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Assessing accuracy in the estimation of spectral content in wave energy resource on the French Atlantic test site SEMREV

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ABSTRACT

This paper presents a detailed assessment of the spectral accuracy of state of the art numerical estimations of wave energy at the SEMREV French Atlantic test site, by comparison with in-situ measurements. Power density frequency spectra from HOMERE Boudiere et al. (2013), the most up-to-date highly refined hindcast dataset, are compared with several measurements from three wave buoys located either offshore or onsite. The spectral signature of the error exhibits a highly non-linear site dependent behavior. Examined in conjunction with usual comparisons of standard integral parameters, this provides meaningful insight into the epistemic uncertainties and errors in different part of the wave energy spectrum. Notably, a complementary analysis of the mean available energy as a function of frequency illustrates the varying degree of impact that inaccuracies in the estimation could have on production by WECs, which are often designed to harvest energy from specific frequency bandwidths.

It notably also enlighten the frequency domains where the input forcing and the accounting or parameterization of processes may still lack accuracy.

Introduction

In the field of renewable energy production, there are particular challenges to estimating wave conditions, as the requirement for accurate data is particularly stringent. Any overestimation that can usually play its role in the conservatism of engineering design chains would be detrimental in terms of misrepresenting power production and associated income. In other words, any misfit in the estimation of the wave conditions can play antagonist roles in the safety and economic viability of an industrial wave energy project. For such structures whose degrees of freedom, accelerations and amplitudes of motions are by nature often beyond the norms of ocean engineering practice, the challenge is not to be underestimated. In this context, accuracy in the assessment of the wave energy resource is crucial. The specificities of the wave energy requirements and the associated uncertainties have recently led the IEC to publish specific standards and guidance on this topic [12]. These guidelines follow common methods used for estimation of the resource at various locations over the globe [e.g. Ref. [21], including SEMREV [10], the French Atlantic test site [15], but are still based on limited research or industrial feedback from proof cases [18].

The aim of this paper is to provide a refined diagnosis, specific by nature to the test location SEMREV and its associated geophysical properties, on the ability of a prescribed tool for the estimation of wave energy resource to properly describe its spectral content. To our knowledge, this issue has received relatively little attention, although some specific WEC configurations have already been compared for estimations from numerical modeling and in −situ measurements [20]. Given the wide variety of WEC in design, principles and efficiency [4], it seems interesting to provide a more general estimation of the resource and its associated epistemic error [9] in order to account for the associated uncertainty when designing a specific WEC for a given location. We use here Foley et al.'s definition of epistemic error as the non-random error related to systematic inaccuracy or unaccounted processes, physically as well as numerically.

This diagnosis takes primarily advantage of the measurements carried out as parts of the infrastructure setup since 2009 for the SEMREV marine renewable energy test site, located on the French Atlantic west coast off shore of Le Croisic. Thus, this paper aims to provide a detailed analysis and feedback on the resource and environment assessment, as part of the upstream research and development of the test site and associated knowledge. We also take advantage of the effort put into setting the public hindcast

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dataset HOMERE up [5]; this hindcast covers the 19-year period 1994–2012, running WaveWatch3 v4.09 and resolving locally the Bay of Biscay with an unstructured grid of resolution ranging from 200 m to 10 km. With an appropriate set of source terms and storage of hourly, fully-resolved directional spectra on a large number of grid nodes, it provides the most accurate data for SEMREV's area to date, based on highly-refined accounting in the physics and description from the data stored [17]. Indeed, the model includes among others specificities source terms which provide refined accounting of wind forcing and dissipation [2,3] specifically tuned with wind input from CFSR 6-hourly database. This configuration has proven to provide the best performances overall for the North East Atlantic region [11,19]. This specific formulation of source terms includes for example a dissipation which allows a more independent accounting of whitecapping between wave scales, as the source term is no longer simply a function of the average steepness of the sea state. With the introduction of a better local wave energy balance in wave number or frequency, this paves the way for more accurate wave energy budgets. The numerical model also accounts for coupling between ranks of nested grids from global scale with regular spherical grids to local unstructured gridded refinements, for tidal influence in term of water depths and flow fields, and for a bottom friction term dependent on the field of sediment characteristics. Most of the specificities of the modeling and description for this database stand actually beyond the most refined requirements in the current IEC standards (i.e. Design purpose – Class 3). As a fully-stored spectral (1D) and spectro-directional (2D) database, it provides over long-term periods the quantities balanced by the model. 1D or 2D spectra are usually the chosen input quantities for research or advanced industrial objectives, so the availability of such a data can be a useful mean eliminate potential over-simplifications in engineering design chains. Nevertheless, the accuracy of the full directional and omnidirectional spectra is to date only qualified indirectly through integral parameters whose spectral content is generally assed through nth moments, or over short durations for the evaluations of specific events and wave systems. Beyond more general oceanographic objectives of accuracy in the estimation of sea states, the requirements of WECs seems to provide a certain interest in the evaluation of a so-called input signal in frequency and its accuracy; a WEC effectively operates as a physical filter and sometimes even resonator on this spectral input quantity.

Site properties

A test site for marine renewable energy devices is obviously intended to the test devices at sea in real condition; but more broadly has an important role in verifying concepts and methods in an emerging field of engineering. This includes estimating sea state conditions and associated resource, and proof checking these estimations against measurements.

SEMREV test site was officially initiated in 2007 [15] and the first sensor monitoring sea states was moored in 2009. Since then two additional wave buoys have complemented the first, so that up to three Datawell WaveRider MkIII [8]. have been monitoring, as continuously as possible (Fig. 1), the conditions onsite and in the area. The data availability over the 2010–2012 common period with HOMERE database is comprised between 65 and 70% for all three buoys. Two nearly co-located buoys called East and West moorings (approximately 1 km apart) enable the collection of data on site in 34 m and 36 m water depth LAT respectively; the third, the Belle-Ile Buoy, is located one off shore, upstream in the sense of most direction of wave propagation, in 56 m water depth LAT (Fig. 2). Data from Belle-Ile buoy and one of the buoys on site (either East or West, depending on availability) are integrated into the French wave observation network Candhis [6] managed by CEREMA. All three moorings comply with Datawell's recommendations [8] in term of geometry and materials. The maximum astronomical tidal range defined at the closest harbor reaches +6.10 m above the lowest astronomic tide, which provides an upper limit for the site located 12 nautical miles offshore.

For the sake of consistency, 1D spectrum retrieved from the heave motion recorded by SEMREV's buoys are computed over the same duration as HOMERE's time step, namely 1 h. This period appear to accommodate both the requirements of a long enough period to retrieve enough spectral discreetness and content, and of a short enough period to preserve the hypothesis of stationarity for the environmental conditions. From previous analysis [17], the tidal modulation from varying currents and mean water level fields does not seem to have an impact on sea states significant enough to prevent the use of 1 h integration periods. The data treatment is carried out a posteriori on the onboard stored data and a standard quality check is performed (e.g. ratio of buoy acceleration to gravitation, single values, etc.).

Thanks to the prior collaboration on the setup of the HOMERE hindcast, specific data is output directly to SEMREV's moorings. Among other characteristics of interest in term of wave resource, the numerical estimation from 19 years HOMERE hindcast of the mean annual wave power J_{1y} at East Buoy on site

$$\bar{J}_{1y} = mean\left(\int \rho g C_g(f,h)E(f)df\right), \tag{1}$$

with C_g and E the wave group velocity and spectral density of a linear wave of frequency f at a local depth h, returns a value of 13.5 kW/m (Fig. 3). The standard deviation reaches 3.1 kW/m and the annual rolling mean value ranges from 7 kW/m to 20,7 kW/m over the period, which all in all demonstrates a strong inter-annual variability. The SEMREV site is naturally sheltered from North-West incoming sea states and naturally open to South-West incoming waves, which contributes to its local variability [10]. In the context of a test at sea of a WEC on SEMREV, in addition to gathering viable hindcast data for the characterization of the variability in power production, the ability to forecast this production by a few hours or days will become an essential management tool.

Assessment of the integral accuracy

In the past, comparisons between wave measurements and estimations from numerical models have been conducted for various purposes, including estimation and extrapolation of extreme conditions [14] or power production of a generic WEC [20], as well as the a review of site properties in terms of wave conditions and their numerical estimation [17]. In this context, the accuracy of HOMERE data has been evaluated on SEMREV's area for standard integral parameters.

The errors between observed and modeled quantities in time are expressed in terms of normalized root mean square errors (*NRMSE*)

$$NRMSE(X) = \sqrt{\frac{\sum (X_{obs} - X_{\text{mod}})^2}{\sum X_{obs}^2}}, \tag{2}$$

normalized bias (*NB*)

$$NB(X) = \frac{\sum (X_{obs} - X_{\text{mod}})}{\sum X_{obs}}, \tag{3}$$

the Pearson correlation coefficients (*CORR*)

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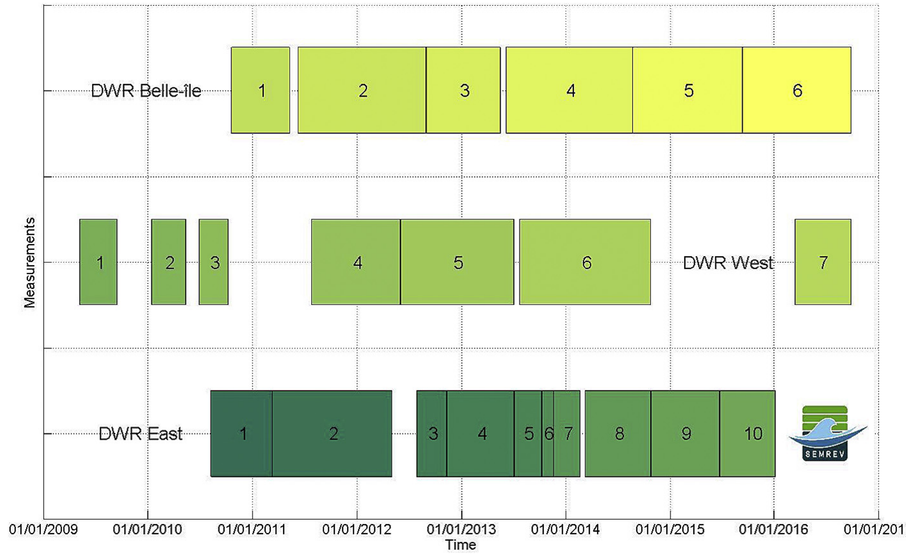

Fig. 1. Gantt diagram for the three wave buoy moorings relevant to the SEMREV test site.

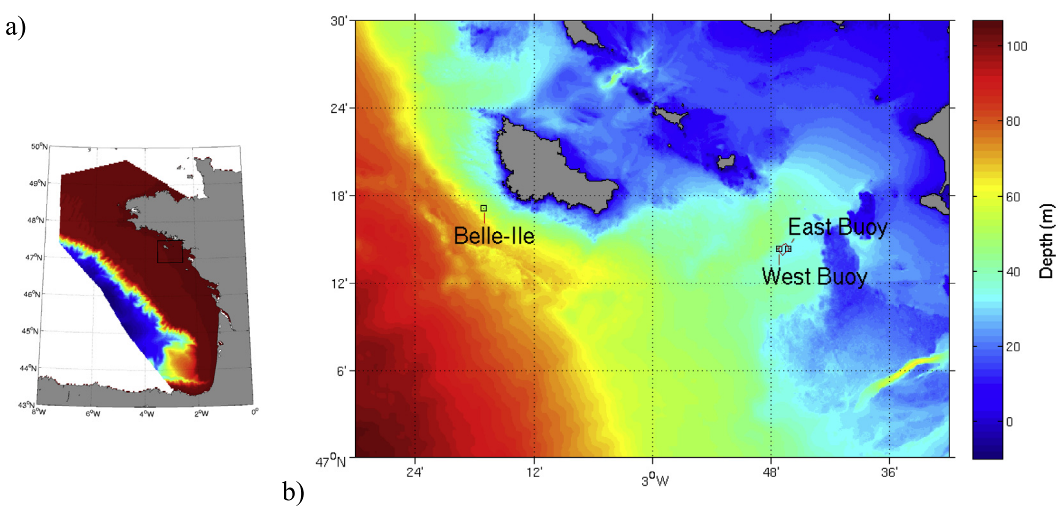

Fig. 2. a) Overview of the area of interest and location in the Bay of Biscay. b) Location of the three moorings for the wave buoys.

$$CORR(X) = \frac{\sum (X_{obs} - \overline{X}_{obs})(X_{\text{mod}} - \overline{X}_{\text{mod}})}{\sqrt{\sum (X_{obs} - \overline{X}_{obs})^2 (X_{\text{mod}} - \overline{X}_{\text{mod}})^2}}, \tag{4}$$

and scatter index ($S.I.$) correcting NRMSE from its bias

$$SI(X) = \sqrt{\frac{\sum \left[(X_{obs} - \overline{X}_{obs}) - (X_{\text{mod}} - \overline{X}_{\text{mod}})\right]^2}{\sum X_{obs}^2}}. \tag{5}$$

The comparisons are commonly presented in term errors in the significant wave height H_s and wave energy period T_e, the two central quantities in the usual estimation of the wave energy resource (e.g. IEC). Those comparisons are completed here with errors on the variance of the elevation spectrum m_0 and omnidirectional wave power J. Table 1 summarizes these errors, comparing measurements to the numerical model HOMERE over the 2010–2012 common period when the data is available and concomitant. The spectral density E computed by the model represents an estimation of the mean spectrum of an underlying sea state; in contrast, measurements of E from the buoys are base on a single realization of the underlying sea state over a certain period, which implies some sampling variability [e.g. Ref. [13]. From Ref. [17]; comparisons of the two nearby buoy measurements on site together with model output at those two locations showed the low influence of this natural sampling variability in front of the model accuracy.

All four integral parameters are computed from the same spectra at each location, but the errors occurring at different frequencies between estimations and measurements play different weights in the estimators of error due to their non-linear relations altogether. The significant wave height is the best-resolved parameter at the three locations with a slight deterioration from the offshore location to the site moorings. The period of energy sees the same increase in the error of the estimation from the offshore buoy to the site. Since processes related to the decreasing depth have more influence on site, it seems likely that these processes are good candidate for the increase of complexity and loss of accuracy

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Fig. 3. Annual mean wave power estimated on SEMREV from HOMERE 19y hindcast.

Table 1
Error assessment over standard parameters between HOMERE data and in-situ observations related to SEMREV test site.

Quantity	Buoy	NRMSE	CORR	NB	SI
Hs [m]	Belle-Île	0.12	0.97	0.00	0.12
	West	0.14	0.97	−0.03	0.14
	East	0.14	0.97	−0.02	0.14
Te [s]	Belle-Île	0.13	0.89	0.05	0.12
	West	0.18	0.79	0.07	0.17
	East	0.17	0.80	0.05	0.16
m_0 [m^2]	Belle-Île	0.21	0.96	0.02	0.21
	West	0.25	0.96	−0.07	0.25
	East	0.25	0.96	−0.06	0.24
J [W m^{-1}]	Belle-Île	0.33	0.93	−0.04	0.33
	West	0.35	0.94	−0.21	0.33
	East	0.33	0.94	−0.18	0.32

in shallower waters. The power per unit width seems on the other hand more poorly resolved both offshore and on site, having an NRMSE of about 33%.

There is no single integral parameter describing fully the available resource and the accuracy of the estimation from those parameters depends greatly from one to the other due to their non-linear relations. Each estimator reflects different non-linear properties of the distribution of wave power, energy or amplitude in frequency. The assessment of this spectral resource and accuracy in its estimations would therefore seem to be an interesting diagnostic tool to provide insight into its observed the observed characteristics.

Assessment of the spectral accuracy

To date and as already mentioned, if a more accurate representation of the performances of numerical models in the furniture of 1D or 2D seems of great interest, no methodology has risen as a widely accepted mean for comparing measurements to estimations or more broadly measurements to each other [e.g. Refs. [1,7,13,22]].

From the perspective of design, hydrodynamic response or power production of WEC-like systems, the use of spectral data is often limited to 1D spectra in amplitude, which provide linear information for spectral as well as time-domain numerical models. The spectral content can be considered as sum of independent frequency bands, and the content in each band over time creates independent time series. Thus, the four previous estimators of error can be used at each frequency or bandwidth over spectral quantities such as wave power, energy or amplitude to provide a simple but efficient spectral signature of the absolute error, in frequency.

Using the wave power per unit width J [W.m^{-1}] defined from the spectral density E and associated group velocity C_g, the spectral quantity for a given central frequency f_i and bandwidth $2\Delta f_i$ is defined as

$$J(f_i, \Delta f_i) = \int_{f_i-\Delta f_i}^{f_i+\Delta f_i} \rho g C_g(f) E(f) df. \tag{6}$$

The wave power per unit width is computed in frequency over the exact same spectral bins for buoy and model data and the conservation of the discrete quantities is preserved in the intermediate resampling processes. Comparisons between model output and measured quantities similar to those presented in Table 1 are conducted here on *J(f)* over the whole duration of the concomitant period at each location. The four spectral signatures of the estimators are plotted from Figs. 4–7. As expected from the previous comparisons on integral parameters, all three signatures show a similar clear spectral non-linear trend over the frequency domain. Wave group celerity been an inverse function of frequency, the low frequency part of the spectrum for which the error is maximum contributes greatly to the power balance and discrepancies in *J*. As one would have expected, the results at on site West and East mooring locations are consistent and homogenous. The minor deviations observed could plausibly be related to the slight differences in the availability of measurement over the 2010–2012 period (Fig. 1). For all three records, low and high frequency parts of the spectrum show quite similar qualitative trends.

First, the low frequency discrepancies between modeling and measurement are more pronounced on site compared to the offshore buoy on the [0.05 Hz, 0.1 Hz] band. The maximum error in term of NRMSE, NBIAS and lowest CORR is reached for both offshore and onsite locations below 0.07 Hz (i.e. wave periods above ~14s). The peak NRMSE error is observed at the lowest resolved frequencies for the offshore location, when on site measurements demonstrate a maximum error above 0.05 Hz. The NRMSE exceeds 100%, and the model consistently overestimates the wave power with NBIAS also exceeding 100% and CORR dropping drastically. This seems to indicate that the transformation of the wave spectra from about 60 m depth to about 35 m lacks accuracy in the numerical model. Investigations should focus on processes at stake at those intermediate to shallow depths such as refraction, dissipation by bottom friction, non-liner transfers or interaction with coastal flows. As the NBIAS reaches a maximum at those frequencies where the CORR also drops at low levels, the SI is not significantly better than the NRMSE. From the behavior of those estimators, it is not clear if one single candidate process would be able to explain the observed behavior: for instance, increasing seabed friction for long waves in the parameterization would help correcting the bias but its effect on the improvement on the SI and the CORR would need to be practically assessed. Identifying one or the other process lacking accuracy for those conditions is beyond the scope of this paper, but it seems that the diagnosis provided here could inform such a task.

On the other hand, there is a common bandwidth where both offshore and onshore comparisons provide the best estimation. Indeed, the lowest NRMRSE, highest CORR and contained NBIAS are reached between about 0.1 and 0.2 Hz for all three records. The NRMSE for the spectral quantity is notably below the NRMSE for the integral parameters, which was at least 33% (see Table 1).

Finally, a distinct pattern differentiates offshore and onsite behavior of the spectral error above the 0.2 Hz band. The

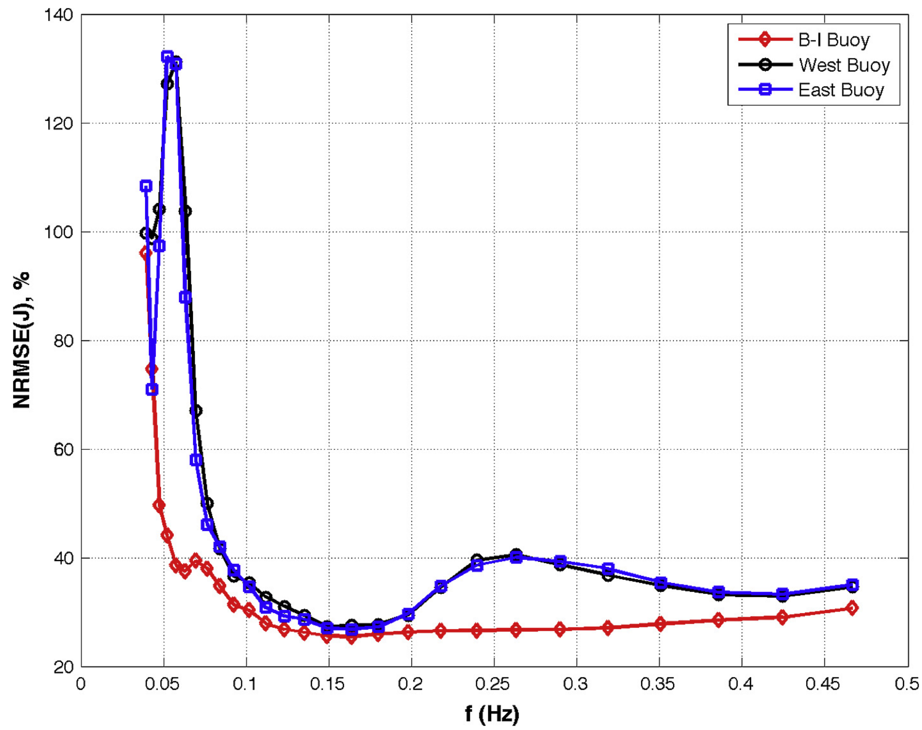

Fig. 4. RMSE of the spectral power resource between measurements and HOMERE.

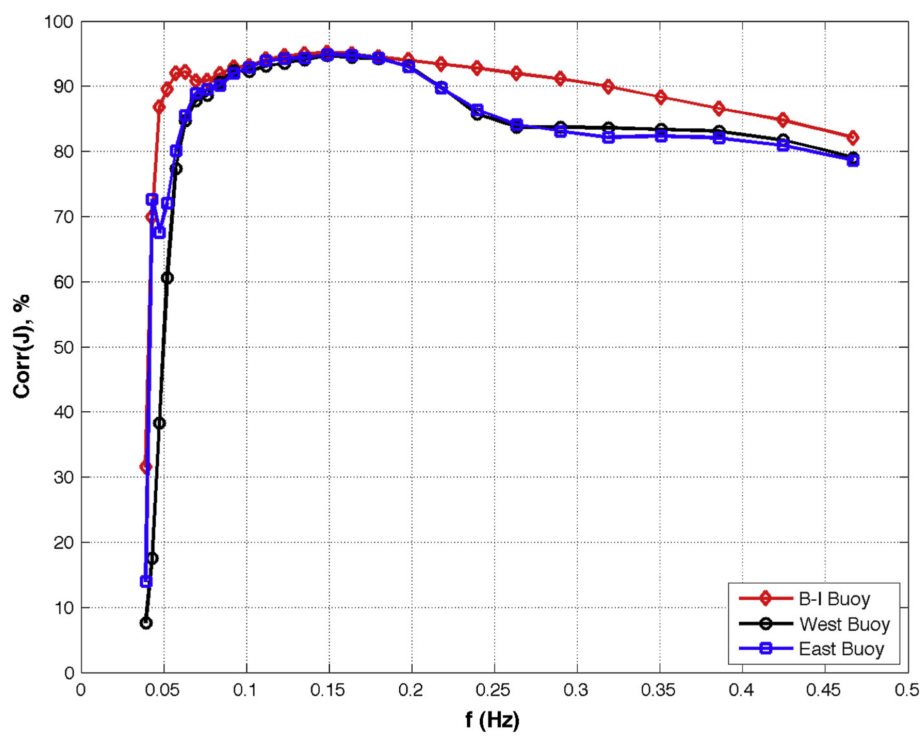

Fig. 5. Correlation of the spectral power resource between measurements and HOMERE.

performance at both West and East buoys decreases significantly, with the model estimating a lower resource than what is actually measured, suggesting that the contribution of local wind seas is not resolved as properly coastally as it is more offshore. The concomitant drop in correlation at those frequencies could indicate that the wind forcing and associated equilibrium is not as accurate near the coast as at more offshore locations. One process or more not accounted by the model is creating a distinctive spectral signature in the 0.25 Hz spectral region.

To complete this evaluation of the spectral accuracy and error

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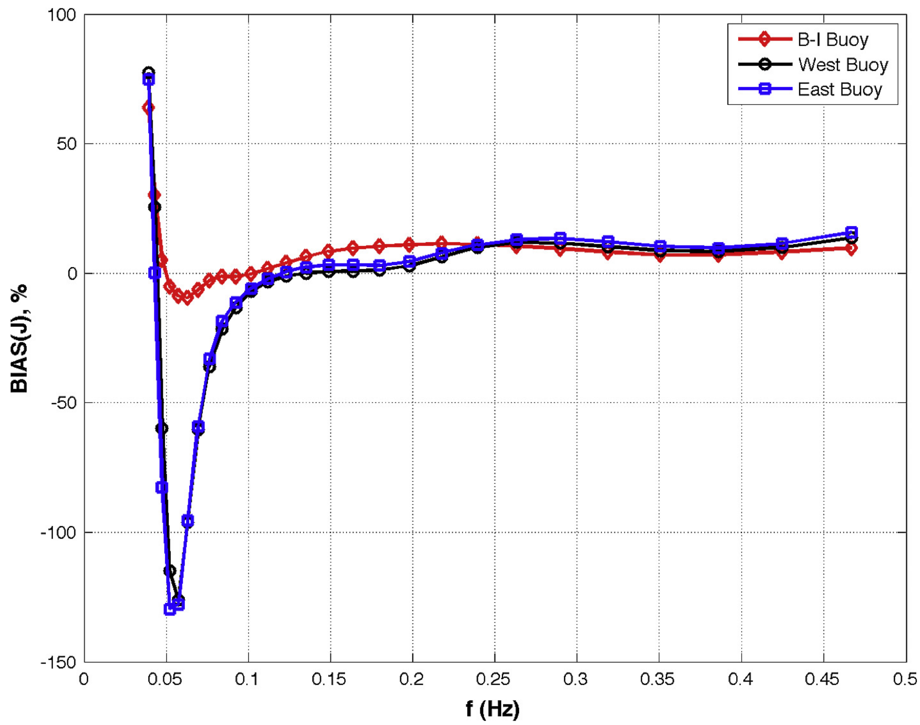

Fig. 6. Normalized Bias of the spectral power resource between measurements and HOMERE.

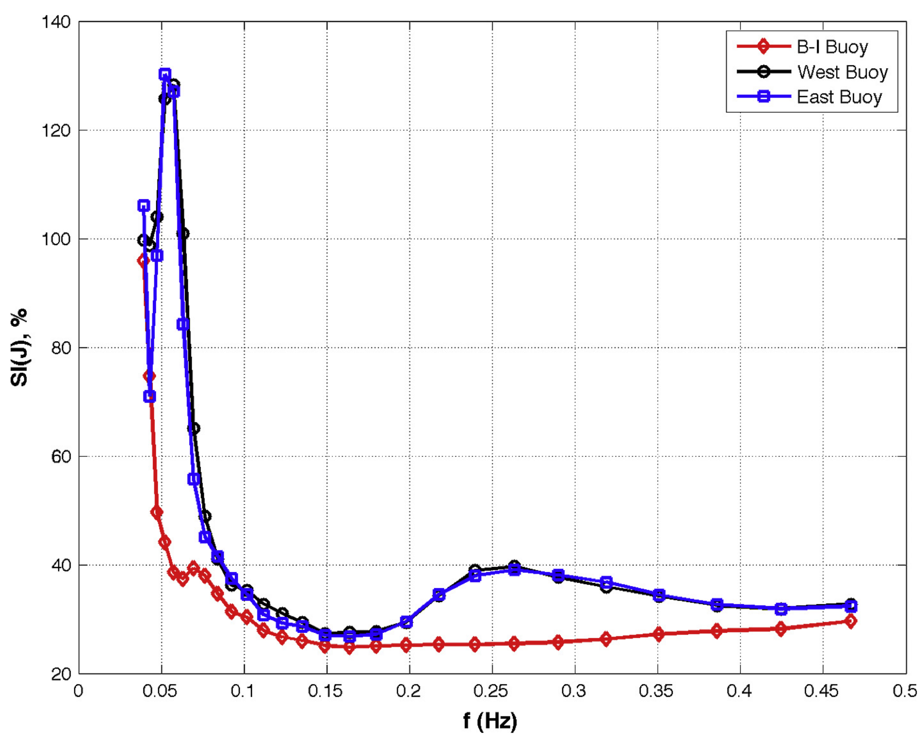

Fig. 7. Scatter Index of the spectral power resource between measurements and HOMERE.

signature, we considered available power and its influence over the global evaluation of the resource in term of wave energy. In other words, how does this error in the available power contribute to a misfit in the overall cumulated energy budget? For instance, a certain delay in the time of arrival of a given sea state between measurements and model would have a great impact on the instantaneous power, but potentially no error on the available energy. With nearly three years of concomitant data, a mean annual energy potential is computed for each frequency bandwidth from the measurements and the numerical estimation (Figs. 8 and 9).

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The results for the East and West buoys are identical demonstrating that the discrepancies in time coverage are small enough to have a low influence on the available energy. Thus, for the sake of clarity, only the results for West buoys are provided here. The estimation of mean annual energy per bandwidth seems well resolved off shore at Belle-Ile buoy, with an overall 4.5% overestimation of the total mean annual energy by the model. However onsite, the influence of the spectral error on the energy is quite significant, leading to 18% and 20.6% overestimations by the model at East and West buoys respectively. The error at these locations would appear to be more systematic and certainly not simply the effect of a misfit in time of arrival or random error in the target value, which would each have had minimal impact on this quantity. In terms of spectral distribution, the shift in the peak available energy at Belle-Ile (11.9s wave period) to 9.8s wave period at West buoy is consistent with the expected sheltering of SEMREV from North-West incoming swells.

All in all, this confirms the initial diagnosis made regarding the effect of the spectral signature of the error on the wave power. The influence of the error in intermediate to shallow depth with respect to the wavelength related to the low frequencies is characterized by a clear overestimation of the resource in this spectral region. For flap-type WEC whose operating bandwidth can reach the same region [16], the influence on the estimation of energy yield could be significant.

Conclusions

A test case study has been conducted in this paper on the estimation of the wave energy resource from HOMERE, the most up-to-date, highly refined public database, and on comparisons with concomitant measurements on the SEMREV marine test site, over the 2010–2012 period. With an objective of estimation for the production of energy from wave energy converters, the properties and specificities of such structures are briefly recalled in order to emphasize the particular requirements in term of sea state description and modeling.

From a comparison of standard integral parameters, which exhibited different behavior at the three reference locations, the non-linearity in the spectral signature of several estimators of the error was ascertained. A simple but efficient method for characterizing this signature was proposed and applied to time series of 1D spectra of wave power, as a function of frequency. This revealed strong and consistent trends in the error signature, which displayed different behavior under offshore open ocean wave conditions than at the more sheltered test site at intermediate water depth. The wave period band [5s,10s] provided the best performances for both offshore and onsite conditions. Performances in its sidebands highlighted specific inaccuracies in terms of wave power estimation. A the offshore location, the least accurate results were observed at the lowest frequencies resolved by the model (i.e. wave periods greater than 20s). In intermediate depths, the error is maximum for wave periods in the range [12s, 20s], for which NRMSE peaks well above 100%. With all estimators showing a decrease of accuracy in this spectral region, it seems that a significant role is played by several physical processes not accounted for in the numerical wave model. On the other side of the spectrum, a secondary peak in error was observed for wave periods below 5s at the test site; however, there was no corresponding peak in error offshore. It is likely that this difference can be explained by input quantities and physical processes related to the equilibrium of wind seas; further work is required to clarify this.

In addition to the comparison in terms of spectral wave power, a complementary comparison of spectral energy was also conducted, evaluated over the 3-year reference period as a mean annual wave energy resource in frequency. This provides a meaningful estimation of the cumulated spectral error and its influence on the estimation of the available resource. For the offshore location the estimation is reasonably accurate with small spectral errors leading

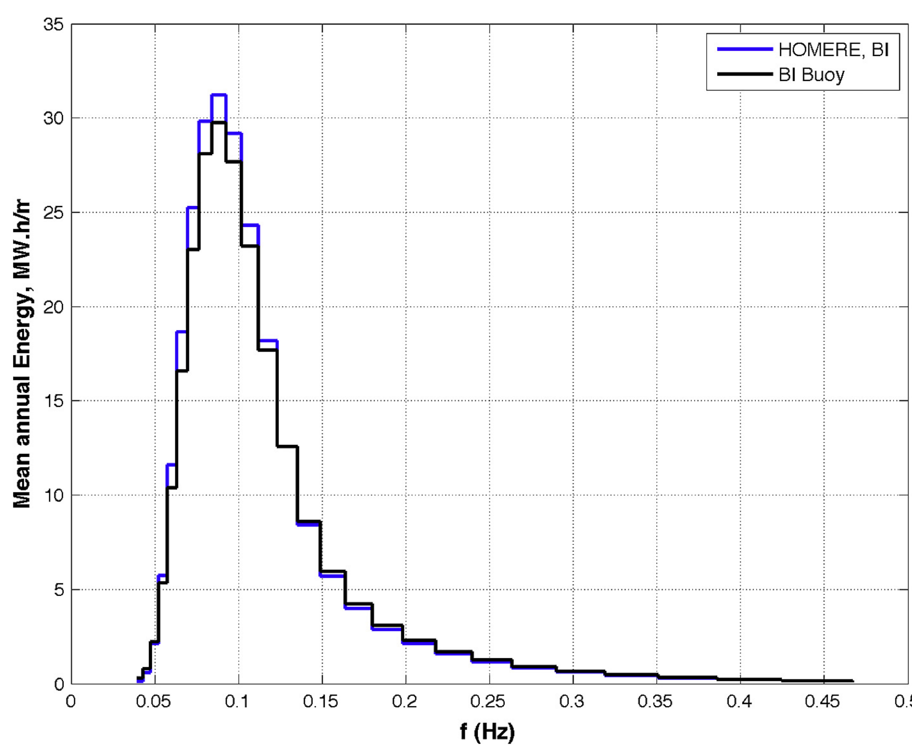

Fig. 8. Mean annual available wave energy in frequency from HOMERE and measurement at BI location.

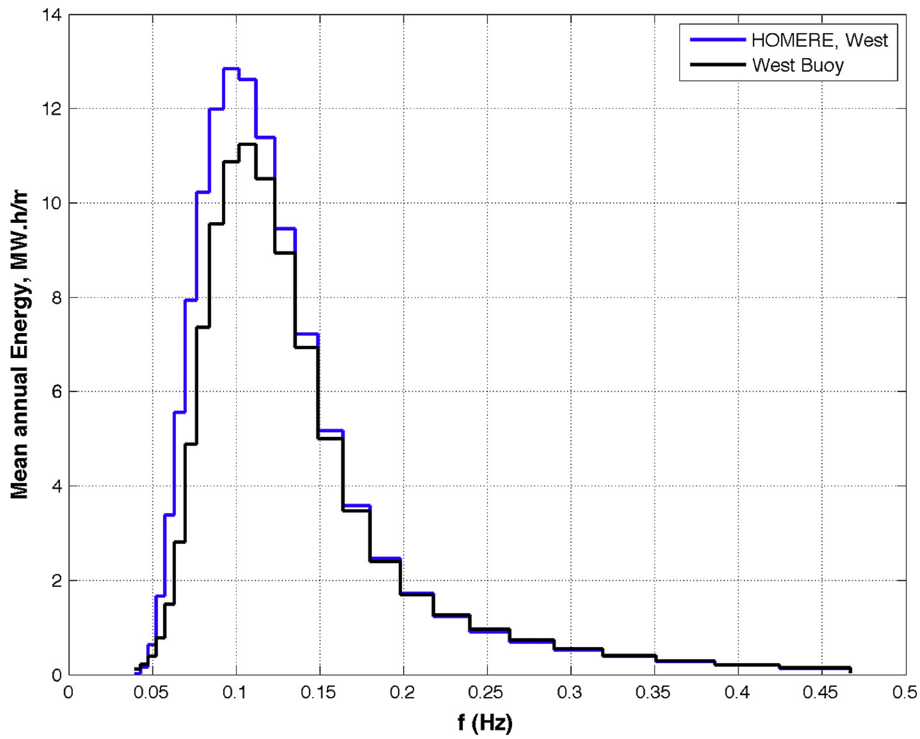

Fig. 9. Mean annual available wave energy in frequency from HOMERE and measurement at West buoy location.

to a +4.5% overall error on the resource. On the other hand, both onsite measurements demonstrate a systemic overestimation of the wave energy up to 20%.

Considering the high level of description in the data used for this study and the subsequent insight achieved into the spectral quantity of errors, it seems that any shortcut in the description of wave energy resource should be handled with great caution. The lack of dedicated research and industrial feedback of proof cases, even for the constitution of the current norms and standards, should underscore the need for in-situ and longterm local measurements of sea states, considered as a resource as well as forcing conditions, in order to specifically qualify the spectral signature of the error in the estimation.

Finally, the specific spectral diagnosis on the estimation of 1D spectra, aimed at addressing the hydrodynamic specificities of wave energy converters, could find interesting applications in the field of ocean engineering as well as oceanography and geophysics. The specific local uncertainties it highlights for a given test site may have significant impact on natural or artificial structures exhibiting a frequency-dependent response, and for which a standard evaluation from estimated spectra could still carry a high level of uncertainty.

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