Analysis of weather windows and impacts of time to repair on device availability at two Wavepiston deployment sites

Colm J. Fitzgerald, Eugenio M. Gelos, Emiel J. Schut, Steen Grønkjær Thomsen, and John V. Ringwood

Abstract—**Wave energy device availability, defined as the proportion of time a device is fully operational and capable of generating energy, depends on the reliability of device components and the downtime between component failure and repair. The time to repair depends on several factors, including potential waiting times for an extended period of benign metocean conditions to allow device access and maintenance activities to proceed. In this study, a weather window analysis is conducted for two candidate sites identified for potential deployment of the Wavepiston wave energy converter using ocean climate reanalysis data. The weather window analysis focuses on how waiting times between weather windows and site accessibility vary with operating thresholds for operations and maintenance (O&M) vessels, e.g significant wave height limits, and minimum weather window durations. In addition to exploring seasonal variations in waiting times and access levels, the effect of daylight-hour restrictions on maintenance activities is also considered. Furthermore, the impact of waiting times and access levels, as proxies for time to repair, on device availability is assessed using a Monte Carlo simulation based on nominal device reliability. The availability study demonstrates how uncertainty in waiting times and access can be propagated into estimates of device downtime and availability, thus providing a more complete picture of the impact of O&M strategies, e.g. daylight only restrictions on maintenance, on energy generation potential.**

Index Terms—**weather windows, Wavepiston, device availability, O&M, wave energy**

I. Introduction

THE high cost of ocean wave energy generation relative to other renewable sources remains a significant hurdle for the wave energy community to overcome if wave energy technology is to contribute to the overall global renewable energy mix [1]–[4]. The levelised cost of energy (LCoE), defined as the lifetime unit cost of energy production, is a widely-used metric in the energy industry for assessing the economic performance of various generation technologies, since it captures the trade-off between energy generation and overall capital and operational expenditure. Device *availability*, defined for offshore renewables as the percentage of time that a device is operational and capable of generating energy [1], [5]–[7], is expected to be lower for wave energy converters (WECs) than for offshore wind, given the similarities in offshore deployment sites and a potentially more challenging operating environment [1], [6]. Similarly, operation and maintenance (O&M) costs, comprising the ongoing costs of device repairs and maintenance required to ensure the device generates energy with only occasional downtime periods, are likely to be at least as significant as for offshore wind platforms, where contributions of up to 30% of the total cost of energy have been estimated [8], [9].

Device failures and consequent repair works affect WEC LCoE directly, from the cost of component replacement or repair and O&M vessel and crew hire, and indirectly, through lost energy generation during device downtime. Downtime costs are incorporated into LCoE estimates through device availability, which depends on both device reliability, i.e., the ability of the system to perform a specific task under certain environmental and operational conditions, and deployment site *accessibility* for maintenance or repair activities. Accessibility is determined by maintenance vessel operating criteria and site metocean conditions [5], [10]. Extended maintenance waiting times, between weather windows that allow safe operation and maintenance (O&M) activities, result in longer repair times, increase direct O&M costs, when maintenance crew and vessels are on standby, and lead to lost revenue due to reduced availability [11], [12]. Therefore, accurate estimates of site accessibility and waiting periods between weather windows, as an indicator of time from failure to repair, are essential for improving device availability estimates and, hence, WEC LCoE assessments.

Weather windows, defined as periods of time during which metocean conditions are sufficiently benign to allow access to a marine renewable energy (MRE) deployment site for O&M activities, are determined primarily based on wave heights relative to operational limits [13]–[15], often complemented by wind speed data and limits [7], [16], [17], and also current speeds [10], [18]. Weather windows are further characterised by the minimum duration required for

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transit and maintenance or installation activities [10]. Weather window analyses may employ a statistical approach, based on wave height occurrence data [10], [15], or a time-series approach, based on multi-annual observational buoy data or oceanographic reanalysis data [10], [16], [17], [19]. A time-series approach is adopted herein, allowing straightforward estimation of weather windows of specified durations and corresponding between-window waiting periods, and incorporation of multiple met ocean variables [13].

By defining weather windows with respect to operating thresholds *and* required durations of offshore tasks, the analysis aims to provide outputs and insights with practical value for economic performance assessment and O&M scheduling. Important weather window analysis outputs for device availability assessments include waiting periods between weather windows and site access levels [5], [10]–[12]. Waiting times between weather windows, in particular, support estimates of time-to-repair, weather-induced downtimes, associated reductions in device availability and additional O&M costs. Site accessibility, defined as the proportion of a certain time interval, e.g., year, season, or month, that weather windows persist and allow access for O&M tasks, can support maintenance scheduling by identifying periods of the year where access levels are particularly high or low.

The motivation for this weather window analysis is to support informed decision making at the early-design stage of the Wavepiston WEC concerning the potential trade-off between device configurations that improve energy absorption but may lead to reduced reliability. One aspect of this energy generation/reliability trade-off is the reduction in device availability, owing to increased device downtime as a consequence of higher failure rates. In order to more accurately estimate device downtime, the repair and maintenance delays arising from site inaccessibility, following a fault or component failure, must be quantified. Therefore, a Monte Carlo analysis of device availability [10], [20] is undertaken based on device failure from nominal reliability data and time-to-repair statistics obtained from the weather window analysis. In this study, the impact of uncertainty, in weather-induced repair delay estimates, on device downtime and availability, is demonstrated with a probabilistic availability calculation for various operating threshold and maintenance duration scenarios. Other practical maintenance considerations, such as safety concerns over offshore O&M work in a low light environment [12], and the associated requirement for daylight hours maintenance work, are also assessed in the weather window and availability analysis.

This study develops a comprehensive weather window analysis of metocean data to support robust estimates of annual site accessibility and maintenance waiting times, based on realistic O&M vessel constraints. It focuses on two deployment sites,

1) at the current full-scale Wavepiston demonstration site, off the east coast of Gran Canaria, Spain, and
2) at a potential commercial site, several kilometres off the north coast of Gran Canaria.

Site access levels and waiting times between weather windows are presented at annual, seasonal and, for accessibility, monthly temporal resolutions to provide a comprehensive assessment of accessibility and to inform a preliminary availability analysis.

TABLE I
ERA5 CLIMATE REANALYSIS METOCEAN VARIABLES USED IN THE WEATHER WINDOW ANALYSIS

Metocean variable	Description	Unit
10 m u-component wind	Horizontal northward wind speed at 10 m above sea surface	m/s
10 m v-component wind	Horizontal eastward wind speed at 10 m above sea surface	m/s
Significant wave height H_s	The average height of the highest third of surface ocean waves comprising swell and wind wave components.	m

II. Weather window analysis

A. Deployment site locations

Wavepiston have deployed a full-scale prototype at the Plataforma Oceánica de Canarias (PLOCAN) test site, which has an Offshore Ocean Platform located 1.5 km off the east coast of Gran Canaria. The PLOCAN test site covers an area with latitudes in the range (28.02°N, 28.06°N) and longitudes in the range (15.3°W, 15.4°W) [21]. Wavepiston also plan to deploy a device at a potential commercial site 1.5 km offshore of the northern coast of Gran Canaria. The weather window analysis is applied to metocean data corresponding to the PLOCAN test site and the potential commercial site, which will be referred to respectively as Gran Canaria East (GCE) and Gran Canaria North (GCN).

B. Metocean data: variables and format

Weather window analysis of the two deployment sites is conducted based on the ERA5 climate reanalysis dataset [22], comprising a large number of atmospheric and ocean-wave variables, inferred at hourly intervals from 1940 to the present, and spatially interpolated to a regular latitude-longitude grid resolution of 0.5 degrees. Table I shows the relevant atmospheric and ocean-wave variables utilised in the weather window analysis outlined herein, i.e. the significant wave height H_s of combined wind waves and swell, and the wind speed at ten metres above the sea surface ($U10 = \sqrt{u^2 + v^2}$) , where u and v are the northward and eastward horizontal wind components. The latitudes and longitudes of the nearest ERA5 grid points to the commercial GCN and test GCE sites are at (28.5°N, 15.5°W) and (28.0°N, 15°W), respectively. Twenty years (2005–2024) of ERA5 significant wave height and wind speed data are incorporated in the weather window analysis in order to sufficiently account for inter-annual variability and rare extreme sea states. It should be

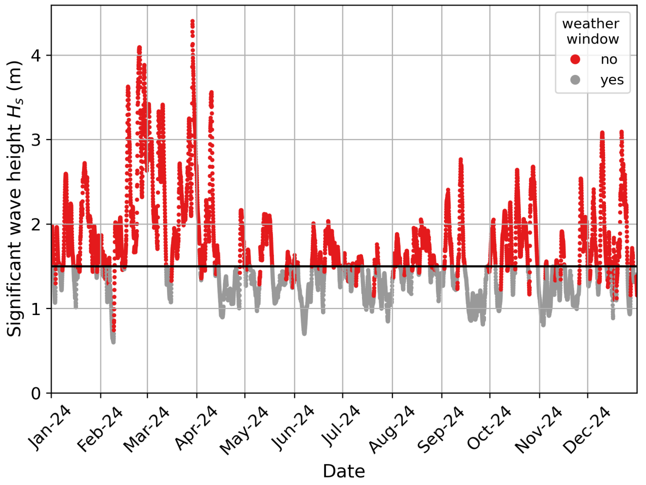

Fig. 1. Weather window or site accessibility status for the GCN site based on 2024 ERA5 wave data from the nearest reanalysis grid point for a threshold significant wave height of 1.5 m (black line) and minimum window duration of 16 hours.

noted, however, that longer time spans of metocean data may introduce historical bias to the analysis, depending on the nature of local trends in metocean conditions as a consequence of oceanic warming [23].

C. Weather window definition

A weather window is defined as a period of time when a metocean variable (or set of variables) remain below a threshold (or set of thresholds), allowing safe access to, and completion of, maintenance, repair, or installation tasks. The accessibility thresholds, and minimum required window duration τ_{min}, depend on the O&M task to be undertaken. In the time-series approach outlined here, based on the ERA5 hourly time-series of significant wave heights, a weather window of minimum duration exists if $H_s < H_{s,lim}$ for τ_{min} consecutive hourly intervals. A 'weather window state' of either 1 or 0 is assigned to each time step, depending on the threshold metocean variable levels, the minimum window duration, and the accessibility of the preceding time steps (Fig. 1). Weather windows of minimum duration τ_{min} are assumed not to overlap, following the approach of Martini *et al.* [16], so that each overall period of accessibility is divided into consecutive τ_{min} hour segments and, where conditions are below threshold limits for less than the minimum duration, the site is defined as inaccessible for the time intervals in that segment, as illustrated in Fig. 2 (upper plot).

A set of significant wave height thresholds and minimum window durations were identified prior to the analysis, based on existing weather window literature and discussions with Wavepiston technical staff. The key significant wave height limits are (1.5 m, 1.75 m, 2.0 m), although a sensitivity analysis will consider limits as high as 3.0 m, which corresponds to a frequently cited maximum H_s threshold for O&M vessels and activities in offshore renewable energy [5], [17], [19], [20]. The key weather window durations considered for activities are 16 h, 24 h and 48 h, with a greater range considered in a sensitivity analysis.

D. Accessibility and access levels

A site is deemed to be accessible for an O&M task if a weather window of some minimum duration exists to allow safe completion of the task. Therefore, site accessibility is simply the proportion of an overall time period when weather windows persist and, for a given metocean time series, vary with the threshold conditions and minimum duration of a maintenance operation. By basing the accessibility estimate on the weather window duration, the approach is broadly similar to assessing accessibility based on a discretisation of the metocean variable time series into intervals of τ_{min} hours [5]. Access levels are computed on a monthly, seasonal, and annual basis to better understand variations in accessibility during the year, which can help support maintenance strategies and scheduling.

E. Waiting times between weather windows

Waiting times between weather windows, i.e. the duration of periods of inaccessibility, are a key output of weather window analyses since, together with reliability data, the waiting times support estimates of device downtime and hence device availability. Waiting times between weather windows are calculated as the length of time elapsed between two consecutive weather windows and examined on a seasonal and annual basis. In this study, repair crew mobilisation times are assumed to be negligible, and so waiting times between weather windows are a proxy for time to repair. This assumption is supported by experience in the offshore wind industry, where poor weather conditions were found to be the primary cause of delayed operations [15].

F. Weather windows considering multiple metocean variables

Significant wave height is the primary metocean variable considered when assessing the safety of O&M vessel and crew access to MRE sites. In addition, wind speed is often considered when deploying crews to MRE sites – particularly for offshore wind platforms but also for wave energy devices. It is straightforward to extend the time-series analysis approach to include wind speed, by jointly comparing the significant wave height and wind speed conditions at each time step to the corresponding threshold levels. A single weather window exists only if all metocean variables are simultaneously (logical AND) below their thresholds for a continuous time interval greater than or equal to the required window duration. Until the practical risk assessment and decision making framework associated with Wavepiston deployment and/or maintenance operations are established, the weather window analysis formulated here is restricted to considering significant wave height and wind speed levels relative to O&M vessel and maintenance activity thresholds and durations.

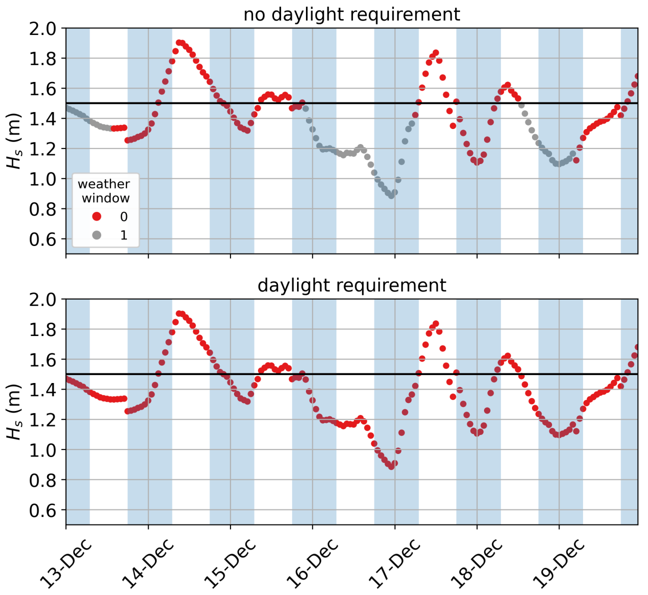

Fig. 2. Weather window status (grey denotes a weather window, red denotes no window) at the GCN site with and without the daylight maintenance requirement between 13th–19th December, 2024 for $H_{s,lim} = 1.5$ m and minimum window duration of 16 hours. Shaded regions denote night-time hours.

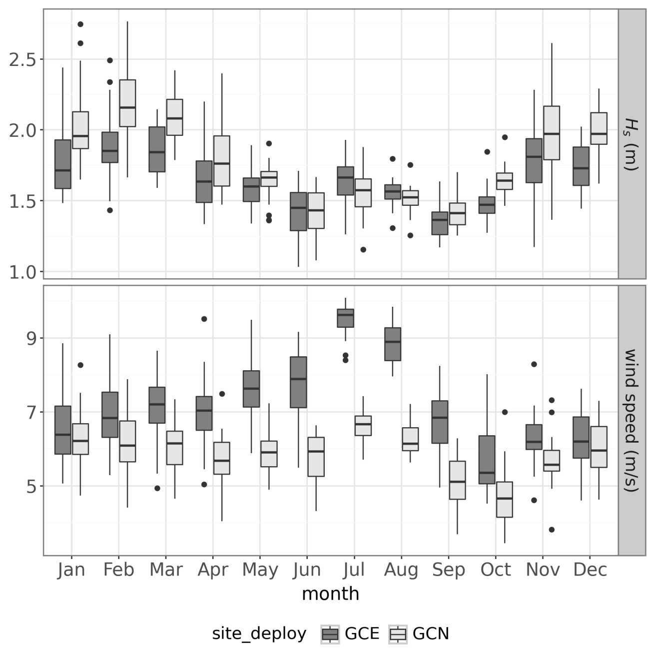

Fig. 3. Monthly significant wave heights H_s and wind speeds from 20 years of ERA5 reanalysis data at grid points representing candidate deployment sites at Gran Canaria North (GCN) and Gran Canaria East (GCE).

G. Daylight hours requirement

The weather window calculation is modified to include a daylight hours constraint on O&M activities by requiring the weather window to encompass the minimum duration for task completion τ_{min} in daylight hours only. That is, only daylight hours are counted when comparing the current window length to the minimum window duration and, crucially, if a metocean threshold is exceeded during the night then the site is considered inaccessible for the candidate weather window period. This assumption is conservative, since the return of the vessel to port for an overnight pause in maintenance activities means any overnight threshold exceedance will not affect the vessel and crew and allow resumption of the activity the following day, conditions permitting. Such brief overnight changes in met ocean conditions are likely to be relatively rare and have minimal impact on weather window analysis outputs.

Daylight hours data are calculated using the Python package 'Skyfield' [24] which uses the official definition of sunrise and sunset from the United States Naval Observatory [25], and allows sunrise and sunset times to be calculated at any location on the Earth's surface. Although visibility during dawn (immediately before sunrise) and dusk (immediately after sunset) may be sufficient for crew transfer activities [12], the level of visibility will vary strongly with local weather conditions. Thus, in this study, daylight hours are defined as the hours between sunrise and sunset. Furthermore, the sunrise and sunset times are rounded to the nearest hour to align with the temporal resolution of the met ocean time series data. By way of example, Fig. 2 demonstrates the impact of the daylight hours requirement on weather window occurrence and access levels for an O&M task with an estimated duration of 16 daylight hours. Although a suitable weather window, where $H_s < 1.5\,m$, occurs from 22:00 December 15th to 07:00 December 17th (33 hours), the window comprises only 11 hours of daylight and thus does not provide a suitable daylight weather window for the planned O&M task.

H. Wave resource and seasons

The impact of the seasonal variations in wave climate on access levels and waiting periods are explored by separating the year into just two 'season' categories – summer and winter. The categorisation of each month into the appropriate season is performed by examining the monthly mean significant wave height data, illustrated in Fig. 3, where more benign wave conditions are shown to exist from May to October ('Summer') and more energetic conditions from November to April ('Winter'), at both Gran Canaria sites. No obvious seasonal pattern is evident in wind speed conditions. Nevertheless, the significant wave height is considered the primary variable for identifying weather windows, and it is natural to categorise the summer/winter periods based on wave conditions.

III. Device availability — impacts of waiting times and site accessibility

A. Availability model

The impact of weather-induced downtime, following device failure, on device availability is explored through a probabilistic availability model, comprising just two components: (i) a simple model of device reliability and failure occurrence and (ii) the site accessibility and time to repair estimation sub-model. This approach implicitly assumes that all device failures are reparable and that there are no logistical or mobilisation delays between failure and the first available weather window for maintenance [11].

A Wavepiston wave energy converter comprises multiple, floating energy collectors (ECs) coupled on a pipe or 'string'. Each EC has a vertical sail that is moved back and forth by the surge motion of incident waves. This horizontal movement drives hydraulic pumps generating pressurised seawater which is piped through the string to a conversion station onshore or on a platform. In the conversion station, the high-pressure seawater is fed to a standard hydraulic turbine to generate electricity and/or used directly in a standard osmosis system for desalination. Non-return valves are included for each energy collector and string so that a failure in any unit does not result in a loss of generation for the whole system. The Wavepiston EC design has been updated and, as part of the EU Horizon SHY project (Grant Agreement No. 101147456), Wavepiston is redesigning the hydraulic PTO technology, and updating its failure modes, effects and impacts assessment.

Comprehensive reliability assessment of WECs is challenging due to the paucity of real world failure data; however, nominal failure rates for specific WEC components may be used as guides for such studies [1], [11], [20]. However, in the absence of Wavepiston component-specific reliability data for the new hydraulic PTO, a generic device failure rate estimate is adopted for the WEC availability model. Therefore, absolute values of reliability, or availability, may be less relevant than the overall sensitivity of these quantities to O&M vessel thresholds, task durations, or other factors.

Stochastic system failure and reliability analysis involves defining a failure rate λ and a failure or reliability distribution. The reliability model adopted assumes the device failure rate is constant throughout the device operational lifetime. Device failures are exponentially distributed to model failures occurring randomly and independently. This is a common approach when detailed information on component failure rates and O&M vessel and crew logistics is absent. More complex reliability models may be adopted, including age-dependent failure rates [11], time- and sea-state dependent failure rates [20], and Weibull-type failure distributions [20], [26]; however, the exponential distribution and constant failure rate approach has been widely applied in WEC and wave-farm availability analysis [26], [27].

A nominal failure rate of $\lambda = 1.75$ yr^{-1} (failures per year) is proposed for the availability analysis, based on previous proposed failures rates from WEC O&M and repair studies [20], [28]. Although not necessarily reflective of a Wavepiston WEC, comprising modular energy collectors with independent failure modes, the use of a single WEC failure rate allows us to focus on the impact of weather-induced repair delays on device downtime and availability.

A 'time domain' Monte Carlo simulation method is used to model the impact of weather window wait times on device availability [13], [20], [26], [29]. This involves time stepping through a defined time interval, and at each time step, following these steps:

1) select a random sample to represent the device status (either operational or failed), and
2) if the device has failed, access to the site is established by selecting a random sample from a Bernoulli distribution, with the probability of access determined by the mean access levels from the weather window analysis.
3) If access is possible:
   - set the time to repair t_r to a single day.
4) If access is not possible
   - the waiting time is randomly sampled from the empirical weather-window waiting time distribution, either on a monthly or seasonal basis, and set the repair time t_r to equal waiting time plus a single repair day.
5) Finally, the downtime is incremented by the time to repair and the time step is advanced by the time to repair before repeating from step 1.

Failure status at each time step is sampled by comparing a pseudo-random number, generated from a uniform distribution [0,1] using a Mersenne-Twister algorithm, to the failure transition probability of the device $\exp(\lambda\Delta t)$, where Δt is the time step, which is a standard approach for such reliability analysis, e.g. [26], [29], [30]. The Monte Carlo simulation method involves repeating the simulations a large number of times to better quantify the uncertainty in the downtime and availability estimates.

IV. Weather window case study

A. Access levels

Site access levels are calculated for each year of the metocean time series at both deployment sites at monthly, seasonal, and yearly intervals. Fig. 4 summarises 20 years of seasonal accessibility estimates, based on a weather window duration of 16 hours with no daylight requirement, for significant wave height thresholds from 1.5 to 3.0 m. The box plots illustrate the sensitivity of site access levels to both season (median winter access levels are 19% and summer access levels are 47% for $H_{s,lim} = 1.5$ m at GCN) and offshore operation threshold H_s values. Accessibility is particularly sensitive to $H_{s,lim}$ at the most restrictive threshold value considered (1.5 m). In summer, the sensitivity of site access levels to $H_{s,lim}$ decreases substantially for thresholds greater than 2.0 m, where access levels asymptotically approach 100%. Inter-annual variability in site accessibility is also captured in Fig. 4 and, in general, decreases as access level increases. Furthermore, two outlier years, with severely restricted winter access to GCN and GCE, are evident in Fig. 4 for H_s thresholds exceeding 1.75 m.

The sensitivity of access levels to minimum weather window durations are more uniform across the range of durations considered, from 16 to 72 hours, as shown in Fig. 5. However, as expected, site access levels are more negatively affected by the daylight hours requirement for maintenance as the minimum window duration τ_{min} increases.

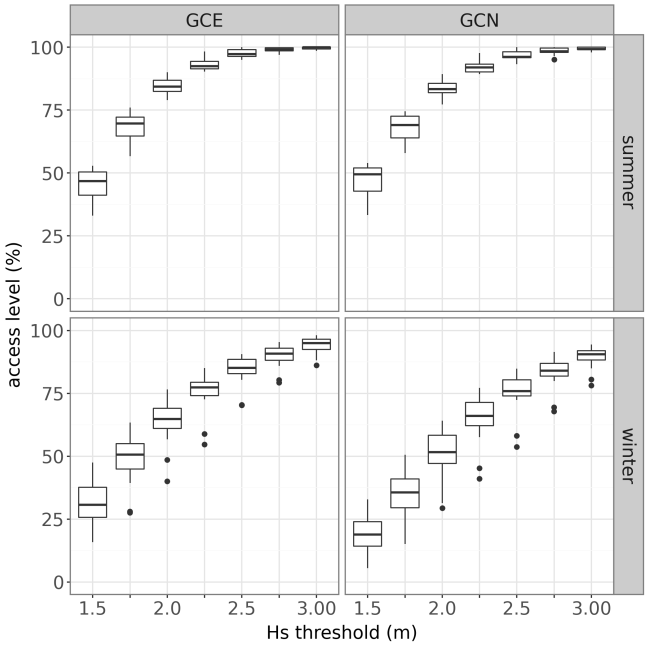

Fig. 4. Sensitivity of seasonal access levels at the Gran Canaria North and East (GCN and GCE) sites to threshold significant wave heights H_s for a minimum window duration of 16 hours, based on 20 years of ERA5 H_s time series data.

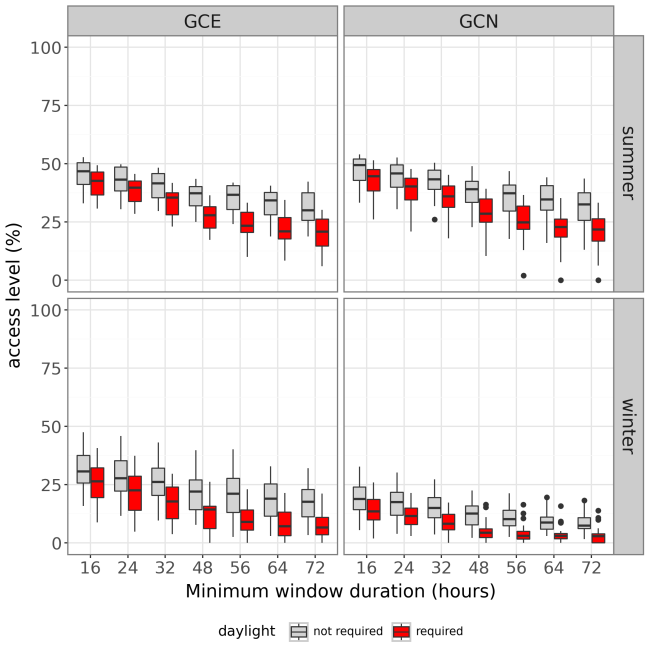

Fig. 5. Sensitivity of seasonal access levels, with and without the daylight requirement, at the Gran Canaria North and East (GCN and GCE) sites, to minimum weather window duration for maintenance access τ_{min} for threshold significant wave heights of 1.5 m, based on 20 years of ERA5 H_s time series data.

B. Waiting times between weather windows

Waiting times between weather windows vary widely throughout the year, depending on the seasonal prevailing metocean conditions, as shown in Fig. 6. Therefore, the waiting periods between windows are calculated at monthly, seasonal (assuming summer and winter seasons only), and yearly intervals for a range of operating thresholds $H_{s,lim} = (1.5, 1.75, 2.0)$ m and window durations τ_{min} =(16, 24, ..., 72) hours.

TABLE II
MEAN MONTHLY ACCESS LEVELS FOR THE GRAN CANARIA NORTH AND EAST (GCN AND GCE) SITES FOR THRESHOLD $H_{s,lim}$ = 1.5 M AND REQUIRED MINIMUM WINDOW DURATION OF 16 HOURS, ALLOWING MAINTENANCE ANY TIME (AT) OR ONLY DURING DAYLIGHT HOURS (DH).

	Mean monthly access (%)			
	GCE		GCN	
Month	AT	DH	AT	DH
January	30	22	15	9
February	25	19	15	11
March	24	19	11	8
April	40	37	31	26
May	41	39	39	36
June	51	48	56	53
July	27	22	41	37
August	39	36	49	44
September	62	58	58	52
October	53	47	41	37
November	35	30	25	19
December	34	27	18	13

The weather window definition in § II-C allows zero waiting times between consecutive weather windows of a specific duration; however, the average waiting periods calculated and presented in Table III incorporate only the non-zero waiting periods. Therefore, the overall impact of weather window downtimes on device availability must consider both the probability of access, measured through access levels, and the average waiting period when the site is inaccessible.

Table III shows the seasonal mean waiting periods for significant wave height thresholds $H_{s,lim}$ of 1.5 and 2.0 m and a required window duration of 16 hours, both with and without a daylight requirement for offshore maintenance operations. The proportional increase in the mean waiting time between weather windows, caused by the daylight maintenance requirement, is greater in winter than in summer, at both sites. In absolute terms, mean waiting times in winter increase by six days at GCN compared to an increase of over one day in summer, at the threshold $H_{s,lim}$ = 1.5 m (Table III). The higher sensitivity to the daylight requirement for waiting periods in winter is unsurprising, because daylight hours are 10 hours in late December, compared to 16 hours in late June.

C. Wind speed thresholds and weather windows

The impact of incorporating operational wind speed thresholds into the weather window analysis is briefly examined, by considering how seasonal access levels vary at GCN and GCE, when complementing the lowest significant wave height threshold $H_{s,lim} = 1.5$ m with three different wind speed limits. The three operational wind speed limits considered are 17 m/s, 11 m/s, and 8.0 m/s based on, respectively, the operating threshold for a tugboat vessel [20], offshore supply vessel [17], and a representative wind speed limit identified in a previous weather window anal-

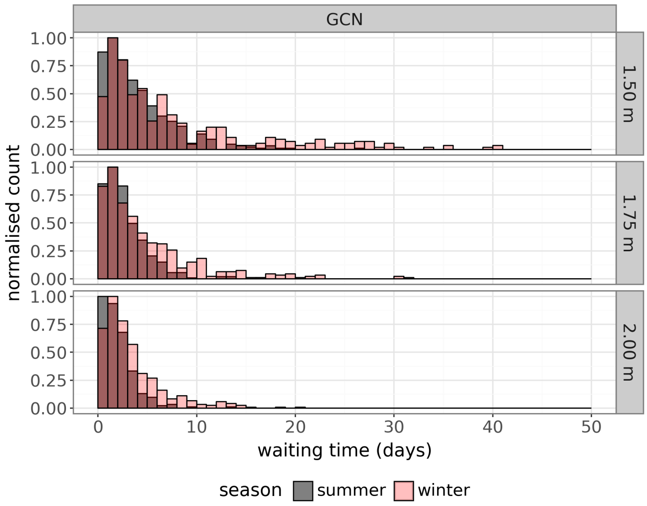

Fig. 6. Normalised frequency distributions (overlaid) of (non-zero) waiting times between weather windows, in summer (grey) and winter (light red) at the Gran Canaria North (GCN) site for a minimum window duration of 16 hours at $H_{s,lim}$ values of 1.5 m, 1.75 m and 2.0 m.

TABLE III
MEAN AND STANDARD DEVIATION (IN PARENTHESES) OF WAITING TIMES BETWEEN WEATHER WINDOWS AT GRAN CANARIA NORTH (GCN) AND GRAN CANARIA EAST (GCE) SITES FOR THREE THRESHOLD $H_{s,lim}$ VALUES, A MINIMUM WINDOW DURATION OF 16 HOURS, BOTH WITH AND WITHOUT A DAYLIGHT HOURS REQUIREMENT.

		Waiting period (days)	
$H_{s,lim}(m)$	Season	GCE	GCN
1.5	Winter	5.4 (*6.2*)	8.3 (*9.5*)
	Winter (daylight)	8.5 (*10.0*)	14.3 (*16.3*)
	Summer	4.2 (*4.1*)	4.1 (*3.6*)
	Summer (daylight)	5.6 (*5.1*)	5.3 (*4.2*)
2.0	Winter	2.8 (*2.4*)	3.5 (*3.1*)
	Winter (daylight)	4.0 (*3.7*)	5.2 (*4.8*)
	Summer	1.9 (*1.6*)	2.0 (*1.6*)
	Summer (daylight)	2.4 (*1.9*)	2.6 (*2.0*)

ysis [10]. In fact, the wind speed inferred during the period 2005–2024, from the ERA5 time series, exceeds 17 m/s during fewer than 20 hourly intervals and so the analysis involving the wind speed limit of 17 m/s is practically equivalent to the previous weather window analysis involving significant wave height thresholds only. Table IV-C shows that the impact of wind speed limits, in addition to the threshold $H_{s,lim}$ of 1.5 m, is negligible apart from during the summer at GCE where a limit of 8 m/s reduces accessibility on average from 45% to 27%. The greater impact of wind speed limits observed at GCE is consistent with the higher wind speeds experienced at this site, particularly during July and August, as shown in Fig. 3.

V. IMPACT ON AVAILABILITY

The impact of weather-induced repair waiting times on device downtime and availability is explored for a single reliability scenario, with and without daylight restrictions on maintenance. The Monte Carlo simulation method described in Section III-A provides a valuable framework to understand and quantify the uncertainty in the estimates of downtime and availability. In this case study implementation, a total of 1000 Monte Carlo iterations are conducted, where each iteration simulates 10 years of device operation using a one-day time step, based on the nominal failure rate $\lambda = 1.75$ yr^{-1}. Downtime and availability estimates are calculated for three threshold $H_{s,lim}$ values and for two minimum window durations of 24 and 48 hours, corresponding to one and two day time steps, respectively. All waiting times are rounded to the nearest day.

Fig. 7 illustrates the number of days of downtime per year at a nominal failure rate of $\lambda = 1.75$ yr^{-1}. The impact of longer waiting times between weather windows, caused by stricter threshold significant wave heights, on average downtimes is immediately evident, alongside the propagation of greater uncertainty in waiting times at more restrictive $H_{s,lim}$ (Fig. 6) to the downtime estimates. Overall, device downtimes

TABLE IV
MEAN SUMMER AND WINTER ACCESS LEVELS AT GRAN CANARIA NORTH (GCN) AND GRAN CANARIA EAST (GCE) SITES AT THREE WIND SPEED LIMIT VALUES, FOR A SIGNIFICANT WAVE HEIGHT THRESHOLD OF 1.5 M, AND A MINIMUM WINDOW DURATION OF 16 HOURS.

		Access level (%)	
Season	Wind speed limit (m/s)	GCE	GCN
Summer	17	46	47
	11	45	47
	8	27	45
Winter	17	31	19
	11	31	19
	8	25	18

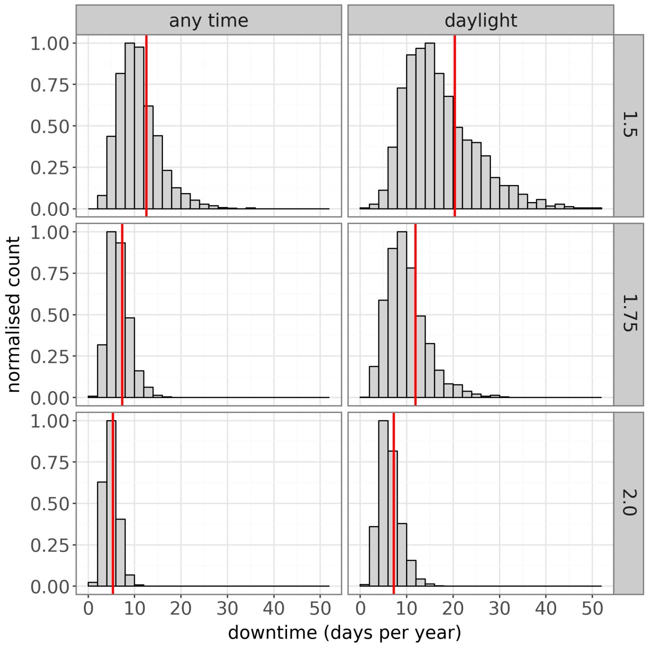

Fig. 7. Normalised frequency distributions of downtimes in days per year as a consequence of weather window waiting times at the Gran Canaria North (GCN) site for a minimum window duration of 24 hours at threshold significant wave heights 1.5 m, 1.75 m and 2.0 m. Vertical red lines indicate mean values.

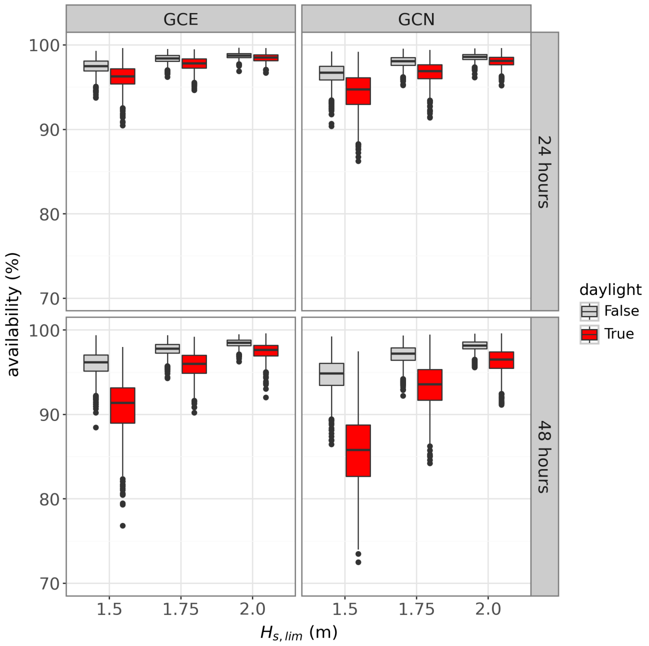

Fig. 8. Device availability at Gran Canaria North and East (GCN and GCE) sites for device reliability of $\lambda = 1.75$ yr^{-1}, a minimum window duration of 24 and 48 hours at threshold significant wave heights 1.5 m, 1.75 m and 2.0 m, for maintenance restricted to daylight hours or allowed any time.

TABLE V
AVERAGE DEVICE AVAILABILITY (%) AT GRAN CANARIA NORTH (GCN) AND GRAN CANARIA EAST (GCE) SITES WITH AND WITHOUT THE DAYLIGHT REQUIREMENT ON MAINTENANCE ACTIVITIES FOR THREE THRESHOLD $H_{s,lim}$ VALUES AND A MINIMUM WINDOW DURATION OF 24 HOURS.

		Availability (%)	
Site	$H_{s,lim}$ (m)	Any time	Daylight only
GCE	1.50	97.4	96.2
	1.75	98.3	97.8
	2.00	98.7	98.4
GCN	1.50	96.6	94.4
	1.75	98.9	96.7
	2.00	98.5	98.0

decrease for higher threshold significant wave heights, as mediated through increased site access levels (e.g. Fig. 4 and 5) and reduced weather window waiting times (see Fig. 6).

The comparison of device availability at the GCN and GCE sites in Fig. 8 reveals that reductions in availability are more pronounced at GCN, where the wave climate is more energetic, than at GCE. Furthermore, the daylight requirement is less restrictive at GCE than at GCN, as is evident from Table V, which shows the mean availability estimates with and without requiring daylight hours for maintenance. Although the changes in availability appear quite small, the corresponding changes in downtime are much greater, as evident from Fig. 7.

VI. CONCLUSIONS

Access levels and waiting times are found to be sensitive to the metocean condition thresholds on significant wave height and wind associated with a particular vessel or offshore operation, particularly between $H_{s,lim} = 1.5$ m and $H_{s,lim} = 2.0$ m at both sites. Many O&M vessels have wave height operating thresholds in this range [10], [17] and, therefore, careful consideration of the trade-off between increased cost of vessel hire and better site access and reduced downtime must be considered when planning repair and O&M strategies. However, such specific scenario-based planning will likely require more accurate device-specific reliability data, or estimates of such.

The weather window analysis indicates large uncertainty in waiting times between weather windows, with the level of uncertainty varying with the operating thresholds and minimum window durations. An additional source of uncertainty lies in the use ERA5 wave data, which is widely accepted to underestimate extremes in wave conditions, based on comparisons with wave buoy measurements [31], [32]. A negative bias in ERA5 H_s data will lead to overestimation of accessibility and underestimation of wait times. However, the magnitude of the negative H_s bias is less pronounced at lower H_s [31], [32], and the wave climate at the Gran Canaria sites rarely exceeds $H_s = 5$ m; therefore, the negative bias in ERA5 H_s data may not unduly impact waiting time and accessibility estimates.

A Monte Carlo simulation approach was adopted to demonstrate how uncertainty can be propagated from time-to-repair to device availability, providing a more complete picture of the impact of weather-induced downtime on availability than is possible by using just the mean time-to-repair. Of course, there are many other uncertainties in the device availability calculations, such as the effect of wave period in combination with wave height on device access, the impact of environmental conditions on failure rates, and logistical uncertainty in O&M crew mobilisation times. However, the preliminary availability investigation presented here highlights how excluding uncertainty from headline availability estimates can obscure the range of possible outcomes that may be relevant when examining trade-offs in O&M costs and availability and for potential investors in wave energy.

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