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A review and proposal of future framework

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Review article

Opportunistic maintenance for offshore wind: A review and proposal of future framework

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ABSTRACT

As new offshore wind development sites move further from shore and existing sites enter their post-subsidy operating period, it is expected that operational expenditure (OpEx) will increase. In order to overcome these challenges, a more flexible and cost-effective maintenance solution is needed. One such solution is opportunistic maintenance (OM). This work provides an overview of the maintenance strategy used within other industries before providing an in-depth review of the work specific to offshore wind. The existing literature fails to agree on the specific definition of the term. This work proposes an all-encompassing definition of the term, reviewing maintenance 'opportunities' and their corresponding 'action/response'. The review found that maintenance opportunities are either internal or weather-based, with each opportunity having a pre-determined trigger/response. This work proposes the introduction of a market-based opportunity, which has not been previously considered. As offshore wind farms now face increasing curtailment and negative pricing threats, this new OM framework, OM+, view these periods as maintenance opportunities. OM+ also provides a new definition for recording and reporting availability — moving from time/energy-based availability to market-based availability.

1. Introduction

As the impact of climate change increases worldwide, several nations have embraced the deployment of renewable generation. There are a number of Net-Zero ambitions and agreements globally such as the Paris Agreement 2015. The UK government set its own target with a commitment to Net Zero by 2050, and the Scottish Government has an even more ambitious target of Net Zero by 2045 [1]. Offshore wind is expected to be one of the key factors contributing to achieving these ambitious goals.

The recent UK contract for difference (CfD) auctions (2019 & 2022), saw offshore wind secure a strike price below the current market rate (2022). However, there are growing concerns surrounding the sustainability of price reduction within the industry. It is possible that these savings could potentially choke the supply chain as increased pressure for cost-reduction savings is passed through it. Now, as offshore wind becomes increasingly cost-effective, it is probable that future sites will operate subsidy-free, as the technology has proven not only to be viable but also to be profitable

Operational expenditure (OpEx) can account for around a third of the total levelised cost of energy (LCoE) [2] making it a key area for cost reduction. Once a site becomes operational, this is one of the few costs that can still be controlled. Now, as sites are maturing, there is an expected increase in annual OpEx due to the ageing of assets. This is then combined with the reality of post-subsidy operation, where income is no longer protected through the CfD. Increasingly, research is focused on the lifetime extension of existing assets that will prolong the operational period under volatile market conditions [3] where components will enter their "wear out" phase. With the loss of a "guaranteed" income, OpEx budget is likely to suffer in a bid to reduce expenses and maximise end-of-life profits. This is then accelerated by the recent trend of increasing commodity turbine prices, further resulting in OpEx budget constraints.

OpEx budgeting is also a key theme for future and newly commissioned sites. Newly consented sites, such as ScotWind and Crown Estate Round 4, are being located in more remote, challenging locations far from shore. The introduction of floating offshore wind (FOW) is expected to result in a reduction in accessibility due to additional restrictions imposed on workability due to the motion of the structure [4, 5]. These factors will increase the criticality of weather windows,

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putting additional stress on operation and maintenance (O&M) activities. Even if protected by CfD or power purchase agreement (PPA), the operational challenges with these sites and required OpEx budgets will have a significant impact on project financing.

1.1. Maintenance framework

To overcome these challenges, flexible and cost-effective maintenance strategies must be utilised. One such strategy, which has been gaining traction in recent years, is opportunistic maintenance (OM). This strategy was first applied to offshore wind in 2009 by Besnard et al. [6] by applying an existing maintenance technique used in the aerospace industry to a small-scale offshore wind site. This strategy typically involves performing multiple repair actions during a single trip offshore triggered by author-defined “opportunities”. This grouping of activities and opportunistic planning allows for sharing resources, such as vessels and crew, between maintenance actions, which results in an overall decrease in OpEx. Dispatch/transport operations are a significant area of cost reduction and have been shown to account for more than 70% of total O&M costs [7,8]. This methodology also has operational safety advantages, as it decreases the number of trips offshore, which is a safety–critical process.

This strategy is commonly used within the industry as it is common to “never waste a weather day” and therefore make effective use of both resources and technicians. However, the existing literature fails to find a universal definition of both OM and an “opportunity”. Part of this work aims to analyse the current literature and the definition of such terms.

As sites enter their post-subsidy operational phase, operational decisions will become more heavily influenced by market conditions, as income is no longer protected from periods of low, or negative, market prices. This will also be a challenge for the next round of UK-subsidised sites. Previous rounds included a rule that stated that generators would not be compensated for power exported to the grid if day-ahead prices dipped into the negative for six hours or more. New CfD sites will no longer be protected from negative pricing periods under the new terms for Allocation Round 4 (AR4). The new contract terms will remove the subsidy from a plant if the price they are assumed to receive from the market is negative [9]. Within current OM literature surrounding offshore wind, the impact of negative pricing on maintenance operations is not considered.

Furthermore, high levels of wind penetration on the system also increase the threat of curtailment. At present, it is reported that offshore wind curtailment within Europe is limited to 5% annually [10], despite current high levels of wind penetration. The Offshore Wind Sector Deal commits to an additional 30 GW of offshore wind installed capacity by 2030 [11], and most recently, the historic ScotWind leasing round allocated over 25 GW of capacity leasing, over doubling the planned and expected, 10 GW allocation [12]. High levels of generation may result in bottlenecks in the grid, such as the B6 boundary [13], and other interconnectors, such as Moyle and GridLink, becoming unsuitable as generation exceeds national demand and interconnector capacity during periods of high wind, leading to the curtailment of wind generation technology.

The authors identify curtailment and negative pricing times as periods of “free downtime”, e.g. periods where the turbine would already be shut down due to external influences. Therefore, it is proposed that these events should be included as ‘opportunities’ within an OM framework, where O&M activities can be scheduled to be performed during these intervals, such as preventive/predictive maintenance actions, scheduled inspections, or annual servicing. The authors propose a future OM + framework that combines existing OM-developed strategies with the addition of external market concerns and their impact on turbine maintenance.

Section 2 summarises current maintenance strategies used within offshore wind, with details of how existing maintenance policies link to the OM strategy. Section 3 provides a background of OM theory and its application within other industries. This section also highlights its relevance to an offshore wind application. Section 4 reviews the existing literature on the use of OM within offshore wind. Section 5 highlights additional market-based opportunities which could be included within an OM framework, which is further explained in Section 6. Finally, a discussion of the findings and recommendations for future work are given in Section 7.

2. Offshore wind O&M strategies

Maintenance strategies within offshore wind are typically classified as scheduled and unscheduled [14]. Unscheduled maintenance, also called corrective maintenance (CM), is a reactive maintenance practice in which components are repaired upon fault without an attempt to preempt failure. While this offers a straightforward solution and minimal initial cost while maximising the remaining useful life (RUL) of components, there is significant unplanned downtime involved and further damage costs due to secondary damage in other components. As the scale of offshore wind farms expands rapidly, a CM strategy is no longer suitable and is gradually being replaced by preventive maintenance (PM) strategies [15].

Preventive maintenance (PM) is classified as scheduled maintenance, which is performed proactively to inspect and repair degrading components in an attempt to reduce unexpected downtime [16]. There are various approaches to determine when exactly to perform the maintenance action, which distinguishes the various subcategories shown in Fig. 1. This can include time-based maintenance, condition-based monitoring (CBM) or predictive maintenance (PrM).

CBM involves ongoing monitoring of component health to identify potential issues at an early stage and determine the most suitable maintenance actions. When a component deteriorates to a particular state, a preventive repair or replacement is undertaken. While this has the advantage of reduced unplanned downtime, this strategy introduces additional upfront capital costs for sensing equipment. Artificial intelligence techniques, particularly deep learning, are now being utilised within the CBM methodology to facilitate in decision-making [17].

PrM instead aims to prevent failures from occurring in the first place, by performing preventative repairs or replacement. Early intervention can save up to 8% of direct O&M costs [18]. Currently, it is more common to use internal combinations of machine learning methods and statistical approaches in data-driven models rather than linking data-driven models with model-based models externally [19,20].

Opportunistic maintenance (OM) aims to carry out maintenance actions whenever the opportunity arises in an effort to further reduce costs. This can result in the sacrifice of the RUL of a component, due to early intervention triggered by a maintenance opportunity. In Fig. 1, both CM and PM are linked to OM. CM can provide an opportunity to carry out PM activities. Opportunities for maintenance are not only limited to CM occurrences, as discussed in Section 4.2. However, the OM strategy focus remains on cost-effective maintenance practices [21,22].

3. Opportunistic maintenance overview

The concept of OM, or opportunistic replacement as it is sometimes referred to, was first proposed by McCall, Radner and Jorgenson in 1963 [23] as an optimal maintenance policy of a single component in a multi-component system. The key methodology within this policy is that maintenance is to be performed on a given part at a given time, depending on the state of the rest of the system. The simple approach of using the opportunity of a component failure to conduct maintenance tasks on other related components was tried and altered to satisfy numerous system conditions. Since then, this methodology/framework has been adapted for several industries.

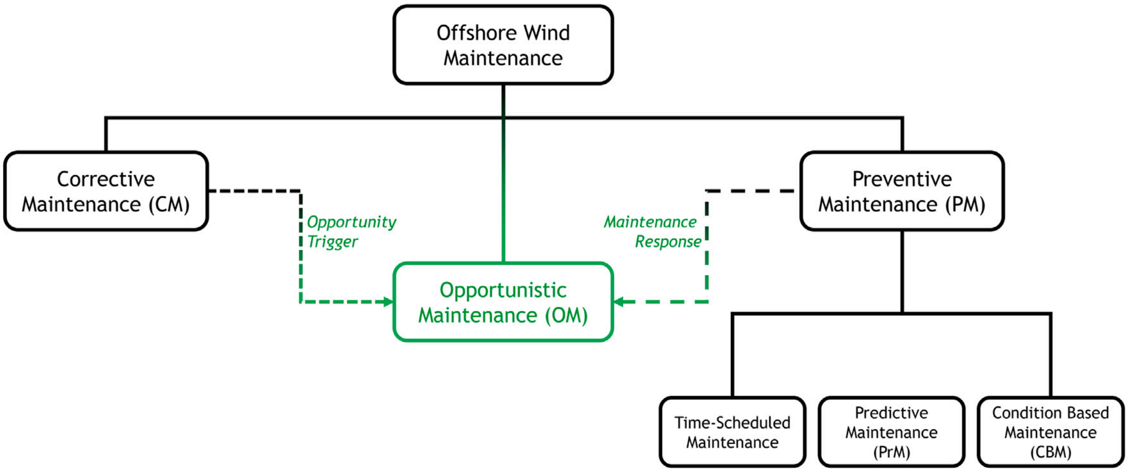

Fig. 1. Offshore Wind Maintenance Strategies and their relation to opportunistic maintenance (OM).

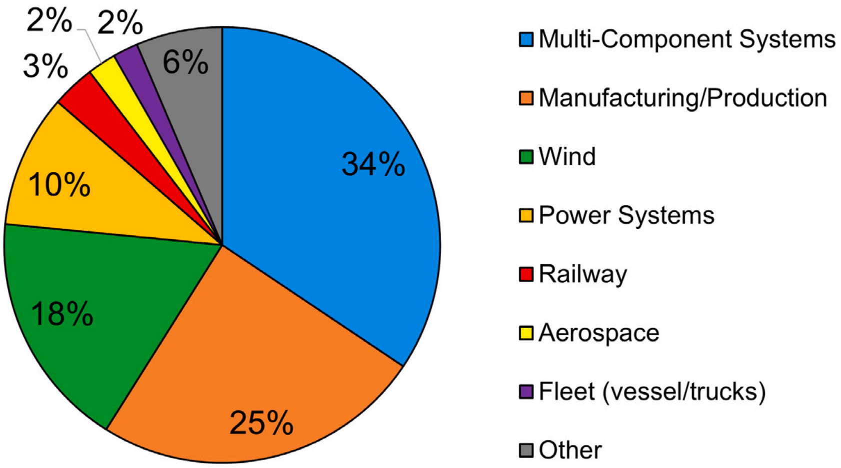

Fig. 2. Split of applications applied with OM publications based on 380 publications on "opportunistic maintenance" 1962–2022.

Several reviews on developments in OM policy and strategy have been conducted, including the most recent by Ab-Samat et al. [24]. The core issue in OM research concerns the technical and economical conditions of the components for conducting replacement or repair. Therefore, taking an opportunity should not have a negative impact on the income/cost of the overall system.

3.1. Key industries

While the focus of this review is publications specifically relating to the application of OM within offshore wind, this section provides a brief overview of the use of the strategy within other industries.

The top industries in which this method has been applied within the literature can be determined. The results are summarised in Fig. 2. The literature was gathered using WebOfScience using the keywords "opportunistic maintenance". All review articles or papers published after 2022 were excluded.

The majority of the existing publications are focused on an unspecified multi-component, or multi-unit, system. The universal definition of the system in terms of independent and dependent components experiencing failure allows the methodology to be applied to a number of specific case studies. The common theme within these publications was that the systems and subsequent subsystems were economically linked.

The most common industry-specific application of the methodology is within manufacturing/production. Manufacturing facilities have the same objectives as offshore wind farms of maximising output, by reducing downtime and improving reliability while maximising availability. Manufacturing facilities consist of a given number of machines, each consisting of a given number of sub-systems/components.

The degradation of manufacturing machines occurs according to their production rates, which affects the availability and quality of their output products [25]. This is the same process seen in offshore wind, where the degradation of the asset can lead to reduced power output.

Like offshore wind, manufacturing also has set limitations surrounding the operation of the system. Maintainability of the systems is challenging due to weather factors [26–29] and the waiting time for parts or staff [30–35]. System outages can also be forced due to lack of demand [36,37] or low commodity prices [27,28,38].

The most common application of OM within this industry is performing scheduled maintenance during unplanned outages [28,32,39–41]. A similar trend is found within the offshore wind literature as seen in Section 4.2.1.

In OM publications on power systems, case studies include nuclear power stations [42,43], transmission systems [44–46], renewable generation [47–49], and oil and gas [50,51].

4. Opportunistic maintenance in offshore wind

OM was first applied to the offshore wind industry by Besnard et al. [6] in 2009, by adapting an OM methodology specific to the

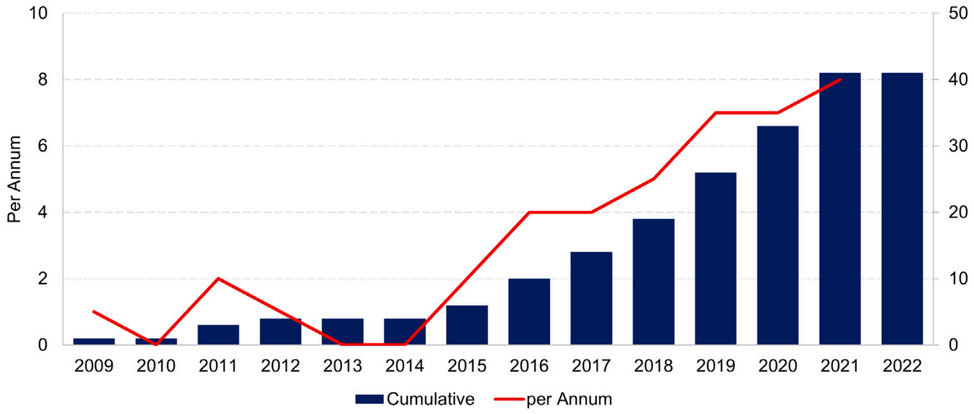

Fig. 3. Total number of opportunistic maintenance publications (both per annumn and cumulative) with focus on offshore wind O&M from 2009–2022.

aircraft industry. The strategy involves performing additional (non-critical) maintenance activities when there is an "opportunity" to do so. The definitive definition of both OM and the arising "opportunity" is still disputed within the literature. However, all agree that the approach encourages a flexible O&M methodology which has economic benefits due to the sharing of resources, and/or performing maintenance activities in economically favourable periods. This section identifies key contributors to the knowledge of OM within an offshore wind context and analyses key trends within the literature. The definition of maintenance actions and opportunities is also explored.

4.1. Literature overview

OM for offshore wind is becoming more popular within the literature and therefore is now included within recent O&M reviews such as [15,22,52,53]. However, to the authors' knowledge, there has yet to be a review focused solely on this strategy. Work by Erguido et al. [54], provides a clear overview of the current state of the literature surrounding OM. This work also analyses the use of the levels of maintenance used including one level, perfect/imperfect and several levels.

Li et al. [55] also include a brief review of the existing literature in their work, where they consider failure modelling, the inclusion of environmental impact, and preventive dispatch. Li et al. [55] introduce the concept of a "maintenance trigger". This is the event which triggers an OM strategy to be applied, also known within this work as an opportunity. Within their review, they concluded that the environmental impact was overlooked and was a key element of the overall OM-based approach. [55] highlight the trade-off between the frequency of preventive dispatch and the cost of performing maintenance which is reflective of that found in the work of Ab-Samat et al. [24] in their review of OM within all industries.

There has been a steady growth in academic interest in the topic, as seen in Fig. 3. Interest in this area has seen a steady growth in the number of publications annually since 2015. 2015 also saw a dramatic increase in annual installed capacity across Europe with 419 offshore wind turbines installed. In terms of installed capacity, this was a 108.3% increase over 2014 and the largest annual increase in capacity to date [56].

4.2. Definition of an opportunity

Within this work, the authors define an opportunity as "*a pre-determined event which triggers a decision to perform a predefined set of tasks*". These opportunities can be simply categorised as internal or external, as first presented by Erguido et al. 2018 [57]. Internal opportunities are from within the wind farm (typically maintenance-based), and external opportunities come from influences out within the wind farm, such as weather. Fig. 4 provides an overview of the classification of the opportunities considered in existing publications. The majority of publications only consider internal opportunities within their OM framework. Opportunity triggers are rarely based solely on external factors, as seen in Kennedy et al. [58].

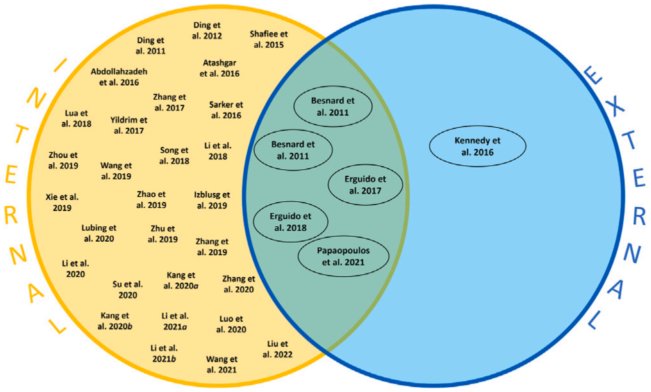

Fig. 4. Classification of opportunities used within the literature.

4.2.1. Internal opportunity

An internal maintenance opportunity is triggered by an action within the wind farm. The most common opportunity within the literature is a maintenance action. If a maintenance action is triggered (either scheduled or unscheduled), then this presents an opportunity to perform additional maintenance activities during a single trip offshore, as staff and vessel resource are already deployed. Other internal opportunities can include incident-based transfers where the arriving environmental impact is set to have a critical impact [59,60]. Classification of internal opportunities is CM only, PM only or CM & PM activities.

As discussed in Section 2, CM activities make up the majority of offshore maintenance actions. Due to the critical nature of these failures and the high cost associated with asset downtime, it is logical that CM activities are viewed as the key opportunity or trigger to perform OM activities. Works by Ding & Tian [61,62], Shaifee et al. [63], Sarker et al. [64] and Li et al. [65] only consider CM opportunities for OM maintenance actions. It is most common for publications to use both CM and PM maintenance actions [6,54,57,59–81].

Fig. 5 shows the proportion of publications which consider CM & PM, CM only, PM only, or a different internal opportunity, "other". Within this work, "other" refers to maintenance actions which were not specifically classified as CM or PM. These included "any maintenance action" [82], and the event of a crew dispatch [70,79].

Table 1
Categorisation of scheduled maintenance activities as opportunities within the literature.

Publication	Predictive maintenance classification			
	Scheduled	Reliability threshold	Defect detection	CBM
Shafiee et al. 2015 [63]			✓	
Abdollahzedeh et al. 2016 [67]		✓		
Atashgar et al. 2016 [68]		✓		
Zhang et al. 2017 [69]		✓		
Lu et al. 2018 [83]	✓			
Erguido et al. 2018 [57]	✓			
Lua et al. 2018 [84]	✓			
Zhou et al. 2019 [72]				✓
Xie et al. 2019 [73]		✓		
Zhang et al. 2019 [74]		✓		
Izblusg et al. 2019 [75]		✓		
Wang et al. 2019 [76]	✓			
Zhao et al. 2019 [85]	✓			
Li et al. 2020 [55]	✓			
Kang et al. 2020 [86]	✓			
Lubing et al. 2020 [78]	✓			
Zhang et al. 2020 [87]	✓		✓	
Su et al. 2020 [88]	✓			
Kang et al. 2020 [77]	✓			
Luo et al. 2020 [89]	✓			
Li et al. 2021 [60]				
Papaopoulos et al. 2021 [79]	✓			
Xia et al. 2021 [80]	✓			
Li et al. 2021 [59]				
Wang et al. 2021 [81]	✓			
Liu et al. 2022 [90]	✓			

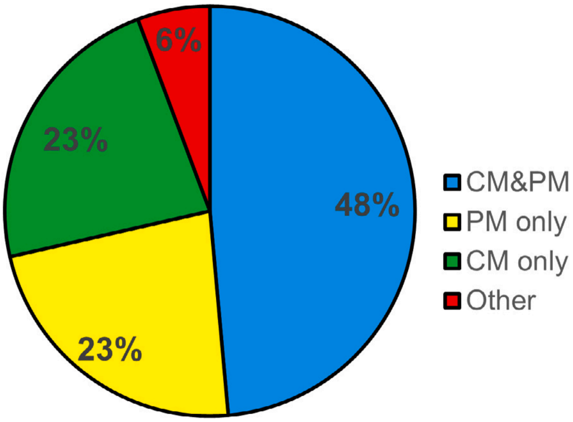

Fig. 5. Types of internal opportunities considered in the existing literature.

In the event of a CM maintenance action, there is an immediate attempt to repair and therefore take the opportunity. However, the treatment of PM opportunities is more complex. PM can range from scheduled maintenance activities based on time, such as inspections, to more complex defects detection and CMB activities. The most common classifications of PM activities used as opportunities are as follows.

- Scheduled: PM triggered based on a pre-defined time schedule
- Reliability threshold: when the reliability threshold is reached, PM is triggered.
- defect detection: if a specific defect on a specific component is detected
- generic CBM: outputs from CMB trigger PM activities

Table 1 summarises their use within the literature.

The most common version of PM used within the literature is generic/scheduled. This is the most simple to implement, as it requires a list of predetermined PM tasks with a specified frequency, duration, and resource requirement. The use of PM based on reliability and defect detection requires a greater understanding of failure distributions and maintenance thresholds.

The work of Zhang et al. [87] uses a defect-centred maintenance approach that examines the impact of environmental disturbance on both the initialisation and propagation of the defect. This then introduces three types of maintenance windows: regular, opportunistic, and postponed, dependent on the severity of the defect detected. Shafiee et al. [63] also introduce defect detection, but only for a single component. If the length of a crack in a blade reaches a predetermined threshold, an opportunity is triggered. In the event of a defect, a complete replacement of the blade is performed, with PM performed on the other blades.

Zhou et al. [72] propose a dynamic opportunistic condition-based maintenance strategy through the use of predictive analysis. When a maintenance lead time is introduced, maintenance actions can be scheduled more economically.

For publications which exclusively consider one type of maintenance trigger (corrective or preventive), the literature can easily be split before/after 2018. A number of works consider only corrective opportunities to perform preventive tasks [6,54,61–66]. This approach is more common in earlier articles (pre-2018). This may be due in part to the infancy of the use of CBM techniques within the industry. Those who exclusively view preventive maintenance as an opportunity and a trigger are more commenting in recent years for example, post-2018 [55,84–90]. Zhang et al. [74] is the only publication, post 2018, which performs "traditional" PM tasks, such as inspections, when operational, based on a PM trigger/opportunity. The PM opportunity is based on condition monitoring, including age-based spare parts replacement upon defect identification. This is illustrated in Fig. 6.

4.2.2. *External opportunity*

An external maintenance opportunity is triggered by an influence independent of the wind farm. Within the existing literature, this is most commonly weather-based using wind speed. If the wind speed falls below the cut-in speed defined by the manufacturer, the turbine will not operate. Therefore, this may be an opportune time to perform maintenance activities. One of the main focuses on operational cost reduction is minimising downtime. Many developers view downtime as an opportunity cost, this is the income which would have been generated had the turbine been operational. Therefore, the opportunity cost occurs during failure and is maximised by prolonged downtime

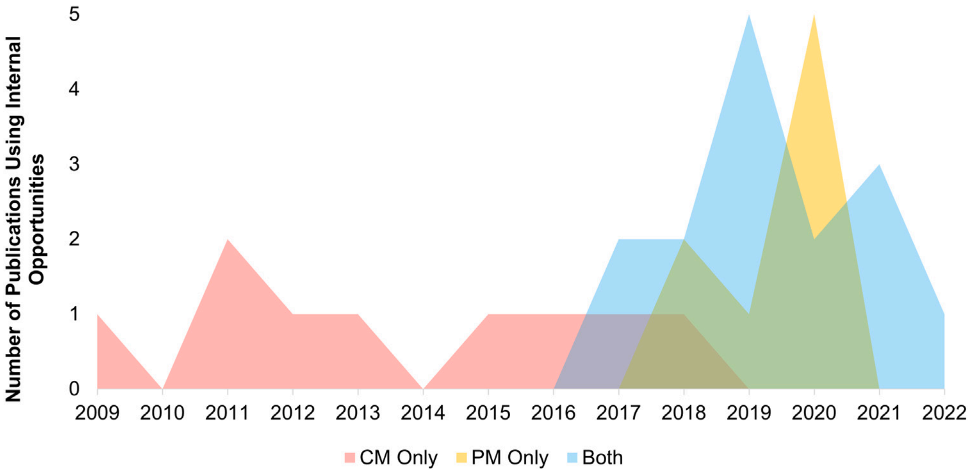

Fig. 6. Breakdown of publications using internal opportunities.

due to weather and travel restrictions. Therefore, there are savings to be made by performing maintenance during periods of low wind speed when revenue will be reduced.

Performing maintenance during periods of low wind speed/power production was first proposed by Besnard et al. 2009 [6]. Besnard et al. 2011 later expanded on this approach [66]. The methodology has since been used in works by Kennedy et al. [58] and Papadopoulos et al. [79].

The works of Kennedy et al. [58] and Besnard et al. [66] are based on the first offshore wind OM publication [6]. It was found that significant cost savings can be achieved by scheduling maintenance tasks at times of predicted low power production. Weather forecasts are generated using short horizon interval which is discretised into time steps, each consisting of one day. This modelling work falls into the realm of operational planning [91], where the chosen strategy is used to inform day-to-day scheduling decisions. The works of Besnard et al. [6,66] considered the impact over the lifecycle of the site.

Works by Eguido [54,57] combine both internal and external maintenance actions. The maintenance decision-making process is based on the dynamic reliability threshold, where the value of the threshold depends on the weather condition. This ties reliability to low wind speeds and ensures that any OM actions/responses to the opportunity of low wind speed are beneficial to the overall system to avoid wasted journeys to the site to perform unneeded maintenance during “favourable” conditions.

Yildirim et al. [70] consider the effects of maintenance on electricity production by coordinating wind turbine maintenance schedules with turbine dispatch. This is based both on the forecast wind power and the electricity price. The optimisation model determines whether it is more profitable to conduct maintenance right away so that the wind turbine can start generating electricity, or if it would make more sense to delay maintenance so that the maintenance can be grouped. The electricity price was varied from $12.5/MWh to $100/MWh to study the sensitivity of market price on O&M performance metrics. As expected, an increase in the price of electricity results in an increase in net profit. There is also a significant dependency between the length of idle time and the price of electricity. As electricity prices rise, the opportunity cost of lost revenue also increases, allowing maintenance policy to schedule more crew visits to minimise loss of production. Although the price of electricity influences the decision, low pricing periods are not considered a distinct opportunity. However, they inform other potential opportunities.

Shafiee et al. [63] include the impact of weather conditions on operations. Within their work, they consider environmental shocks to the system. The impact of such a shock can be minor or catastrophic. However, the environmental shock then triggers PM activity, which is viewed as an opportunity. Therefore, Shafiee et al. [63] only consider internal opportunities, however, these opportunities are influenced by external parameters.

The works of Li et al. [59,60] also consider environmental impacts/incidents within their work. They consider maintenance opportunities created by the degradation of failures and incidents, in addition to age-based PM. If the arriving environmental impact is critical so that the component fails, the maintenance opportunity will appear. However, as in Shafiee et al. [63], the environmental impact triggers the need for maintenance action. Therefore, it could be argued that this should also be classed as an internal opportunity with external influence.

Papadopoulos et al. [79] create a unique model that combines dispatch, production, and access-based opportunities. This model is benchmarked against the [6] model, which does not account for access-based opportunities. Papadopulous et al. [79] is the only publication considered that views *any* period of weather access as an opportunity. 12 MW turbines are used within the case study, in line with current deployments. As the rated power of the machine increases, as does the opportunity cost during downtime. Therefore, the validity of an access-based OM strategy will be determined by the opportunity cost vs the cost of dispatch. Papadopoulos et al. [79] also acknowledge the impact of the variable price of electricity. [79] use two distinct case studies. The first does not consider electricity price variability in order to ensure that the differences in the maintenance performance is solely attributed to the impact of accessibility, production loss and crew dispatch. The second case study introduces market electricity prices from the US transmission organisation, PJM, and also includes curtailment of 2%. Curtailment is deducted from the final production revenue output, the specific time occurrence of the curtailment is not included. Although Papadopoulos et al. [79] acknowledge the influence of market conditions, they do not view these periods as an opportunity. Therefore, the only external opportunity is weather-accessibility based within this work.

4.3. Maintenance action/response

The overall OM strategy consists of two distinct parts, the opportunity and the response/maintenance action. Like internal opportunities, the response/maintenance action is typically divided by PM or CM activities. In the literature, it is most common to respond to an opportunity trigger with a PM action, as PM activities are known in advance and therefore can be scheduled or placed on a waiting list accordingly. As PM tasks can be scheduled ahead of time, downtime is already minimised if scheduling is proactive. As the cost of repair and technician salary cannot be altered, sharing of resources, e.g. vessels, is one of the few ways in which this cost can be reduced.

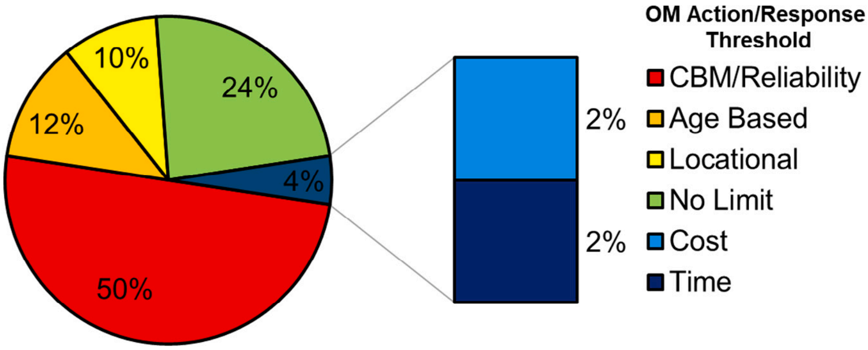

Fig. 7. OM Action/response thresholds imposed within the literature.

Besnard et al. [6,66] define PM as all maintenance tasks performed that reduce the probability of failure before it occurs. Preventive maintenance tasks are performed at fixed time intervals of 6 months, 1 year, or 5 years. They include visual inspections, changes of consumables (greasing, lubrication, oil filters), oil sampling, and re-tightening of the bolts. A similar approach is taken by [58]. With a predefined set of PM tasks with a set future deadline by which they must be completed. This is the most simple definition of a PM action.

Of all of the publications considered, only one publication does not respond with a PM action. Yildrim et al. [70] respond to an opportunity with any maintenance action. This work considers a trade-off between a sensor-driven optimal maintenance schedule and the grouping of wind turbine maintenance activities through OM. The maintenance response can be CM or PM depending on the economic benefit of performing such activities.

4.3.1. OM maintenance action thresholds

PM activities are often based on some predetermined threshold, as discussed in Section 4.2.1. However, this methodology also applies to OM response activities, where additional OM response/action is only performed during periods of opportunity if a specific criterion is met, which typically satisfies some economic requirement.

Due to the introduction of monitoring software and a more in-depth understanding of reliability, some components will only be maintained, preventively, if some predetermined threshold is reached. Therefore, it is common for an OM limitation or threshold to be placed within the strategy where the response/action to the opportunity will only be taken if certain criteria are met. The most common limits/thresholds were: age-based, CMB/reliability, time and cost as shown in Fig. 7.

Half of existing publications place a basic reliability or CMB-based limitation on any maintenance action in response to an opportunity. Further detail of the specific literature and their corresponding PM maintenance thresholds is given in Table 2.

Ding & Tian [61,62] were the first to impose a limitation on response to an opportunity. They introduce an age threshold, in addition to different imperfect maintenance thresholds for failed turbines and working turbines. When a downtime opportunity is created by the failed components, the maintenance team may perform PM for other components satisfying pre-specified age thresholds. The same age-based limitation methodology is applied by Shafiee et al. [63], Sarker et al. [64], Abdollahzadeh et al. [67] and Xie et al. [73]. This method involves assigning a component age that is renewed each time a replacement/repair takes place. These works also give consideration to imperfect maintenance strategy whereby a component's age is only returned to zero if a complete replacement is conducted, and the age is only reduced for minor repairs.

The most common limitation/threshold is a CBM/reliability-based. This follows the same procedure as an age-based limitation, where a specific (reliability-based) threshold must be reached before maintenance is conducted. Within these works, the reliability threshold not only limits the OM action but also informs the type of OM action which will take place. These works often use a multilevel maintenance framework, from complete replacement to imperfect maintenance; the type of maintenance carried out depends on the input from the reliability of the component. This methodology is applied in [54,57,65,67–70,74–76,82,83,85,88].

Location limitations were imposed in the works of Zhang et al. [87], Kang et al. [77] and Liu et al. [90] which was first introduced by Song et al. [82]. Song et al. [82] combined location limits with the reliability threshold, where the aim of the work was to optimise the turbine layout taking into account the impact of maintenance. The turbines were grouped into geographical clusters where OM activity could only be carried out if the failed turbine was within the same cluster as a turbine that met the reliability threshold conditions. This was imposed to reduce the fuel consumption of vessels and limit time offshore. This approach is well suited to larger sites, such as Doggerbank, as the distance between turbines can be as large as 100 km. Song et al. [82] was the only work that included time as a limiting factor. This was closely aligned with the travel distance between the geographical clusters.

Li et al. [55] was the only publication that explicitly considered cost as a limiting factor through an economic assessment that compared the cost of repair versus the cost of downtime to determine whether an OM activity should be performed. It is recommended that future publications include this as a limitation as economic advantage is one of the key factors of an OM based strategy, as highlighted in [24].

4.4. Combined strategy

The overall OM strategy consists of both opportunities/triggers and responses/actions. Although it was most common for a strategy to contain multiple opportunities, this was typically addressed by a single type of maintenance action. The combinations of opportunities and responses are shown in Fig. 8. The most common OM strategy presented in the literature is to use ***corrective or preventive opportunity*** to perform ***preventive maintenance action***, as seen in [57,60,67–69,72–77,80,81,83,90]. Unexpected failures, or corrective maintenance, constitute the largest part of OpEx [92] breakdown, and therefore utilising CM activities for OM opportunities spreads the resource cost across multiple maintenance activities and, therefore, reduces the cost per maintenance action. By responding with a planned/expected PM action, there is still a degree of certainty within the operation. However, this will depend on the weather conditions on-site. An overview of the combined OM strategy is given in Fig. 8.

The combination of PM opportunity and trigger is commonly referred to as *group maintenance*. This is a subset of OM where activities are scheduled to occur in parallel. This has the same advantages as OM due to the sharing of resources and reduced time at sea. This methodology is more suited to PM tasks as pre-planning can be performed to determine whether *if* specific tasks can be performed simultaneously or not. This is also the most common OM application seen within

Table 2
Maintenance limits imposed on PM maintenance actions in response to an opportunity.

	Maintenance action limit					
	Age-based	CBM	Locational	Reliability	Time	Cost
Ding et al. 2011 [61]	✓					
Ding et al. 2012 [62]	✓					
Shafiee et al. 2015 [91]		✓				
Sarker et al. 2016 [64]	✓					
Abdollahzadeh et al. 2016 [67]	✓			✓		
Atashgar et al. 2016 [68]				✓		
Zhang et al. 2017 [69]				✓		
Yildrim et al. 2017 [70]		✓				
Erguido et al. 2017 [54]				✓		
Li et al. 2018 [65]				✓		
Song et al. 2018 [82]			✓	✓	✓	
Lu et al. 2018 [83]		✓				
Erguido et al. 2018 [57]				✓		
Zhou et al. 2019 [72]		✓				
Xie et al. 2019 [73]	✓					
Zhang et al. 2019 [74]				✓		
Izblusg et al. 2019 [75]				✓		
Wang et al. 2019 [76]		✓				
Zhao et al. 2019 [85]		✓				
Li et al. 2020 [55]						✓
Lubing et al. 2020 [78]		✓				
Zhang et al. 2020 [87]		✓	✓			
Su et al. 2020 [88]		✓		✓		
Kang et al. 2020 [86]			✓			
Luo et al. 2020 [89]		✓				
Li et al. 2021 [60]		✓				
Li et al. 2021 [59]		✓				
Wang et al. 2021 [81]				✓		
Liu et al. 2022 [90]			✓			

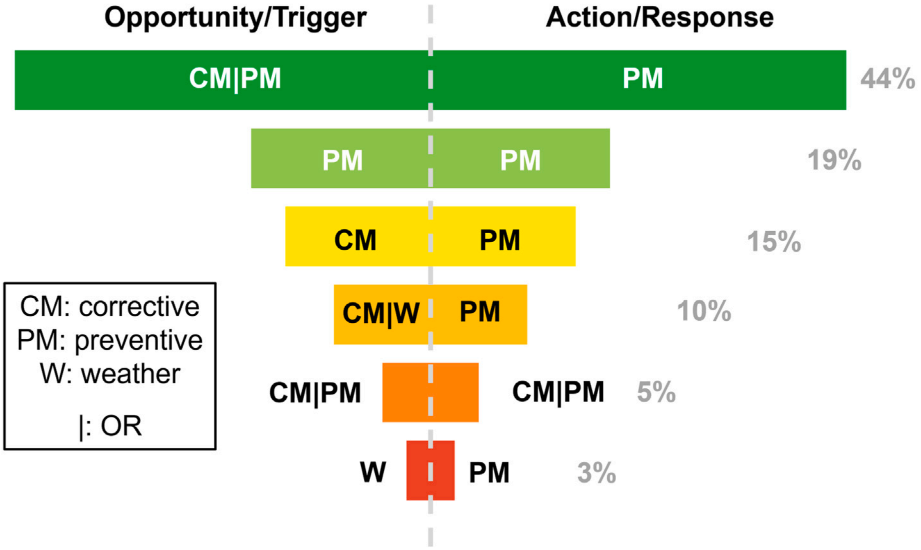

Fig. 8. Breakdown of the full OM strategy consisting of an opportunity/trigger and a corresponding action/response.

the industry, particularly in terms of summer seasonal campaigns. PM activities do not hold the same criticality as CM tasks therefore, more refined effort can be placed to effectively schedule PM operations during favourable times.

4.5. Modelling results and limitations

Literature findings agree that there can be significant OpEx savings achieved by adopting an OM-based strategy. It is difficult to draw conclusions between the results presented in the literature due to the differences in reporting on key performance indicators (KPIs), and their associated benchmarks. The impact of KPIs on O&M activities has been explored by Hawker et al. [93] and Gonzalez et al. [94]. Both works found that different parties within the supply chain will have different KPIs which in some cases can be conflicting.

The most common KPI in the literature was total annual OpEx, as shown in Fig. 9. However, there were different benchmarks in which OpEx was compared including the CM-based approach [61,62,68,72], “standard” maintenance techniques [58], routine maintenance [70], single component replacement [65], and a time-based maintenance approach [77,83,86]. Routine maintenance as used by Yildirim et al. [70] is most commonly aligned with a scheduled maintenance-only approach. Due to the differences in benchmarking, it is difficult to draw conclusions between the results. However, OpEx savings are typically around 20% to 50% compared to a non-OM-based strategy. The most common benchmarking metric used was a business-as-usual single CM repair approach.

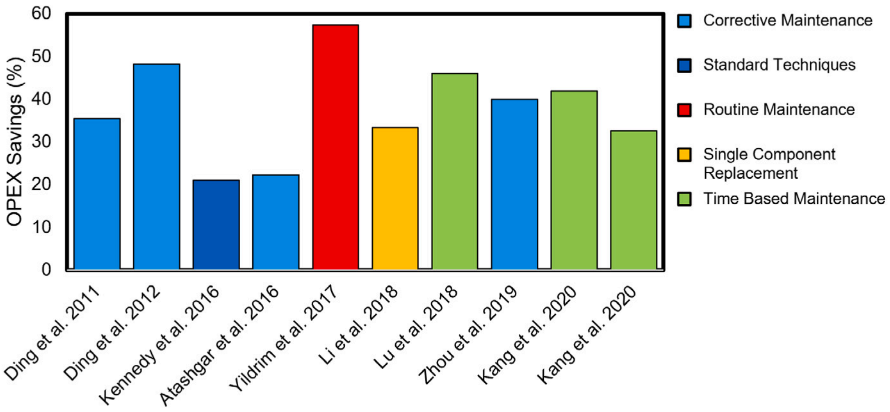

Fig. 9. OPEX savings comparisons with OM benchmarks.

Table 3
Weather limitations imposed on maintenance actions.

	Wind speed	Significant wave height (Hs)	Other
Besnard et al. 2011 [66]	12 km/h	1.5 m	
Kennedy et al. 2016 [58]	12 m/s	1.5 m	
Zhang et al. 2017 [69]			weather restriction
Yildirim et al. 2017 [70]			weather restriction
Song et al. 2018 [82]	unspecified		
Lua et al. 2018 [84]			accessibility
Xie et al. 2019 [73]	10 m/s	2 m	
Zhang et al. 2019 [74]			weather restriction
Kang et al. 2020 [86]		3.5 m	
Lubing et al. 2020 [78]	10 m/s	2 m	
Zhang et al. 2020 [35]			weather restriction
Kang et al. 2020 [77]		3.5 m	
Papadopoulos et al. 2021 [79]	15 m/s	1.5 m	

4.5.1. Limitations

However, these impressive results may not be a realistic representation of the true challenges associated with an OM-based approach. To effectively execute the framework, it must take into account the weather conditions under which maintenance can be performed. The weather window methodology is typically used to schedule maintenance activities (both CM and PM). A weather window is known as a period of uninterrupted access where maintenance actions can be carried out safely [95]. Accessibility to the site is a growing concern as sites move further from shore, resulting in harsher weather environments and increased travel time from port. If an OM strategy is to be adopted, then it must be considered that there is a suitable weather window which can accommodate the original trigger (e.g. PM or CM) **and** the additional maintenance action/response.

Within offshore wind O&M, weather accessibility restrictions are typically based on wind speed and significant wave height (Hs) thresholds. Imposed wind speed limits are placed on lifting activities, such as blade operations, and are limited to 12.5 m/s [96]. Vessels have both Hs and wind speed limitations, with a wind speed limit of typically around 20 m/s [97,98]. The Hs limit is dependent on the vessel selection. Typical Hs limitations for vessels are 1.5 and 3–4 m for the crew transfer vessel (CTV) and the service operational vessel (SOV), respectively. It is most common for Hs to be the key limitation imposed on the weather window. Weather limitations used within the reviewed literature is given in Table 3. A summary of the weather restrictions within OM literature is given in Table 3.

The majority of publications reviewed within this work omitted the inclusion of weather limits on maintenance actions. Publications such as Besnard et al. [6], and Li et al. [59,60] state that weather limitations are removed as a constraint.

Of the publications which do include weather limitations, these tend to include both Hs and wind speed limits specific to vessel capabilities [58,66,79]. Both Besnard et al. 2011 [66] and Kennedy et al. [58] also include the possibility of introducing a Hs limitation for helicopter operations. Both Xie et al. [73] and Lubling et al. [78] include the same Hs and wind speed limit. However, it is not specified if these are vessel specific.

Kang et al. [77,86] uses a Hs limit of 3.5 m for both works. This is in line with the limitations of an SOV, rather than a CTV as seen in other publications.

Several publications referenced an unspecified “weather restriction” within their work [69,70,74,87]. Song et al. [82] imposes an unspecified wind speed limitation.

Lua et al. [84] examine the impact of accessibility and downtime on the OM strategy - but weather limitation values are not provided.

Although the works of Erguido et al. [54,57] and Izquierdo et al. [75] do not impose weather restrictions on site accessibility, wind speed is a direct input to the OM-decision-making process. As wind speed and Hs are coupled, periods of low wind speed, where maintenance actions are preferred, are likely to correspond to periods of low Hs, and therefore will be accessible.

The works of Zhang et al. [69,74] and Lubing [78] are the only works which consider the additional time required to conduct additional OM maintenance tasks during periods of opportunities, resulting in the need for a prolonged weather window.

The original work of Besnard et al. [6] included the need to include weather limitations as an area of future work. In the later work in 2011 [66], accessibility limitations are imposed. However, the impact of the inclusion of weather limits on income and other KPIs is unknown, as the results cannot be directly compared due to differences in the case study used and the reported KPIs.

In order to avoid underestimating the impact of OM on weather window requirements, and also accessibility. It is important that the prolonged time at sea is captured within simulations [70]. However, at present the inclusion of weather considerations is currently lacking from the literature.

4.6. Industry practice and contractual limitations

The implementation of OM within the industry is common, particularly during periods of low wind speed. It is common practice to “never miss a weather day”. If a vessel is chartered, the agreement is typically for a 12-hour daily operating period. At offshore wind projects, vessels are usually chartered on a continuous and long-term basis. The potential savings of this approach will be determined by the charter agreement in place [99]. If under a voyage charter agreement, fuel consumption and crew expenses are covered within the agreement, making it advantageous for the operator to use the vessel as much as possible during the charter period. However, time charter agreements will require a cost analysis of the running costs of the vessel, such as fuel and crew, versus the potential maintenance savings of a weather-based OM strategy.

Grouping smaller maintenance tasks together is also common practice for small jobs, such as changing signs, implementing small design upgrades, or replenishing turbine equipment such as first aid kits, food rations, or eyewash stations where the items have an expiration date. As these maintenance actions are non-critical to the operation of the site, there is typically a large window in which these tasks can be completed, making these suitable for an OM approach.

As well as being more efficient, there is also a safety advantage, as the total number of transfers will be reduced. There are some trends in the SPARTA data which show reducing numbers of transfers - it is not clear what the cause of these are but is likely that increased bundling of tasks is contributing to this trend [100].

Despite the high potential savings found within the literature results, particularly those using PM action responses, it is important to be aware of the practical limitations of contractual agreements between the original equipment manufacturer (OEM) and the owner. During OEM Service Contract periods it is the turbine OEM who provides technicians and schedules maintenance work on site. If a PM maintenance action is triggered while the turbine is still under warranty, the OEM may choose not to carry out this work as they will incur additional costs and may not incur performance penalties under their contractual agreement if they wait for additional failures to emerge. Therefore, PM responses/actions may not always be possible as part of a wider OM strategy. Many operational sites have moved away from OEM contracts and now perform maintenance directly themselves and would be incentivised to use OM to prevent failures and enable low-wind speed days to be used for OM rather than risk prolonged downtime in the event of a sudden failure.

5. Additional external factors and market opportunities

During the next decade, the UK is set for rapid expansion in the offshore wind sector. In 2019, the Offshore Wind Sector deal put forward a proposed 30 GW of installed offshore wind capacity by 2030 [11]. The Committee on Climate Change have suggested that the UK may need to reach 75 GW of offshore wind by 2050 to satisfy the UK’s net zero targets [101].

Although these ambitious targets show confidence in the ability of the sector and are expected to have a positive impact on climate change, the expected impacts that an increasing offshore wind capacity within GB could have negative impacts on key electricity market parameters. With a high increase in wind (onshore and offshore) capacity within the UK, the current network capabilities in Scotland and Northern England may become constrained. The expected results of this include damage to the system and network, increased unnecessary wind curtailment, and increased frequency of negative prices within the electricity market.

Following the review of the literature presented in Section 4, maintenance opportunities can be categorised as internal or external. It is found that the most common opportunity was internal, with external opportunities being weather-related. While some works such as [54,57,79] acknowledged the impact of external market parameters such as electricity pricing, this was used to inform decisions rather than as independent opportunities. This section introduces novel market-based external opportunities which arise from periods of negative pricing and curtailment. As these events will result in the shutdown of the turbine, they provide maintenance opportunities.

5.1. Curtailment

At present, offshore wind curtailment rates range between 4% and 5% in both Europe and the US. Studies [10], including Brouwer et al. [102] report that wind curtailments are mainly driven by network constraints. The current boundary capability is limited to 6.1 GW due to a thermal constraint at the Harker substation. The lack of interconnection from high utilised wind resource areas, far from where population and demand are concentrated, can result in curtailment of wind generation, as well as wholesale price volatility. European Union Twenties Project examined market scenarios for 2020 and 2030 in Northern Europe finding that large-scale offshore wind development is likely to lead to an increase in curtailment, due to both an increase in wind generation and the additional variability from offshore wind plants concentrated in a geographic region. Market simulations show that wind curtailment is expected to increase by over 2000% - from 0.4 TWh in 2020 to 9.3 TWh in 2030 [103].

All else being constant, the curtailment rates of offshore wind (and other renewable generation sources) are generally expected to increase coincident with higher penetration levels. This curtailment of renewable energy sources imposes limits on the achievement of climate change targets and can have a negative impact on the financing of future projects. High rates of curtailment may hamper investment in new renewable projects. Therefore, it is vital to take advantage of these periods of curtailment as opportunities to deploy a flexible maintenance framework.

5.2. Electricity market

Negative prices occur in situations of oversupply when the marginal generator would prefer to pay the price rather than reduce its output. An increase in renewable generation has been shown to lead to a price drop, as seen in the German market analysis performed by Ketterer et al. [104] and Parachiv et al. [105]. More recently, Fraundorfer et al. [106] explored the same problem within the Brazilian emerging market, where the same trends in a drop in electricity price as the penetration of renewable generation on the grid increased. This phenomenon is called merit-order effect for low levels of load, an increase in renewable generation has a price-dampening effect and may lead to negative prices. Since electricity cannot be stored at a wholesale scale, electricity prices are highly volatile, with the existence of both positive and negative price peaks.

Trends in negative pricing can be seen internationally. In 2020, average wholesale electricity prices in the United States fell to their lowest level since the beginning of the 21st century. Negative wholesale prices in real-time occurred in about 4% of all hours and wholesale market nodes in the US. Although this increase in negative pricing could be attributed to the COVID-19 pandemic, Seel et al. [107] found that there was a trend prior to this period that indicated that resources such as wind and solar had already established a trend towards lower wholesale prices. However, it was found that the negative pricing was not evenly distributed across the US and was concentrated in areas of high renewable penetration. With the US beginning their deployment of offshore wind, it is currently unknown the revenue mechanism which will be taken for these future sites, therefore they could be exposed to these market conditions. This indicates that high-density offshore wind locations within the UK, such as the Doggerbank region, will experience higher levels of negative prices compared to sparser areas such as the west coast.

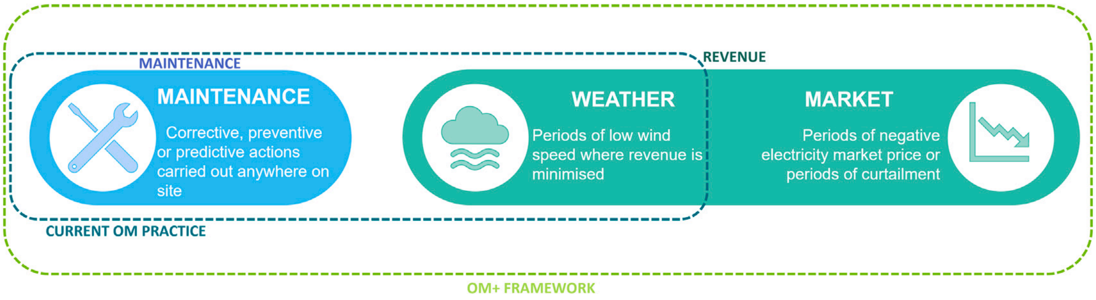

Fig. 10. OM+ definition of an opportunity.

At present, most offshore wind sites operating in the UK are protected from volatile electricity market prices due to CfD contracts. However, CfD contracts only have a lifetime of 15 years. With a large interest in life extension, it is likely that current sites will operate within the post-subsidy market for more than 10 years [3]. The loss of guaranteed price revenue in conjunction with the reality of ageing assets and components is expected to put increased pressure on the site's operations, as OpEx is one of the few remaining expenses that can be controlled.

However, it is not just post-subsidy sites which will be exposed to potentially extreme market conditions. CfD Allocation Round 4 contracts have plans to remove a plant's subsidy if the price they are assumed to receive from the market becomes negative [9]. Previously, CfD sites were protected from periods of negative pricing through the scheme. The new rules state that support payments will not be paid in any period where the day-ahead market price (i.e. their reference price) is negative. If this rule continues to be applied for future CfD auctions (AR4+), it will apply to all new wind and solar generation and they will not be willing to sell power at a negative price in the day-ahead market. This will effectively set a floor price of zero in the day-ahead markets.

6. Proposal of future framework

Based on the findings from the literature and the acknowledgement of the threat of market-based external factors, the authors propose a new future framework for OM, OM+. The literature has shown that there is, at present, no clear definition of the strategy or the definition of an opportunity. The new framework defines an opportunity as "any period where the turbine production is less than a predetermined threshold or any time a maintenance crew is dispatched". This definition encompasses all opportunities provided in the literature, both internal and external, and additional market factors explored in Section 5. With a crew dispatch being for both CM and PM activities. This maintenance opportunity can then be responded to by PM or CM activities dependent on the level of planning/operational information available.

Periods of forced shutdown, during negative pricing and curtailment, can be viewed as opportunities to perform maintenance activities. These are periods of "forced downtime" which can be used to the advantage of the operator. These periods of downtime can be viewed as ***"free downtime"*** from a maintenance perspective. This proposed framework, OM+, is described in Figs. 10.

The OM+ framework divides opportunities into maintenance-based and revenue-based. Maintenance-based opportunities are identical to the internal opportunities discussed and defined in Section 4.2.1. Any crew transfer for any maintenance action can be classed as an opportunity. The revenue-based opportunities include both weather and market opportunities. Weather opportunities include periods of low wind speed, based on a threshold set by the operator. Market opportunities include both periods of negative pricing and periods of curtailment as discussed in Section 5.

Once an opportunity is triggered, the need for additional maintenance must be checked. Other requirements include the suitability of available weather windows and the availability of resources such as personnel and spare parts before attempting OM.

6.1. OM+ availability

In addition to the OM+ process, this work also suggests a new definition for recording and reporting availability. During the early years of the industry, availability tended to be time-based, $\mathrm{A}_{\mathrm{time}}$ (also known as operational availability, A_{o}). However, as the industry has progressed, availability is now typically reported as yield or energy-based availability, $\mathrm{A}_{\mathrm{yield}}$. However, both existing methods to calculate availability fail to incorporate the impact of curtailment and negative pricing. In addition to the proposed OM+ procedure, this work also presents a new measure of availability. The proposed Market-Based Availability ($\mathrm{A}_{\mathrm{market}}$) includes the impact of negative pricing and curtailment on the operation of the asset. Differences between the three definitions of availability are described in Eqs. (1)–(3).

$$A_{time} = \frac{U_{time}}{U_{time} + D_{time}} \tag{1}$$

$$A_{yield} = \frac{E_{exported}}{E_{potential}} \tag{2}$$

$$A_{market} = \frac{E_{exported} + E_{market}}{E_{potential}} \tag{3}$$

Where U_{time} is the number of hours the turbine was operating, D_{time} is the number of hours the turbine was not operating and E_{market} is the energy that could have been exported during periods of reduction and/or negative pricing. $E_{exported}$ is the total energy exported from the site, and $E_{potential}$ is the maximum theoretical export if all turbines at site were continuously operating.

As highlighted in Section 4.5, different stakeholders in the project respond to different KPIs. Therefore, market conditions must be incorporated into KPI monitoring to avoid contractual discrepancies and ensure that KPIs represent the operating conditions to meet contractual agreements.

6.2. Ranking of opportunities

The proposed framework includes numerous opportunities. However, some of these may contradict others, for example, performing maintenance during periods of low wind speed where the electricity price may peak could result in a potential loss of earnings. This concept is explored through the use of a case study based in the United States using the Skipjack site.

Electricity price data is taken from the open source data repository of PJM [108]. PJM is a regional transmission organisation covering the east of the US. The site is assumed to generate revenue from the wholesale electricity market and is located within the DOM transmission zone within the PJM region. Weather data is taken from the LAUTEC ESOX ERA 5 database for the same year [109]. Results are shown in Fig. 11.

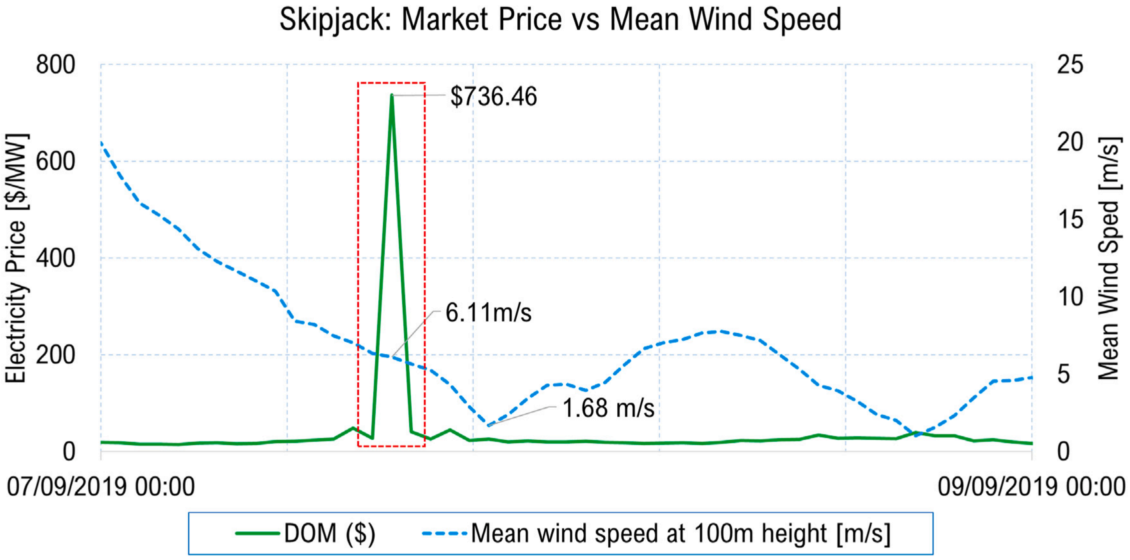

Fig. 11. Electricity price and hourly wind speed time series based on location of US Skipjack site.

This case study highlights the importance of ranking opportunities and prioritising market price. Fig. 11 shows a falling wind forecast, which would present itself as a maintenance opportunity, when viewed in isolation. However, when analysing the electricity market price, it shows a peak in pricing. Therefore, by taking low wind speed as an opportunity, there is a penalty taken in terms of potential profitability.

6.2.1. *Internal ranking*

As discussed in Section 4.3.1, half of existing publications place a basic reliability or CMB-based limitation on any maintenance response to an opportunity. It is expected that for market based maintenance, a similar threshold/ranking system will also be required to determine which turbines should benefit from the maintenance opportunity. Ranking can consist of a number of criterion including:

- Reliability: turbines with the lowest remaining useful life/ quantified reliability are maintained first. As seen in [54,57,65, 67–70,74–76,82,83,85,88].
- Locational: if technicians are already at site when opportunity occurs, a locational limit may be placed on potential turbines for repair [77,82,87,90].
- Power Output: where turbines with historically high power outputs are prioritised over other turbines.
- Numbered: Each turbine is maintained in turbine number order, regardless of output, location or remaining useful life.

6.2.2. *Limitations and challenges*

It is important to understand the complexity of the electricity market and curtailment decisions, and their influence and impact on offshore wind development. The market price is driven by the scale of industry development, supply and demand status, government policies, global politics and individual generation agreements etc. These factors therefore also have a significant impact on curtailment rates for current, and future, offshore sites.

The impact of wind energy forecast error can have a significant impact on the electricity market prices [110]. The two are co-dependent and therefore an accurate forecast of UK market prices for offshore sites is also required.

For curtailment, the suitability of this framework, in practice, will be determined by the notice period given for the curtailment of assets. Changes in the market can be both instantaneous and suffer from delayed effects. In order to make use of the proposed market-based maintenance opportunities, accurate prediction of weather windows and available resources will be required for quick decisions to be made.

6.3. *Additional opportunities*

The author's definition of an opportunity does not define the maintenance action which should be taken. In some cases, this may not be an opportunity to perform maintenance, but an opportunity to explore additional revenue streams in periods of forced downtime.

The identification of periods of curtailment and negative pricing may also provide opportunities for developers to explore additional revenue opportunities such as hydrogen production during these periods of "free" downtime. McDonagh et al. [111] have studied preliminary work on this concept. This development leads to an interesting balance between maintaining the main source of income (the wind farm) vs. maximising additional revenue streams (hydrogen production).

The Offshore Wind Policy Statement of the Scottish Government sets out a vision for up to 11 GW of offshore wind capacity in Scotland by 2030 [112]. This target has been greatly accelerated by the 2022 ScotWind leasing round which saw over 25 GW of offshore wind allocated. It is estimated that up to 240 GW of offshore wind could be deployed in the UK by 2050 to produce green hydrogen for export to Europe [113]. Scotland has a growing offshore wind sector, but with increased requirements for grid infrastructure upgrades and risk of curtailment, hydrogen production could act as an alternative revenue stream to electricity supply to support continued offshore wind development, while serving to decarbonise 'difficult-to-abate' sectors.

The introduction of floating turbines also provides additional opportunities to perform OM. The challenges associated with turbine motion, in addition to the remote/far from shore location of these sites, make an OM strategy advantageous for this technology. Currently, there is still no consensus on the maintenance methodology for performing major component replacements. As a result of the water depths, using heavy lift vessels is unfeasible. One proposed solution is the tow to shore strategy (T2S). This process involved disconnecting the turbine from its moorings before towing the structure back to shore/port where maintenance will take place. This is expected to be a high-cost and time-intensive process. A review of the existing literature surrounding O&M for FOW and an overview of additional challenges can be found in McMorland et al. [114]. Therefore, the periods in which the turbine is returned to shore also introduce the opportunity to perform scheduled maintenance activities at port, such as inspections and small replacements. This will help reduce the cost of the T2S process, as the cost is shared between multiple maintenance activities, not just major component replacements.

7. Conclusions

In this work, a review of the application, and suitability, of OM to offshore wind has been discussed. Previous utilisation of the practice within manufacturing and other industries such as power systems show clear similarities to the O&M activities required for an offshore wind farm. Therefore, the advantages of the strategy utilisation within these industries can be replicated within an offshore wind context. There is a clear growth in the interest of OM within offshore wind as highlighted in Fig. 3. From the literature overview, specific to OM within offshore wind opportunities can be divided by internal or external. The most common opportunity was CM actions, which were responded to by a set of predetermined PM activities. While the literature failed to provide a cohesive definition of the OM strategy, each application of the technique consisted of an opportunity/trigger which had a corresponding response/action. Simulations of the technique have shown that this methodology can provide OpEx savings of up to 20%. However, there are still several gaps within the literature:

- **Additional time at sea**: the performance of OM activities reduces overall time at sea, however can prolong the time spent on a single trip. A cost benefit analysis was shown in [55], however this should be given more priority in the decision making process. As highlighted by Ab-Samat et al. [24] in the review of all OM publications, there should not be a negative economic impact of taking a maintenance opportunity.
- **Met-ocean limits:** at present, the majority of the literature ignores met-ocean limitations within their OM framework. Those which do include Hs and wind speed limits are typically that of a CTV, apart from the work of [77,86]. As sites move further from shore, it is more likely that an SOV approach be utilised. Therefore, it is recommended that this be included in future case studies
- **Limited external opportunities**: within the literature, external opportunities were limited to weather-based events. Other external factors such as market pricing and curtailment are set to have significant impact on future operation of offshore sites and therefore should be given consideration.

In response to the limited external opportunities presented in the literature, this work introduced an OM+ framework which included internal, weather external and market-based opportunities. This framework also provided a more inclusive definition of the OM methodology as “any period where the turbine production is less than a predetermined threshold or any time a maintenance crew is dispatched”. By introducing market-based opportunities, the concept of “free downtime” is proposed to make effective use of forced outages at the site. This work also highlights the potential for OM to be applied to major component replacement operations for floating wind during tow to shore procedures to reduce the overall cost of maintenance by planning PM activities to take place at port.

The framework also introduces the next-generation “Availability” measurement, moving away from time and yield-based measurements to a market-based approach. As demonstrated in sec 6.2, not all opportunities are equal, as taking one opportunity may result in the loss of another. Therefore, an optimisation framework is required to determine which opportunity is most appropriate in different scenarios in order to generate the most income for the site.

As OM becomes more prominent within offshore wind applications, it is important to encapture the key motivation of the strategy, which is to be economically beneficial.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jade McMorland reports financial support was provided by Engineering and Physical Sciences Research Council.

Data availability

No data was used for the research described in the article.

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