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Techno-Economic Analysis of On-Site Energy Storage Units to Mitigate Wind Energy Curtailment: A Case Study in Scotland

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Abstract: Wind energy plays a major role in decarbonisation of the electricity sector and supports achieving net-zero greenhouse gas emissions. Over the last decade, the wind energy deployments have grown steadily, accounting for more than one fourth of the annual electricity generation in countries like the United Kingdom, Denmark, and Germany. However, as the share of wind energy increases, system operators face challenges in managing excessive wind generation due to its nondispatchable nature. Currently, the most common practice is wind energy curtailment in which wind farm operators receive constraint payments to reduce their renewable energy production. This practice not only leads to wastage of large volumes of renewable energy, but also the associated financial cost is reflected to rate payers in the form of increased electricity bills. On-site energy storage technologies come to the forefront as a technology option to minimise wind energy curtailment and to harness wind energy in a more efficient way. To that end, this paper, first, systematically evaluates different energy storage options for wind energy farms. Second, a depth analysis of curtailment and constraint payments of major wind energy farms in Scotland are presented. Third, using actual wind and market datasets, a techno-economic analysis is conducted to examine the relationship between on-site energy storage size and the amount of curtailment. The results show that, similar to recent deployments, lithium-ion technology is best suited for on-site storage. As case studies, Whitelee and Gordon bush wind farms in Scotland are chosen. The most suitable storage capacities for 20 years payback period is calculated as follows: (i) the storage size for the Gordonbush wind farm is 100 MWh and almost 19% of total curtailment can be avoided and (ii) the storage size for the Whitlee farm is 125 MWh which can reduce the curtailment by 20.2%. The outcomes of this study will shed light into analysing curtailment reduction potential of future wind farms including floating islands, seaports, and other floating systems.

Keywords: wind energy curtailment; energy efficiency; wind farms; storage technologies; cost-benefit analysis; techno-economic analysis; "Case of Scotland"

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1. Introduction

To tackle global warming and reduce the overuse of fossil fuels, there has been a growing push towards the use of renewable energy in electrical power generation. Moreover, energy security concerns have intensified after the global oil crisis in 1973 [1], electricity generation with local resources has gained significant attention, and securing energy supply has become a national policy for most nations. To support green energy, more than 150 countries around the world have signed the Paris Agreement which charters a new course of actions to reduce carbon emissions from all sectors including electricity generation [2].

Renewable energy is becoming a major pillar of the energy supply around the world. Wind energy is one of the most effective and sustainable solutions to meet the energy requirement. This energy source is helping to transmit away from fossil fuels, and it is very competitive in price, performance, and dependability. According to the International Energy Agency (IEA) report, green electricity is on track to become the largest power source by 2025, displacing coal, which has dominated the electricity sector for the past 50 years [3]. According to the previous applications and research, wind power is completely compatible with environmental sustainability and tends to be an infinite energy source with decreasing levelized cost of energy (LCOE) trend in the current century as one of the leading renewable energy sources [4–7]. The capacity of wind power has increased four times since 2010 [3] and global wind energy generation capacity has reached 650.8 GW in 2019 [8].

Over the last couple of decades, the main supply of electricity in the UK has been mainly carbon-based sources such as coal, oil, and natural gas. However, the country has shown significant progress in deploying renewable energy supply due to green policies and investments. Currently, the UK is at the forefront globally on its path to net zero greenhouse gas emissions by 2050. For instance, the UK has made a good progress in reducing its greenhouse gas emissions in the nearly 10 years since the Climate Change Act was passed in 2008 and carbon emissions were decreased by 42% between 1990 and 2016 [2]. Moreover, the UK has been implementing a comparatively satisfactory process to decarbonise its economy by applying this knowledge to generate renewable energy like investing in offshore wind turbine technologies [9]. Additionally, particular support systems are proposed to encourage wind farms [10] in this country which are:

- Feed in Tariffs—proposed for a limited scale action [11].
- Renewables Obligation (RO)–Renewables Obligation (RO)—this scheme is an obligation of electricity suppliers in the UK to resource a rising rate of renewable energy in their electricity consumption or effective payments for certificates instead [12].
- Contracts for Difference (CfDs)—this is a kind of grant for renewable projects through an auction process for selected candidates. They get a fixed Strike Price for the period of the agreement which is regularly 15 years to minimise the consumer's prices [13].

Aforementioned incentive programs have been pushing the wind power capacity at higher levels since their first introduction in May 2018. Combined onshore and offshore wind power capacity in the country reached over 24 GW in 2019. Onshore wind energy still makes up the largest share of wind capacity, however, offshore farms have seen a greater growth rate in recent years [14]. The fleet of renewable energy sources are responsible for the UK's new record generation that came in at 47.4 GW at the end of the first quarter of 2020, a 5.2% increase on 2019′s first quarter, primarily due to increased offshore wind capacity which grew by 19% (or 1.6 GW) [15]. As one of the most popular and the biggest source of renewable energy, wind energy plays a key role in the UK's carbon-free target. However, wind farms suffer from curtailment in the UK, particularly in Scotland and details are explained in the next section.

Due to its abundant wind resources, Scotland has become the renewable powerhouse of the UK. The transition to a low carbon energy system ensuring the economic opportunities in new renewable technologies is a major policy focus in Scotland. The Scottish government has launched the country's first Energy Strategy, which includes a GBP 20 million Energy Investment Fund to build on the GBP 60 million Low Carbon Innovation Fund to provide support for the country's Renewable Energy Investment Fund and renewable and low carbon infrastructure [16]. In 2019, the country generated 30.5 TWh of electrical energy from renewable sources, 13.6% up on 2018 [17]. The Annual Energy Statement 2020 said that Scotland's heat demand is still primarily made up of fossil fuels but progress on renewables has been made, with the amount of renewable heat generated in 2019 up 4.8% on the previous year [18]. Wind farms generated two-thirds of all renewable electricity output and almost half of the total generation in Scotland [19]. All these improvements lead to an increase in the short-term security of electricity supply and system efficiency, but it also causes an additional increase in the need for storage systems and policy advancement. Curtailment has become one of the most serious challenges for renewable energy integration into the energy systems. In this publication, the curtailment of wind will be discussed as the largest part of the renewable energy in Scotland.

Wind curtailment can be described as an involuntary decrease in the output energy of the wind farm from what could be generated under orderly situations [20]. There are a number of drivers behind the wind energy curtailment but mainly the transmission network congestion is one of the main reasons. In general, transmission congestion would be the result of wind farms that are on the outskirts of cities. In these areas, generally, the grid system is not physically strong, because the existing power grids were laid out before the wind farms were deployed and designed to serve low population [21]. Therefore, wind farms need to decrease their output to keep the system frequency within operational limits and avoid interconnection problems, where the minimum production thresholds of the low or baseload generators are adequate to meet the needs [20]. There is oversupply curtailment during the nights or in common holiday times like Christmas if a significant amount of wind resources is accessible. As discussed in [21], one of the solutions to tackle wind curtailment is to reduce the minimum operating constraint when retrofitting or replacing thermal plants.

On the other hand, system balancing will be another problem for an interruption and preventing the penetration of oversupply into the grid system. Electricity supply and demand must be balanced timely. Therefore, if high wind energy output coincides with low demand on windy days, wind farms possibly will be required to cut their production to avoid overloading and harming the transmission system during the times of complete volume productions from the wind plant [20]. However, this combination of high wind output at low demand times is relatively infrequent [22]. Wind curtailment is a powerful local issue due to connection congestion in the United Kingdom between Scotland and England [23]. The majority of the UK's wind farms are located in Scotland. As shown in Figure 1, the area has big energy output but comparatively low energy demand. However, the grid connections between Scottish wind farms and British cities are not sufficient to transmit this energy from Scotland to England. This significant amount of energy is inadequate to be stored or used to produce other services or other technologies like carbon capture storage (CCS) technologies. Total annual electricity consumption by the local authority in Scotland, as shown in Figure 1, is comparable with the installed wind turbine capacities and their curtailed electricity.

To that end, the contributions of this paper are enumerated as follows. First, we present an in-depth analysis of wind farms, major factors for curtailment, and associated financial ramifications and constraint payments. Second, we provide an overview of existing energy storage technologies and assess their suitability for wind farm curtailment applications. Third, we carry out a techno-economic analysis of site-specific potential storage systems for selected wind farms using actual datasets. Fourth, we carry out a sensitivity analysis between storage capacity change and the curtailment reduction or payback period of the investment. This paper uses location specific data sets as vast majority of the curtailment occurs in the selected Scottish wind farms. To the best of author's knowledge, this is the first study conducted for wind farms in the UK.

2. Literature Review

Over the last few years, there has been a growing body of literature on the operation and the applications of ESS for renewable energy [24–26] as well as techno-economic analysis of storage units are reported in [27–30]. The authors of [24,25] present a generic overview of storage units and how they can help to host higher shares of renewables. Similar to the analysis that is provided in this section, mechanical, electrochemical, and electrical storage units are discussed, and their suitability is evaluated based on the application and the type of renewable energy project. In [26], a more specific literature review on ESS for wind energy is presented. In [27], an overview of life cycle analysis of energy storage units is discussed in detail. In [29], an analysis of energy storage units to reduce wind curtailment in Crete is presented. In this application, non-interconnected (off-grid) island case is considered and due to availability of natural resources compress-air energy storage technology is chosen. In [30], a techno-economic analysis of mobile lithium-ion batteries to reduce wind curtailment is discussed for off-grid applications. In this application, the curtailed energy is stored in a mobile storage lithium-ion battery and consumed at social events such as festivals and concerts.

In [31], the authors examined the Texas grid and concluded that for a renewable penetration of 80% (70% wind plus 30% solar), a 414 GWh energy storage would be needed if a curtailment up to 10% is allowed. It is further shown that the storage requirement would reduce to 139 GWh if the allowed curtailment rate is increased to 20%. In a similar study conducted in California [32], it is estimated that 186 GWh of storage is needed to achieve 85% renewable penetration if 20% curtailment is allowed. It is noteworthy that economic aspects of the storage units were not considered and only the relationship between storage size and curtailment ratio is considered. On the other hand, this paper presents a techno-economic analysis by taking into account financial parameters related to life cycle of storage projects and calculating the amount of energy curtailment with respect to storage size.

2.1. Constraint Payments, Energy Wastage, and Financial Losses

Wind farms in Scotland have been built in the low demand areas with limited capability to deliver the energy to the rest of the Britain. This causes the curtailment of around 32% of the capacity of annual output in the Whitelee wind farm located in Glasgow during 2015–16. This issue continues to exist [33,34] and curtailment rates reach up to 26% for other wind farms. In the following years, the wind curtailment rate exceeds 30% in some onshore wind farms [35,36]. The financial ramifications of curtailment have been growing steadily. In 2019, constraint payments exceeded GBP 130 million, and the amount of electricity discarded reached 1.9 TWh [36]. This discharged electricity worth more than GBP 357 million and totally reached GBP 0.49 billion with constraint payments. Moreover, the size of the wasted energy accounts for nearly GBP 2.8 billion/year in the UK when an average variable unit price (p/kWh) is taken as 18.8 p.

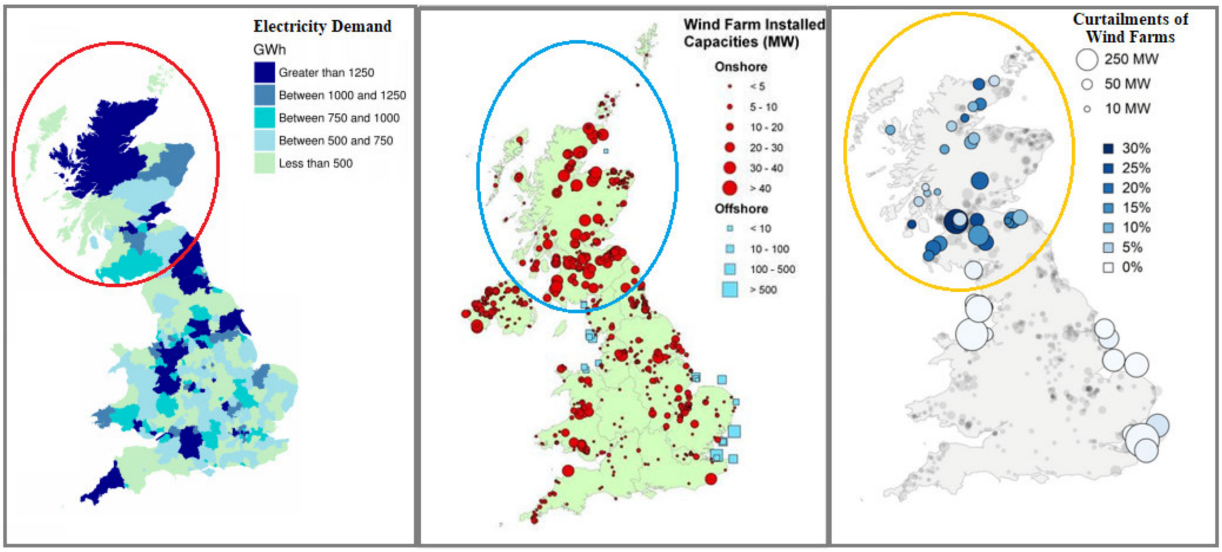

Figure 1. Comparison of electricity demand by the local authority, installed wind turbines capacities and curtailments in the UK, adapted from [35,37,38].

Scottish onshore farms have very high curtailment lost during the decade [35,36]. More than 600 new wind turbines projects were planned in the last five years and most of them are planned to be done in Scotland where the curtailments already occur at high levels. Understandably, a large amount of curtailment of renewables without adequate compensation to renewable producers could be an obstacle to achieving greener energy and targets of GHG reduction [23].

The trend of the curtailment rates has an upward trend since 2010 and the volume-weighted curtailment rates reached more than 15% in 2016 from 1% in 2012 [35,36]. Figure 2 shows more details about curtailment in the UK in the last 10 years. Although the year 2020 only includes three quarters (9 months) of the year it already reaches the highest curtailment ever by 2.5 million MWh.

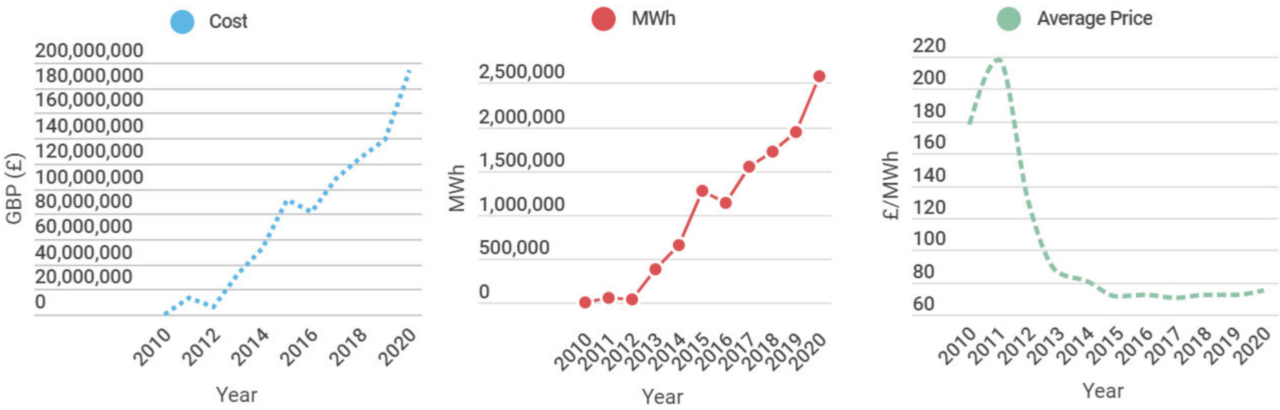

Figure 2. Balancing mechanism wind farm constraint payments in the UK adapted from [36].

National Grid offers favourable bids to the wind farms and renewable energy firms to reduce their output in exchange for remuneration payment. According to McPhee [33] and [36], the price of power cuts by wind plants to prevent excessive energy production has been costing more than GBP 607 million over the last decade in Scotland which shares almost 90% of the payments. In 2019 alone, constraint payments to onshore Scottish wind farms were GBP 130 million receiving 94% of the total in 2019 in the UK. Last year, the cost exceeded GBP 130 million in payments. Most of these payments took place for Scottish wind farms because the government has actively encouraged the wind farms. More interestingly, these figures reveal that these farms made comparable profit by switching off the generation (GBP 70 per MWh) than producing electricity (GBP 49 per MWh) [39]. For instance, the Whitelee wind farm in Scotland has received an annual payment of nearly GBP 20 million during 2015 and 2016 financial years. Whereas, the same wind farm has received GBP 106.5 million in constraint payments for their curtailments between 2013 and 2019 [34].

2.2. *Energy Storage Systems for Wind Farm Curtailment*

Energy storage systems (ESS) have emerged as viable technology option to address the preceding issues by providing a "buffer" zone between supply and demand [40]. Colocating ESS and wind energy has become popular and offers a number of benefits in addition to reducing wind curtailment; ESS could aid maintaining generation schedules, hence, reduces imbalance charges and avoids penalties for not meeting the minimum performance measures. On-site ESS could further provide ancillary services such as frequency support, reactive power provisioning, and black start during outage periods [41]. Considering the previous discussion, ESS are needed in wind farms in Scotland. In fact, Scottish Power Renewables, a major utility company in the UK, recently initiated a project to install a 50 MWh battery to Whitelee wind farm and project completion is due by Q1 2021 [42,43]. This recent investment also validates the research need in this field. Therefore, a possible case study can contribute to tackling problems in Scottish onshore and offshore wind farms. It can create a meaningful economic contribution to the country for the near future. However, there is limited research available in this area. Therefore, research needs to analyse that research gap to help researchers to understand more about the possibility of using a storage system to reduce wind energy curtailment within Scotland. Amiryar and Pullen [44] believe that storage is ideal to balance the market when there is low demand, low production cost, or when the accessible energy sources are not sufficient. Energy storage systems have the potential to contribute to the process of energy in various ways. Some of the most important ones are listed below:

- Increases the efficiency of intermittent renewable sources that can be integrated into intelligent integrated energy systems,
- Leads to reducing the need for maximum production capacity,
- Supports grid stability (grids provide solutions in restricted areas),
- Allows performance development and cost improvement,
- Supports the energy security of nations [45],
- Optimises the demand and supply tension [44].

These technologies include turning and storing the electrical energy of an accessible reservoir within a different sort of power. This can be transformed backward electrical power if demanded. The energy forms can be stored as mechanical, chemical, thermal, or magnetic. The most suitable and available energy storage technologies can be listed as follows [46].

2.2.1. Mechanical Storage Systems (MSS)

Modern MSS transfer electrical energy to mechanical energy and the energy is stored kinetically as a rotating wheel or potential energy in the form of pumped water [45]. Their common applications are pumped hydro storage (PHS), compressed air energy storage (CAES) and liquid air energy storage (LAES). The unit that converts energy between electrical and mechanical energy is an electric motor, which acts as an electric generator when the stored energy is discharged [47]. The efficiency of mechanical energy storage systems is higher than thermal and also some electrical and chemical storage systems but only slightly longer discharging durations than electric storage systems. The energy storage density is a prominent element in choosing the storage system [48].

PHS has the biggest capacity systems that are pumped hydro-power plants for storage of electricity today [40]. Globally, the PHSs are the large storage technology. Capacity of PHSs is 99% of all operating large application of energy storage [49]. Two water reservoirs as upper and lower are a necessity to help water move between levels for PHS. Then electricity can be used to create gravitational potential energy which is transferable to electricity by converting to kinetic when it is needed. The dependency of the round-trip efficiency process is related to on pump, motor, turbine and generator efficiencies and also evaporation rates. It is not unconventional for these plants to expect a 70–85% round-trip efficiency [50]. Even though the most existing and mature technology for utility-scale storage (USS) application is PHS, the greatest challenge to the widespread adoption of PHS is that it needs large areas and special topography for reservoirs [20] Another disadvantage of PHS is that the system is not suited for distributed production. Due to the low energy density of pumped storage schemes, they are really only applicable for large-scale grid applications.

CAES could be attributed to basic gas turbine plants which have additional cavern to be used for storing the compressed air. The con is that it requires the cavernous space. The energy storage method has been used effectively for the last decade, especially since it is applied widely in the mining industry. The significant advantage is that no toxic chemicals are used [51]. CAES systems differ widely with regard to cycle efficiency, however, the greatest decline in the area of around 70% to 89% [52]. The key benefits are a reduction of peak loads, decline in the use of fossil fuel in power plants, and the integration of CAES technology into wind generation technologies. However, building or sitting CAES facilities have difficulties. Until today, no suitable location for underground CAES has been identified in Scotland.

LAES is considered as an extremely simple technology which minimises the exhaust noise and includes the use of renewable electricity to cool air at $-196'$°C c ($-320'$F).

The low pressure and insulated vessels are used to store the liquid air. When liquid air is released, it becomes a gas and rapidly increases the volume by driving a turbine to generate electricity [45]. LAES consists of three major components, including charging, and the large-scale LAES energy storage plants with a capacity of hundreds of MWs output could last for a long time. As an example, Highview Power in Scotland has built the first grid-scale liquid air energy storage plant in the world, which could be used to replace the battery storage Liquid Air. It has many advantages over batteries as it is made mainly from the industrial air liquefier and directly from the steel components. However, geographical difficulties, round trip efficiency and lower energy density may play a game changer role for this technology [53]. In addition, industrial waste heat/cold from applications of thermal, generation plants, steel mills and LNG terminals could be used to improve systems efficiency [54].

2.2.2. Electrochemical Energy Storage Systems (EESS)

The EESS, also known as “battery”, are commonly used as storage systems; a reversible chemical reaction to store and discharge batteries within more than one electrochemical cell. They have not been commonly applied for USS, but the increase in advanced technologies lead this storage system to be more commonly applicable in near future. Additionally, the rapid decline in battery costs makes them more popular. According to Martin and Murach [55], the further decrease in their cost will make it feasible to use them for large-scale applications luckily to reduce the curtailment of wind plant applications in Scotland. Additionally, these systems continue to be optimised in terms of cost, lifetime, and performance, leading to their continued expansion into existing and emerging market sectors. This growing demand (multi billion dollars) for electrochemical energy systems along with the increasing maturity of several technologies is having a significant effect on the global research and development effort which is increasing in both in size and depth. A number of new technologies, which will have substantial impact on the environment and the way we produce and utilise energy, are under development [56] Their most comment application in the literature is lead-acid batteries, supercapacitors, flow batteries, and lithium-ion batteries.

Lead-Acid Batteries

Generally, lead-acid (L/A) batteries may be identified as a mature technology in terms of rechargeability and a secure market background. The self-discharge feature of them is prominent in comparison with batteries while low maintenance necessities are one of their advantages. As another option, limited energy solidity limited period of service, environmentally unfriendly content, and the recommended low depth of discharge can be seen as the disabilities of this specific technology [57]. However, there are good reasons for its popularity; lead acid is reliable and cheap on a cost-per-watt basis. Lead-acid allows the battery to be cost-effective for automobiles, golf cars, forklifts, marine and uninterruptible power sources [58]. Both electrodes are transformed to lead sulphate during discharge and the concentration of the sulphuric acid electrolyte is reduced as it becomes larger [59].

Lithium-Ion Batteries

At the beginning of the 1990s, rechargeable Li-ion batteries have been marketed by Sony Corporation and it has quickly been one of the highest demanded technology for mobile phone users [60]. This need led this technology to have enormous developments in a short time like it happens today with electric vehicles (EVs). The Li-ion is one of the lithium-based battery systems which has a very large variety as shown in Figure 3.

A typical Li-ion battery consists of three tightly spirally wound layers acting as a positive electrode, negative electrode, and separator surrounded by a liquid electrolyte in a cylindrical metal housing as is shown in Figure 3. Considerably low price, high energy and power density are advantages of Li-ion batteries, shown in Figure 4. In comparison with other battery technologies, at the same time, high speed and power discharge ability, perfect round-trip efficiency, comparatively extended life, and limited self-discharge rate are promising options for large applications [60]. Advantageous features and promising ways to further improve the basic features of Li-ion batteries have made them the dominant for small applications such as mobile phones and laptop computers are largely used by Li-ion batteries. Li-ion batteries have also dominated the latest evolving battery technologies of EVs. It is considered that the fast growth in the EVs market is likely to lead to a significant increase in the Li-ion battery industry turnover that will be USD 93.1 billion with 17% of compound annual growth rate by 2025 [61]. As a large application under these advanced developments, at nonpeak hours, charged Li-ion batteries can feed the grid system during peak hours. This can also be applied to EVs leading to the development of these battery systems, becoming more commercial and significantly reducing the cost of using Li-ion batteries likely to increase their efficiencies, lifetimes, and reliability of alternative system reliability like off-grid photovoltaics [62].

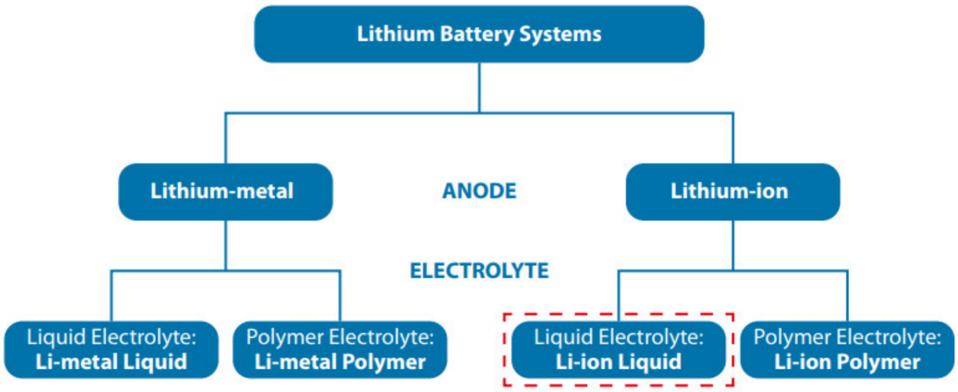

Figure 3. Lithium battery systems [60].

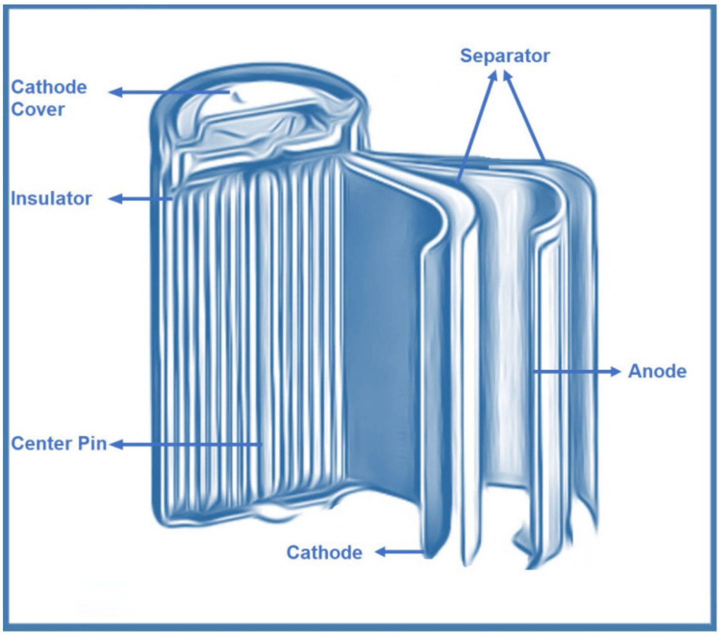

Figure 4. Structure of Li-ion battery reproduced from [63].

Chemical Energy Storage Systems

Hydrogen and methane as SNG are a more adaptable way of storing energy with the current technologies at present and they may play an important role as energy storage for wind turbine curtailments. Therefore, this study will cover only hydrogen energy storage and methane energy storage as they are commonly available and economical chemical energy storage systems [64]. Energy stored in the form of hydrogen or methane can be used by all three sectors—electricity, heating, and transport. There is already a large existing infrastructure for transporting, distributing, and exploiting methane in gas-fired boilers and CHP in the heating sector; in gas vehicles and gas ships (LNG) in the transport sector; in gas turbines, combined cycle gas turbine plants, and CHP in the electricity sector [65].

2.3. Mathematical Models for Energy Storage Systems

In energy storage research, mathematical models to estimate the storage state of charge are widely used in optimisation of the energy storage, power grid, and demand response operations. One of the most commonly used mathematical models is Tremblays model which enables to simulate lead-acid, lithium-ion, and nickel-metal batteries. Tremblay models consider nonlinear dependence of the load voltage on the state of charge (SoC). Tremblays model is based on the Shepherd ratio which contains a nonlinear term characterising the magnitude of the voltage polarisation depending on the current amplitude and actual SoC. Another commonly used model is Volterra's model which characterises the systems state change and relates to the memory given by an integral over a time period in the past. A more detailed analysis of analytical battery modelling is presented in [66].

3. Research Method

This part proposes the methodology applied to examine the cost and benefits of different scenarios for the selected wind farms case. A techno-economic analysis framework is developed to explore the interplay between on-site storage size, wind energy curtailment, and associated financial implications. The flowchart for the suggested method is depicted in Figure 5. The main steps of the illustrated method are summarised as follows:

- Stage 1 is developing a tool to examine the size of storage required to utilise curtailed wind energy for a wind power plant. The first step of this part is developing a tool to utilise curtailed wind energy. The second step is assigning random demand/supply figures to test the performance of the tool. The final step is testing the performance of the tool.
- Stage 2 is the case study selection. Wind farms are chosen among the ones that suffer the most from curtailment in Scotland. However, any wind farm can be chosen if they are having curtailment problems and offer easy access to data.
- Stage 3 is about the application of the tool into the chosen cases. Firstly, running the tool with real data from the selected wind power plant based on the different scenarios takes place in this stage. Then, investigation takes place to figure out the capacity of the potential storage systems based on the site-specific requirements for the selected wind farm. After that, this stage carries out sensitivity analysis between storage capacity change and the curtailment reduction or payback period of the investment.
- Stage 4 is the final one in which the cost–benefit analysis of the selected scenarios is performed and results of the research are documented. This technique identifies the costs and benefits to compare them to discuss if the costs outweigh the benefits or vice versa. While reporting the result outcomes, different techniques may be used to examine the sensibility of the results.

As a first step, a tool is developed with an excel solver that calculates the pay-back period of a chosen capacity of storage by using the following set of equations explained below. In this calculation, an energy storage will be charged only with curtailed energy. Additionally, storage units will immediately feed the grid within the next timeslot after the end of curtailment. Recorded real data of generation of wind farms (TG) (MWh) and curtailment record of the wind farm before application of the battery system $C_{BS(1)}$ (MWh) for each half-hour time-period for each time-period, $i = 1, \ldots, N$, are required to calculate results from the model for a particular financial year (start of April to end of March). Stored energy after efficiency losses ($SE_{AEL(i)}$) is illustrated as calculated by the following set of equations:

$$SE_{AEL(1)} = IF(C_{BS(1)} * S_E > S_L; S_L; C_{BS(1)} * S_E) \quad (1)$$

$$\begin{aligned} SE_{AEL(2)} = SE_{AEL(2)} = IF(AND(C_{BS(2)} = 0; TG_{(2)} + SE_{AEL(1)} \\ \leq EE_c); 0; IF\left(AND\left(C_{BS(2)} = 0;\ TG_{(2)} + SE_{AEL(1)} > EE_c\right); TG_{(2)} + SE_{AEL(1)} \\ - EE_c; IF\left(SE_{AEL(1)} + C_{BS(2)} * S_E\right) >\ S_L; S_L; SE_{AEL(1)} + \left(C_{BS(2)} * S_E\right)\right)) \end{aligned}$$

$$\begin{aligned} SE_{AEL(i)} = SE_{AEL(i)} = IF(AND(C_{BS(i)} = 0; TG_{(3)} + SE_{AEL(i-1)} \\ \leq EE_c); 0; IF\left(AND\left(C_{BS(i)} = 0;\ TG_{(i)} + SE_{AEL(i-1)} > EE_c\right); TG_{(i)} + SE_{AEL(i-1)} \\ - EE_c; IF\left(SE_{AEL(i-1)} + C_{BS(i)} * S_E\right) >\ S_L; S_L; SE_{AEL(i-1)} + \left(C_{BS(i)} * S_E\right)\right)) \end{aligned} \quad (2)$$

$$\begin{aligned} SE_{AEL(N)} = IF(AND(C_{BS(N)} = 0; TG_{(N)} + SE_{AEL(N-1)} \leq EE_c); 0; IF(AND(C_{BS(N)} = 0; \\ TG_{(N)} + SE_{AEL(N-1)} > EE_c); TG_{(N)} + SE_{AEL(N-1)} - EE_c; IF\left(SE_{AEL(N-1)} + C_{BS(N)} * S_E\right) >\ S_L; S_L; \\ SE_{AEL(N-1)} + \left(C_{BS(N)} * S_E\right)))), \end{aligned} \quad (3)$$

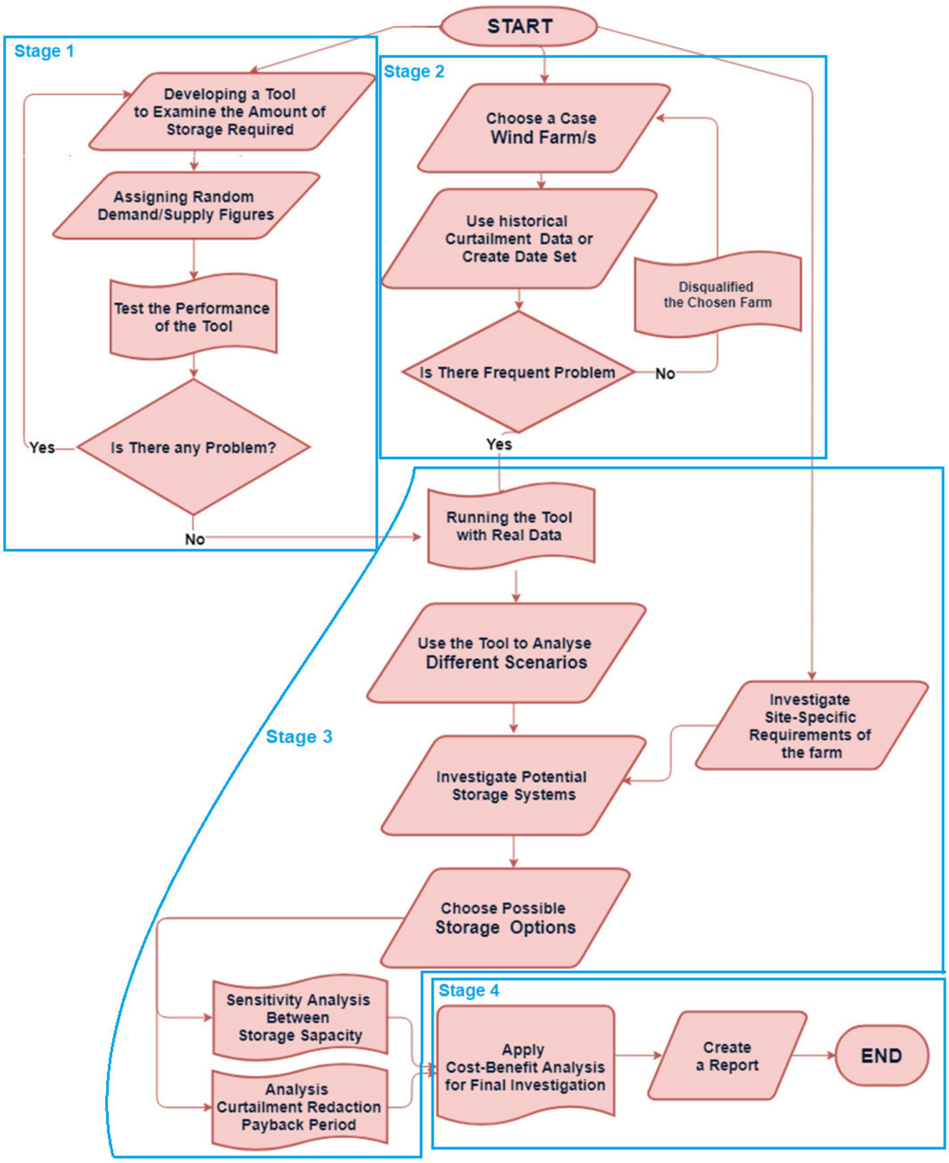

Figure 5. Flow chart of the model developed to apply for this study.

where EE_c is the export capacity of the wind farm (MWh), S_E is the efficiency of the charger-discharge cycle (0–100%), and S_L is the energy storage capacity level (MWh). Equation (1) simply corresponds to the initial time step and stored energy is calculated and stored if there is available space in the battery. Similarly, Equations (2) and (3) correspond to intermediate and final steps and the amount of stored and curtailed energy from previous time steps taken into consideration when checking energy storage size constraint. In a similar manner, calculation of curtailed energy after storage (MWh) (C_{AS}) for each half hour time-period is written as follows:

$$C_{AS(1)} = C_{BS(1)} * S_E - SE_{AEL(1)}$$

$$C_{AS(2)} = (((C_{BS(2)} + S_{AEL(2)}/S_E) * S_E - SE_{AEL(2)})/S_E - \left(S_{s(2)}/S_E\right)$$
$$C_{AS(i)} = (((C_{BS(i)} + S_{AEL(i)}/S_E) * S_E - SE_{AEL(i)})/S_E - \left(S_{s(i)}/S_E\right)$$
$$C_{AS(N)} = (((C_{BS(N)} + S_{AEL(N)}/S_E) * S_E - SE_{AEL(N)})/S_E - \left(S_{s(N)}/S_E\right),$$

where S_E is the efficiency of the battery cycle, SE_{AEL} is stored energy after efficiency loss (MWh). Moreover, the amount of stored energy (MWh) (depicted by SE_S) sold at each half-hour time-period is formulated as follows:

$$SE_{S(n)} = EE_{T(n)} - TG_{(n)},$$

and total sold energy is calculated by

$$SE_{TS} = \sum_{1}^{n}\left(SE_{S\ (n)}\right),$$

where EE_T is total exported energy (MWh), TG denotes power generation (MWh), SE_{TS} is total stored energy. Furthermore, total exported energy (MWh) (denoted by EET) for each half hour time-period is iteratively calculated as follows.

$$EE_{T(1)} = TG_{(1)}$$

$$EE_{T(2)} = IF(C_{BS(2)} > 0; C_{BS(2)};\ IF(TG_{(2)} + SE_{AEL(1)} > EE_C; EE_C; TG_{(2)} + SE_{AEL(1)}))$$
$$EE_{T(i)} = IF(C_{BS(i)} > 0; C_{BS(i)};\ IF(TG_{(i-1)} + SE_{AEL(i-1)} > EE_C; EE_C; TG_{(i)} + SE_{AEL(i-1)}))$$
$$EE_{T(N)} = IF(C_{BS(N)} > 0; C_{BS(N)};\ IF(TG_{(N-1)} + SE_{AEL(N-1)} > EE_C; EE_C; TG_{(N)} + SE_{AEL(N-1)})),$$

where C_{BS} curtailment before storage (MWh). Moreover, the following formulations are used to calculate the outputs of the proposed method. The percentage of reduction in curtailed energy is calculated by

$$C_R = ((SE_{TS} * 100))/C_{TBS}/S_E.$$

Calculation of total reduction in curtailed energy (MWh) (denoted by C_{TR}) is performed by using the following relations:

$$C_{TR} = \frac{C_{TBS}}{S_E}.$$

In the above equation, C_{TBS} is total curtailment before storage for the one-year period from real data (MWh) and similar to previous cases, S_E is energy storage efficiency. Moreover, financial savings from curtailment, shown with CS (GBP£) is calculated by,

$$C_S = C_{TR} * \text{CF},$$

where CF is average cash flow bids (£) per MWh. The total energy storage cost per MWh (C_{TS}) is calculated by multiplying unit cost with S_L which is storage level (MWh).

$$C_{TS} = S_L * C_{sc},$$

where C_{sc} is storage cost per MWh. Monetary earnings from the curtailment (EC in £) are found by

$$E_C = SE_{TS}*\text{EP},$$

where SE_{TS} is total sold stored energy (MWh) and EP denotes average electricity price (£) per MWh. Total budget required to fund a possible storage investment (£) (TB) is the summation of earning and savings from wind curtailment, that is

$$\text{TB} = E_C + C_S.$$

Calculation of payback period (P_P) of the storage investment under assumptions.

$$P_P = (S_L * C_s)/TB,$$

where is S_L is storage level (MWh). Next, we present case studies and calculate the amount of curtailment reduction and associated energy storage size for the Scottish windf arms.

4. Results and Discussion

The techno-economic framework presented in the previous section was applied to four cases, namely Whiteley Stage 1, Whiteley Stage 2, Whiteley Stages 1 and 2, and Gordonbush wind farms. Whitelee wind farm is located near Glasgow and Gordonbush wind farm in the North of Scotland. Locations of the selected wind farms are shown in Figure 6. For the case studies, the following assumptions are made:

- Whitelee wind farm has two stages. The export capacity of the wind farm was assumed as 161 MW for Whitlee-1 108.5 MW for Whitelee 2 and in total 269.5 MW for Whitelee 1 and 2 for the period of 2013–2014; 152.5 MW for Whitelee 1, 103 MW for Whitelee 2, in total 255.5 MW for Whitelee 1 and 2 for the period of 2014–2015 and 35 MW for the Gordonbush wind farms for both periods;
- As the appropriate storage type was selected as Li-ion batteries, the efficiency of the battery cycle was taken as 85% [67];
- Average cash flow bids (£) per MWh was taken as GBP 76.532 [46];
- Li-ion battery cost per MWh was taken as GBP 207,000 [68];
- Average electricity price (£) per MWh was taken as GBP 45.903 [69];
- The data was recorded as a financial year (start of April to end of March) instead of a calendar year. Therefore, the data range chosen for wind farms starts from the beginning of April 2013 to the end of March 2015;
- Life of the lithium-ion battery is assumed to be 15 years with today's technologies. However, by considering future technological breakthroughs, this study did not consider any lifetime limits and ignored when the results of payback periods exceeded 15 years.

Each wind farm responds differently when the various capacities of the storage system are applied to reduce the amount of curtailed electricity. The application of the model determines that Whitelee Stage 2 has a slightly better response than Stage 1 in terms of reduction rate in curtailment with an increase in storage capacity. As it is seen in Table 1, the Gordonbush wind farm has 46,467 MWh curtailment in 2014 (financial year). It is only 18.5% of total curtailment in the Whitelee wind plant which has 251,794 MWh curtailment in the same period. Whitelee 1 and 2 curtailments are 21.4% of their total generation and it is 4.5% less compared to Gordonbush. Each wind farm responds differently when the various capacity of storage system is applied to reduce the amount of curtailed electricity. Whitelee Stage 2 has a slightly better response than Stage 1 in terms of reduction rate in curtailment with an increase in storage capacity. As illustrated in Figure 7, the percentage of the curtailed electricity reduction in Stage 2 decreases faster than the decrease in Stage 1. When both use 1000 MWh battery, Stage 1 reduced the curtailment only by 51.8%, and Stage 2 reduced by 72.8%.

Figure 6. Location of case wind farms (Source: References [70,71].

Table 1. Total generation, curtailment and percentage of curtailments in Whitelee and Gordonbush in 2014 (financial year) (authors' own work carried out with Microsoft Excel).

Wind Farm	Generation (MWh)	Curtailment (MWh)	Curtailment Percentage
Whiteley Stage 1	725,072	170,842	23.60%
Whiteley Stage 2	453,093	80,952	17.90%
Whiteley Stage 1&2	1,178,165	251,795	21.40%
Gordonbush	274,299	46,467	16.90%

Figure 8 shows the payback period for Stages 1 and 2 in the Whitelee wind farm under different capacities of storage. For instance, a 100 MWh lithium-ion battery requires 14 years of the payback period for Stage 1 and it is almost 19 years for Stage 2.

Figure 9 compares reduction rates in curtailments for all scenarios for a different capacity level of storage applications. The figure shows that the reduction in curtailment rate decreases faster in Gordonbush compared to Whitelee, because Gordonbush capacity and actual curtailment rates are smaller than the rest of the possibilities. Opposite trends in Figure 10 show that payback periods in Gordonbush are higher than Whitelee 2 and Whitelee 1 and 2. However, Whitelee 1 still requires a longer time to pay back any level of storage investments.

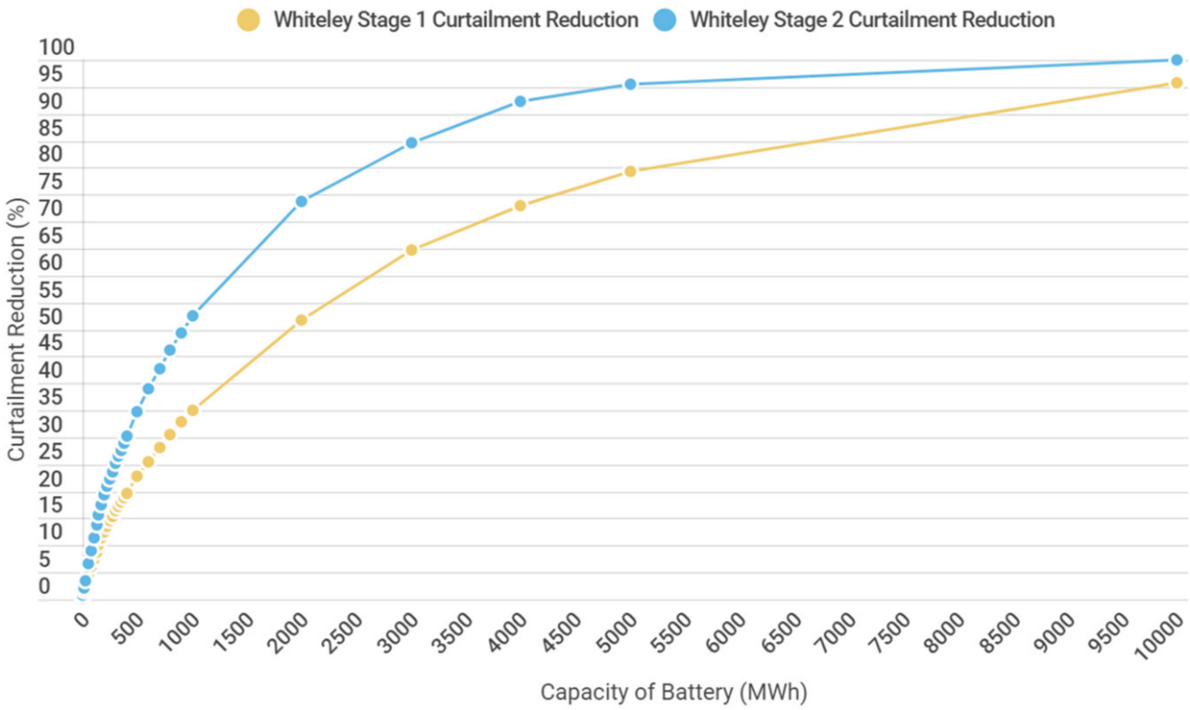

Figure 7. The percentage of the curtailment reduction in Stages 1 and 2 in Whitelee wind farm under different capacity of storage (authors' own work).

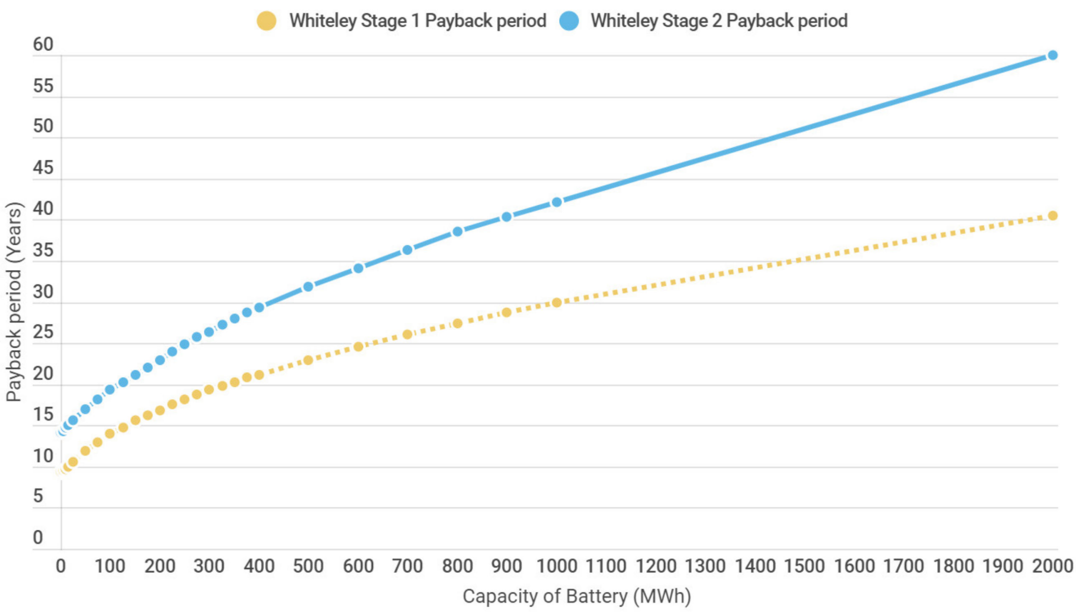

Figure 8. The payback period for Stages 1 and 2 in Whitelee wind farm under different capacity of storage (authors' own work).

On the other hand, Figure 11 shows curtailment reduction per MW unit has a much sharper decrease in Gordonbush and Whitelee in Stage 2 application than the separate application of Whitelee Stage 1 and Whitelee 1 and 2. This figure also demonstrates that the smaller capacity of the storage system reduces more curtailments in Whitelee 1 and 2 as a quantity.

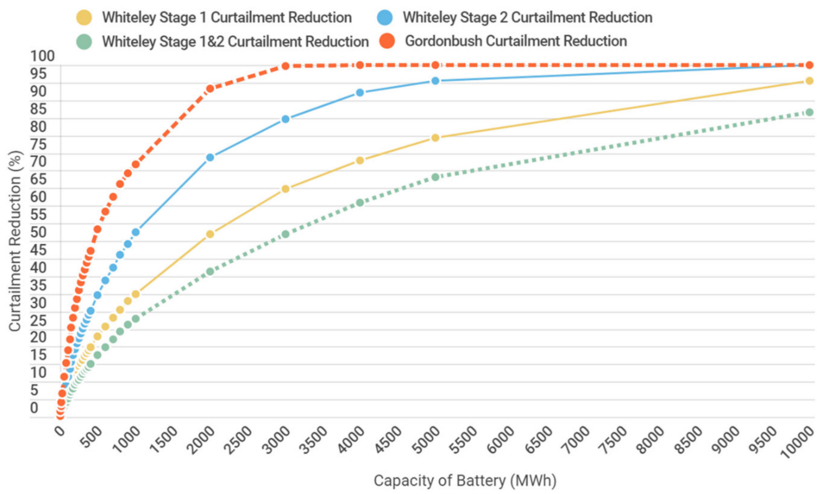

Figure 9. Percentages of curtailment reduction by applying one storage for Gordonbush and Whitelee wind farms (authors' own work).

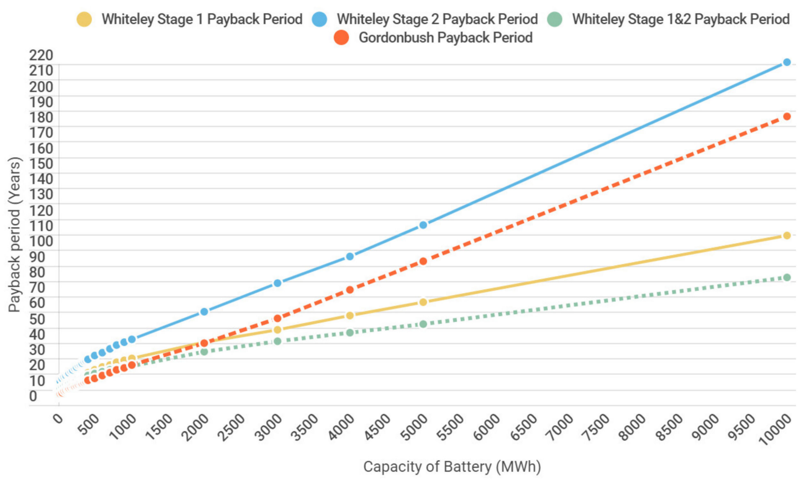

Figure 10. Payback periods for different capacity levels applied for Gordonbush and Whitelee wind farms (authors' own work).

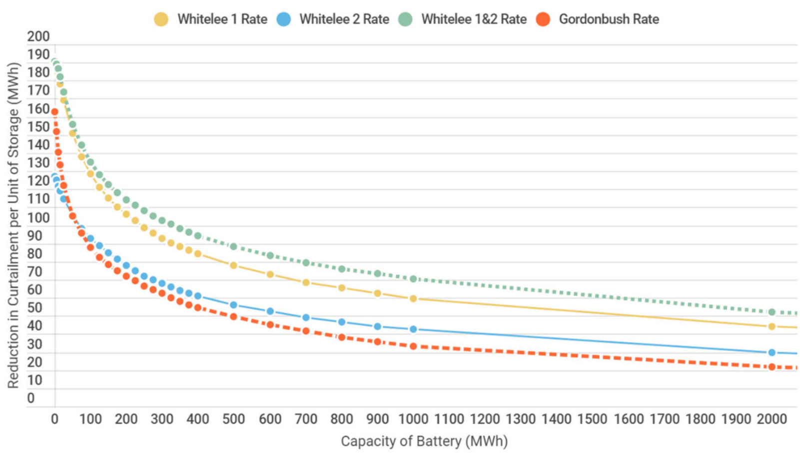

Figure 11. Curtailment reduction per unit (MW) of storage for Gordonbush and Whitelee (authors' own work).

Table 2 shows the payback period and curtailment reduction rates for all cases. This lithium-ion battery has the capability of around 18–19% reduction in Whitelee and Gordonbush wind farms in 20 years payback period. However, battery prices are going to decrease and have negative environmental impacts in long term. When the Li-ion battery cost per MWh is decreased to GBP 100,00 from GBP 207,000 in the next decade, the payback time of the investment will be much shorter as shown in Table 2. It seems that investment in Li-ion batteries will be more feasible with the reduction of their cost. For 10 years payback period, Gordonbush will be capable of reducing more than 19% of their curtailment. This reduction rate for the same time period will be 19.3% for Whitelee 1 and 2, 15.7% for Whitelee Stage 2, and 18.9% for Whitelee Stage 1.

Table 2. Payback period and curtailment reduction rates for all cases (authors' own work).

Capacit of Battery (MWh)	Whiteley Stage 1 Payback Period	Whiteley Stage 1 Curtailment Reduction	Whiteley Stage 2 Payback Period	Whiteley Stage 2 Curtailment	Whiteley Stage 1&2 Payback	Whiteley Stage 1&2 Curtailment	Gordonbush Payback Period	Gordonbush Curtailment Reduction
1	9.4	0.112	14	0.157	9.4	0.076	11	0.35
5	9.5	0.553	14	0.773	9.5	0.376	12	1.634
25	11	2.472	16	3.537	10	1.726	15	6.582
50	12	4.412	17	6.522	12	3.098	17	11.32
75	13	6.061	18	9.106	12	4.294	19	15.44
100	14	7.511	19	11.49	13	5.353	20	18.93
125	15	8.849	20	13.71	14	6.346	22	22.19
150	16	10.11	21	15.71	15	7.291	23	25.31
175	16	11.31	22	17.55	15	8.197	24	28.28
200	17	12.45	23	19.31	16	9.079	25	31.07
225	18	13.51	24	20.84	16	9.932	26	33.57
250	18	14.49	25	22.29	17	10.74	27	35.9
275	19	15.42	26	23.71	17	11.5	28	38.15
300	19	16.32	26	25.11	17	12.26	29	40.19
325	20	17.21	27	26.43	18	13.01	30	42.03
350	20	18.07	28	27.7	18	13.7	31	43.76
375	21	18.92	29	28.93	19	14.36	32	45.47
400	21	19.74	29	30.17	19	15.02	33	47.15
500	23	22.82	32	34.71	20	17.52	36	53.34
600	25	25.56	34	38.96	22	19.88	40	58.29

Limitations of the Study

The present study has the following limitations. First, the study used half an hour resolution data and the results may change if higher resolution data is used. Even though hourly resolution is commonly used in the literature, variations on the renewable output could be better captured with higher data resolution. Second, the payback period depends on the current financial parameters and incentives. Changes in the financial schemes may have an impact on the cost-effectiveness of storage units. Third, the study considered Scottish wind farms which represent nearly 94% of the constraint payments in the UK. These figures may reduce if a high voltage interconnection between Scotland and the rest of the UK is built, and smaller storage sizes may be needed.

5. Conclusions

This research aimed to examine the storage application to minimise the curtailment of wind energy and analyse the behaviour of reduction rate and a payback period of a potential storage investment in the chosen wind farms in Scotland. Current literature in curtailments of wind energy and their increase in global and national levels were examined to understand its influences on wind farms' future. Additionally, the literature has analysed possible potential large-scale storage systems for wind farm applications. The developed method included a software model, applied to the chosen wind farms, Whitelee and Gordonbush, to investigate the possible reduction in their curtailments. Li-ion battery was used to investigate payback periods and it is a response to the expected future price decrease. Moreover, each wind farm has a different sensibility to increase storage capacity. Instead of applying separate storage for each stage of Whitelee, one storage system for each stage may create faster payback. The research also showed that as a smaller capacity wind farm, Gordonbush, the reduction rate of curtailment reduction per unit of MWh of storage is higher for small battery applications up to 50 MWh compared to Whitelee Stage 2. This research confirms that large-scale energy storage systems are capable of solving the curtailment problem. When wind curtailment is controlled with the help of storage systems, it does not only help performance development of the wind farm and profit improvement but also supports grid stability and energy security of the country.

Based on the current situation of Scotland's wind profile, curtailment already exceeded an unacceptable level, and which is increasing gradually. Possible potential large-scale storage systems for wind farm applications were considered and analysed. Large-scale energy storage systems are capable of solving the curtailment problem comity. There is a possibility of a 30% reduction in a curtailment in 15 years payback period in the case of lithium battery price of GBP 100,00 MWh (megawatt hour). Some investable levels of storage capacities could have a vital reduction in the curtailment rate for curtailed wind farms, Whitelee and Gordonbush, to investigate the possible reduction in their curtailments. Each wind farm has a different sensibility to increase storage capacity. Instead of applying separate storage for each stage of Whitelee, one storage system for each stage may create faster payback. As a final remark, improvement in grid infrastructure and the use of a large number of EVs in the future may be considered in further research to reduce curtailment problems of wind farms. Wind farms will benefit by increasing their output. The national grid can pay less constraint payments to wind farms. Moreover, this study can contribute to future projects and missions like future floating islands, off-grid systems, CCS applications, and energy mission of COP26 will take place in Glasgow in Scotland. Reducing wind curtailment by applying battery systems can contribute to that aim to reduce global and UK carbon emissions to "net zero" by 2050.

Maximising the output of wind energy generation is a central pillar towards climate action. This is important for multiple stakeholders and lies at the intersection of environmental, political and economic domains. From the government's point of view, reduced constraint payments will have a positive impact on future renewable energy investments and lower the operational cost of wind farms. Higher shares of wind energy will support environmental sustainability and lower carbon emissions. This way, governments will get closer to reaching net-zero goals and meeting commitments shaped by Paris Agreement goals. From the general public standpoint, ratepayers will enjoy lowered electricity prices.

Gender studies have shown that improving access to energy reduces the gender gap for pay, as reliable energy supply leads to a reduction in time burdens for household responsibilities (disproportionately addressed by women), increases the time available for education and participation in the labour force [72]. Thus, this lowered wind curtailment will improve baseline conditions for disadvantaged groups by impacting both their social and economic standing. One way to evaluate the gender and social dimensions of renewable energy systems is analysing employment trends. As more renewable energy projects are introduced, there will be more employment opportunities for the local communities. Data from the United States and Canada shows that renewable energy sector is considerably more gender diverse than the fossil fuel industry [73].

Siting on-site storage units could be part of policy strategy for the future deployments. Currently, many wind farm projects are deployed in Scotland due to low land acquisition cost and less restrictive planning schemes. As constraint payments grow, wind farms create a foreseeable market risk. To that end, policies enforcing storage units will cushion the financial risks associated with excess energy.

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