COMMISSION OF THE
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Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

Grant agreement number: 213380

EquiMar

Deliverable D7.4.1

Procedures for Estimating Site Accessibility

and

Appraisal of Implications of Site Accessibility

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Deliverables D7.4.1 and D7.4.2

Procedures for Estimating Site Accessibility

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Appraisal of Implications of Site Accessibility

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Summary

This report includes both an evaluation of procedures for estimating site accessibility and an appraisal of the implications of site accessibility for large-scale deployment of both wave and tidal stream devices and thus represents deliverables 7.4.1 and 7.4.2.

Several methods are reviewed for estimating the duration of accessible wave conditions on the basis of the probability of significant wave height exceedance. One of these methods is employed to investigate how the number of occurrences of accessible conditions and the waiting on weather allowance may vary with the annual average significant wave height of a site. Wave climates with average significant wave height in the range 1.5 to 3.5 m are considered. For a threshold wave height of 2 m at these sites, weather windows have average duration of between 2.5 and 1 day and require average waiting on weather of between 2 and 6 days. An estimate is subsequently made of the vessel time required to install a nominal array of 100 MW output.

Whilst a statistical approach is straightforward to apply to a single environmental variable, it is not straightforward to apply to a tidal stream site where wave height and both wind- and current-speed are relevant. A time-series method is employed to analyse ten years of environmental variables at a representative tidal stream site. The average waiting time between a 1 day weather window suitable for offshore work is extremely sensitive to current speed and seasonal variations occur due to wind-speed and wave-height. For the site considered it is estimated that between 2 and 5 turbines could be installed per month if installation can be conducted during current speeds up to 1.3 m/s but this falls to consistently less than 2 per month if offshore work is conducted whilst the current speed is less than 1.13 m/s.

CONTENTS

1 INTRODUCTION

An economic assessment of commercial marine energy projects must consider the cost of installation and maintenance. To estimate the installation costs associated with a marine energy project it is necessary to estimate the duration of offshore vessel time required. It is known from experiences of offshore wind that these costs are sensitive to the type and duration of offshore work. Vessel rates may vary considerably due to both demand variation and the need to await environmental conditions that are suitable for installation. This is because installation of both wave and tidal stream devices must be conducted when environmental conditions are sufficiently benign to allow safe operation of offshore vessels and handling of material and equipment. Suitable environmental conditions depend on the vessels employed and the task conducted but important parameters include wind speed, significant wave height and current speed. For projects comprising a small number of devices or located at relatively calm sites, sequential installation may be possible using a single vessel. Since commercial scale projects are likely to be deployed at sites where waves and currents are more energetic than both demonstrator projects and many offshore wind projects, the duration of conditions suitable for access will be shorter and waiting on weather intervals will be longer. Thus, for projects comprising large numbers of devices, which may be located at more energetic sites, installation may require parallel use of a number of vessels. The type and number of vessels and duration of vessel use strongly influence construction costs and maintenance costs so it is useful to understand how these constraints vary with device type and site.

In this study, a brief review of installation activities is given to provide an indication of the duration of tasks and constraints imposed by environmental conditions. Subsequently several methods are briefly reviewed for estimating the duration of accessible conditions. Separate approaches are then applied to wave and tidal-stream sites to quantify sensitivity of duration to average site conditions and to the required operational conditions.

1.1 INSTALLATION ACTIVITIES

Indicative installation & maintenance activities for marine energy projects have been listed in various reports (Previsic et al. 2004, Carbon Trust 2006 amongst others). Specific tasks associated with installation and maintenance of Pelamis wave energy devices are listed by Previsic et al (2004) (Table 3.3). A summary of published estimates of duration of several tasks and the environmental conditions required for their conduct is given in Table 1.1.

Task	Duration (hours)	Max current speed (m/s)	Max sea-state (Hs)	Max wind speed (m/s)	Vessel	Source
Tidal stream installation						
Transit port to site	3.5 to 7 hrs	1 to 2.6	1 to 2.5	5 to 11	-	EdF
Install foundation & turbine	1 to 3 hrs	1 to 2.6	1 to 2.5	5 to 11	-	(2008)
Install electrical equipment	4 to 8 hrs	1 to 2.6	1 to 2.5	5 to 11	-	‘’
Transit site to port	2.5 to 7 hrs	1 to 2.6	1 to 2.5	5 to 11	-	‘’
Wave device installation						
Transit port to site	Distance & vessel speed				AHTS	EPRI (2004)
Install electrical umbilical	10	-	2	-	AHTS	‘’
Install Pelamis device	4	-	2	-	AHTS	‘’
						‘’
Bi-annual maintenance	4	-	2	-	AHTS	‘’
Corrective maintenance	4	-	2	-	AHTS	‘’
Vessel types						
Jack up barge		1.6	1.5	20		BWEA
Crane (shear leg)		-	1.5	-		(2004)
Crane (derrick)		-	2	-		‘’
AHTS[1]		1.1	2	25		‘’
Cable laying[1]		2.5	3.5	15		
Offshore supply[1]		0.8	2	11		

Table 1.1: Environmental conditions and duration of various offshore installation activities from EdF and other sources

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[1] http://www.bourbon-offshore.com/en/marine-services/support-offshore

Duration of accessible conditions will also influence maintenance strategy and this will affect both the annual operating expenditure and the availability of the device. As a rough guideline, Bussel and Zaaijer (2001) suggest that the duration of a typical biennial wind turbine service requires 40-80 man-hours approx. whereas a major turbine overhaul, conducted every 5 years and involving replacement of major components, requires approx. 100 man-hours. The requirements for wave device maintenance are discussed in Equimar D5.6.

1.2 VESSEL RATES

Rates vary considerably with vessel type and with demand. Indicative values are given in Appendix A.

1.3 ACCESSIBLE CONDITIONS

To understand viability of a project installation schedule it is important to understand the duration (τ_{ac}) for which environmental parameters are less than a threshold level.. For example, the significant wave height (H_s) must be less than the specified wave height required for access (H_{ac}). To determine the aggregate duration of intervals for which this condition is satisfied it is necessary to consider the probability of occurrence and the persistence of conditions.

1.3.1 Occurrence

The probability that an arbitrary sea-state will have a significant wave height less than the required accessible condition is referred to as the probability of occurrence of accessible conditions and denoted $P(H_s < H_{ac})$. Thus the annual duration of accessible conditions may be estimated as $\tau_{ac} = 8760P(H_s<H_{ac})$. A basic assessment of the viability of an installation strategy is to confirm that the total planned maintenance is less than the aggregate duration of all sea-states that are suitable for the activity. If the aggregate duration of scheduled maintenance activities exceeds the aggregate period for which the wave conditions are sufficiently calm to allow site access, then the chosen strategy is not valid for the site. In this case, either an alternative approach should be sought or lower availability accepted.

1.3.2 Persistence

The duration for which significant wave heights remain, continuously, below the value required for access is referred to as the persistence of accessible conditions. A more detailed assessment of installation or maintenance strategies can be conducted by comparing the duration of all periods of accessible wave conditions (whilst $H_s<H_{ac}$) to the number and duration of individual tasks.

1.3.3 Estimating Accessible Periods

Perhaps the most straightforward method for estimating the duration of accessible wave conditions is by analysis of records of the time variation of significant wave height. Data sources include BODC measurements and output from the UKMO hindcast continental shelf model and other European metocean models (sources of wave data are detailed in Equimar D2.1). Such methods are appropriate for detailed design but may be overly complicated for the purposes of site comparison. A time-series approach is applied to three environmental parameters at a tidal-stream site in Section 4 and 5 of this report.

Whilst time-series data is available for many locations, data analysis is time-consuming and so simpler methodologies may be appropriate for the purpose of site evaluation, particularly wave sites. Typically the summary data for a wave site is in the form of an occurrence matrix; i.e. a scatter plot of the cumulative duration of periods for which the irregular wave field can be characterised by the pair of variables significant wave height, H_s, and period (e.g. some measure T). A scatter plot alone only provides the probability of occurrence of a sea-state, however, several methods are available from which the duration of accessible conditions can be estimated. Several statistical methods have been developed for estimating the durations of persistence intervals from available frequency histograms of significant wave heights. Brief reviews are given by Graham (1982) and Kuwashima & Hogben (1986). Three approaches are briefly reviewed:

i) NMI method based on Weibull model of significant wave height exceedance
ii) Markov chain model
iii) modified NMI method based on a log-normal distribution

All methods take as their input a normalised frequency histogram $P(H_s)$ describing the probability of occurrence of a particular significant wave height from which the cumulative probability of exceedance $P(H_s > H_{ac})$ of accessible wave height (H_{ac}) is obtained directly. The modified NMI method also requires additional data concerning the absolute rate of change of significant wave height (i.e. whether significant wave height is increasing or decreasing between successive samples).

NMI Method:
This method is relatively straightforward to apply and reasonable agreement with time series analysis has been observed for significant wave heights in the range 2 – 4 m. Based on methods proposed by Graham (1982), that used empirical derived relationships for a basic Weibull equation to predict wind speed and wave height persistence statistics, Kuwashima and Hogben

(1986) describe a method using input data of cumulative probability distributions of significant wave height to generate corresponding cumulative distributions of mean duration of persistence of exceedance or non-exceedance expressed in terms of a two parameter Weibull distribution. The model uses site specific parameters and empirical expressions to generate results that have been shown to be validated in a wide range of cases. Comparison is drawn between 2 year time-series of significant wave height data (3 hr intervals) from oil and gas sites in UK waters demonstrating reasonable agreement. Further comparison is drawn with sites off the coast of Hong Kong and South Africa. Reasonable agreement was obtained for sites with intermediate significant wave heights (2 to 4 metres) but for lower and higher H_s the agreement became increasingly weak with only one or two observed points on the predicted results. (Note: comparison is plotted on a log-log scale so it is not straightforward to quantify discrepancies).

Markov Chain Model

This approach is marginally more accurate than NMI but is complex to apply since requires involves more stages of calculation. Anastansiou and Tsekos 1996 suggest a method for generating persistence statistics from relatively short records using a first order Markov process (Coe & Stern, 1982). The Markov method establishes a transition matrix that is defined in terms of the recorded probability distribution at the site. The transition matrix is described as the “fingerprint” of the process for that site. From this fingerprint the estimated persistence statistics can be calculated. Their study initially considers only two states where conditions are above or below a threshold state, the method is then expanded by increasing the number of elements in the transitional matrix to include a higher number of states which gives a better description of the of the persistence statistics. The method allows seasonal variations to be removed by analysing a length of record of two-three months out of a considerably longer record; this has been shown to give good agreement with empirical relationships suggested in Kuwashima and Hogben (1986) derived over a longer interval.

Modified NMI Model

Mathiesen 1994 develops a parametric model in which persistence intervals are based on both the long term distribution of significant wave height and the absolute rate of change of significant wave height. The tail of the Weibull model is also replaced by a log-normal model to improve fit to measured persistence intervals. Since the rate of change of significant wave height (rather than just sea-state occurrence statistics) must be obtained from time-history of significant wave height the original wave data could be analysed directly.

2 WAVE ENERGY SITE ACCESSIBILITY

Following a review of methods for estimating accessible conditions from statistical data only, the NMI method is considered for several wave sites. This approach requires only the probability of significant wave height exceedance as input. The procedure followed is described in Appendix B and is similar to methods described by Graham (1982), Kuwashima & Hoben (1986) and BMT (2003). In Sections 2.1 – 2.3, the approach described is applied to several wave climates.

2.1 PERSISTENCE BASED ON ANNUAL STATISTICS

Figure 2.1 shows a three parameter Weibull distribution that provides the least squares best fit to data representing the probability of exceedance of a specified significant wave height $P(H_{ac}>H_s)$ at a site with annual average significant wave height $H_{s,av}$= 2.6 m. Weibull parameters x_0 and b are calculated by Equation (B.3) for a specified value of k.

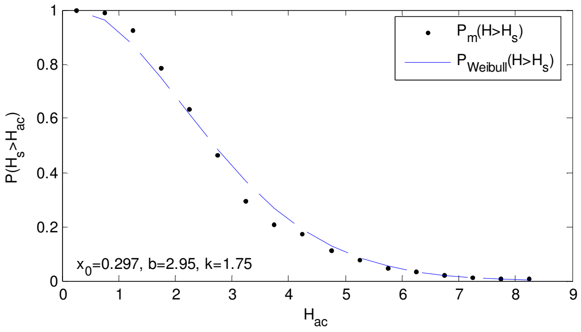


Figure 2.1: Probability of significant wave height exceeding access wave height during typical year. Wave data is for South Uist as presented by Shaw 1982.

The aggregate annual period for which the significant wave height remains lower than a specified wave height is given by the product $\tau_l = 8760P(H_s > H_{ac})$ where 8760 the average number of hours per yerar. This annual aggregate period is composed of a numerous shorter events interspersed by intervals of more severe wave conditions. The mean duration of periods during which a specified accessible wave height is not exceeded is given by Equation (B.2) and plotted in Figure 2.2:

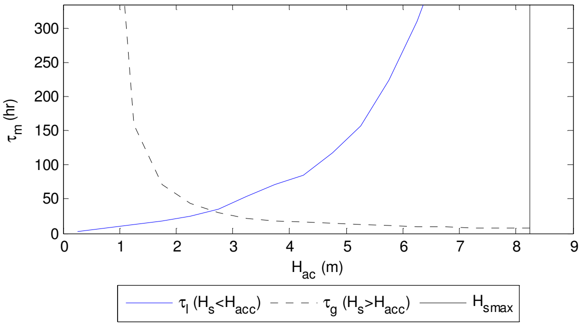


Figure 2.2: Mean duration of periods during which significant wave height is continuously less than access wave height (H_{ac}) and continuously greater than access wave height.

For this data, the significant wave height is less than 2 m during intervals of, on average, 24 hours duration and is less than 4 m for, on average 80 hours. The period for which accessible conditions persist trends to infinity (the duration of the wave record) as the accessible wave height trends towards the maximum recorded significant wave height (8.3 m in this example). Using the calculated parameters x_0, b and k (see Appendix B) the distribution of period length about the mean duration $\tau_l(H_s<H_{ac})$ can be estimated. For maintenance and installation activities it is of interest to quantify the number and duration of weather windows for a specific value of H_{ac}. Figure 2.3 below shows the fraction of time for which the significant wave height is less than H_{ac} for continuous periods in the range $0 < \tau < 240$ hours (e.g. 0 to 10 days). Whilst 20% of all sea-states have a significant wave height of less than 2 m, less than 17% of sea-states have both a significant wave height of less than 2 m and occur within an interval of more than 24 hours duration. This figure reduces to 14% for durations of 48 hours.

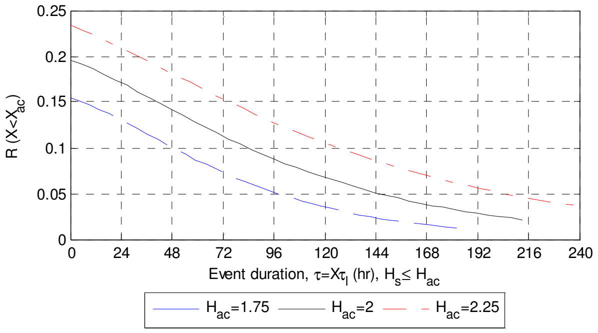


Figure 2.3: Probability of occurrence of accessible event of duration greater than (or equal to) τ.

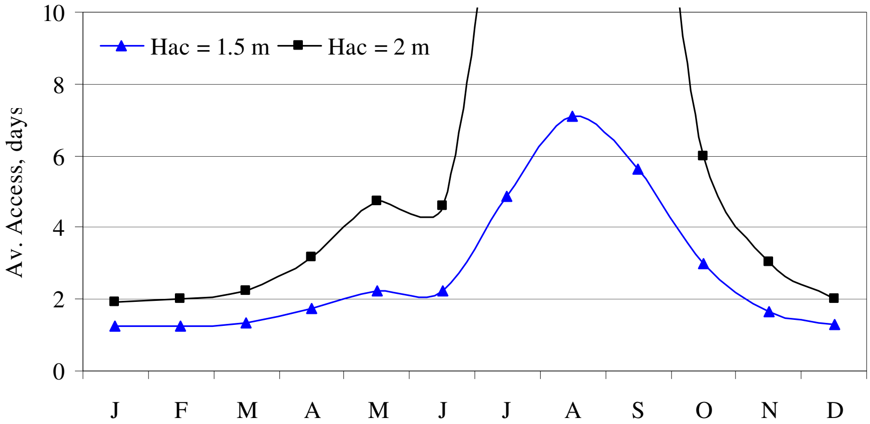
Note that Figure 2.3 is dependent on the quality of fit between the input statistical wave data and the three parameter Weibull distribution. A ±10% variation of each of the three Weibull parameters (x_0, b and k) may cause a variation of probability of accessible conditions of around 5%. However, this uncertainty is generally smaller than the variation due to the accessible wave height considered. A ±12.5%variation of the accessible wave height employed for analysis results in a ±25% change of the probability of occurrence of accessible conditions (Figure 2.3). All accessible events are of duration $\tau > 0$ so the intersection with the y-axis in the above plot represents the total fraction of accessible conditions. This approach provides an estimate of the aggregate duration of wave conditions suitable for completion of tasks of a particular duration. Evidently there is a substantial reduction in the probability of an accessible event as the required duration is increased. The gradient of this slope is dependent on the site specific statistical wave height data.

2.2 MONTHLY VARIATION

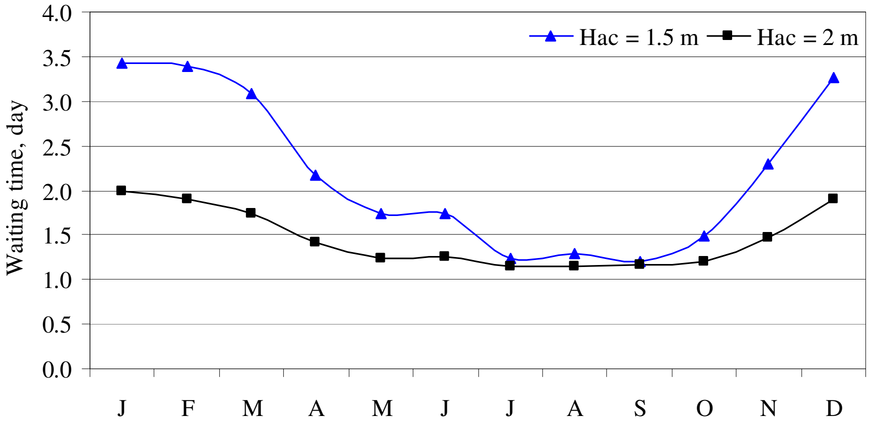
The previous section is based on an annual occurrence matrix so seasonal variation of conditions cannot be inferred. In this section the monthly variation of accessible conditions is briefly analysed for a site with an annual average wave power density of 23 kW/m based on data presented by Previsic et al. (2004). At this site wave power density ranges from 8 kW/m, during the summer months, to around 36 kW/m during the winter months. Wave heights of less than 1.5 m or less than 2 m are considered as suitable for offshore activities. An estimate of the number of accessible events of duration τ_{ac} during an interval D is given by estimating the number of events as $N_{ac} = DR(T > \tau_{ac})$ and the average time interval between events is therefore $(D - N_{ac}\tau_{ac}) / N_{ac}$. In the following, the number of accessible events per month (D=31 days) and per year (D=365 days) are considered.

For this site, during the summer months (Apr-Sep), a negligible fraction of the accessible conditions persist for less than one day (τ < 1 day). Therefore, the fraction of accessible wave events persisting for τ > 1 day closely approximates the annual probability of accessible wave conditions. During the winter months (Oct-Mar), the fraction of accessible events which persist for less than 1 day increases to 30% of the total fraction of accessible events. On average, accessible events of continuous duration greater than 1 day represent more than 85% of the aggregate accessible conditions. Therefore, an estimate of the probability of accessible conditions occurring continuously for 1 day could be estimated as 15% less than the probability of occurrence of a given significant wave height.

For the same site and period, the average time between each accessible event varies from a little more than a day during the summer to an average of 3 days during the winter (Figure 2.4(b)). Thus, during the winter an average of eight days vessel time would be required to complete 2 days of offshore installation whilst H_s < 2 m. In contrast, during the summer conditions a vessel that is available for the entire month could conduct offshore installation an average of 15 days per month.



a) Average number of accessible wave conditions of 24 hour duration per month



b) Average interval between accessible conditions of 24 hr duration.

Fig 2.4: Monthly variation of accessible conditions at a site with annual average significant wave height $H_s = 1.3$ *m and average wave power 23 kW/m. Average duration of accessible conditions and average waiting time for one day of accessible conditions shown for* $H_{ac} = 1.5$ *m and 2.0 m.*

2.3 SITE VARIATION

To improve understanding of site-variation of accessible conditions, the method outlined in Section 2.1 is applied scatter plots for several UK sites as published by HSE (2001). This annual data is sufficient for estimating annual energy production but provides no information regarding seasonal variation of conditions. To facilitate comparison between sites, each scatter plot is characterised by the annual average significant wave height, annual average period and average power density. Although power density is also dependent on wave period, the range of average site conditions considered ($H_{s,av}$ in the range 1.0 to 3.2 m) correspond to wave power densities of between 5 and 50 kW/m. The sensitivity of the duration of accessible conditions to threshold wave height is considered.

Figure 2.5 shows the average duration of a weather window for three threshold wave heights. Clearly, low values of significant wave height occur continuously for only very short periods; $H_s < 1$ m persists for less than 2 days. However, wave device installation is unlikely to require such calm conditions and $H_s < 2$ m may be adequate (Table 2.1). As would be expected, the duration of accessible conditions reduces with increasing annual average significant wave height. Average weather window duration decreases by a factor of approximately 2.5 for each doubling of site significant wave height. For an accessible wave height of 2 m, average weather window duration is longer than two days only if the average significant wave height of the sites is less than 1.75 m. This annual average corresponds to a wave power density of 17 kW/m. Average weather window duration is approximately one day for sites with significant wave height greater than 2.5 m and wave power density greater than 30 kW/m.

Site variation of the duration of accessible sea-states is shown in Figure 2.6. Accessible intervals, τ_{ac}, of zero duration (a single sea-state), one- and two-day duration are shown as $R(T > t_{ac})$. Intervals of significant wave height less than 2 m (Figure 2.6(a)) occur almost continuously (80% of the time) for $H_{s,av} \sim 1$ m reducing to 25% of the time for $H_{s,av} \sim 2.5$ m. In contrast, significant wave heights less than 1 m (Figure 2.6(b)) occur around 40 % of the time for $H_{s,av} \sim 1$ m but less than 10% of the time for $H_{s,av} > 2.5$ m.

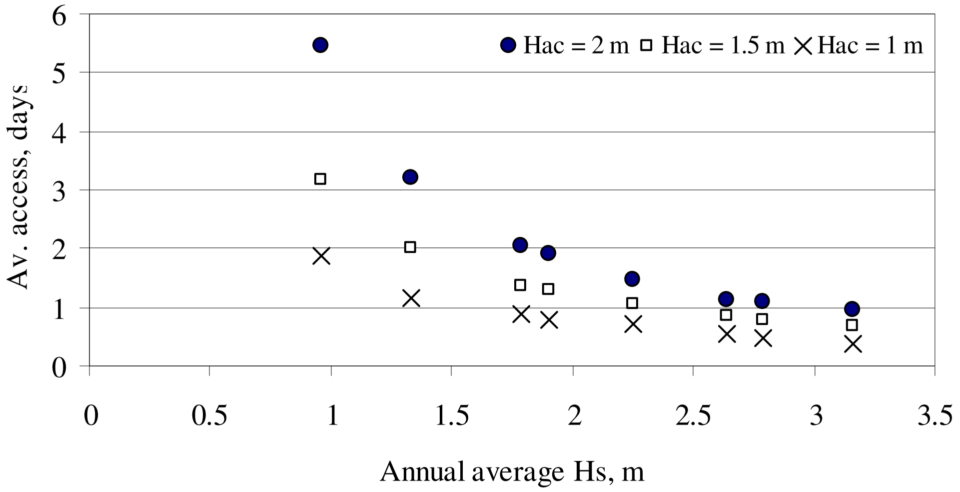
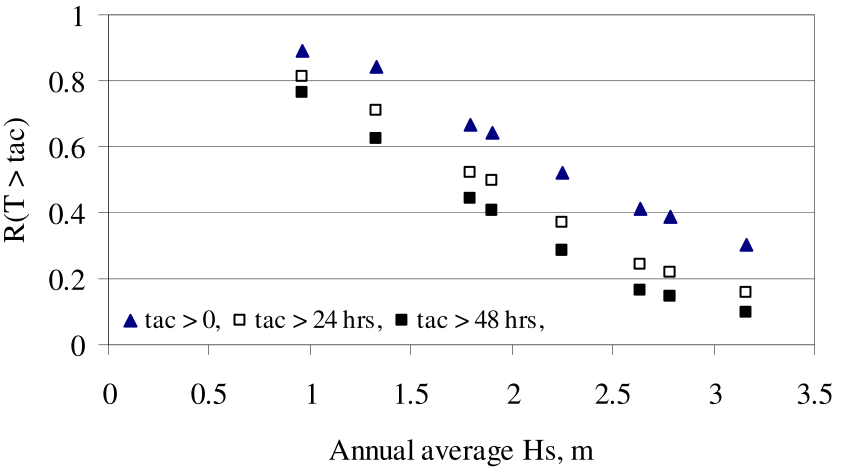
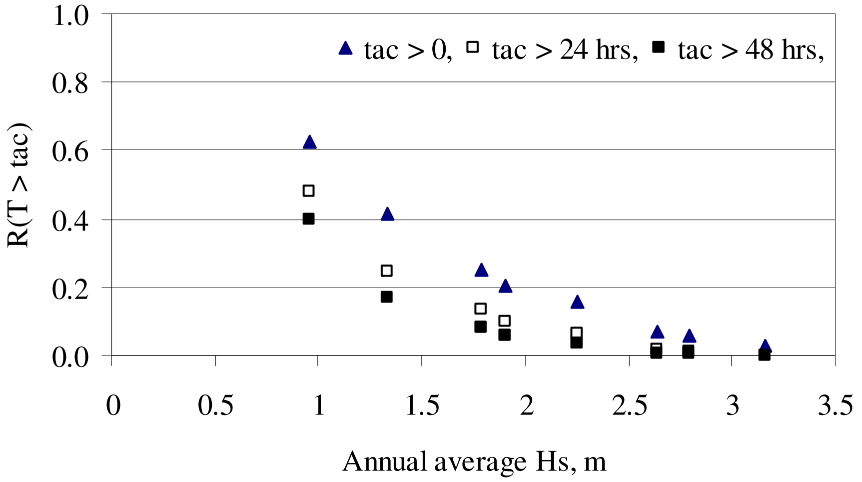


Figure 2.5: Mean duration of intervals of calm conditions at several sites characterised by annual average significant wave height.



(a) Accessible conditions defined as significant wave height less than $H_{ac} = 2$ m



(b) Accessible conditions defined as significant wave height less than $H_{ac} = 1$ m

Figure 2.6: Probability of occurrence of accessible conditions persisting for 1 day or more at several sites as characterised by annual average significant wave height.

3 LARGE-SCALE DEPLOYMENT OF WAVE-DEVICES

In the previous sections a method for estimating the duration and occurrence of intervals during which the significant wave height is lower than a threshold wave height H_{ac} is described and applied to several wave climates. In this section, the implications of these access limitations are briefly discussed in terms of two scenarios: i) the number of devices that could be installed during an average year based on the number of occurrences of a 24 hour weather window and ii) the rate of installation that would be required to deploy a wave power project with a nominal average output of 100 MW. Average output is considered rather than rated power to minimise speculation regarding device design.

Since the wave climate differs between sites, an estimate of the number of devices required at each site is assumed based on the performance of an idealised device in the average wave conditions at the site. Average output from a single wave energy device is assumed to be equivalent to the point absorber limit for performance in regular waves that are of equal power density to the irregular wave fields at the site. Regular wave period is defined equal to the average period at the site ($T_{e,av}$) and wave amplitude is defined as a function of annual average significant wave height ($H_{s,av}$). Average power output from a device is therefore estimated as $P = 122\ H_s^2 T_e^3$. This approach is intended only as an indication of the relative number of devices required at each location and does not represent a real device since the performance of suitably dimensioned devices is not available for these locations. As a point of comparison, this assumption yields an average output of 800 kW from a site with average power density of 30 kW/m reducing to 450 kW and 175 kW from sites with average wave power densities of 20 and 10 kW/m; this is approximate but consistent with performance estimates for existing devices so provides a basis for relative comparison between sites. Following this approach, an estimate of the average power output per device and the number of devices required to attain 100 MW average power output is given in Table 3.1. The range of device output and number of devices reflects the range of technologies presently in development from small devices defined for mass production and installation at low energy sites ($H_{s,av}$ < 2 m) through to larger individual devices designed for energetic conditions with Hs,av > 2m.

Table 3.1: Annual average significant wave height and period and estimated device number assuming idealised point absorber model (see text) to describe mean power output. Figures are indicative only.

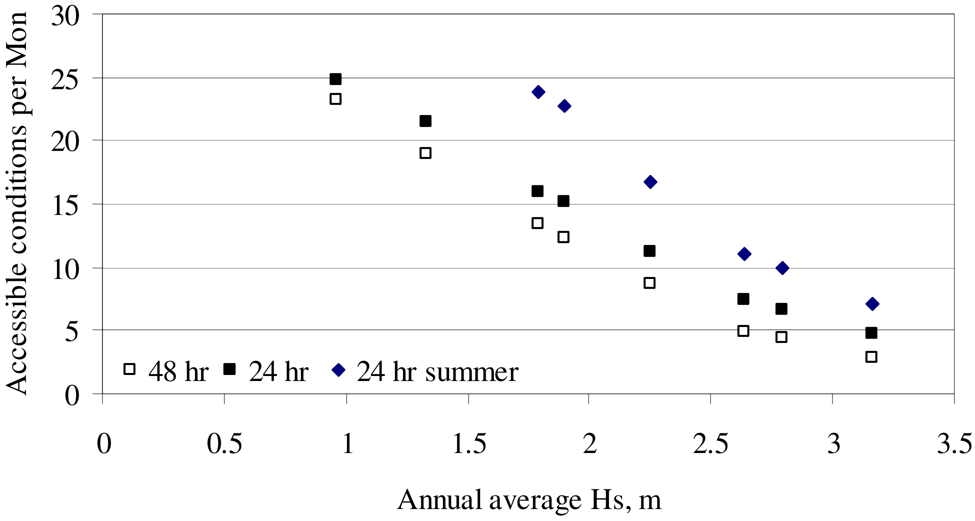
$H_{s,av}$ (m)	$T_{e,av}$ (s)	Site power (kW/m)	Single device output (kW)	Number of devices (estimated).
0.96	5	2.3	15	8800
1.33	5.7	5	40	3100
1.79	6.9	11	130	1000
2.25	7.5	19	260	480
1.9	8.8	16	300	415
2.64	9.6	34	750	170
2.79	9.6	37	840	150
3.16	9.8	49	1150	110

The number of occurrences and mean waiting interval between each occurrence of accessible conditions (H_s < 2 m) of one- and two-day duration for a typical month is given in Figure 3.1. Monthly analysis is not conducted for these scatter plots but there will clearly be a large seasonal variation. With reference to Figure 2.4 an estimate of seasonal variation is obtained for these sites by assuming that 75% of accessible conditions occur during six summer months only (i.e. three times as many occurrences during summer months than winter months).

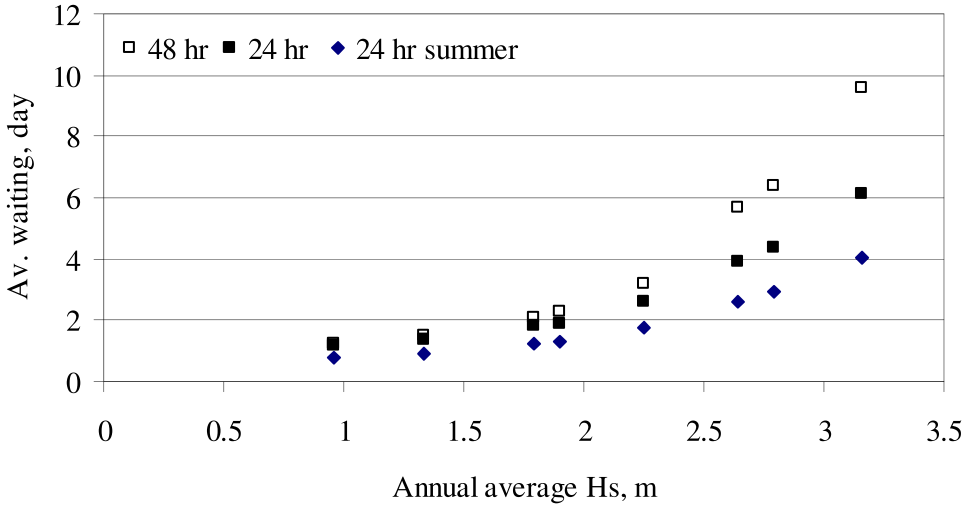
For sites with an annual average significant wave height less than 2 m, significant wave height is expected to be greater than 2 m for 14 days or more during an average month and an average waiting time of between 1 – 2 days is required. Access constraints are likely to be minimal during summer months at these sites. However, due to the relatively low power density at these locations (< 20 kW/m), large numbers of devices would be required and it would be necessary to install multiple devices during each weather window. For example: at a site with annual average significant wave height of 1.5 m, a 100 MW farm would require installation of around 10 devices per day of accessible conditions.

For intermediate sites (annual average significant wave height 2 – 3 m and bulk wave power density 20 – 40 kW /m) significant wave heights are lower than 2 m for between 7 and 14 days per month and a waiting on weather allowance of 2 - 3 days is required. Thus, if the time required to install a single device is approximately 1 vessel-day, it may be possible to install 150 – 200 devices within a single year.

For sites with annual average significant wave height greater than 3 m, accessible conditions may only occur for 5 days per month and a waiting allowance of 5 – 6 days would be required per weather window. Since vessel rental is required for waiting conditions as well as operation this has a direct impact on cost. Twice as many days may be available during summer months and, since the wave resource is greater in these regions, fewer devices will be required for a target power output than at low energy sites. In a typical year 40 – 60 days may be suitable for installation. Installation of two devices per weather window would be required to install 100 devices (Table 3.1) within a year. On average, this would require the vessels used to be available continuously for six months but only used for less than 60 days. For these sites it may be necessary to design installation strategies that can be completed whilst significant wave height greater than 2 m.



a) Number of occurrences (N_{ac}) of accessible conditions in an average month.



b) Average number of days waiting for an interval of accessible conditions.

Fig 3.1: Site variation of accessible conditions of 2- and 1-day duration during an average month. Values marked for 1-day interval during summer months assume 75% of accessible conditions occur during six month period Apr – Sep.

4 TIDAL STREAM SITE ACCESSIBILITY

EDF R&D developed the AMER ("Accessibilité des Eoliennes en Mer") software to assess and quantify the accessibility of a specific tidal farm site, when the definition of operational characteristics and metocean data are provided. The software is based on time-series analysis of given metocean data at a single site-representative location.

4.1 TIME-SERIES ANALYSIS

The environmental conditions expected to limit installation and maintenance operations are metocean data such as wind speed, wave height, wave period and current speed over a specified period. The limiting conditions cannot be reduced to one variable as the tidal currents are likely to raise accessibility problems (the tidal site having been being chosen for its particularly high tidal current speeds) and extreme wave or wind conditions can disturb open air operations. The characteristics of the operation that are taken into account are its duration and the threshold value of each environmental variable that permits safe completion of the operation (see Table 1.1). Both duration and threshold variables depend on the type of vessel to be used, the specification of the tidal energy converter (TEC) and and their associated safety requirements.

The AMER software provides, in a simple manner, an estimation of several different indicators of accessibility of a tidal turbine farm. With reference to Figure 4.1, the indicators reported include:

- The average waiting time (denoted "WT", per month and season) between consecutive windows of favourable weather conditions,
- The accessibility period (denoted "A", per month and season), within a favourable window during which it is possible to commence an operation of duration "D".

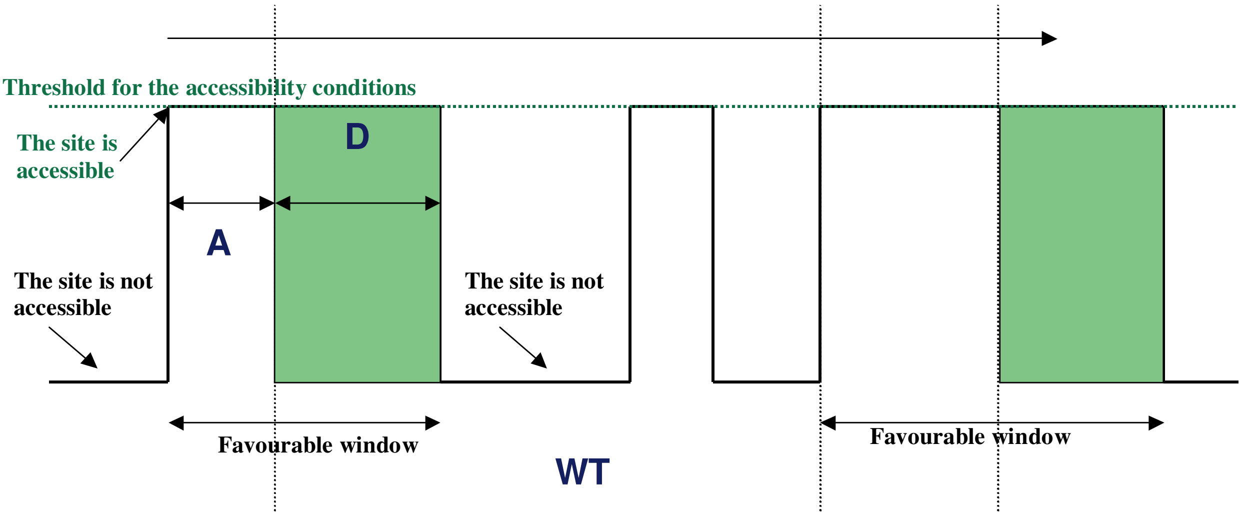


Figure 4.1 : The different indicators of the accessibility

Presented below are the results from AMER for a representative tidal site. Flow velocities at the site are of the order of 2.5 m/s during a spring tide and 1.5 m/s during a neap tide. Flow direction reverses between flood and ebb tides. The operations considered describe the installation of a single tidal energy conversion device (TEC) from a port (denoted "A") that is located close to the site. It is assumed that this port is fully equipped and sized for the operations considered. The time-series of environmental variables employed covers an interval of ten years (the longer the interval, the more reliable the results). The metocean data studied in this example are the significant wave height (Hs), the wind velocity (Vw) and the depth-averaged current velocity (Vc). Sea-state and meteorological parameters are usually derived from hindcast models (for example, ANEMOC for wave climate and ERA40 for meteorological data). Tidal current speeds could also have been derived from models, but more precise results are obtained from the harmonic analysis of *in situ* measurements.

The installation operation is divided into three distinct stages. The first stage corresponds to the transportation of the TEC from the port to the site (subject to low environmental constraints). During the second stage, the TEC is lowered down to the sea bed (subject to strong environmental constraints). The final stage consists of the return from the site to the departure port (environmental constraints are therefore equivalent to those at the first stage). The accessibility is given as the mean waiting time for a metocean access window, depending on the month of the year and the season. This value provides the order of magnitude for planning disruptions (which can bring qualified human resources and marine equipment to a standstill) and so can help with estimating the resultant costs.

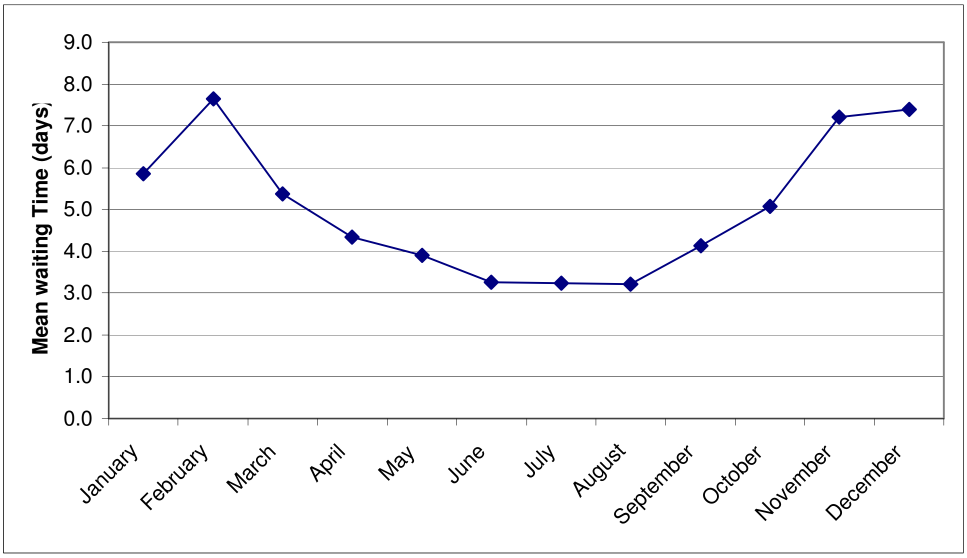


Figure 4.2 : Example of the change in the mean waiting time(in days) for a window of favourable metocean conditions of approximately 12 hours depending on the month of the year.

Figure 4.2 illustrates the monthly variation of mean waiting time over an average year. Typically, the results indicate that the summer months, when wave and wind conditions are usually calmer, facilitate installation, whereas the waiting time increases significantly during the autumn and the winter. Such operations should preferably be undertaken within the period running from April to September. Figure 4.3 represents the corresponding maximum average delay for each month (see previous definition). It does not take into account the duration of the operation.

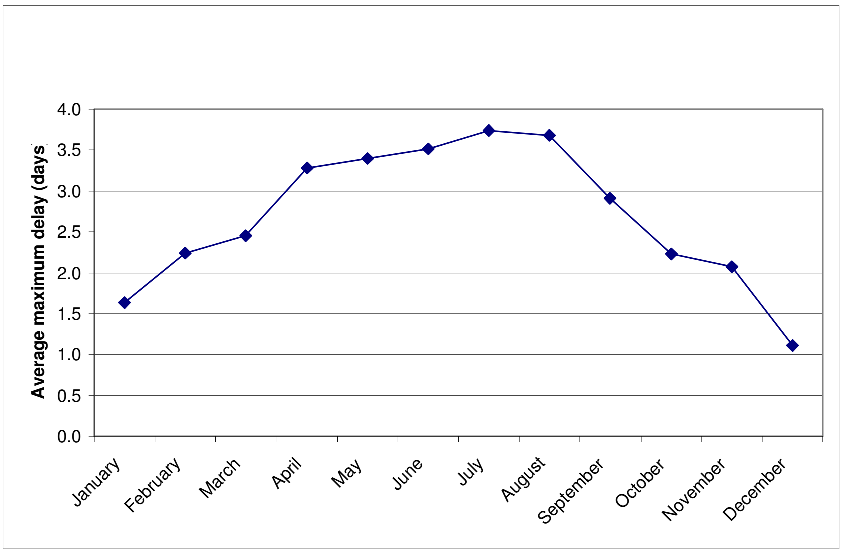


Figure 4.3: Example of the change in accessibility period (in days) for a window of favourable metocean conditions of approximately 12 hours depending on the month of the year.

4.2 CONSTRAINTS

The occurrence of favourable metocean conditions occurring for a period of approximately 12 hours has been considered. The accessible period required and the magnitude of the three metocean parameters considered as constraints to the operation mainly depend on the type of vessel employed and the procedure followed to install the turbine. A sensitivity study is pursued in order to improve understanding of the relative importance of each of these environmental constraints for this generic site.

Sensitivity of accessibility to the tidal current speed limit :

The current speed limit varies according to the stage of the installation process (transportation, deployment or return to port). This limit is higher (less onerous) for the transportation to site and the return to port than it is for the deployment stage. This is because a small current is preferred to zero current to stabilise installation activities and because deployment is a more complex process. In Figure 4.4 the "Tidal current speed limit" corresponds to the value given for the deployment stage. The values imposed for the transportation stages are obtained by proportionality.

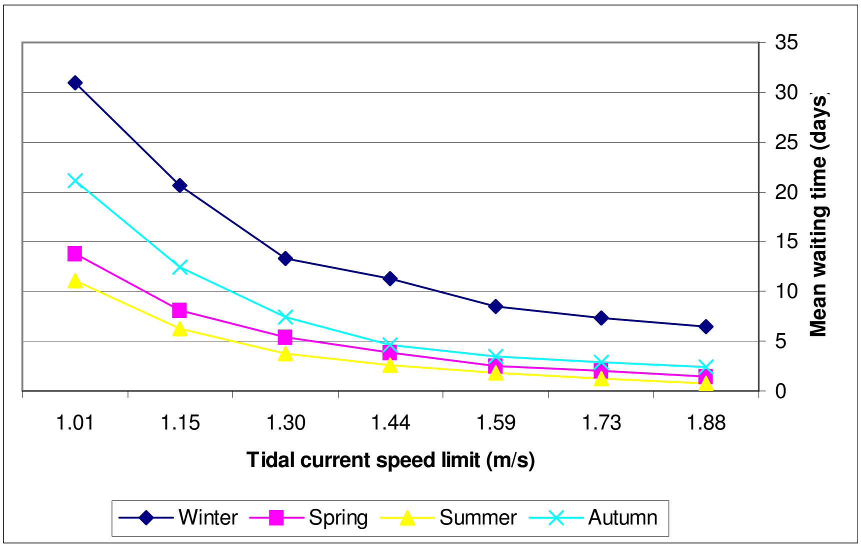


Figure 4.4: *Sensitivity of accessibility to the tidal current speed limit depending on the month of the year. Threshold wind speed of Vw = 8 m/s and threshold significant wave height Hs = 1.5 m.*

It is worth noting that if the installation of the turbine must be executed at a low current speed (e.g. < 1.5 m/s), the waiting time is increased dramatically (up to 10 or 12 days in summer and spring which are the best periods in which to operate in terms of wave conditions and wind speed). There is a sharp increase in the mean waiting time when the current speed limit is below 1.30 m/s. This is due to the tidal current distribution: it becomes more and more difficult to find windows during which the current stays below this threshold. For more energetic sites (those with higher average tidal current speeds), the threshold could be higher. In extreme cases this might preclude the feasibility of the installation or require a modification to the installation procedure/equipment. Similarly, at sites with complex flow patterns, for example where the ebb and flood flows do not dominate, flow speed may not reduce to zero (i.e. the polar of velocity and direction may trace an ellipse) and so installation procedure / equipment will need to be given particular consideration.

Sensitivity of accessibility to the wind speed and the significant wave height limits :

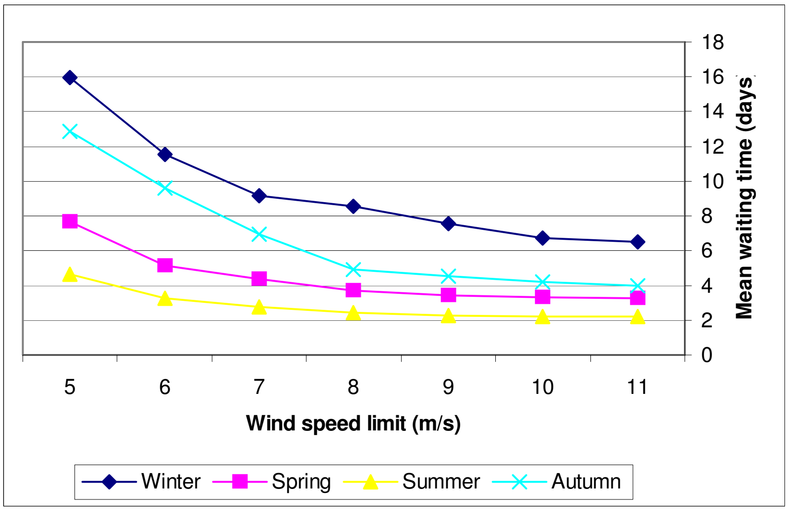


Figure 4.5 : Sensitivity of accessibility to the wind speed limit, depending on the month of the year. Threshold current speed Vc = 1.5 m/s (for the deployment stage) and threshold significant wave height Hs = 1.5 m.

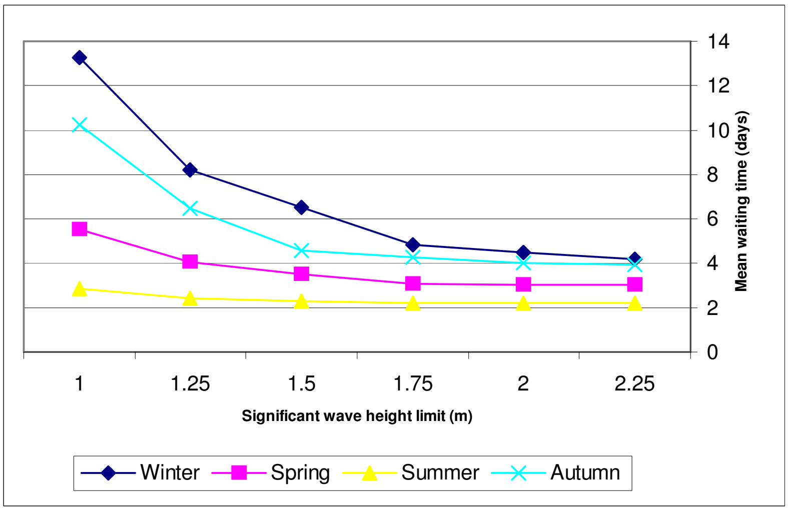


Figure 4.6 : Sensitivity of accessibility to the significant wave height limit, depending on the month of the year. Threshold current of Vc = 1.5 m/s (for the deployment stage) and threshold wind speed of Vw = 8 m/s.

The results demonstrate strong seasonal variation which is consistent with historically observed wave and wind conditions. Lowering the limits during the summer would not have a serious impact on accessibility since this increases the waiting on weather time by a factor of between 0.5 and 2 (wind and wave) only, whereas the same changes in winter dramatically increase the waiting on weather time – by a factor of 2.5 to 3 (wind and wave) and up to 6 on current speed.

5 LARGE SCALE DEPLOYMENT OF TIDAL STREAM DEVICES

Since construction & maintenance costs are dependent on the duration of vessel use and the vessel hire rate, and the hire rate is known to increase with market demand, the influence of limited site accessibility on installation scheduling is considered in brief for a tidal stream farm.

Figure 5.1 gives an estimation of the number of TECs that could be installed throughout the year using a single vessel. The results are derived using the AMER software for the following operational limits and a total working time of 16 hours:

- Stage 1 : Vc = 2.50 m/s, Vw = 8 m/s, Hs = 1.5 m (night labour is allowed for this stage),
- Stage 2 : Vc = 1.33 m/s, Vw = 8 m/s, Hs = 1.3 m (only day labour is allowed for this stage),
- Stage 3 : Vc = 2.50 m/s, Vw = 8 m/s, Hs = 1.5 m (night labour is also allowed for this stage).

During a typical year, approximately 45 turbines of 500 kW rated power could be installed at the representative site considered. Thus, an installation rate of 23 MW per year could be achieved. For a 100 MW tidal farm to be constructed in one year, 4 vessels would be required. In practice, it is unlikely that renting the required equipment to install a device in December would be deemed economically acceptable since only 1 or 2 turbines could be installed during the entire month. If it is assumed that the installation process would only be carried out from April to September then only 28 turbines per year could be installed by one vessel and 7 vessels would be required to install a 100 MW tidal farm in a year. However, the availability of the required vessels and equipment might be limited, for example, due to their use in the offshore wind farm industry during the same period.

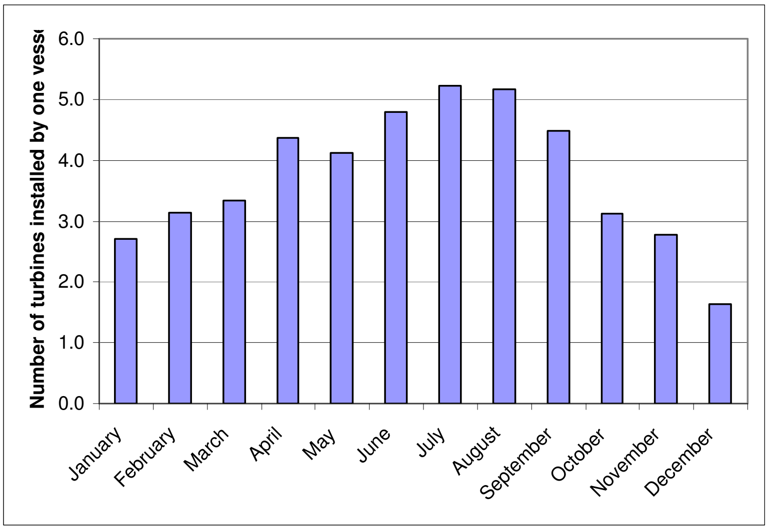


Figure 5.1: Large scale deployment: number of turbines that could be installed during each month of a year by a single vessel assuming that installation is completed during an operational duration of 16 hours and the following constraints – Stage 1 & 3: Uc < 2.50 m/s and Stage 2: Uc < 1.33 m/s.

As shown previously, accessibility is very sensitive to the tidal current speed limit. We can illustrate this point by decreasing the current speed limits by 15 % (Stage 1: Vc = 2.13 m/s, Stage 2: Vc = 1.13 m/s, Stage 3: Vc = 2.13 m/s) with all other limits being constant. We obtain the results provided in Figure 5.2, whereby 15 turbines could be installed per year (7.5 MW) and simultaneous operation of 14 vessels would therefore be required to install 100 MW in one year.

These results depend on the assumption that the installation of one machine can be achieved by indefinite repetition of the same three installation stages. However, large scale deployment could also raise additional access problems that are not considered in this study. For example due to the formation of a wake downstream of the turbines; the installation of a tidal farm will be carried out incrementally, causing the original hydrodynamic conditions to be disturbed by the fluid-structure interactions. The flows could become much more turbulent and lead to more complex under-water operations (especially during the lowering of the device). Other difficulties could arise from the general layout of the farm if, for example, it comprises a “high” density of turbines and/or a complex cabling network to manage.

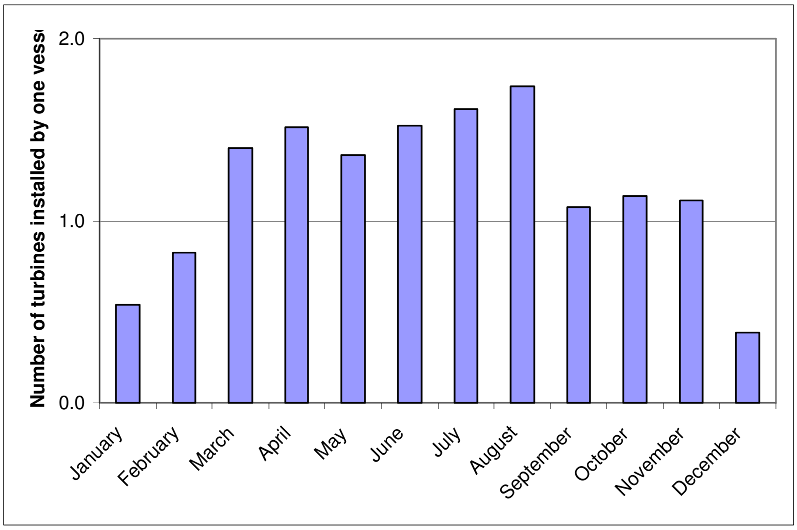


Figure 5.2: Large scale deployment: number of turbines that could be installed during each month of a year by a single vessel assuming that installation is completed during a weather window of 1 day and the following constraints – Stage 1 & 3: Uc < 2.31 m/s and Stage 2: Uc < 1.13 m/s. .

6 CONCLUSIONS

The type of installation tasks required for marine energy moorings and support structures has been reviewed in Deliverables 7.3.1 – 7.3.3. Installation costs are dependent on the type of vessel employed, the duration of vessel use and the vessel rate. Experience of offshore wind installation indicate that vessel rates can increase significantly with demand and so it useful to understand the duration of offshore installation activities for marine energy projects. Methods for estimating the duration for which environmental conditions are suitable for conducting installation (and maintenance) activities are reviewed. At locations where a single environmental variable is important, statistical methods can be applied. Such approaches have previously been demonstrated to be effective for a relevant range of average wave conditions (H_s ~ 2 – 4 m). In addition, since minimal input data is required, statistical approaches are suitable for site evaluation purposes. At locations where several environmental variables are important, the most straightforward method is to analyse time-series of relevant variables.

A time-series analysis method is applied to a tidal stream site and a statistical method to several wave sites to obtain estimates of the duration of accessible conditions. The implications of the duration and frequency of occurrence of accessibility are discussed with reference to installation of large scale marine energy projects of the order of 100 MW average power output. Separate wave and tidal stream projects are considered. The quantities reported indicate onerous constraints on the duration of environmental conditions that are suitable for offshore work.

Such limited access conditions directly affect the choice of installation method and the must be considered when assessing the method and rate of deployment and maintenance of devices. This directly affects the vessel time and hence cost that must be included in an economic assessment. For wave energy sites, there is a clear seasonal variation of the duration of accessible conditions and the average waiting time between accessible conditions. For a site with wave power density of around 23 kW/m, the average waiting time during the winter is roughly three times as much as during the summer. At sites with lower wave power density, conditions are more favourable for access but efficient installation methods and continuous vessel use may still be required for large-scale deployment. At sites with higher wave power density accessible conditions occur infrequently.

Access constraints are more onerous for tidal stream sites. In particular, the duration of suitable conditions at tidal stream sites are extremely sensitive to the maximum current speed in which installation vessels can operate. If operation is possible during current speeds of up to 1.13 m/s up to 45 turbines (approx.) each of 500 kW rated power could be installed at the representative site considered. Thus, continuous use of a vessel for one year would enable installation of only 23 MW installed capacity. Although the quantities reported in this study are only indicative, the methods provide a basis for assessing the accessibility of a site such that the viability of installation approaches and the contribution of vessel rates to capital cost and operating cost can be evaluated.

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APPENDIX A: VESSELS

A major difference between the cost of offshore and onshore construction work is that all offshore work must be conducted from a suitable vessel. A wide range of vessels have been developed by the oil and gas industry ranging from general towing or supply vessels to highly specific craft. Most vessels are operated by supply boat companies and are rented by oil companies either by day or on a longer term basis for specific projects. Initially, the marine energy industry is likely to employ the same contracting process although a marine energy specific vessel market may develop with the industry. For some marine energy conversion schemes it may be cost effective to construct special purpose vessels that can undertake installation and maintenance tasks with greater efficiency. A specialist vessel has been developed by OpenHydro to facilitate installation and some wave devices are designed to allow most operations to be conducted by small vessels (Pelamis Wave Power).

In Section A.1, the types of vessel commonly employed by the oil and gas industry are reviewed. Information is presented on the typical uses of each vessel and, where data is available, the cost to rent or build a modern vessel. In Section A.2, the factors affecting the day rate of vessels are discussed and indicative average day rates for different classes of vessel are summarised.

A.1 VESSEL TYPES

The principal classes of vessel employed by the oil and gas industry are:

A.1.1 Anchor Handling Towing Supply (AHTS)

Employed to tow rigs from one location to another and are equipped with powerful winches which are used to lift and position the rig's anchors. AHTS vessels can also carry moderate amounts of supplies (drilling fluid, drill pipe) to support offshore construction projects. Specified in terms of horsepower (BHP) and towing capacity. Approx 1562 (+120 new builds) worldwide (Clarkson research). Modern deep water vessels cost between $20-40M, have high horsepower (>8000 BHP) and winch strength and length (>250 tons, this determines the size of anchor and maximum placement depth). Modern vessels have dynamic positioning and can carry more supplies than their 25-year-old peers.

A.1.2 Offshore Supply Vessels (OSVs)

Deliver variety of supplies to drilling rigs and platforms (PSVs generally larger). Specified in terms of cargo carrying capacity (dead weight tons, dwt), or by boat length (length and capacity are highly correlated). Approx 1014 (+84 new builds) worldwide. Majority built in '70/80s. Typical boat ~ 180 ft. (55m) long, can carry about 1200 barrels (of liquid mud) and about 1000 tons (dwt) of deck cargo Station keeping by manual manoeuvring. Modern boats cost approx $15-30M, carry ~4000 barrels, 2-4000 dwt deck cargo and have GPS station keeping. However, not all modern OSVs are suitable for deepwater operations (including several operated by the worlds largest work boat company Tidewater).

A.1.3 Crew Boats

For personnel transfer. Much smaller than AHTS or OSV, typically range from 75 ft to 190 ft (23m – 58m). Crew boats are typically specified by cruising speed. Modern Fast Supply Vessels (FSV) cost around $2.5-6.5M and can also carry (limited) supplies. Approx 500 worldwide.

A.1.4 Other Types of Vessels

There are around 700 types of vessel, in addition to the three classes defined above, other classes of interest to the marine energy industry are:

Rescue Vessels:	Regulatory requirement in North Sea. ~ 235 in service.
Offshore tugs:	Conventional towing and some anchor handling tasks.
Utility/Workboats:	Construction support and maintenance tasks. 85-150ft
Multi-Purpose Supply Vessels (MPSV):	ROV ops, deep water lifting and installation.

A.2 VESSEL RATES

Boat types, typical rates and regional differences are discussed by Barret (2005) in a report produced by Fortis Bank. New-build costs for a competitive vessel are in the range of $20-40Million. Between Jan 2000 and Nov 2003 tidewater ordered 93 vessels at a total cost of $1.15Billion (~$12M per vessel) (MarineLog Nov'03). Vessels have a useful life of around 25 years. Boat owners charge a daily fee for the use of a vessel. Rates can range from **$2000/day** for a crew boat during lean times up to **$40,000/day** for an anchor handler during peak times. The daily rate depends upon a multitude of factors including:

- Type: Typically crew boats (min) – supply boats – anchor handlers (max)
- Age: Modern vessel rates up to $5k/day more than old vessels.
- Vessel location

- Contract length: two main types are –
  spot market – contracts last as long as the task (North Sea, Gulf of Mexico)
  long term – months to years (West Africa, Brazil)
- Supply or Demand at time of contract

Information on vessels and vessel rates is closely guarded by fleet owners and so is not readily available to the general public (www.tdw.com). Some information on vessel day rates is published in shipping periodicals such as marinelog (www.marinelog.com). For example; Marinelog Nov 2003 provides information on Tidewaters day rates during 2003. In the second and third quarters of 2003, Tidewaters Mexican OSV fleet earned average day rates of approximately $13k (Q2: 13.3 and Q3: 12.6) with a utilization rate of approx 70% (Q2: 68%, Q3: 84%). Over the same quarters the remainder of the Mexican fleet operated with an average day rate of around $6k due to a relatively low utilisation rate of approx 20%. The average day rate for the international fleet was similarly around **$6k/day** despite mean utilization rates of approx 70%.

Generally, rates are higher for North Sea vessels than Gulf of Mexico vessels. Marinelog Jan 2001 reports that day rates for Trico Marines North Sea supply boats averaged $10k compared to $6k in the gulf of mexico during 2000Q4 (North Sea 99Q1: $11.4k, 99Q4: $8.8k, 00Q1: $8.6k, 00Q4: $10.4k) . Figures published in Trico Marines Q4 Fiscal 2004 report suggest their North Sea supply boat day rate has remained reasonably stable averaging $11.3k and $10.9k during 2003 and 2004. The average day rate for North Sea crew boats is reasonably stable at approx $2.5-3k. Trico Marines North Sea day rates are in reasonable agreement with those of Seacor over the same period. The variation of Seacors average day rate over the period 1995-2004 is plotted in Figure A1.

Figure A.1:History of day rates for Seacors boats – by vessel type (from Barrett, 2005)

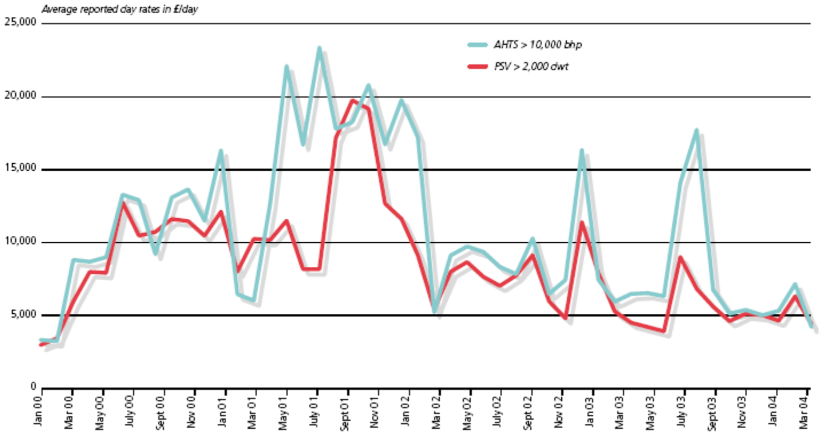

Figure A.2:North Sea supply vessel market (from Barry Ragliano Salles, Ann. Rev. 2003)

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APPENDIX B: NMI METHOD

B.1 WEIBULL APPROXIMATION TO EXCEEDANCE

Probability P that a randomly chosen value of H_s exceeds a defined threshold wave height H_{ac} is estimated from a three parameter Weibull distribution:

$$P(H_s > H_{ac}) = \exp\left(-\left(\frac{H_{ac} - x_0}{b}\right)^k\right) \tag{1}$$

The site specific Weibull coefficients (x_0, b and k) are obtained by fitting Equation (1) to statistical data derived from wave measurements. Rearranging Equation (1) gives:

$$bP' + x_0 = H_{ac}\text{, where } P' = [-\ln(P)]^{1/k} \tag{2}$$

Arena and Fedele (2001) employ an iterative least squares procedure as described by Goda (1999) to obtain the Weibull coefficients which give the best fit to a measured distribution of significant wave height exceedance. An alternative approach is to obtain, for a given value of k, the values of b and x_0 which provide a least squares fit to Equation (1). The optimal three parameter fit can then be determined by iteration of k.

$$k = \frac{\ln[-\ln(P)]}{\ln(P')} \tag{3}$$

The duration of each period of accessible wave conditions ($H_s<H_{ac}$) is distributed about a mean of τ_{ac} which is related to the Weibull parameters through the following expressions:

$$\tau_{ac} = \frac{1-P}{P}\frac{A}{[-\ln(P)]^{\beta}} \tag{4}$$

Here, P is the probability of exceedance of H_{ac} as defined by Equation (1) and variables A and β are defined by:

$$A = \frac{35}{\sqrt{\gamma}}, \tag{5}$$

$$\beta = 0.6\gamma^{0.287} \tag{6}$$

$$\gamma = k + \frac{1.8x_0}{\overline{H} - x_0}\text{ and} \tag{7}$$

$$\overline{H} = b\Gamma\left(1 + \frac{1}{k}\right) + x_0 \tag{8}$$

B.2 WAVE HEIGHT PERSISTENCE

Kuwashima and Hogben (1986) (see Tucker and Pitt, 2001) define the distribution of duration of accessible intervals in terms of site-specific Weibull parameters. The probability Q that accessible wave conditions $H_s<H_{ac}$ persist for a normalised duration X_i is approximated by a two parameter Weibull distribution:

$$Q(X_i > X_{ac}) = \exp(-CX_i^{\alpha}) \tag{9}$$

Parameteres C and α are a function of x_0, b and k which describe the probability of exceedance of the site:

$$C_{ac} = \left[\Gamma\left(1 + \frac{1}{\alpha_{ac}}\right)\right]^{\alpha_{ac}}, \tag{10}$$

where $\Gamma(Z)$ denotes the Gamma function of Z and,

$$\alpha_{ac} = 0.267\gamma\left(\frac{H_{ac}}{\overline{H}}\right)^{-0.4} \tag{11}$$

By defining the normal duration of an accessible period (X_i) as a function of the mean period of persistent accessible wave conditions (τ_{ac}) the distribution of weather window duration at the site can be determined:

$$\tau_i = X_i \tau_{ac} \tag{12}$$

The number of occurrences of a continuous period of duration τ_i during which wave height remains suitable for site access ($H_s<H_{ac}$) is determined by:

$$N_i = \frac{Q(1-P)D}{\tau_i} \tag{13}$$

Finally, the cumulative probability of the significant wave height remaining less than a specified accessible wave height H_{ac} for a duration $t_i>t_{ac}$ is:

$$R_i = \frac{1}{D}\sum \tau_i N_i \tag{14}$$

Thus, assuming a knowledge of the site specific Weibull coefficients (x_0, b and k), the duration for which a given period of calm conditions persist can be estimated by application of Equations (9) - (14). The process outlined is similar to the description given by BMT (2001).

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