENCES

[1] Electric Power Research Institute, "Time and Locational Value of DER: Methods and Applications," *EPRI Report 3002008410*, pp. 1–8, 2016.

[2] Todd Olinsky-Paul, "Energy Storage: The New Efficiency - How states can use energy efficiency funds to support battery storage and flatten costly demand peaks" *Clean Energy Group Report*, pp. 1–102, 2019.

[3] S. Pietrosanti, W. Holderbaum, and V. M. Becerra, "Optimal Power Management Strategy for Energy Storage with Stochastic Loads," *Energies*, vol. 9, no. 3, pp. 1–17, March 2016.

[4] P. Finn and C. Fitzpatrick, "Demand side management of industrial electricity consumption: Promoting the use of renewable energy through real-time pricing," *Appl. Energy*, vol. 113, pp. 1–11, 2014.

[5] *EirGrid* and *SONI*, "Annual Renewable Energy Constraint and Curtailment Report 2017," *Report*, pp. 1–27, June 2018.

[6] Reid Dorsey-Palmateer, "Effects of wind power intermittency on generation and emissions," *The Electricity Journal*, vol. 32, 25-30, 2019.

[7] Transpower Discussion Document, "Battery Storage In New Zealand," *Report,* available at https://rise.esmap.org/data/files/library/new-zealand/1%20Renewable%20Energy/RE8.4%20Battery%20Storage%20in%20New%20Zealand.pdf, September 2017.

[8] Bálint Hartmann, István Vokony, Péter Sorés, and István Táczi, "Service aspect assessment of energy storage under the ownership of distribution system operators," *Journal of Energy Storage*, vol. 25, 2019.

[9] Steve Fine, Paul De Martini, Samir Succar, and Matt Robison, "The Value in Distributed Energy: It's All About Location, Location, Location," ICF International, *Whitepaper*, pp. 1–11, 2015.

[10] Sydney P. Forrester, Ansha Zaman, Johanna L. Mathieu, and Jeremiah X. Johnson, "Policy and market barriers to energy storage providing multiple services," *The Electricity Journal*, vol. 30, 50-56, 2017.

[11] Zhiyi Li, Mohammad Shahidehpour, Ahmed Alabdulwahab, and Yusuf Al-Turki, "Valuation of distributed energy resources in active distribution networks," *The Electricity Journal*, vol. 32, 27-36, 2019.

[12] Michele Gaspari, Arturo Lorenzoni, Pablo Frías, and Javier Reneses, "Integrated Energy Services for the industrial sector: an innovative model for sustainable electricity supply," *Utilities Policy*, vol. 45, 118-127, 2017.

[13] Amanda Bradshaw, "Regulatory change and innovation in Latin America: The case of renewable energy in Brazil," *Utilities Policy*, vol. 49, 156-164, 2017.

[14] Cédric Clastres, Jacques Percebois, Olivier Rebenaque, and Boris Solier, "Cross subsidies across electricity network users from renewable self-consumption," *Utilities Policy*, vol. 59, 100925, 2019.

[15] Michael Hogan, "Follow the missing money: Ensuring reliability at least cost to consumers in the transition to a low-carbon power system," *The Electricity Journal*, vol. 30, 55-61, 2017.

[16] E.A.M. Klaassen, R.J.F. van Gerwen, J. Frunt, and J.G. Slootweg, "A methodology to assess demand response benefits from a system perspective: A Dutch case study," *Utilities Policy*, vol. 44, 25-37, 2017.

[17] Enrique Israel Rivero Puente, Helena Gerard, and Daan Six, "A set of roles for the evolving business of electricity distribution," *Utilities Policy*, vol. 55, 178-188, 2018.

[18] Sara Priestley, "Net zero in the UK," House of Common Library *Briefing Paper*, Number CBP8590, 16 December 2019.

[19] *SONI*, "Strategy 2020-25: Transform the Power System for Future Generations," Strategy 2020-2025 *Report*, www.soni.ltd.uk, September 2019.

[20]   Francisco Flores-Espino and Tian Tian, Ilya Chernyakhovskiy, and Megan Mercer, "Competitive Electricity Market Regulation in the United States: A Primer," *Technical Report* NREL/TP-6A20-67106, December 2016.

[21]   Dariel De Sousa, Katie Amanatidis, Rafael Perez, and Stephanie McLennan, "National Energy Regulation Handbook," Energy Consumers Australia *Handbook*, Maddocks [6707107.002: 17971707_1] - Version 1.0, 14 October 2016.

[22]   *OECD*, "Germany - Regulatory Reform in Electricity, Gas, and Pharmacies," Organisation for Economic Co-Operation and Development, Country *Report*, 2004.

[23]   Gillian Simmonds, "Regulation of The UK Electricity Industry," *CRI Industry Brief,* 2002 Edition, May 2002.

[24]   The Utility Regulator, "Annual Report 2018-2019," *Report*, available at https://www.uregni.gov.uk/sites/uregni/files/media-files/Utility%20Regulator%20Annual%20Report%202018-2019.pdf, 2020.

[25]   *EirGrid*, "Quick Guide to the Integrated Single Electricity Market; the I-SEM Project version," pp. 1–11, available at http://www.eirgridgroup.com/__uuid/f110639e-9e21-4d28-b193-ed56ee372362/EirGrid-Group-I-SEM-Quick-Guide.pdf, 2016.

[26]   Northern Ireland Electricity Networks, "NIE Networks RP6 Business Plan 2017-2024," NIE Networks RP6 *Report*, 2017.

[27]   Joern Hoppmann, Joern Huenteler, and Bastien Girod, "Compulsory policy-making—The evolution of the German feed-in tariff system for solar photovoltaic power," *Research Policy*, vol. 43, 1422-1441, 2014.

[28]   Clifford Chance, "Renewable Incentives Guide: Towards A Subsidy-Free World?" *Incentive Guide*, 6th Edition, available at /2018_Renewable_Incentives_Guide_6th_edition_6040128.pdf, 2018.

[29]   John Bowman, "The greenhouse effect," *Land Use Policy*, https://doi.org/10.1016/0264-8377(90)90002-G, vol. 7, Issue 2, pp 101-108, July 2002.

[30]   Committee on Climate Change, "Reducing UK emissions: 2020 Progress Report to Parliament," *Progress Report*, available at https://www.theccc.org.uk/publication/reducing-uk-emissions-2020-progress-report-to-parliament/, accessed June 2020.

[31]   Department for the Economy (DfE), "Energy in Northern Ireland 2020," *Report*, available at https://www.economy-ni.gov.uk/publications/energy-northern-ireland-2020, accessed June 2020.

[32]   National Statistics, "Renewable electricity in Scotland, Wales, Northern Ireland and the regions of England in 2018," Special feature *Report*, available at https://www.gov.uk/government/statistics/regional-renewable-statistics, 26 September 2019.

[33]   Department of Enterprise, Trade and Investment, "Sustainable Energy Action Plan 2012-2015 and beyond," Energy Policy *Report*, available at https://www.nienvironmentlink.org/cmsfiles/policy-hub/files/documentation/Energy/Sustainable-Energy-Action-Plan.pdf, May 2012.

[34]   Northern Ireland Statistics and Research Agency and Department for the Economy, "Electricity Consumption and Renewable Generation in Northern Ireland: Year Ending December 2018," *Publication Issue No 10*, March 2019.

[35]   *EirGrid and SONI*, "The DS3 Programme: Delivering a Secure, Sustainable Electricity System," pp. 1–16, available at http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-Programme-Brochure.pdf   and   http://www.soni.ltd.uk/how-the-grid-works/ds3-programme/, accessed January 2020.

[36]   Department for the Economy, "The Northern Ireland Renewables Obligation (NIRO): An Outline of its Operation," available at https://www.economy-ni.gov.uk/sites/default/files/publications/economy/NIRO-how-it-works.pdf.

[37]   Northern Ireland Assembly, "Incentivising renewable electricity – a comparison of Renewable Obligation Certificates and Feed-in tariffs," Research and Library Service Research *Paper*, NIAR 300-10, 13 September 2010.

[38]   *EirGrid and SONI*, "Annual Renewable Energy Constraint and Curtailment Report 2018," *Report*, pp. 1–26, May 2019.

[39]   *EirGrid* and *SONI*, "FlexTech Consultation 2019, A Flexible Technology Integration Initiative," pp. 1–21, available at http://www.soni.ltd.uk/media/documents/FlexTech-Consultation_30092019.pdf, 30 September 2019.

[40]   *SONI*, "DS3 System Services Statement of Payments," *Statement of Payment,* available at http://www.soni.ltd.uk/media/documents/DS3-SS-Statement-of-Payments-2019-20.pdf, October 2019.

[41]   *EirGrid* and *SONI*, "DS3 System Services Market Ruleset Recommendation Paper," pp 1–28, available at http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-System-Services-Market-Ruleset-Recommendations-Paper-16052018.pdf, 31 May 2018.

[42]   *EirGrid* and *SONI*, "DS3 System Services Tariffs for Regulated Arrangements," pp. 15–18, available at http://www.eirgridgroup.com/site-files/library/EirGrid/OPI_INV_DS3-System-Services-Tariffs-for-Regulated-Arrangements-FINAL-23.10.2017.pdf, 23 October 2017.

[43]   *EirGrid* and *SONI*, "DS3 System Services: Portfolio Capability Analysis," pp. 1–15, available at http://www.eirgrid.ie/site-files/library/EirGrid/DS3-System-Services-Portfolio-Capability-Analysis.pdf, November 2014.

[44]   *EirGrid* and *SONI*, "DS3 System Services Scalar Design," pp. 1–64, available at http://www.eirgridgroup.com/site-files/library/EirGrid/OPI_INN_DS3-System-Services-Scalar-DesignFinal_231017.pdf, 23 October 2017.

[45]   *EirGrid* and *SONI*, "DS3 System Services Interim Tariffs Decision Paper," pp. 36, available at http://www.eirgridgroup.com/site-files/library/EirGrid/DS3-System-Services-Decision-Paper-on-Interim-Tariffs-FINAL.pdf, 24 August 2016.

[46]   *EirGrid* and *SONI*, "Consultation on Connecting Further Generation in Northern Ireland," pp. 39–44, 31 January 2018.

[47]   M. Aneke and M. Wang, "Energy storage technologies and real-life applications – A state of the art review," *Appl. Energy*, vol. 179, pp. 350–377, 2016.

[48]   A. Azzuni and C. Breyer, "Energy security and energy storage technologies," *Energy Procedia*, vol. 155, pp. 237–258, 2018.

[49]   Ling Ai Wonga, Vigna K. Ramachandaramurthy, Phil Taylora, J.B. Ekanayake, Sara L. Walker, and Sanjeevikumar Padmanaban, "Review on the optimal placement, sizing and control of an energy storage system in the distribution network," *Journal of Energy Storage*, vol 21, 489–504, 2019.

[50]   S. Koohi-Fayegh and M.A. Rosen, "A review of energy storage types, applications and recent developments," *Journal of Energy Storage*, vol 27, 101047, 2020.

[51]   *Power NI*, "Unit Rate Prices," Plans & Discounts *Article*, available at https://powerni.co.uk/plan-prices/compare-our-plans/tariff-rates/, accessed January 2020.

[52]   *SSE Airtricity*, "Our Tariffs," Plans & Products *Article*, available at https://www.sseairtricity.com/uk/home/help-centre/our-tariffs, accessed January 2020.

[53]   *SSE Airtricity*, "1 Year Keypad Electricity Tariffs," Tariff Quote *Document*, available at https://www.sseairtricity.com/assets/Tariffs/ElecNI/Oct-19/1YR-KEYPAD-9.pdf, 2019.

[54]   Khoa Xuan Le, Ming Jun Huang, Christopher Wilson, Nikhilkumar N. Shah, and Neil J. Hewitt, "Tariff-based load shifting for domestic cascade heat pump with enhanced system energy efficiency and reduced wind power curtailment," *Appl. Energy*, vol. 257, 113976, 2020.

[55]   Energetics, Norton Rose Fulbright and WWF-Australia, "NSW Guide to Corporate Power Purchase Agreements," *Report*, ISBN 978-0-646-99210-5, October 2018.

[56]   Rocky Mountain Institute, "The Economics of Battery Energy Storage - How Multi-use, Customer-sited Batteries Deliver the Most Services and Value to Customers and Grid," *Report*, available at https://rmi.org/wp-content/uploads/2017/03/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf, pp. 14-16, October 2015.

[57]   Patrick J. Balducci, M. Jan E. Alam, Trevor D. Hardy, and Di Wu, "Assigning value to energy storage systems at multiple points in an electrical grid," *Energy & Environmental Science Review*, DOI: 10.1039/c8ee00569a, 2018.

[58]   Xin Li, Konstantinos J. Chalvatzis, and Phedeas Stephanides, "Innovative Energy Islands: Life-Cycle Cost-Benefit Analysis for Battery Energy Storage," *Sustainability*, September 2018.

[59]   Linda Barelli, Gianni Bidini, Paolo Cherubini, Andrea Micangeli, Dario Pelosi, and Carlo Tacconelli, "How Hybridization of Energy Storage Technologies Can Provide Additional Flexibility and Competitiveness to Microgrids in the Context of Developing Countries," *energies*, August 2019.

[60]   Kyle Bradbury, "Energy Storage Technology Review," *Review*, https://www.kylebradbury.org/docs/papers/Energy-Storage-Technology-Review-Kyle-Bradbury-2010.pdf, 2010.

[61]   *Lazard*, "Lazard's Levelized Cost of Storage Analysis – Version 3.0," *Technical Report*, available at https://www.lazard.com/media/450338/lazard-levelized-cost-of-storage-version-30.pdf, 2017.

[62]   *ADB*, "Handbook on Battery Energy Storage System," Asian Development Bank *Book*, ISBN 978-92-9261-470-6 (print), 978-92-9261-471-3 (electronic), Publication Stock No. TCS189791-2, DOI: http://dx.doi.org/10.22617/TCS189791-2, 2018.

[63]   *IRENA*, "Electricity Storage and Renewables: Costs and Markets To 2030," International Renewable Energy Agency, Abu Dhabi *Report*, ISBN 978-92-9260-038-9, 2017.

[64]   Electric Power Research Institute, "Electricity Energy Storage Technology Options: Applications, Costs, and Benefits," *A White Paper Primer* 1020676, pp. 1–170, 2011.

[65]   U.S. Department of Energy, "Grid Energy Storage," *Report on grid energy storage*, December 2013.

[66]   Logan Goldie-Scot, "A Behind the Scenes Take on Lithium-ion Battery Prices," BloombergNEF *Article*, available at https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/, accessed January 2020.

[67]   International Energy Agency, "Capital cost of utility-scale battery storage systems in the New Policies Scenario, 2017-2040," IEA *Data and Statistics*, available at https://www.iea.org/data-and-statistics/charts/capital-cost-of-utility-scale-battery-storage-systems-in-the-new-policies-scenario-2017-2040, accessed June 2020.

[68]   Invest Northern Ireland, "Wind Power: A best practice guide for Northern Ireland business," *Sustainable Development – Team Text Relay,* Number: 1800102890698273, pp 26–86, available at https://www.investni.com/sites/default/files/documents/static/library/invest-ni/documents/wind-power-a-best-practice-guide-for-businesses-in-northern-ireland.pdf.

[69]   *IRENA*, "Renewable Power Generation Costs in 2018," International Renewable Energy Agency, Abu Dhabi *Report*, ISBN 978-92-9260-126-3, 2019.

APPENDIX A

LOAD FLOW EQUATIONS FOR TECHNICAL ANALYSIS OF ELECTRICAL NETWORK:

Given that the net complex power into a bus *i* is given as:
$$S_i = P_i + jQ_i = (P_{Gi} - P_{Di}) + j(Q_{Gi} - Q_{Di}) \tag{A.1}$$
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:
$$I_i = \sum_{k=1}^{n} Y_{ik} V_k \text{ ; for } i = 1, 2, 3, ..., n \tag{A.2}$$
where Y_{ii} – also known as the *self-admittance* – is the *i*th 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 *i*th and a *k*th node – given as the negative of the sum of all the admittances between the *i*th and the *k*th nodes; meanwhile, $Y_{ik} = Y_{ki}$.
The complex power into the bus *i* could be written as:
$$S_i = P_i + jQ_i = V_i I_i^* \text{ ; for } i = 1, 2, 3, ..., n \tag{A.3}$$
where V_i is the voltage at the *i*th bus and I_i^* is the current flowing through the bus in complex conjugate.
$$\text{this implies, } S_i^* = P_i - jQ_i = V_i^* I_i \text{; for } i = 1, 2, 3, ..., n$$

$$S_i^* = P_i - jQ_i = V_i^* (\textstyle\sum_{k=1}^n Y_{ik} V_k); \text{ for } i = 1, 2, 3, ..., n \tag{A.4}$$

If the real and the imaginary sections of Equation (A.4) are compared, then

$$P_i = R_e\{V_i^* \textstyle\sum_{k=1}^n Y_{ik} V_k\}; \quad Q_i = -I_m\{V_i^* \textstyle\sum_{k=1}^n Y_{ik} V_k\}; \text{ for } i = 1, 2, 3, ..., n \tag{A.5}$$

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 (A.5), the *static load flow equations* can be expressed for the real and the reactive power respectively as:

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

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

APPENDIX B

Table B.1: Effect of Storage Efficiency on Recoverable Wind Energy and Market Gain

(a) Using 90% Efficient Storage System				
Total Number of Wind Turbines	Total Recoverable Energy (kWh)	Market Value of Recovered Energy (£)	Gross Annual Gain (£)	On-site Wind Energy Consumption (%)
2	541,602.00	64,992.24	33,398.79	48.40
4	2,315,597.72	277,871.72	142,795.19	94.58
6	4,605,078.02	552,609.36	283,979.81	139.83
(b) Using 85% Efficient Storage System				
2	511,513.00	61,381.56	29,788.11	47.91
4	2,186,953.41	262,434.41	127,357.87	92.49
6	4,349,240.05	521,908.81	253,279.27	135.67
(c) Using 80% Efficient Storage System				
2	481,424.00	57,770.88	26,177.43	47.42
4	2,058,309.09	246,997.09	111,920.56	90.40
6	4,093,402.69	491,208.32	222,578.77	131.52

Table B.2: Results of Upscaling Only for Increasing Self-consumption of Wind Energy

(d) + 2MW/4MWh Battery				
+No Wind Turbine at Cost; Aggregated Cost of Li-ion Battery	Total Costs of Equipment Upgrade (£ Million)	Storage/Turbine Lifespan (Years)	Gross Annual Gain (£)	Payback Period (Years)
Storage only at £100/kWh	0.40	10-15/8-13 & 17-22*	29,788.11	13.4
Storage only at £180/kWh	0.72	10-15/8-13 & 17-22*	29,788.11	24.2
Storage only at £260/kWh	1.04	10-15/8-13 & 17-22*	29,788.11	34.9
(e) +2 Turbines (Enercon_E48 800KW) + 2MW/12MWh Battery				
+2 Turbines at £1.7/W; Storage at £100/kWh	3.92	10-15/20-25	127,357.87	30.8
+2 Turbines at £1.7/W; Storage at £180/kWh	4.88	10-15/20-25	127,357.87	38.3
+2 Turbines at £1.7/W; Storage at £260/kWh	5.84	10-15/20-25	127,357.87	45.9
(f) +4 Turbines (Enercon_E48 800KW) + 2MW/40MWh Storage				
+4 Turbines at £1.7/W; Storage at £100/kWh	9.44	10-15/20-25	253,279.27	37.3
+4 Turbines at £1.7/W; Storage at £180/kWh	12.64	10-15/20-25	253,279.27	49.9
+4 Turbines at £1.7/W; Storage at £260/kWh	15.84	10-15/20-25	253,279.27	62.5
* The two turbines on-site were deployed in 2008 and 2017; these have remaining lifetime between 8-13 and 17-22 years respectively.				

APPENDIX C

Table C.1: Deploying Storage for Self-consumption of Wind Energy and for Different Levels of Ancillary Services

(a) + 2MW/4MWh Storage						
+No Wind Turbine at Cost; Aggregated Cost of Li-ion Battery	**10% Capacity to Ancillary Services (MWh per year)**	**Payback Period at 10% Service (Years)**	**20% Capacity to Ancillary Services 1 (MWh per year)**	**Payback Period at 20% Service 1 (Years)**	**20% Capacity to Ancillary Services 2 (MWh in 12.5 years)**	**Payback Period at 20% Service 2 (Years)**
+2 Turbines at £1.7/W; Storage at £100/kWh	1,171.20	9.5	2,342.40	7.4	9,307.50	3.1
+2 Turbines at £1.7/W; Storage at £180/kWh	1,171.20	17.1	2,342.40	13.3	9,307.50	5.7
+2 Turbines at £1.7/W; Storage at £260/kWh	1,171.20	24.7	2,342.40	19.1	9,307.50	8.2
(b) +2 Turbines (Enercon_E48 800KW) + 2MW/12MWh Storage						
Storage at £100/kWh; +2 Turbines at £1.7/W	3,513.60	23.9	7,027.20	19.5	27,922.50	9.3
Storage at £180/kWh; +2 Turbines at £1.7/W	3,513.60	29.7	7,027.20	24.2	27,922.50	11.6
Storage at £260/kWh; +2 Turbines at £1.7/W	3,513.60	35.6	7,027.20	29.1	27,922.50	13.9
(c) +4 Turbines (Enercon_E48 800KW) + 2MW/40MWh Storage						
+4 Turbines at £1.7/W; Storage at £100/kWh	11,712.00	25.1	23,424.00	18.9	93,075.00	7.7
+4 Turbines at £1.7/W; Storage at £180/kWh	11,712.00	33.6	23,424.00	25.4	93,075.00	10.3
+4 Turbines at £1.7/W; Storage at £260/kWh	11,712.00	42.1	23,424.00	31.8	93,075.00	12.9

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered
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