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To cite this article: D. Buhagiar *et al* 2019 *J. Phys.: Conf. Ser.* **1222** 012038

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Increasing the Value of Offshore Wind by Integrating On-Board Energy Storage

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Abstract. Energy storage technologies are considered a promising solution for overcoming one of the most pertinent hurdles to high renewable energy penetration: the mismatch between energy supply and consumer demand. The intermittent nature of variable renewable energy technologies at high penetration rates leads to a loss of value for each unit of energy produced. Generation-side energy storage can allow wind turbines to alter their generation strategies and derive additional value through improved market participation. On-board storage leads to more efficient use of space and a potential for cost reductions. In the present work, a brief review of existing work on these aspects was undertaken, followed by a time-series analysis of an offshore 6 MW wind turbine coupled to an energy storage system. The performance of the *wind+storage* system was simulated using one year of data from the *Egmond aan Zee* offshore wind farm site. A statistical analysis was undertaken to estimate the required charge/discharge cycles and establish the required storage capacity under different operating conditions. A lithium-ion battery was then considered as the competing energy storage technology, and a cumulative damage model was applied based on the depth-of-discharge characteristics. Findings indicate that despite their competitive capital costs, battery technologies would have a limited lifetime resulting from high charging/discharging cycles. A more viable approach in the long-term could be to opt for technologies that are less dependent on charge/discharge cycles and which have a lifetime that can match that of the wind turbine itself.

1. Introduction
After long disregard, energy storage is now receiving significant attention by the energy industry; and particularly in the renewables sector, thanks to an increasing requirement for flexibility, intermittency regulation and the provision of an uninterruptable power supply [1]. According to published estimates [2], 50-90 GW of deployable electrical power from energy storage is required by the year 2050, considering a net output variation in wind power of 15-30%.

Integrated energy storage solutions can significantly increase revenue from a renewable energy system such as wind farms due to their capabilities when it comes to grid stability, load shifting, operational support, as well as increasing overall power quality and reliability [3]. It also allows the wind farm to provide Energy Storage as a Service (ESaaS) [4].

In the present work, the potential value-adding benefits of integrating energy storage at the point of generation are investigated, along with caveats of existing battery technologies due to the harsh nature of charging cycles associated with the reduction of intermittency from wind power generation.

2. Background: Increasing the Value of Wind Energy

One unit of electricity from whichever source, at any point in time, should have the same intrinsic monetary value. However, from a supply-demand perspective, 1 MWh of energy generated during times of high demand can attain a higher market value than the same 1 MWh generated during times of lower demand. This basic principle leads to what has been referred to as the "self-cannibalisation effect" of Variable Renewable Energy (VRE) generators [5]. The issue arises from the fact that the abundance of the VRE itself tends to depress market prices during periods of high availability. This can be observed in Figure 1. VRE technologies therefore lose market value [6], since their variability makes it more difficult for an accurate and strategic supply-demand match [7].
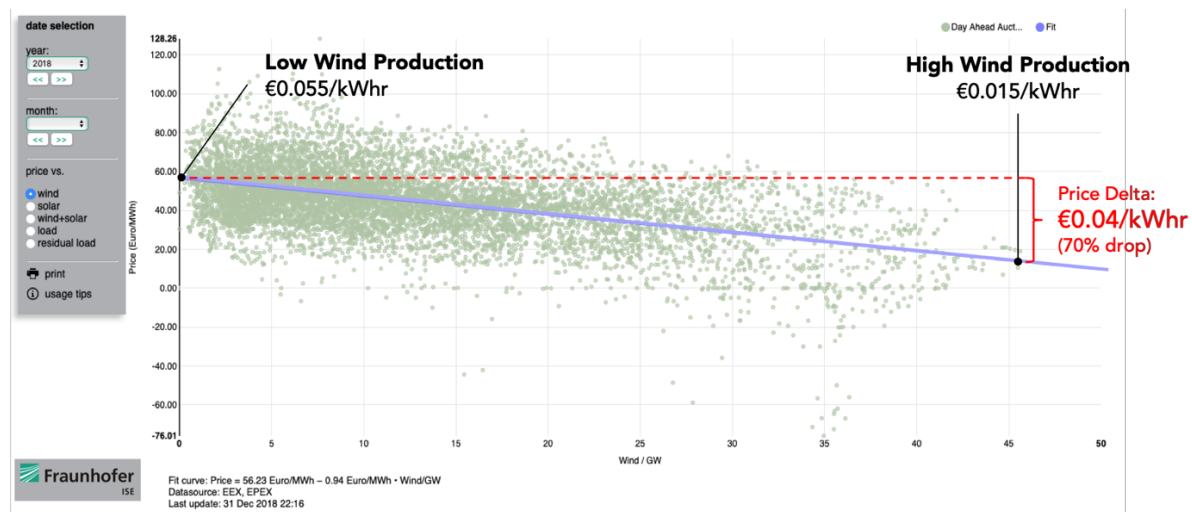

Figure 1: Spot prices vs. wind power in Germany during 2018 (source: [8])

Wind power exhibits intermittency on various time scales, often resulting in a supply variable that is disproportionate to the typical demand variability [9]. The variable nature of wind energy coupled with zero fuel costs implies that at times price suppression can lead to even negative prices [10]. This results from excess production, typically at times when prices are already low and wind power generation is particularly high. Hirth and Müller [5] state that this value drop can be significant, such that with 30% wind penetration its variable input can be worth 20-50% less than electricity from a steady production source. This impact on market value is detrimental to the competitiveness of VREs, and therefore to the decarbonisation of the energy system.

It is evident that the deployment of large quantities of wind power in the grid calls for suitable grid integration measures and an increase in flexibility. Some grid integration measures related to *generation strategies* and means of adding flexibility through *energy storage* are briefly discussed in this section.

2.1. Generation Strategies

Before attaining the high penetration rates when energy storage becomes a fundamental element for VRE integration, the VRE generators themselves can contribute through strategic generation and alternative market participation. Mills and Wiser [11] derive the economic value of wind as the sum of the *energy (market) value*, *capacity value*, *ancillary services value* and *forecast error value*. The *forecast error* is the result of deviating from the day-ahead generation schedule, and is typically *negative* if wind is traded passively on the day-ahead market (without selling regulating power). For the sake of brevity, a thorough overview of generation strategies is omitted in the present work, which instead expands on energy storage as a means of increasing the value of wind power.

2.2. Energy Storage

Beyond penetration levels where generation strategies can mitigate intermittency issues, energy storage becomes a key enabling technology for the wide-spread use of VREs [12]. But even before this happens, renewables with schedulable output (such as hydropower), can already bring about a net increase in the value of wind energy. Hydropower is essentially a form of generation integrated energy storage [13], since the reservoir acts as a storage system for the natural resource prior to generation. Of course, it can also operate as a fully-fledged electrical energy storage system through the use of reversible pump-turbines (Pumped Hydro Storage – PHS). An interesting scenario is illustrated by Hirth [14], where it is shown that at 30% wind penetration, 1 unit of wind energy in Sweden can be worth 12-29% more than the same unit in Germany. This higher value results from the fact that Swedish grids have a significant quantity of installed hydropower, which adds additional flexibility that can compensate for wind power output variability. Pérez-Díaz and Jiménez [15] showed that particularly for isolated power systems with high wind penetration, such as the Canary Islands, the implications of PHS on reducing scheduling costs can result in significant wind-integration cost savings, and therefore an overall increase in the per-unit value of wind energy.

Apart from geographically-restrictive PHS, lithium ion (li-ion) batteries have also become a formidable contender for grid-scale storage thanks to significant cost reductions, and the prospects of further price drops. When combined with a VRE technology such as wind power, the combination can form a virtual power plant [16]. This allows wind power to become a dispatchable resource and participate in real-time markets along with the potential to provide ancillary services. One such service is Frequency Containment Reserve (FCR), which is particularly lucrative for batteries, and is the primary revenue source in current market conditions. Batteries are suitable contenders for such a service since it typically requires low Depth-of-Discharge (DoD) micro-cycles, which prolong the lifetime of the battery system [17]. When it comes to *energy-shifting* applications, where the energy storage system absorbs supply surpluses to then be used to supplement deficits, batteries tend to suffer due to the requirement for deeper DoD, which significantly reduces their lifetime. Li-ion battery lifetime is notoriously difficult to predict, and practical lifetimes have been shown to deviate significantly from manufacturer quoted values [18]. The actual lifetime not only affects the return on capital investment, but also the viability from an environmental stand-point, since li-ion batteries are particularly difficult to recycle [19]. As such, a life-cycle perspective is crucial to evaluate the viability of battery storage for energy-shifting in wind power applications [20].

3. Methodology

The present study focuses on the integration of energy storage at the point of generation of a wind energy production system. The following approach is adopted:

- A hypothetical 6 MW offshore wind turbine with an integrated energy storage system is considered.

- Open-source, year-long offshore wind data from the *Egmond aan Zee* site [21] is used to simulate the behaviour of the energy storage system as it operates to provide a range of services to the Energy Management System (EMS). The data corresponds to a mean wind speed of 9.06 ms^{-1} at 112 m above mean sea level, and a wind turbine capacity factor of 50.4%. Simulations use the 10-min average wind speed records. Wake losses are neglected since the scope is limited to a single turbine.

- Two different operational strategies requiring storage are considered (Figure 2):
    (i) *Stepped Output*: a fixed power output is supplied over a specified time window (up to 6 hours), based on the forecast mean output during that window. Any deviations are compensated for by the energy storage system.
    (ii) *Ramp Regulation*: the power delivered to the grid corresponds to a moving average over a specified window (up to 8 hours), such that sharp increases/decreases in wind turbine output are compensated for by the energy storage system.

- Statistical methods are applied to assess the implications of the observed performance attributes on the required technical characteristics of the storage system (capacity, power rating, response time, etc.).

- A cumulative damage model is applied to estimate the expected lifetime of existing battery-based solutions when applied to this context.

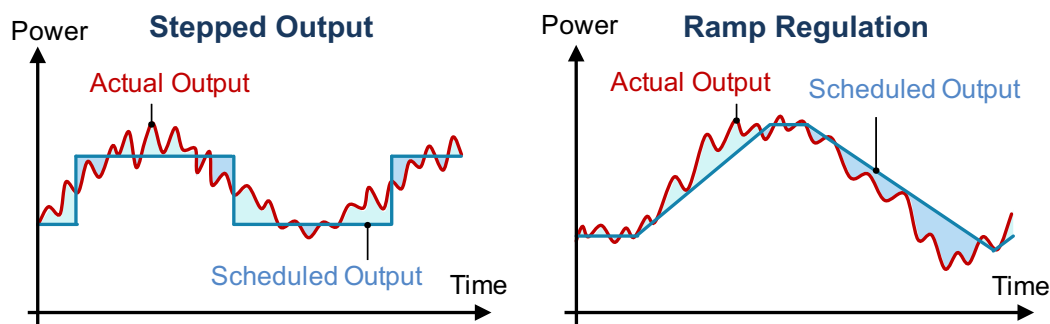All numerical modelling, statistical operations and data visualisation is carried out using MATLAB®.

Figure 2: Output power for stepped output (Left) and ramp regulation (Right) operational strategies. Shaded blue regions correspond to deviations that are compensated for by the energy storage system.

3.1. EMS Operational Strategies

The EMS interfaces between the wind turbine generator and energy storage system use two distinct operational strategies (Figure 2).

(i) Stepped output: In the first case, the system delivers a fixed power output for specific number of hours (windows of up to 6 hours are considered). This output power is established by taking the arithmetic average wind power for that window, based on the wind speed time series and the wind turbine power curve. In this case, the wind time series is historical in nature, but in practice, forecasting methods can be adopted. Based on this average value, the EMS will direct energy flows to charge/discharge the energy storage system, and compensate for deviations between the actual wind turbine output and the defined average power output. In this case, the value of wind power is increased by converting it from an intermittent output into a schedulable, on-demand, supply.

(ii) Ramped output: In the second case, rather than deliver a fixed output the EMS operates to time-average the output. A moving average is adopted, taking into account the data points falling within the defined averaging window. Based on this principle, at each time-step, the EMS refers to the required power output as computed by the moving average filter, and compares this to the actual power output. Any deviations are compensated for by routing power to charge/discharge the energy storage system. Such an averaging process improves the characteristics of the output power by eliminating sharp (ramping) power fluctuations that can cause grid instability. Compensating for these fluctuations typically requires other grid services to be available at an additional cost.

In both cases, a hypothetical energy storage system with infinite capacity is considered. The state-of-charge is represented as statistical distribution in time (number of occurrences for binned values), which allows for determining the required storage capacity for each mode of operation.

3.2. Cumulative Damage Model

Miner's Law is a cumulative damage model [22] that assesses the fraction of product life consumed by exposure to a series of stress cycles at differing levels of severity. The rule states that if there are k different stress levels and if the number of cycles to failure at the ith stress S_i is N_i, then the damage fraction C is given by:

$$\frac{\sum_{i=1}^{k} n_i S_i}{N_i S_i} = C \tag{1}$$

where n_i is the number of cycles accumulated at S_i and C is 1 at the point of system failure.

If a lithium-ion battery were to be used to smoothen the output of the 6 MW wind turbine in the above scenarios, its lifetime would significantly depend on the DoD sustained throughout its operational lifetime. Therefore, in order to determine the lifetime of the battery, Miner's Law is applied, whereby the stress level is taken to be the DoD due to its effect on the lifetime of the battery. Battery failure is defined as the point at which the effective capacity drops to 80% of the original [22].
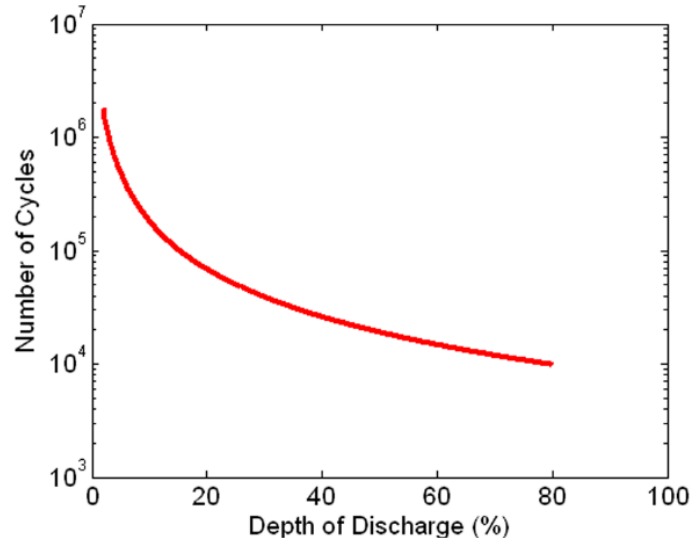

Figure 3: Typical *lifetime-DoD* curve at 25˚C for a *SAFT* Li-Ion battery (source: [23])

Using a typical *lifetime-DoD* curve for a li-ion battery, such as that shown in Figure 3, one can see that, for example, the battery exhibits a lifetime of 8,000 cycles at a DoD of 100%. However, lower DoD cycles can result in much higher lifetimes, since the relationship is non-linear.

In the present work, the damage fraction sustained throughout the year under investigation can be determined by considering the various DoDs of the storage system as it operates to provide the desired mode of operation specified by the EMS, and taking their total sum. Therefore, the damage fraction sustained during a year of operation is given by:

$$C = \frac{\sum DoD}{100 \times L} \tag{2}$$

where $\sum DoD$ is the sum of the DoD timeseries for the one-year simulation and L is the lifetime (in number of cycles) of the energy storage system.

Since failure occurs at a damage fraction of 1, and assuming that subsequent years exhibit identical discharge behaviour, then the lifetime of the battery in years can then be determined. For this method to be consistent with the most standard universal definition of DoD [22], this value was computed based on instantaneous capacity at the end of a discharging period (at the time-step where the system stops discharging) and not the instantaneous level of charge at each time step, see Figure 4.
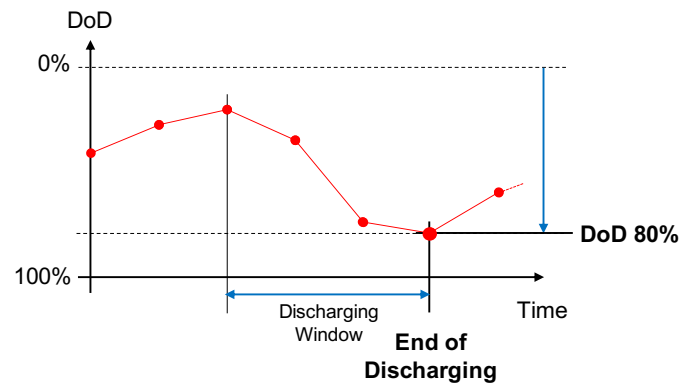

Figure 4: Illustration of how the DoD is established for the cumulative damage model.

For the purpose of establishing the DoD, and then applying the cumulative damage model, the storage capacity must be established *a priori*. This is based on the findings extracted from the statistical distribution of the time-series of instantaneous stored energy (state-of-charge), obtained for each of the operational strategies outlined in Section 3.1.

4. Results

For both (i) *stepped output* and (ii) *ramp regulation*, a statistical analysis is carried out on the time-series of the energy storage system's state-of-charge. This allows key results to be extracted, such as the required storage capacity for each mode of operation, and the estimated number of cycles over a 30-year operating window. Selected results for stepped output and ramp regulation operating modes are shown in Figure 5 and Figure 6, respectively.

These results allow for the determination of the required energy storage capacity, which is based on the maximum value of energy stored throughout the year. The number of energy storage cycles is also estimated by considering the number of occurrences that the system will switch from charging to discharging mode (Figure 4). Other definitions of a charge-discharge cycle can be applied, although technology-specific definitions have been avoided to make the findings applicable to a wider range of storage solutions. Extracted values are shown in Table 1. These values are conservative, since round trip energy losses are ignored, and the required capacity is based on the system handling 100% of the regulation requirements, which might not be the most practical or cost-effective approach.

Table 1: Storage system capacity and number of cycles over a 30-year operating window.

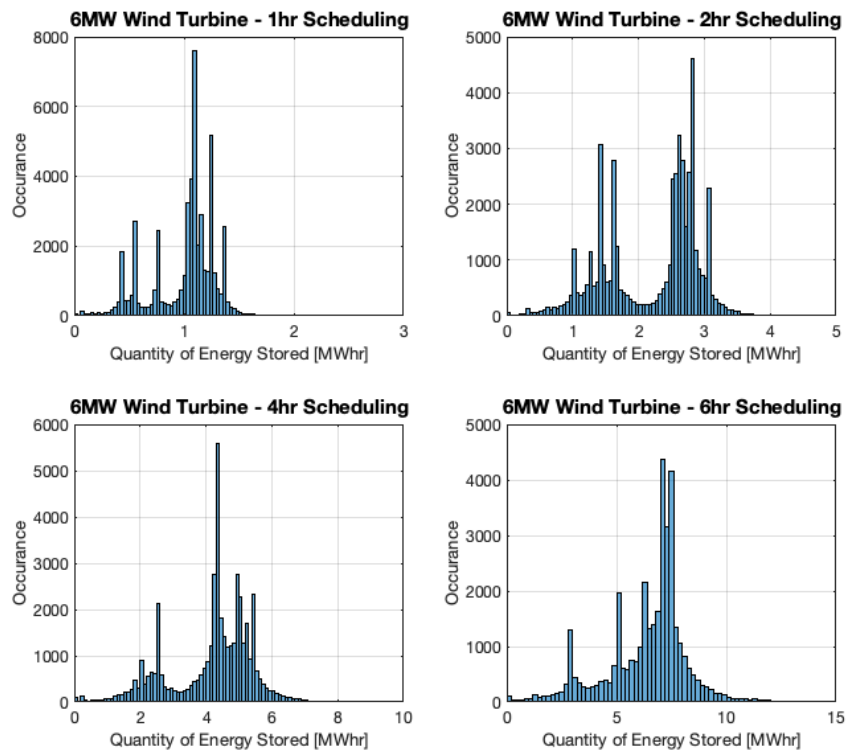| Stepped Output			Ramp Regulation		
Scheduling Window Hours	Storage Capacity MWh	Storage Cycles n_i	Averaging Window Hours	Storage Capacity MWh	Storage Cycles n_i
1	1.6	197,700	2	4	165,210
2	3.8	138,600	4	5	120,420
4	7.5	94,110	6	6	102,750
6	12	63,900	8	7	89,130

Figure 5: Distribution of energy stored during one year of operation, for scenarios during which the wind turbine output is fixed for 1, 2, 4 and 6 hours.
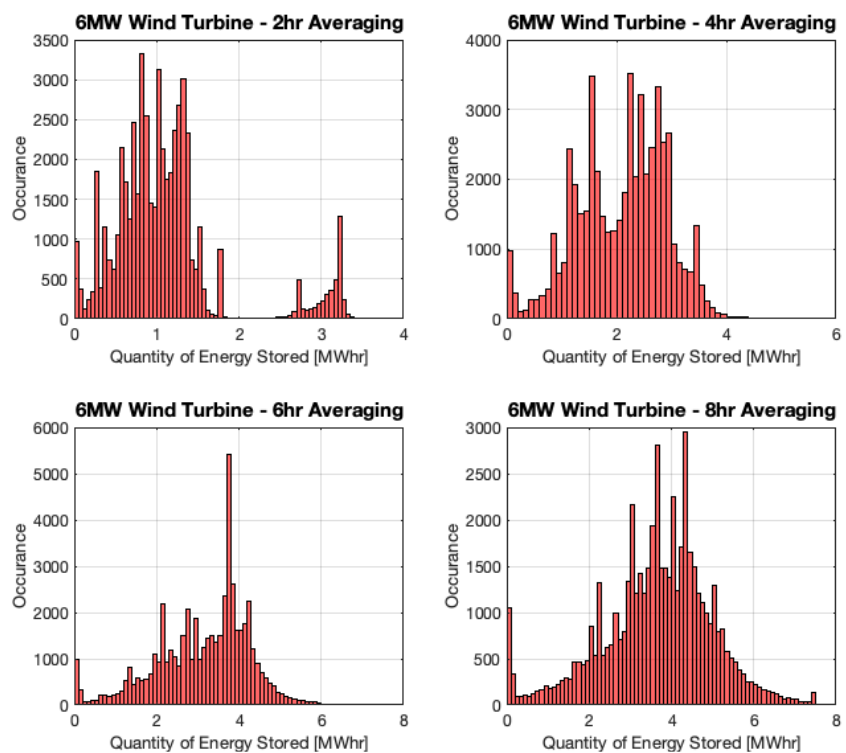

Figure 6: Distribution of energy stored during one year of operation, for scenarios during which the wind turbine output corresponds to the moving average for 2, 4, 6 and 8-hour averaging windows.

The time-series of stored energy can also be used to compute the instantaneous DoD of the energy storage system for the different operational strategies. This is taken to be the state-of-charge at which the system switches to charging mode following a period of discharging (Figure 4). DoD is fundamental when estimating the expected lifetime of the energy storage system. Lifetime is crucial to increasing the net value, since a cost-effective energy storage solution will be one that does not require frequent replacements, particularly in the context of a system deployed offshore.

For the purpose of establishing the effective lifetime of a battery through the application of Miner's Law, a hypothetical li-ion battery with a lifetime of 8,000 cycles at 100% DoD, having a capacity based on the mode of operation (Table 1) is considered. Based on these criteria, and using Miner's law, in the case of a 4-hr stepped output, the lifetime of the li-ion battery in this context was determined to be around 5.5 years. This relatively short lifetime is due to rapid charging/discharging cycles, and frequent occurrences of high DoD. The latter can be observed in Figure 7 where it is shown that the DoD is greater than 28% for 90% of the occurrences. Expected li-ion battery lifetime for the various operational strategies outlined in Table 1, are shown in Table 2.
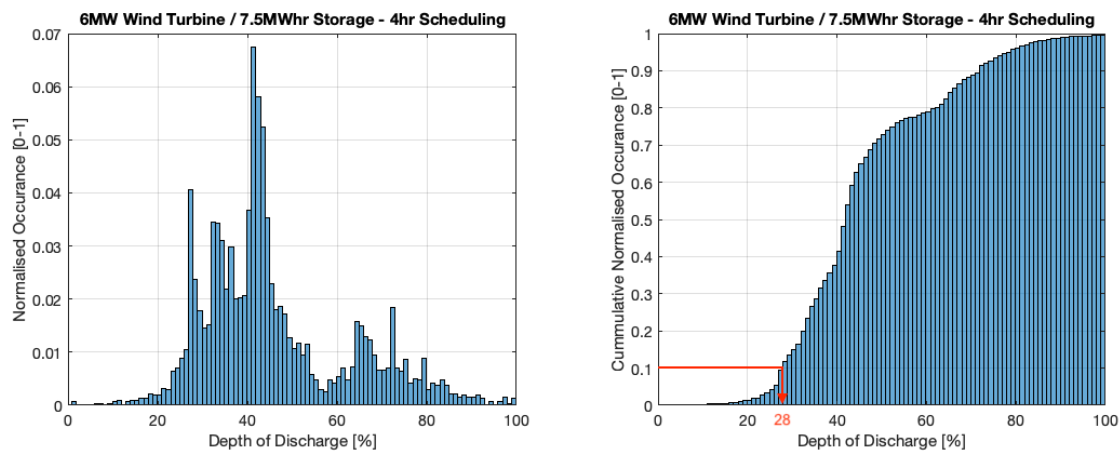

Figure 7: Distribution of DoD for one year of operation, with wind turbine output fixed for 4 hours.

From the lifetimes computed in Table 2 one can note that in all cases the lifetime is relatively short, compared to the 25-30 year operating window of typical offshore wind turbines. Moreover, it can be observed that the lifetime seems to increase as the scheduling/averaging window increases. This effect is observed since, with every increase in the hourly window, the storage capacity is also increasing. This implies that the storage system sustains lower DoD cycles, despite the longer time window. However, it must be noted that the capacity increase is significant. Assuming a fixed unit capital cost (€/kWh), in order to increase the lifetime from 3.14 years to 7.64 years (a factor of 2.4), and the scheduling window from 1 to 6 hours, the total cost would increases by a factor of 7.5.

Table 2: Effective lifetime for a li-ion battery determined by Miner's Law under different operational strategies. The battery has a specified lifetime of 8,000 cycles at 100% DoD.

Stepped Output			Ramp Regulation		
Scheduling Window Hours	Storage Capacity MWh	Effective Lifetime Years	Averaging Window Hours	Storage Capacity MWh	Effective Lifetime Years
1	1.6	3.14	2	4	2.03
2	3.8	3.41	4	5	3.37
4	7.5	5.51	6	6	4.27
6	12	7.64	8	7	5.07

5. Conclusion

Generation-side energy storage can add value to wind energy by mitigating price suppression resulting from congested energy grids, particularly during periods of high wind energy supply. Simulation results using one year of real wind data for a North Sea site and the corresponding operation of a 6 MW wind turbine operating in conjunction with an energy storage system were used to establish the storage capacity required under different modes of operation. The use of a li-ion battery system with a specified lifetime of 8,000 cycles at 100% DoD was evaluated using a cumulative damage model (Miner's Law). Results indicate that the battery system would reach end of life well before the wind turbine. In the best case scenario (12 MWh system for 6 hour scheduling), the lifetime was found to be 7.64 years.

One possible solution to increase lifetime is to oversize the battery bank, and therefore reduce occurrences of high DoD. However, this implies a significantly higher capital expenditure and hinders the net value delivered by energy storage to the wind farm. It also results in higher spatial requirements, making it unfeasible to integrate within existing wind turbine structures. Another approach is to utilise alternative technologies whose lifetime is less sensitive to charge/discharge cycles and which in effect have a lifetime that can match that of the wind turbine itself. Systems such as hydro-pneumatic accumulators [24] could be ideal, since they use infrastructure that is already well-understood in the offshore sector and can withstand up to 100,000 cycles. Moreover, they avoid significant safety and environmental challenges posed by batteries, particularly when these are implemented in the offshore context, due to issues with flammability and use of hazardous materials.

Integrating on-board energy storage could result in additional revenue streams and increase the net value for offshore wind farms. The key issue is to adopt storage technologies that can handle the intermittency associated with wind power and that can maintain operation throughout the lifetime of the turbine with minimal intervention. Environmental issues and safety must also be considered, especially if a storage system is to operate in the marine environment. As such, alternative technologies to batteries could be more suited due to the longer service life. The right energy storage technology could be a key enabler to increase the value of offshore renewables.

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