WEC Survivability Threshold and Extractable Wave Power

Conference Paper · September 2015

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Abstract— **Wave resource assessment and mapping for the deployment of wave energy converters is generally produced analyzing long term databases built running wave hindcast models. As a matter of fact, wave power time evolution shows a large variability and in some areas, a significant amount of this power is actually concentrated during short duration highly energetic events. During such storms, weather conditions can reach levels above the operability threshold of a wave energy converter. In such conditions, the wave energy device is set in a survivability mode, a configuration in which no power can be extracted and available resource should be considered blank for a proper assessment.**

Taking advantage of the availability of a new high resolution wave hindcast extending from the South of the North Sea to the Bay of Biscay a new wave resource assessment study is conducted, taking into account theoretical survivability thresholds.

Wave energy flux regional maps accounting for survivability thresholds together with statistical studies conducted at regional and local scales including assessment of energetic events persistence and sensitivity to the survivability threshold provide some interesting insight on the weight of the stormy events in the evaluation of the actually extractable power.

Keywords— **Wave resource assessment – Survivability – Mapping – Hindcast – Wave energy converters**

I. INTRODUCTION

An important element in the early stages of design studies for the development of marine structures, including marine energy converters, is the assessment of the environmental climatology. Indeed parameters characterizing the evolution of environmental elements such as wind, waves and currents are the input data to most loading and response assessment studies and as such are to be accurately statistically described. In the specific case of the design of marine energy converters, the resource, that is the incoming available power, is an additional major parameter to be investigated and properly assessed.

Wave resource assessment and mapping for the deployment of wave energy converters is generally produced analyzing long term databases built running wave hindcast models or obtained from in-situ measurement or remote sensing datasets. Various wave power atlases have been produced over the past decades, from the global scale [1], [2] to more regional or local scales, [3], [4], [5]. Based on the various data sets made available over the recent years, resource assessment studies were conducted taking into account the seasonal [6] or regional variability [7]. An interesting conclusion of the study conducted by [8] on the influence of various parameters, such as spectral or directional spreading, or even seasonality, indicated that some of the most interesting areas for wave energy extraction are not necessarily correlated with the most energetic areas providing the largest raw resource.

Following that path, it seems of the greatest interest to assess at a regional scale the importance of the most energetic wave events and their contribution to the total extractable power.

As a matter of fact, wave power time evolution shows a large variability at various scales and in some areas, especially in the so-called “storm belts”, in the mid-latitudes, a significant amount of this power is actually concentrated during short duration highly energetic events. During such storms, weather conditions can reach levels above the operability threshold of a wave energy converter. In such conditions, the wave energy device is set in a survivability mode, a configuration in which no power can be extracted and available resource should be considered blank for a proper assessment.

Hence, the aim of the study presented in this paper is to evaluate, taking advantage of the availability of a new high resolution wave hindcast database extending from the South of the North Sea to the Bay of Biscay, the sensitivity of the evaluation of the actually extractable wave power considering various theoretical survivability thresholds.

In the following, the dataset used for the study is first presented. Survivability is then discussed, as an introduction to the definition of the theoretical survivability thresholds. Assessment of the extractable power as a function of the survivability thresholds is conducted at regional scale in the third part, so as to characterize the global variability of the resource and the sensitivity to these thresholds. In the fourth part the results of an analysis conducted at local scale, considering four different locations along the west coast of France, in the Bay of Biscay are presented. Elements such as storms occurrence or persistence are also discussed together with the influence of the seasonal variability. Finally, major results are commented in the conclusions.

II. ASSESSMENT AT REGIONAL SCALE

Taking advantage of the development of a high resolution wave hindcast database, a regional analysis is conducted at first, over the whole domain covering the Channel and the Bay of Biscay, so as to assess the influence of storms and strong events on the global wave climatology and more specifically on the evolution of the energy flux, as a function of a significant wave height survivability threshold.

A. *Wave Hindcast Dataset*

The dataset used for this study is extracted from the HOMERE database [9].

This database was built running the wave model WaveWatch III® in a configuration based on an up-to-date parameterization for wave generation and dissipation terms [10], [11], also taking a realistic sea-bed roughness mapping into account.

The model is forced using the wind field from the CFSR reanalysis [12] that was produced at NCEP in 2010. Forcing also includes water levels and tidal currents which were recomposed from an atlas of harmonic components built from a dataset computed using the MARS 2D (Model for Applications at Regional Scale) hydrodynamic model [13]. Mesh size of the high resolution unstructured computational grid evolves from about 10 km offshore down to 200 m near-shore. Optimization criteria for grid resolution refinement take into account both the depth variation and the wave propagation velocity.

Parameters used in this study, namely significant wave height, H_s, energy period T_e and energy flux CgE were extracted from the dataset of global parameters [14], computed on the high resolution unstructured computational grid covering the Channel and the Bay of Biscay (Fig. 1).

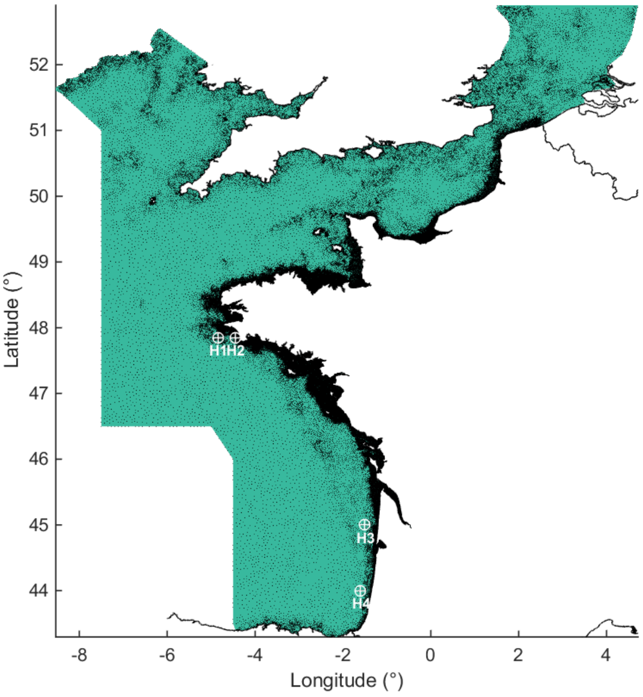

Fig.1 Mapping of the hindcast database high resolution computational grid.

$$Hs = 4\sqrt{E} \tag{1}$$

Where E is the total energy associated with the directional spectrum $S(f,\theta)$:

$$E = \iint S(f,\theta)\,df\,d\theta \tag{2}$$

$$T_e = \frac{\iint f^{-1} S(f,\theta)\,df\,d\theta}{\iint S(f,\theta)\,df\,d\theta} \tag{3}$$

$$CgE = \rho g \iint C_g(f,d) S(f,\theta)\,df\,d\theta \tag{4}$$

where ρ is the sea water mass density, g, the gravitational constant and $C_g(f,d)$ the group velocity of the wave with frequency f, also depending on the local water depth d.

Unless otherwise specified, statistical results were obtained using the whole duration of the dataset, covering 19 years (1994 – 2012) with a one hour time step.

B. *Survivability threshold*

An important element investigated in wave energy converters design studies, as for any other marine structures, is the response to extreme loading, usually associated with extreme wave conditions. Both the structural and the dynamic response are investigated, especially for moored systems and the structure is designed so as to withstand this extreme loading, according to standards such as those of the Oil&Gas industry which generally involve application of safety coefficients to mitigate the risk associated with uncertainties.

However, in the case of wave energy converters, designed with the goal of responding to waves so as to extract the maximum available power over time, such an approach would probably be too conservative and would most certainly induce a loss of efficiency of the device, which could eventually be critical from a purely economic point of view.

Clearly, there is no other choice, when deploying a WEC at a given production site, than designing the structure so that it can withstand the extreme loading expected in that area. However, the design can be optimized considering that the Power Take-Off (PTO) of the system, a priori the most dynamic but also probably most fragile part of the device should be put on hold during the most energetic events, those inducing a loading or a dynamic response above a given survivability threshold.

Such condition, when the PTO is set on hold is generally referred to as the survivability mode [15], a configuration in which no power can be extracted and available resource should be considered blank for a proper assessment of the extractable resource.

Choice or definition of the survivability threshold is highly dependent on the response of the device itself. It can also certainly be optimized depending on the control strategy that can be developed, whether it is based on wave by wave tuning, on approaches such as quiescent period control [16] or “slow control” [17], [18] for instance. However these control methods have their own limitations [19], [20] and it is unlikely that they would allow a continuous power extraction in harsh conditions.

In the context of this study, more specifically focused on the analysis of the resource, we chose not to define a survivability threshold adapted to a specific wave energy device but intend to propose a set of realistic survivability thresholds with the objective of evaluating the impact they might have, at regional and local scale, on the assessment of the extractable power.

Even though the main parameter of interest for resource assessment is the energy flux *CgE*, we define here the survivability threshold as a function of the significant wave height and then assess the associated extractable power and its variability.

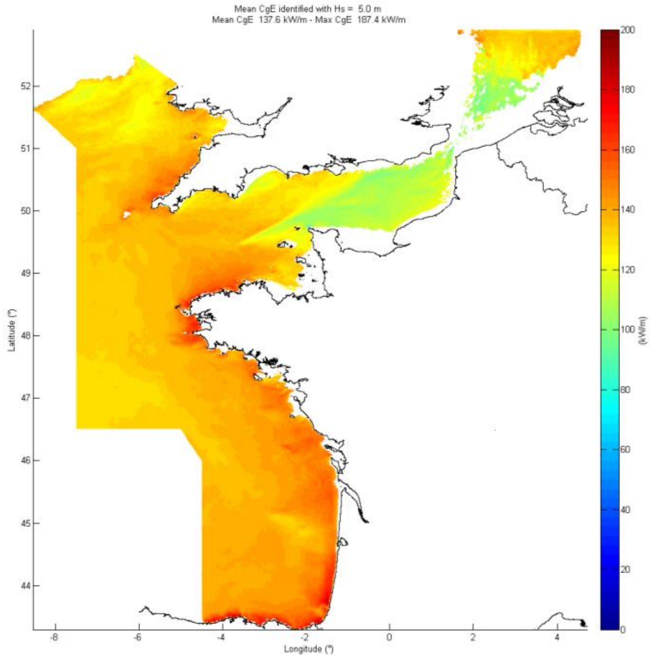

Fig.2 Mapping of wave energy flux CgE for Hs~5 m.

As wave energy flux evolves with the joint squared significant wave height and energy period, its actual averaged value may vary in space for a given significant wave height. Hence time averaged energy flux were computed over the whole computational domain considering only sea-states with $H_s = H_{st} \pm 0.05\ m$ where H_{st} is the significant wave height threshold value defined as survivability limit.

An example of this variability in space is given Fig. 2 where a map of the time averaged energy flux for $H_{st} = 5m$ is plotted. White areas correspond to locations where this value is never reached (H_s actually always remains below the 5m threshold). A significant variability is observed for instance between the eastern part of the Channel, dominated by wind seas and where long swells seldom travel; and the south-eastern part of the Bay of Biscay where long swells propagated from north Atlantic storms are common.

According to the definition of survivability discussed here above, a value of $H_{st} = 5m$ could be considered relatively low. However, considering the average power, that is the average energy flux per unit width of wave crest associated with this significant wave height, CgE_{st}, a wave energy device having a width D would be experiencing an average power $P = CgE_{st}.D$. It can be considered that the maximum power would be associated with the highest wave in the sea-state with the given significant wave height H_{st} and associated energy period. Under the assumption that the wave distribution within the sea-state follows a Rayleigh law, the height of the highest wave in the sea-state can be estimated as about twice the significant wave height. The period associated with this highest wave is generally considered close to the peak period, which according to the assessment conducted at locations H1, H2 ,H3 and H4 discussed in the following chapter would be such that $T_p \sim 1.25.T_e$.

Considering on the one hand the deep water approximation of the energy flux for a given sea-state [6]:

$$CgE = \frac{\rho g^2}{64\pi} H_s^2 T_e \tag{5}$$

and on the other hand the power associated with the highest wave:

$$CgE_{max} = \frac{\rho g^2}{32\pi} H_{max}^2 T \quad \approx \frac{\rho g^2}{8\pi} H_s^2 T_p \approx \frac{10\,\rho g^2}{64\pi} H_s^2 T_e \tag{6}$$

the order of magnitude of the power associated with the highest wave in the sea-state is estimated about 10 times higher than the average power.

Hence, considering for instance a wave energy converter of relatively moderate but realistic size, having a width of 10 m; this device could potentially be facing an incoming maximum power of about 13.8 10^3 kW (mean value for H_s = 5 m). A level of "instant" power which would require a powerful Power-Take-Off, especially for a device without control or even with a "slow control" strategy [16], which is out of the range of many devices designed so far. However, this approach being relatively conservative under the assumptions taken and considering that efficient control strategies [18] could be developed allowing devices to handle wider ranges of input power, additional values of significant wave height survivability threshold are considered in this study, up to 7 m ($H_{st} = [5, 5.5, 6, 7]m$).

C. *Power variability and Survivability threshold*

Global evolution of the power as a function of the survivability threshold is investigated at first. The average and maximum values of the energy flux associated with each of the selected H_{st} values and evaluated over the whole domain and over the whole 19 years of the database are given table I.

It can be pointed out that the amount of power associated with the events with higher *Hs* is not negligible as the mean power associated with H_s=7m is more than twice that of events with H_s =5m. Additionally, a rather strong variability is observed as the maximum identified energy flux is about 35%

higher than the mean value for the lowest H_{st} and of 33% for the highest H_{st}, showing a rather large span of variability.

TABLE I
AVERAGE CGE FOR GIVEN THRESHOLD HS

Hs Threshold	**CgE (kW/m)**	
	mean	Max
5m	138	187
5.5m	173	234
6m	214	288
7m	309	410

A map of the total yearly mean energy flux, computed over the 19 years of the database is plotted Fig. 3 as a reference. Maximum power, over 45 kW/m, is identified off-shore in the north-western part of the Bay of Biscay. It reduces to about ~25 to 30 kW/m in the south-eastern part of the Bay of Biscay and to values lower than 15 kW/m along the southern coast of Brittany, down to the Gironde estuary and in the eastern Channel.

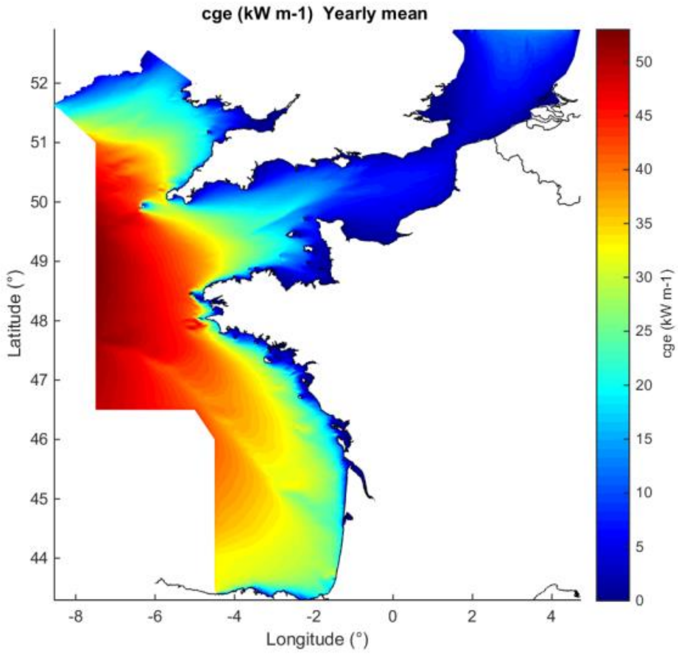

Fig.3 Mapping of the yearly mean CgE (kW/m)

Mapping of the mean annual CgE evaluated considering only sea-states with significant wave height $H_s < H_{st}$ (Fig. 4) provides information on the regional variability of the extractable power. The eastern channel is not much affected as significant wave height seldom reaches levels higher than 5 m in that area. The most energetic part of the offshore domain in the Bay of Biscay clearly sees its mean power reduced for all the survivability thresholds.

Figure 5 are drawn maps of the percentage of the annual power below the threshold, for the four values of H_{st}.

$$100 * \left[\frac{CgE_{total} - CgE_{<H_{st}}}{CgE_{total}}\right] \qquad (7)$$

A 5 m threshold could be considered a rather drastic choice as it induces a loss of about 40% of the energy offshore. However, in the coastal areas where devices are more likely to be deployed, the loss of energy associated to this threshold reduces to values between 10% and 20%. A 7 m threshold (lower right plot) would induce a more limited loss of power even in coastal areas (below 10%) especially in the south-eastern part of the Bay of Biscay as strong events are seldom in that area. Occurrence and persistence of energetic events is discussed in the following paragraph.

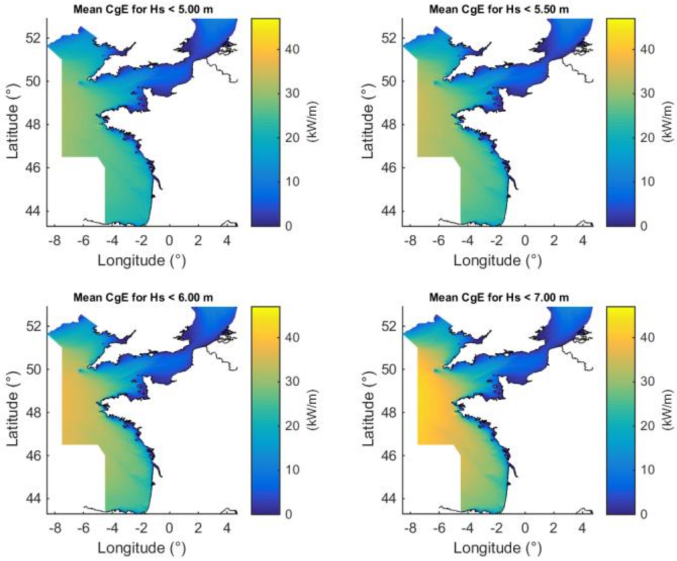

Fig.4 Mapping of mean annual CgE considering only H_s<H_{st}

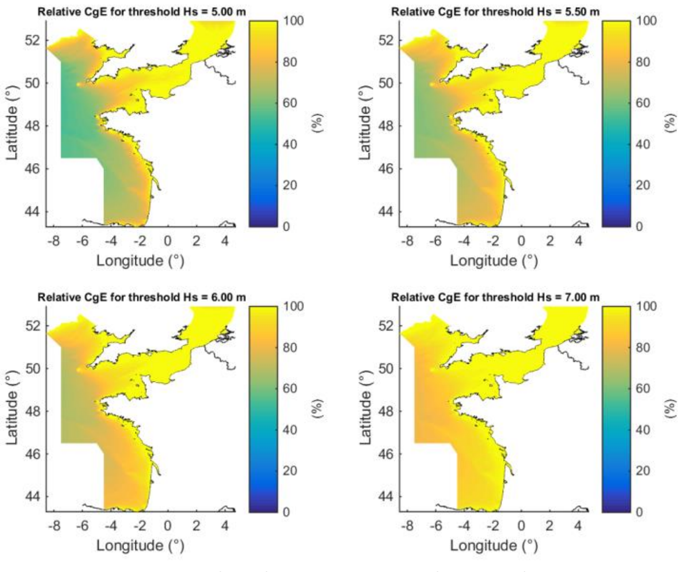

Fig.5 Mapping of % of annual power as a function of total power considering only H_s<H_{st}

D. *Strong events occurrence and persistence*

Time evolution of the strong events, above the given survivability threshold is worth investigation as it can also affect design choices or control strategies.

Occurrence of energetic systems above the selected significant wave height thresholds is relatively limited. Less than 5 % of the time all over the domain for $H_{st} = 5\,m$ and globally less than 2 % in coastal areas where WECs are likely to be deployed, except along the coast of Brittany (Fig. 6) in the Iroise Sea. This duration reduces to less than 1% for $H_{st} = 7\,m$ (Fig. 7). It can be reminded that 1% corresponds to about half a week per year.

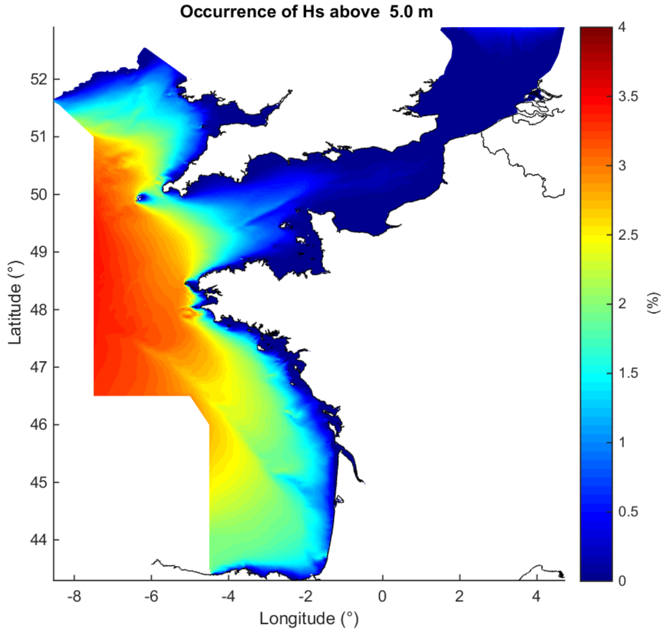

Fig.6 Mapping of the occurrence of sea-states with Hs> 5.0 m (% of time)

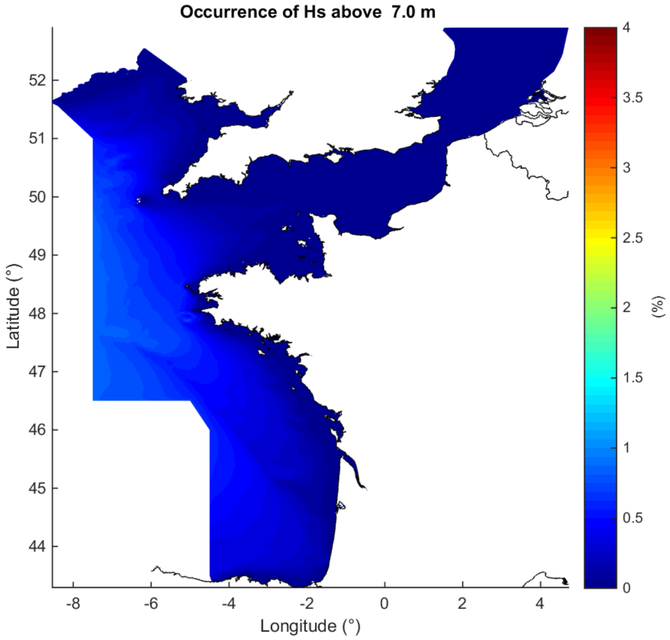

Fig.7 Mapping of occurrence of sea-states with Hs>7.0 m (% of time)

Additional elements regarding variability of extractable power, including seasonal variability, are discussed in the following chapter where a local analysis is conducted so as to provide a more quantitative assessment.

III. LOCAL ANALYSIS

In order to complement the regional analysis and provide more insight on some specific elements such as storms persistence or power decrease due to survivability thresholds, a local analysis is conducted, considering four distinct locations along the French coast in the Bay of Biscay. Coordinates of the four locations, denoted *H1*, *H2*, *H3* and *H4* and visible on the map in Fig. 1, are given table II. The two northernmost sites *H1* and *H2* are located on the same latitude in the Audierne Bay, close enough one to the other to allow assessment of the local variability in space. *H3* and *H4* are farther apart along the south-western coast, in locations with slightly different climatologies.

TABLE II
LOCATION OF CONTROL POINTS

Site	Longitude	Latitude
H1	-4.85°W	47.85°N
H2	-4.45°W	47.85°N
H3	-1.50°W	45.00°N
H4	-1.60°W	44.00°N

A. *Power variability and survivability threshold*

We investigate here the loss of incoming power as a function of the survivability threshold. In table III are given the total average energy fluxes per year for the four locations together with the percentage of energy loss induced by the application of the survivability thresholds (power being set to zero for sea-states with $H_s > H_{st}$ and ratios calculated according to eq. (7)).

Site *H1* is clearly more energetic than the three others and application of a threshold induces important loss of energy, about 33% for $H_{st} = 5m$ and still around 9% for $H_{st} = 7\,m$. This result indicates that a large amount of the power at site *H1* is concentrated during high amplitude events.

The overall mean power per year at the three other sites is in about the same range, at about 2.1 10^5 kW/m/year at *H3*, minus 9% at *H2* and plus 11% at *H4*. However, it is observed that the relative loss of power is lower at H3 than it is at the two other locations when survivability thresholds are applied.

This shows for instance that power is more evenly distributed over time at site *H3* than it is at site *H2* with a higher proportion associated with milder sea-states having a significant wave height below 5 m.

TABLE III
LOSS OF INCOMING POWER

Site	Power overall kW/m/year	Hs>5m (%)	Hs>5.5m (%)	Hs>6m (%)	Hs>7m (%)
H1	3.404 10^5	33.64	25.87	18.67	9.16
H2	1.942 10^5	16.74	10.61	6.89	2.05
H3	2.112 10^5	13.58	8.04	4.66	1.52
H4	2.36 10^5	20.57	14.37	9.55	3.53

In order to assess this in more details the mean, median and maximum values of the incoming power, overall and taking into account the application of the four selected thresholds are calculated for the four reference sites.

These values are presented altogether in table IV hereafter.

TABLE IV
Statistics of CgE associated with Hs thresholds

Site	CgE Overall (kW/m)			CgE- Hs=5m (kW/m)			CgE -Hs=5.5m (kW/m)			CgE - Hs= 6m (kW/m)			CgE -Hs=7m (kW/m)		
	Mean	median	max	mean	median	max	mean	median	max	mean	median	max	mean	median	max
H1	38.8	16.2	1267.5	25.8	13.5	218.3	28.8	14.4	262.6	31.6	15.0	315.6	35.3	15.8	461.6
H2	22.2	9.0	600.1	18.4	8.5	210.4	19.8	8.7	249.3	20.6	8.9	279.5	21.7	9.0	372.4
H3	24.1	10.9	905.4	20.8	10.3	202.9	22.2	10.6	221.4	23.0	10.8	263.4	23.7	10.9	321.2
H4	26.9	10.8	1134.5	21.4	9.9	240.4	23.0	10.3	296.6	24.4	10.5	357.1	26.0	10.7	443.6

Again, site *H1* is identified as the most energetic with an average overall power of 38.8 kW/m and a maximum identified power of 1267.5 kW/m, more than twice the maximum identified at location *H2*, on the same latitude but in slightly shallower waters.

H3 and *H4* have the same median power, about 20% higher than the one observed at *H2*. However a large variability is observed on the maximal values at these three locations, maximum at *H4* being for instance about 88% higher than it is at *H2*.

Application of the survivability thresholds will of course induce a drastic limitation of the maximum value, at all sites and especially at the most energetic ones. However, it is interesting to note that the maximum value at *H2* constantly remains higher than the maximum value at *H3*, whatever the threshold, considering that the overall maximum identified at the latter was about 50% larger than the one at the most northern site and that the median value is only reduced by about 6% at both sites when applying the lowest threshold.

An interesting result relative to the application of these survivability thresholds is also observed between sites *H2* and *H3*. Indeed, applying a threshold of 5.5 m at site H3 will allow an extractable power equivalent to the overall available power at *H2*, with a much more reduced maximum energy flux potentially impacting the power take-off, at only 221.4 kw/m, and losing only about 8% of the overall locally available power.

As already stated, we focus in this study on the power loss that may be induced when considering survivability thresholds, related to the highest events. However when assessing the total extractable power, it should be considered that wave energy converters can also be stalled in the case of low sea-states, either because of their intrinsic limitations or voluntarily, as a controlled procedure for mitigation of fatigue aging for instance. In order to assess the contribution of these lower sea-states to the total power resource, the percentage of time during which the significant wave height remains below the theoretical threshold $Hs=0.75m$ together with the associated relative loss of power (computed using eq. (7)) are evaluated and presented in table V. These results show that even though the occurrence of low sea-states is not negligible, up to 13.5% of the time at location *H2*, the associated loss of power appear to be rather limited, always below 1% even at *H2* and close to 0.5% at locations *H3* and *H4*. It can be considered negligible compared to the loss induced by the survivability thresholds assessed in the study (see table III), except maybe for the case $H_{st}=7\ m$.

TABLE V
% of time below threshold and Power loss for Hs <0.75m

Site	**Time (%)**	**Power loss (%)**
H1	2.95	0.11
H2	13.47	0.87
H3	7.21	0.43
H4	8.94	0.47

A more detailed assessment of the contribution of the lower sea-states to the total available resource is worth investigation but is out of the scope of the present study.

It should also be noted that no lower limit to the significant wave height was introduced in the assessment of the available power and for all results presented in this paper, power resource was evaluated considering $0 < H_s < H_{st}$.

B. *Strong events occurrence and persistence*

As for the case of the regional description we investigate here the time evolution of the energetic events at the local scale.

In table VI are gathered the values of the percentage of time during which sea-states have a significant wave height below the reference survivability thresholds, at each of the four locations.

TABLE VI
Percentage of time below threshold (%)

Site	**Hs<5m**	**Hs<5.5m**	**Hs<6m**	**Hs<7m**
H1	94.61	96.44	97.81	99.18
H2	98.25	99.07	99.48	99.88
H3	98.35	99.19	99.60	99.91
H4	97.72	98.64	99.22	99.78

Globally, significant wave height of sea-states at sites *H2* to *H4* exceed the lowest threshold *Hs* = 5m only about 2% of the time, that is about a week per year. This value is of about 5.4%, that is about 20 days per year, at site *H1* but will reduce to less than 1 % for the highest threshold *Hs*= 7m.

Mean duration of events with *Hs* above the reference survivability thresholds are gathered in table VII. This persistence is relatively limited at all locations, remaining shorter than a day for the lowest threshold and even closer to half a day at sites *H2* and *H3* where events have a similar duration. This information might be of interest, for instance for the definition of control strategies for a given device.

TABLE VII
MEAN PERSISTENCE OF EVENTS ABOVE THRESHOLD (HOURS)

Site	Hs>5m	Hs>5.5m	Hs>6m	Hs>7m
H1	20.9	19.8	15.8	12.3
H2	13.3	10.4	9.1	6.4
H3	12.7	11.9	8.9	8.6
H4	17.9	14.6	11.7	8.3

C. Seasonal variability

Analysis of the seasonal evolution is interesting as it provides additional information on the distribution of the strong events, which can also be of use for the choice of a deployment site for given survivability thresholds.

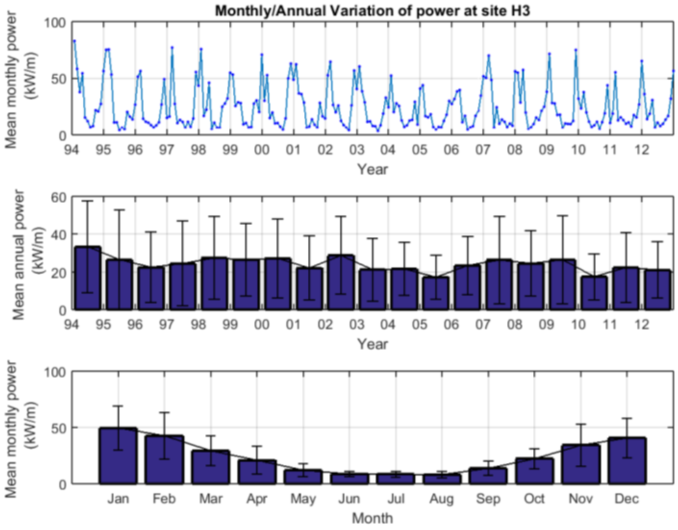

Fig.10 Power Seasonal/Interannual variability at site *H3*

Seasonal variability is clearly visible on the time series of the monthly mean values of the energy flux over the 19 years of the hindcast dataset (Fig. 10) at site *H3*, with “winter” energy flux ranging between 78 kW/m and 43 kW/m and “summer” average energy flux around 10 kW/m. The histogram of the annual means (middle plot) shows that these can be up to 41% higher and 25% lower than the global yearly mean power (24.1 kW/m). Error bars superimposed on these annual means indicate the associated standard deviation of the monthly means.

The monthly variation is described by the histogram on the lower plot showing monthly means greater than ~35 kW/m (up to 50 kW/m in January) over the period from November to February, and below 12 kW/m from May to August.

Similar trends are observed for the monthly and annual variability of the energy period T_e. The overall average energy period is 8.91 s, and inter-annual variation is limited (less than 1 s). The seasonal variation of the period with monthly means ranges from 7.41 s during the summer months to 10.1 s during the winter period. Such amplitudes of seasonal variability, which can also be observed at the other locations and are typical of the Bay of Biscay [22], can be of importance when defining a survivability threshold for a wave energy converter.

Especially of interest is the range of variability of periods, as an optimal control of the device may help raising the survivability threshold. Indeed, such strong seasonal variability emphasizes the need for an optimally defined survivability threshold as a large part of the energy will be concentrated during the strong winter storms, hence might be only partially extractable during that period and the device and its control strategy should be optimized so as to properly respond to the lower sea-states occurring during the summer season.

IV. CONCLUSIONS

We investigated in this study the variability of the extractable wave power for given survivability thresholds of wave energy converters.

Using a 19 years high resolution wave hindcast database, assessment of the power actually extractable by wave energy converters, identified taking into account theoretical survivability significant wave height thresholds, was conducted at both regional and local scales along the French coast in the Channel and the Bay of Biscay.

It was observed that in energetic areas a significant amount of the incoming power should be considered as not extractable as it is concentrated during short duration energetic events, having a high significant wave height, above given survivability thresholds.

It was also shown that in areas with a more balanced distribution of the energy it is possible to define a reasonable survivability threshold, preventing from potentially damaging powerful events whilst inducing a limited loss of extractable power.

Temporal variability was also investigated, through assessment of occurrence and persistence of energetic events, as well as seasonality as these elements might affect the choice of the survivability threshold.

These results support, at a regional scale, the idea that some of the most interesting areas for wave energy extraction are not necessarily correlated with the most energetic areas providing the largest raw resource.

However further assessment should be conducted, considering not solely the resource but taking also into account the response of a wave energy converter.

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