Production and Dissemination of Marine Renewable Energy Resource Information

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***Abstract* — This paper investigates the capacity of appropriate Earth Observation Systems (EOS) – *in situ* and satellite measurements, numerical models – to deliver basic variables from which high level information relevant for Marine Renewable Energy (MRE) resource assessment can be generated. In addition, an operational solution for the production and dissemination of such information is proposed and set up.**

First, the parameters expected by end-users for accurate MRE resource assessment are identified. It turns out that a combination of appropriate spatial coverage and resolution, duration of time series and accuracy has to be met for the EOS data set to be relevant for the production of such parameters. Consequently, long term, high resolution hindcasts of sea states are identified as offering the best compromise over *in situ* and remote sensing measurements, which are best suited for models calibration and validation. Based on this analysis, a 19-year sea-state hindcast, Homere, has been selected. Homere accurately delivers relevant basic variables at appropriate time and spatial scales, over an area covering the south of the North Sea, the Channel, and the Atlantic coast of France and has been used to produce high level, end-user oriented information for the characterization of marine energy resource. Finally, dissemination tools, respecting international standards of interoperability, have been developed with a user-oriented state of mind in order to deliver the information.

***Keywords*— Marine energy, Earth observation system, hindcast database, dissemination, open data**

I. INTRODUCTION

Marine energy is a fast developing industry and research domain if we rely on the recent evolution of the number of patents or scientific publications related with Marine Renewable Energy (MRE) ([1], Fig. 1). Several recent papers and reports address the topic of marine energy potential in terms of resource, technology and development maturity either in France, Europe or worldwide ([1], [2], [3], [4], [5], [6]). Also, many MRE-related projects are being funded at the national or European level (EMACOP, MaRINET, OceaNET, OCEANERA-NET, etc.).

Amongst the pool of information/guidelines considered to be relevant for supporting the marine energy sector, precise characterization of physical environmental constraints specific to the marine environment, usually reduced to the expression “marine resource assessment”, is one of the key elements. Such information is quite a recent topic and its nature and scope follows an ongoing research and end-users’ consultation process. The aim of this paper is to demonstrate the added-value brought by the Earth Observation Systems (EOS), as referred to by the Global Earth Observation System of Systems (GEOSS), *i.e*. integrating data coming from remote sensing, *in situ* measurement networks and large scale numerical models, for the assessment of marine resources. The first part is dedicated to presenting the basics of marine resource assessment, focusing on wave and tidal current technologies, which experience steadiest development and highest investments. Then, the suitability of each EOS to produce basic variables relevant for marine resource assessment is investigated and discussed. Afterwards, focus is brought on the production of marine resource assessment parameters from Homere database ([7]) and on their dissemination. Finally, the capacity of Homere-like databases against on-site measurements for appropriate assessment of MRE resource is developed within the Discussion part, and added value of the dissemination platform that is being developed is addressed in the Prospects part.

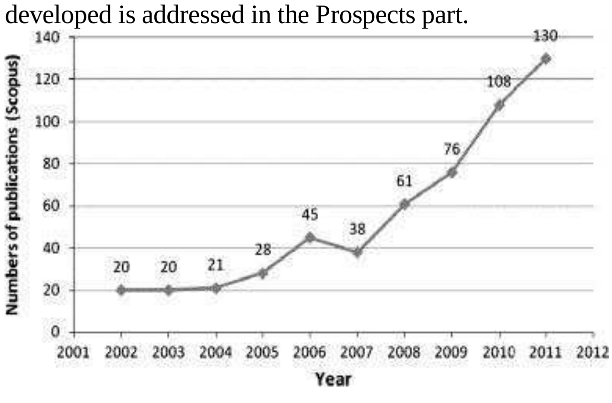

Fig. 1: Number of published articles where the terms “ocean energy” or “marine energy” appear in keywords, abstract or title (from [8]).

II. MARINE ENERGY RESOURCE ASSESSMENT

Resource assessment is possibly the most critical component of the site selection process for the deployment of a marine renewable energy farm. It is aimed at i) achieving an understanding of wave and tidal climate from which estimates of energy production can be made, ii) providing information for engineering design and operating management. Therefore, it should provide an estimate of the available energy resource and an assessment of the operating and survival characteristics of a specific site. The potential resource for energy production should be ascertained, including seasonal and inter-annual variations, and constraints on resource harvesting should be identified. In this part, some technology-specific key parameters will be presented that are suitable for wave and tidal resource assessment, as well as for installation and operating conditions.

A. Wave Energy

1) Technology: Amongst others, comprehensive and up to date report on wave energy technologies and status is presented in [9]. Also, more details about wave extraction equipment and theory can be obtained from the reference work [10].

Wave energy research has not yet led to a dominant wave energy conversion technology, with new devices and concepts being proposed continually. This is partly due to the different characteristics of the wave resources available at various water depths, which will ultimately require different technical solutions for power capture. In addition, and depending on the concept, wave energy devices have not reached the same stage of development. Many projects are still in the concept validation phase. Amongst more than 100 existing pilot and demonstration projects throughout the world, only a handful of technologies have undergone large scale testing and are close to commercialization.

The wide variety of technologies yields a lack of industrial cohesion and limited supply chains for the variety of components required. Also, evaluation and comparison of technologies and their potential for large scale development is difficult.

2) Key wave parameters: Following extensive consultation with marine energy stakeholders, [11] have identified basic key wave parameters that should be obtained through the marine energy resource assessment process (Table 1). All wave parameters presented in Table 1 can be computed from the directional wave spectra, as measured by dedicated devices, or simulated by state of the art wave models. Non-directional spectra miss the directional characteristics of the wave field (Fig. 2).

The wave spectra describe the relationship between the spectral density of free surface elevation (m^2s) and the frequency (Hz). The convention is to describe the spectrum in non-directional form S(f), which is expanded by a directional distribution D(f, θ) where f and θ are the frequency and direction respectively. The directional spectrum is given by:

$$E(f,\theta) = S(f).D(f,\theta)$$

Key wave parameters are calculated from the non-directional spectra, using spectral moments. The n^{th} spectral moment is defined as:

$$m_n = \int_0^\infty f^n S(f)\,df$$

The wave power density per linear meter of wave crest (kW/m) is given by (deep water approximation):

$$P = \frac{\rho\, g}{64\,\pi} H_{m0}^2\, T_e$$

Where ρ and g are the seawater density and the acceleration due to gravity respectively. P corresponds to the basic quantity rendering the power per unit of wave crest contained in the wave train.

B. Tidal Current Energy

1) Technology: Amongst others, comprehensive and up to date report on tidal current technologies and status is presented in [12].

Tide-related currents represent a major ocean energy resource. Tidal current technologies have had more than 40 new devices introduced between 2006 and 2013. Some have successfully undergone full scale demonstration testing. Tidal technologies are expected to commercialize earlier than wave technologies, as evidenced by the number of tidal concepts that have managed to generate electricity during full-scale demonstration with devices in the range of 1 MW. Unlike wave technologies, there seems to be a convergence in tidal current technologies towards horizontal axis designs (76% of the devices), which are similar to designs (albeit smaller) used for wind turbines. 12% are vertical axis turbines and other technologies encompass reciprocating devices (2%), tidal kite and Archimedes screw.

TABLE 1: KEY WAVE PARAMETERS TO BE COMPUTED FOR WAVE RESOURCE ASSESSMENT, ADAPTED FROM [11]

	Symbol	Formulation	Notes
Significant wave height	H_{m0}	$4\sqrt{m_0}$	Statistical measure of the largest wave heights
Mean Wave Period	T_{02}	$\sqrt{\frac{m_0}{m_2}}$	Measure of the mean time between wave cycles
Energy wave period	T_e	$\frac{m_{-1}}{m_0}$	Period of a monochromatic wave of height H which contains the same mean energy as the irregular sea where H_{m0} = sqrt(2)H during T_e.
Peak wave period	T_p	$\frac{m_{-1}\, m_1}{m_0^2}$	Inverse of the most energetic frequency of the energy spectrum
Mean direction	Θ_m		Mean direction of propagation of wave energy
Spectral bandwidth	ϑ	$\left(\frac{m_0\, m_2}{m_1^2} - 1\right)^{\frac{1}{2}}$	Characterize the spectral spread of the sea-state

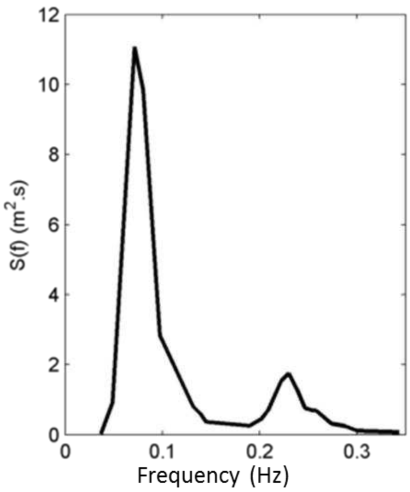

Fig. 2: Example of non-directional wave spectrum

2) Key tidal parameters: The principal goal is to assess the power generation capability of a tidal flow. The total energy available in the flow is given by:

$$E_{Tot} = \int_t \rho A|u|^3 dt$$

where ρ is the density of the water, u is the flow velocity, A is the flow cross-sectional area and t is time.

Tidal ranges can provide a quick overview of hot spots, worldwide, with greatest ranges yielding higher resource. Tidal currents can be easily predicted but are highly sensitive to local scale features such as local bathymetric constrictions or capes. This contributes to the fact that accurate tidal resources are largely unmapped. Major tidal streams have been identified along the coastlines of every continent, making it a global resource, albeit very localized.

The key parameters that should be obtained and reported through the resource assessment are the mean high and low water levels at spring and neap tide, the tidal constituents of sea surface elevation and currents (Table 2) as well as the flow velocity exceedance curves.

C. Weather Windows

Verifying that all aspects of a project, including deployment, service and recovery can be conducted safely is an additional issue for MRE projects.

The statistical characterization of weather windows for a particular site is used by the operation and maintenance teams to design tasks so they can be safely carried out in appropriate sea conditions, within a specific time frame. Also, this information is of primary importance when estimating the availability of the devices which, eventually, will impact the energy production and the profitability of the project.

Operational criteria for the characterization of sea states are usually based on the wave height. The information should be compiled in three formats:

- wave height exceedance,
- event duration occurrence,
- event temporal spacing.

TABLE 2: KEY TIDAL PARAMETERS TO BE COMPUTED FOR TIDAL RESOURCE ASSESSMENT

	Symbol/ Formulation	**Notes**
Mean high water springs	MHWS	Average height of the high water occurring at the time of spring tides
Mean high water neaps	MHWN	Average height of the high water occurring at the time of neap tides
Mean low water springs	MLWS	Average height of the low water occurring at the time of spring tides
Mean low water neaps	MLWN	Average height of the low water occurring at the time of neap tides
Tidal constituents of sea surface elevation and currents	$A.\cos(\omega t + \varphi)$	Harmonic elements in the formulas for tide and tidal currents. A is the amplitude, ω is the pulse and φ is the phase of the constituent.

D. Extremes and Long Term Extrapolation

Estimates of the *m*-year return value of significant wave height – the value which is exceeded on average once every *m* years, typically 20-year to 100-year – are needed for the safety control and design of ships and offshore structures such as marine energy converters. This information typically provides engineers with “metocean” conditions which induce loadings and response of the structure capable to lead to its failure. The probability of occurrence or exceedance of such conditions during the operational life of the structure should be sufficiently low to correspond to an acceptable risk.

The low level of probability considered, combined with (mostly) short duration of the time series available, make that these extreme conditions have generally not been encountered during the duration of observation/simulation of the “metocean” parameters. Therefore, extreme values are extrapolated from standard distribution functions matched with exceptional values of time series of shorter duration. The result, however, can be very sensitive to the extrapolation model and to the accuracy of the exceptional values extracted from the time series.

III. EARTH OBSERVATION SYSTEMS FOR MARINE ENERGY RESOURCE APPLICATION

Earth Observation Systems as referred to by the Global Earth Observation System of Systems (GEOSS)[1], i.e. integrating data coming from remote sensing, in situ measurements and large scale numerical models, are expected to produce relevant information for marine energy applications.

A. Measurements

Resource measurement is a fundamental part of any resource assessment study for marine renewable energy

[1] http://www.earthobservations.org/

development. It provides the only means of quantifying the available resource with high degree of accuracy, providing spectral wave data, tidal components and time series of raw data.

Wave buoys are the preferred method for in situ measurement of wave spectra ([13]). However, they are costly floating surface devices, and therefore are vulnerable to collision, interference and severe weather conditions. An alternative method is the use of Acoustic Doppler Profilers (ADPs) which can be deployed on the seabed. Benefits of using ADPs for wave measurements include subsurface (seabed) positioning, capacity to measure both wave spectra and current velocity profiles and relatively affordable price. However, and for wave energy deployment, ADPs are reaching their operating limits at 50 to 60 m depths. Moreover, they cannot transmit data to shore unless advanced mooring/transmission system is set up. Remote sensing instrumentation includes satellite, aircraft and terrestrial sensors. The parameters accurately retrieved from satellites (H_{m0} and T_p) are not sufficient for accurate wave resource assessment and are mostly used for model calibration. Land-based high frequency (HF) radar is a relatively new technology for wave and tidal resource assessment and has the potential to combine the benefits of measured data with the geographical coverage provided by local to regional modelling.

For tidal energy, summary statistics of current profiles are the basics to assess the performance of the device, in addition to peak ebb and flood currents at neap and spring tides. These parameters can be derived from time series essentially obtained from ADP sensors. One month measurement campaign is the minimum duration to be able to distinguish the main tidal constituents from harmonic analysis and predict tidal streams in the future. Such predictions cannot account for flow variations related with atmospheric and other non-periodic effects, which are likely to be of lesser importance at sites with energetic tidal flows. Turbulence parameters that affect the efficiency and survivability of the device can also be determined from the analysis of current time series, provided the sampling rate of the current meter is sufficiently high.

B. Modelling

Modelling sits alongside measurements as an essential component of any wave and tidal resource assessment study. While measurements will always be necessary in order to provide calibration and validation data for models, models are able to provide wide spatial coverage and long-term datasets that cannot be retrieved through measurements alone.

Numerical simulations that could appropriately be used for wave resource assessment should provide basic variables over a refined grid (< 200 m in coastal areas) and during a minimum of about 20 years.

For tidal resource assessment applications, hydrodynamic models simulating coastal flows at regional down to local scales (10 to 50 m resolution) are appropriate. The simulation of current velocities averaged over the water column can be sufficient (2D hydrodynamic models) for resource assessment purposes provided that they are run using a combination of high resolution bathymetry and refined mesh. 3D models provide current velocity information for several levels of the water columns. Considering their high requirements in computational capacities, they should only be used at advanced stage of development of a tidal energy project, and for very site-specific simulations.

C. Current Uses of EOS for Marine Energy Applications

Some advanced products specifically dedicated to wave energy resource assessment and based on sea state hindcasts have been published ([14], [15], [16], [17]). In particular, wave and tidal resource assessment presented in [3] and [4] are based on the processing of Homere basic variables and could be considered as a reference work for preliminary resource assessment.

A Geographical Information System (GIS) dedicated to MRE is developed by the CEREMA, the CETE Normandie Centre and Ifremer. It allows efficient overview of more than 100 GIS layers of marine and coastal data related with MRE. It is updated with new layers on a regular basis and aims at establishing the most appropriate sites for the deployment of MRE farms.

However, information currently available from most sources are not suitable for the marine energy resource assessment regarding accuracy, completeness, easy-to-access information and following criteria:

- Spatial resolution is too low (usually > 1 km) and limits the relevance of corresponding information to early stage of development of an MRE project.
- Basic wave variables delivered are not always appropriate (T_e is typically missing) or computed from parametric spectrum rather than full directional spectrum.
- Sea level and wave/current interactions are typically not taken into account which impacts the accuracy of the model, especially in coastal waters.
- Information for extensive resource characterization is too limited (little information on weather windows, extreme values or wave scatter diagrams).
- Dissemination tools/formats often require some level of computing knowledge to get access to the information.

This kind of information can also be purchased from consulting agencies that offer end-users oriented products and services. They usually use a combination of open source models and data sets as a basis for the production of relevant, target-oriented and cost-efficient information. When a specific measurement campaign is necessary, the prices of the service can reach very important amounts. Fugro Oceanor, BMT Argoss, Actimar (France) and OpenOcean (France) are some of the main companies in this field.

IV. Information Production and Dissemination

Homere database ([7], [18]) is a sea state hindcast produced by Ifremer in order to fulfil the requirements for Marine Energy Converters design and optimization. It is built on a refined grid with spatial resolution down to 200 m near the coast, over a domain extending from the south of the North Sea down to the north of Spain. Homere provides 19-year long, hourly time series of all the basic variables necessary to generate accurate description of the spatial and temporal variability, and statistics of MRE resource from a national scale down to the scale of a production site.

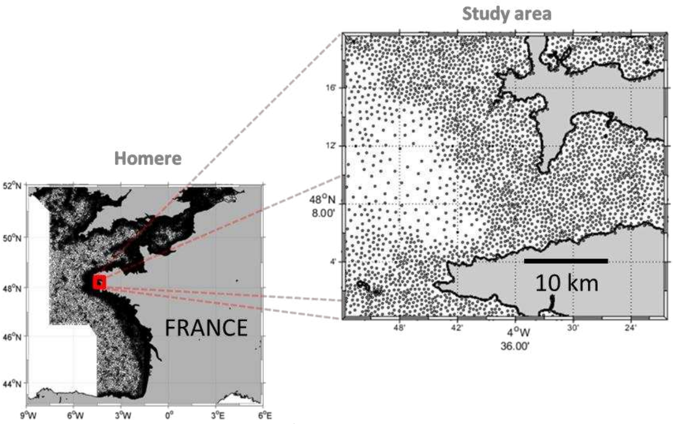

Fig. 3: Geographical coverage of Homere and study area detailing Homere Computational Grid Points (HCGP) distribution

All the high level information produced in this work is based on the processing and analysis of the basic variables delivered by Homere which is, to our knowledge, the most advanced and appropriate source of data for proper MRE resource assessment. The objective is to deliver to marine energy stakeholders information that supports the different stages of development of a marine energy project. Note that characterizing the uncertainty of the information produced, albeit highly recommended, will not be tackled in the present article. We are relying on the fact that Homere has experienced a full range of calibrations and validation tests against *in situ* and satellite measurements (8 different altimetry sensors) as well as against the National Oceanic and Atmospheric Administration's (NOAA) model. The correlation coefficients between H_{m0} measured by wave buoys at 15 different sites and H_{m0} taken from Homere vary between 0.89 and 0.97. When compared to altimetric data, the correlation coefficient reaches at least 0.97, and is between 0.94 and 0.97 when H_{m0} values are compared with NOAA's outputs for deep and intermediate water depths. Further results about Homere's validation are detailed in [18] and testify to the accuracy of the variables computed.

A. Information Produced

A number of indicators relevant for marine energy applications have been produced on a limited geographic area (study area, Fig. 3). This area was chosen because strong tidal currents and significant wave energy resource combined with important spatial gradients could be expected. Those gradients show how much appropriate spatial resolution, down to a couple hundred meters in coastal areas, is essential for accurate resource assessment and optimal site selection. The choice of the information produced was based on the description of the relevant parameters for marine energy resource assessment presented in Part II. Two different kinds of information were produced: spatialized information and point information.

1) Spatialized information: For spatialized information, one single numerical value of a specific quantity is assigned to each Homere Computational Grid Points (HCGP), e.g. annually-averaged H_{m0}, winter-averaged wave power density, 20-year return value of H_{m0}, etc. All these quantities can be displayed, for instance, as colour maps (Fig. 4, Fig. 5) with spatial resolution depending on the local density of the HCGP. Spatialized information that has been computed within the frame of this work is presented in Table 3.

Fig. 4 clearly shows Homere's potential in terms of accurate localization of marine energy sites with most interesting resource. It also emphasizes the very high seasonal variability at sites where the resource is most important. Therefore, and considering the important issue of extracting power from a variable resource, it might be more reasonable to target sites with lower resource, but also lower seasonal signal.

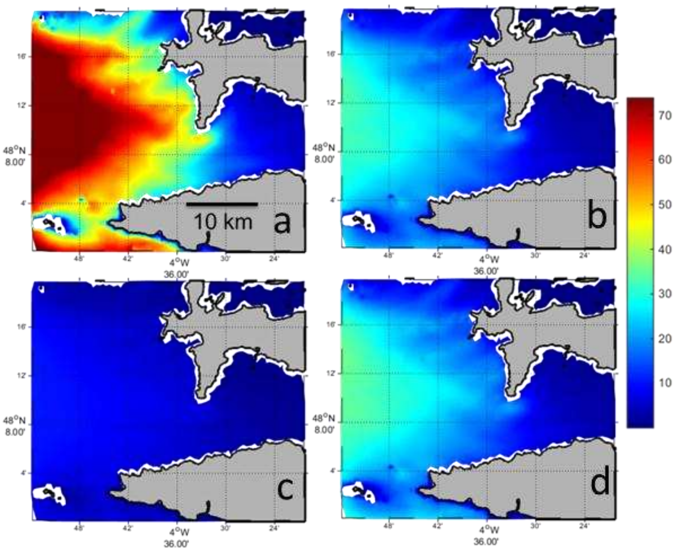

Fig. 4: Seasonal averages of wave power density P (in kW per m of wave front). a) winter, b) spring, c) summer, d) fall.

The capacity of a wave device to extract energy from a certain sea state is given by its power matrix (Fig. 5, middle panels). Wave scatter diagrams describe the probability of occurrence of those sea states. Scatter diagrams are highly site-specific, especially in coastal/shallow areas, and power matrices are highly device- and design-specific. Combining both, it is possible to give a first approximation of energy generation by a wave device at a certain site. For instance, right panels of Fig. 5 show that the energy produced by the first technology (in kWh per kW of nominal power installed) is likely to be much lower than the energy yield of the second technology. It means that the power matrix of the second technology matches much better the resource of the investigated area than the power matrix of the first technology. The information delivered is twofold. Not only does it inform the wave device developers about the power matrix and corresponding design they should target for their system, but also does it directly assess the amount of electricity production. Similar information can be produced using Homere's basic variables for tidal devices, provided the power curve of the device is known.

TABLE 3 : SPATIALIZED INFORMATION PRODUCED

	Annual Avg./Std	Seasonal Avg./Std	Monthly Avg./Std
H_{m0}	✓	✓	✓
Te	✓	✓	✓
Tp	✓	✓	✓
P	✓	✓	✓
Θm	✓	✓	✓
Extreme values	NA	NA	NA
Tidal Current Ellipses	✓		
Power of Flow	✓		
Max. Flow Velocity	NA	NA	NA
Techno.-Spec. electricity production	✓	✓	✓

2) Point information: Point information refers to HCGP-specific quantities that are represented by a set of numerical values/graphs/tables, e.g. scatter diagrams, exceedance tables, monthly variability, etc. Point information that has been generated at every single HCGP of the study area is presented in Table 4. Some examples of such information are presented in Fig. 5. Fig. 5a is showing the height-dependant directional distribution of the wave field. We can observe that for this site, wave azimuth window is quite narrow, with a large majority of the waves coming from the west. This information is capital when addressing the issue of farm layout, directionally sensitive devices, anchoring design, etc. Fig. 5b shows the probability of exceedance of a certain wave height and participates in characterizing the access to the site, fatigue aging, loadings on structure, etc. The site-specific wave scatter diagram, used for first approximation of energy yield by a certain wave device is presented in Fig. 5c. Fig. 5d and 5e give the same information as Fig. 5a and 5b but for the current. Fig. 5f1, 5f2 and 5f3 present the annual evolution of monthly wave height, period and power. Low variability of these parameters is preferred when estimating the exploitability of a site. Precise statistics defining the conditions of accessibility of a certain site, often based on the significant wave height, is essential when designing operation and maintenance strategy. This information is delivered in Fig. 6.

Combining the pool of both spatialized and point information allows accurate characterization of the resource. Precise inter-site comparison is also permitted considering the geographical extent where this information is being produced.

B. Information Dissemination Strategy

The purpose is to have high level information relevant for marine energy at end-users' disposal. In consequence, appropriate strategy for disseminating previously generated information is necessary.

In order to make the information as widely disseminated and used as possible amongst the MRE community, attention has been paid to consider and use international and recognized open standards to support interoperability. The Open Geospatial Consortium (OGC) is developing and implementing a series of open standards for geospatial content and services. Amongst those services, the Web Map Service (WMS) is a standard for serving georeferenced map images over the Internet. To enable the "search and discovery" of the information produced, metadata has been created for each WMS. It ensures the user to have access to the most critical information about the map/data that are being displayed (*e.g.* image format, map bounding box, coordinate reference system, abstract, etc.). Metadata meeting the recommendations of the ISO 19139 international standard have been created then deployed into an OGC CSW (Catalog Service for the Web) compliant Catalog. Using such standard and interoperable approach enables information layers and corresponding metadata to be accessed by any desktop, web-based or mobile software respecting OGC standards. Access to resulting information from the current work is achieved through the webservice-energy.org GEOSS Community Catalog: http://geocatalog.webservice-energy.org

Thanks to imbedded interactive map display function to view and possibly query result maps, the Catalog enables to access the numerical values of spatialized information using a WMS "GetFeatureInfo" operation for any HCGP. This operation opens up a window where the values of the main sea-state parameters at the requested point are displayed. From the same window, point information as defined in the previous chapter can be accessed through a dedicated URL. For instance, graphs representing the monthly variations of H_{m0}, T_e and wave power density can be accessed clicking on the corresponding link. The same operation is used to access scatter diagrams, weather windows and any other HCGP-specific information defined in Table 4.

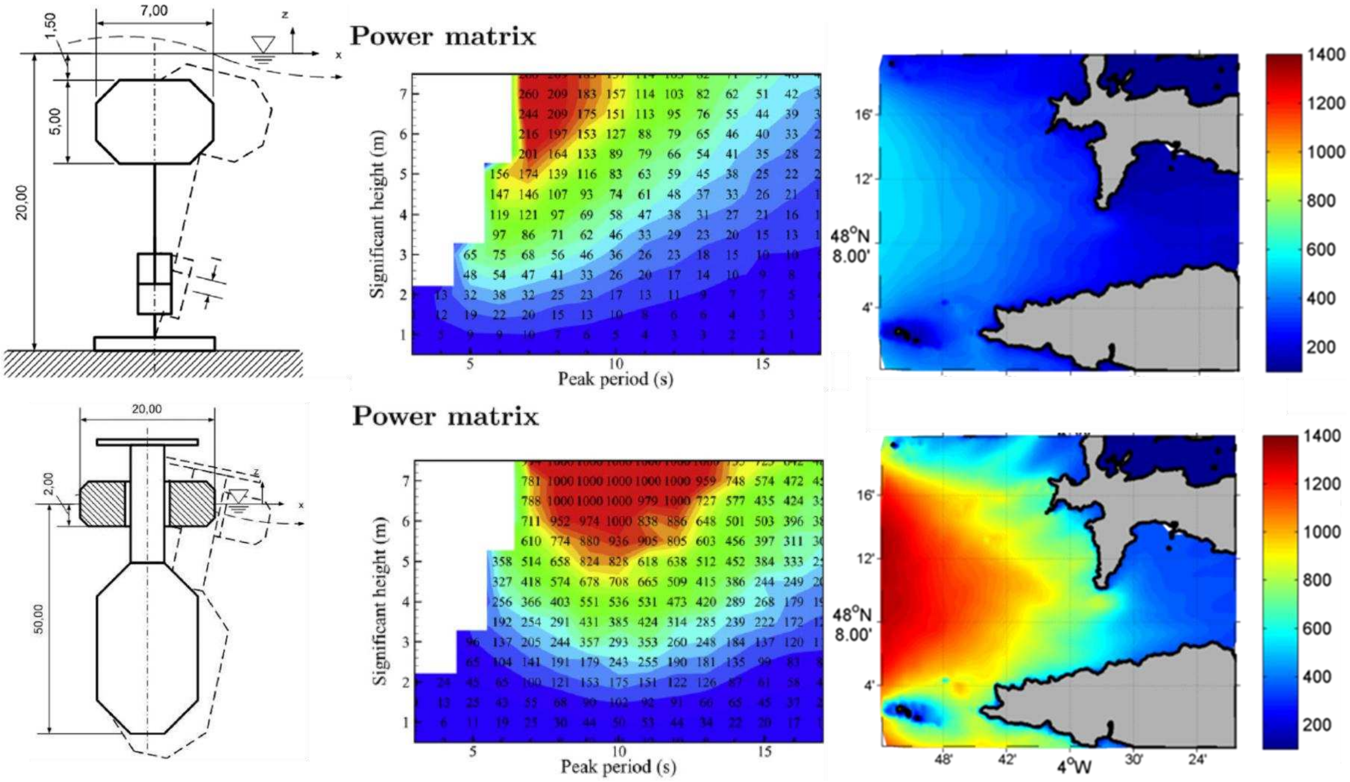

Fig. 5: Wave technology-specific annual electricity production (in kWh/kW installed) for a submerged, bottom-referenced heaving buoy (upper panel) and a floating, two-body heaving converter (lower panel). Technology-specific power matrices were taken from [19], and were used against each HCGP-specific (H_{m0}, T_p) scatter diagram to assess the electricity production over the area. Note that energy yield calculations do not take into account the technology-specific constraints such as limitations in deployment depth or farm effects. This figure essentially focuses on how much the fitting between the power matrix and the local resource influences the energy yield.

Access to MRE resource assessment is still under development and only a limited number of information is currently delivered at each point. The quantity of information will increase as the development continues. We are also considering providing a dedicated tool to generate tailor-made interactive outputs. Please contact the authors for details about upcoming and planned developments.

V. Discussion

As water depth decreases (typically shallower than about 100m), spatial variability of off shore sea conditions gradually switches from being essentially driven by ocean-atmosphere exchanges of momentum, to being driven by bathymetric/topographic features. In coastal areas, it is common that for atmospheric variations, characteristic length scales are much longer than for bathymetric gradients. Spatial gradients of sea states have therefore much shorter length scale near the coast (typically a few hundred of meters) than offshore (typically a few kilometers to tens of kilometers).

Table 4: Point information produced

	Annual	**Seasonal**	**Monthly**	**Interannual variability**	**Monthly variability**
Scatter diagrams (H_{m0}, T_e/T_p/T_{02})	✓	✓			
Weather windows	✓	✓			
Flow velocity exceedance curve	✓				
Wave rose (H_{m0}, Θ_m)	✓	✓	✓		
Current rose	✓				
Techno.-Spec. electricity production				✓	✓

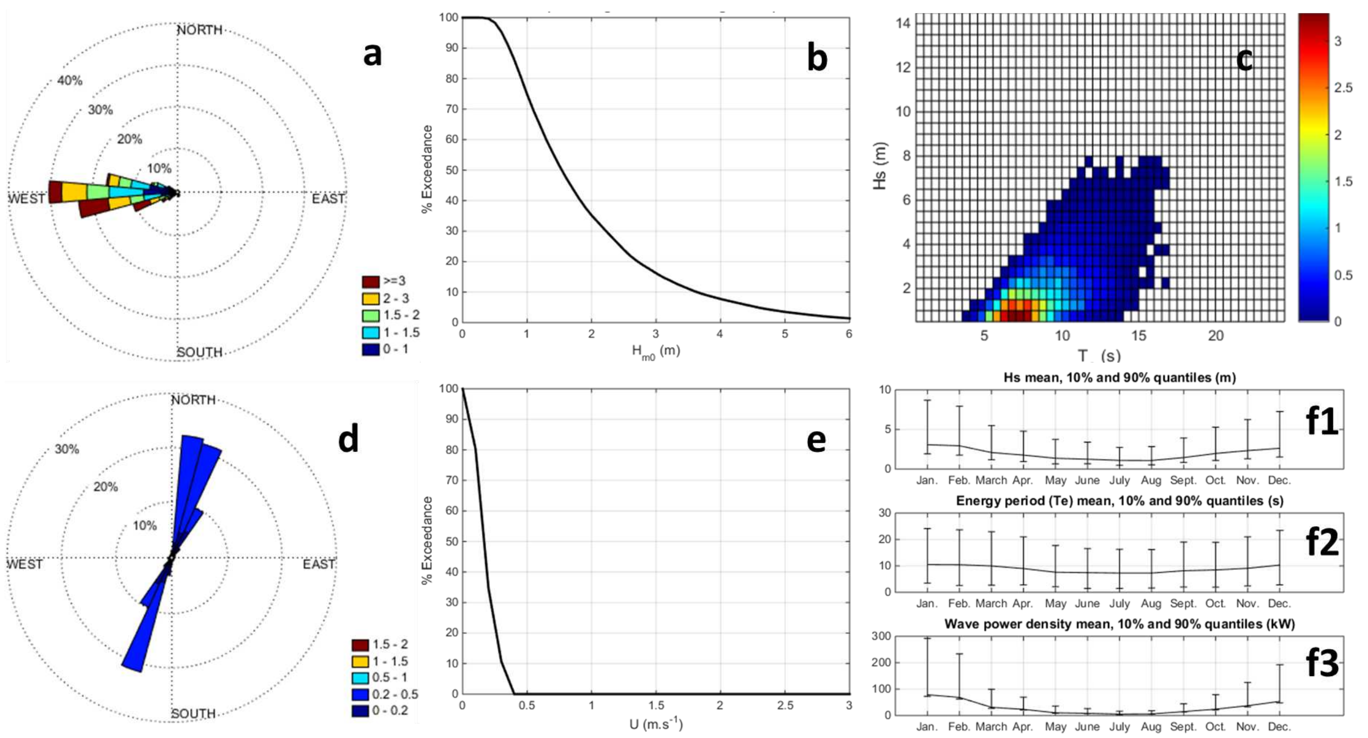

Fig. 5: Yearly characteristics of the sea sate for one specific HCGP. Similar information has been computed at all HCGP. a) Color-coded distribution of wave azimuth, colors are based on H_{m0} values; b) H_{m0} exceedance curve; c) Scatter diagram of (H_{m0}, T_e); d) Color-coded distribution of current direction, colors are based on current velocity values; e) Current velocity exceedance curve; f1-f2-f3) Monthly means 10% and 90% quantiles of H_{m0}, T_e and wave power density respectively.

Minimum length of windows (hrs) — % Occurence

H_{m0} (m)	3	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96
2.5	82	82	82	81	81	80	79	79	78	77	77	77	76	76	75	75	74
2.4	81	81	80	80	79	78	77	77	76	76	76	75	75	74	73	72	72
2.3	79	79	78	78	77	76	75	75	74	73	73	72	71	70	70	69	68
2.2	77	77	76	76	75	74	73	73	72	72	71	70	69	69	68	67	67
2.1	75	75	74	73	73	72	71	71	69	69	67	67	66	66	65	65	64
2	73	72	72	71	70	69	68	68	67	66	65	64	63	63	63	62	62
1.9	70	70	69	69	67	67	66	65	64	63	62	62	61	61	61	60	59
1.8	68	67	66	66	65	64	64	63	61	60	59	59	58	57	57	56	55
1.7	65	65	64	63	62	61	60	59	58	57	56	55	55	54	54	53	51
1.6	61	61	60	59	58	58	56	55	54	54	52	51	51	50	49	48	47
1.5	58	57	56	56	55	54	52	52	50	50	48	48	47	47	45	44	44
1.4	54	53	52	52	50	50	49	48	47	45	45	43	42	42	41	40	39
1.3	50	49	48	47	46	46	44	44	42	41	40	39	38	37	36	36	35
1.2	45	45	43	43	42	41	39	39	37	36	35	35	34	34	32	32	31
1.1	40	40	39	38	37	36	35	34	32	32	31	30	28	27	26	26	25
1	35	34	33	32	32	31	30	29	27	27	25	24	23	23	22	22	21

Least-Median-Longest waiting period between windows (weeks) — Maximum wave height (m)

	1	1.5	2	2.5
At least 6 hrs long	0-0-10	0-0-8	0-0-3	0-0-2
At least 12 hrs long	0-1-10	0-0-8	0-0-3	0-0-2
At least 24 hrs long	0-1-15	0-0-8	0-0-5	0-0-2
At least 48 hrs long	0-1-22	0-0-8	0-0-5	0-0-4

Fig. 6: Characteristics of the weather windows for one specific HCGP. Upper panel: event duration occurrence; lower panel: event temporal spacing

In the current situation, a majority of MRE projects or MRE-related prospection focus on depths shallower than 100 m, and are taking place between the preliminary and the development stages. According to Fig. 7, on-site measurements are either appropriate for evaluation of the resource during early preliminary stage (global network, Fig. 7, dark gray) or from very advanced development stage onward (site-scale network, Fig. 7, gray). The spatial distribution of the global network is presently insufficient and too unevenly distributed for precise, spatially resolved description of the resource in shallow waters. Moreover, unless an MRE project is precisely planned close to this measurement site, site-scale measurement networks are not suitable for this exercise either, due to the site-exclusive information they are providing. In consequence, on-site measurements are missing the transition between the first 2 stages of development of an MRE project.

In contrary, hindcasts like Homere, if correctly calibrated and validated by onsite measurements, perfectly fill the gap (Fig. 7, light gray). HCGP density relevantly adapts with bathymetry in order to describe the sea state variations at appropriate resolution. In addition, time series are sufficiently long for strong statistics and trends to be inferred from a national, down to a site scale.

VI. Conclusion

We have investigated the suitability of Earth Observation Systems as referred to by the Global Earth Observation System of Systems (GEOSS), i.e. integrating data coming from remote sensing, *in situ* measurement networks and large scale numerical models, to provide relevant basic variables for marine resource assessment. First, the most appropriate sources of data have been identified and then they have been exploited to produce high level, marine energy-oriented information. Finally, the information produced has been disseminated with a user-oriented and interoperability state of mind. More precisely, the main outcomes of this work are threefold:

i) The capacities of each category of Earth Observation Systems for marine energy applications, in particular their relevance for marine resource assessment, have been identified. On-site measurements and remote sensing systems are mostly suitable for the calibration and the validation of numerical models. Sea state hindcasts that combine sufficient spatial coverage, high spatial resolution (few hundred of meters) and long simulation time series (several decades) offer the best potential to deliver the basic variables from which marine resource assessment can be inferred.

ii) From Homere database, which has been identified as the most appropriate hindcast for the collection of basic variables, we have produced a number of high level information relevant for marine resource assessment. Two kinds of information were computed. Spatialized information can be displayed as colormaps showing the spatial distribution of some specific variables (e.g. average significant wave height, maximum flow velocity, etc.). Point information is point-specific and consists in graphs/tables/scatter diagrams. It was computed at each output point of Homere database.

iii) The information produced is being implemented in the webservice-energy catalog, and disseminated following GEOSS recommendations on interoperability. Spatialized information is displayed as color maps selected by the user. Point information can be accessed by the user by clicking on any grid point, and following the various information-specific links.

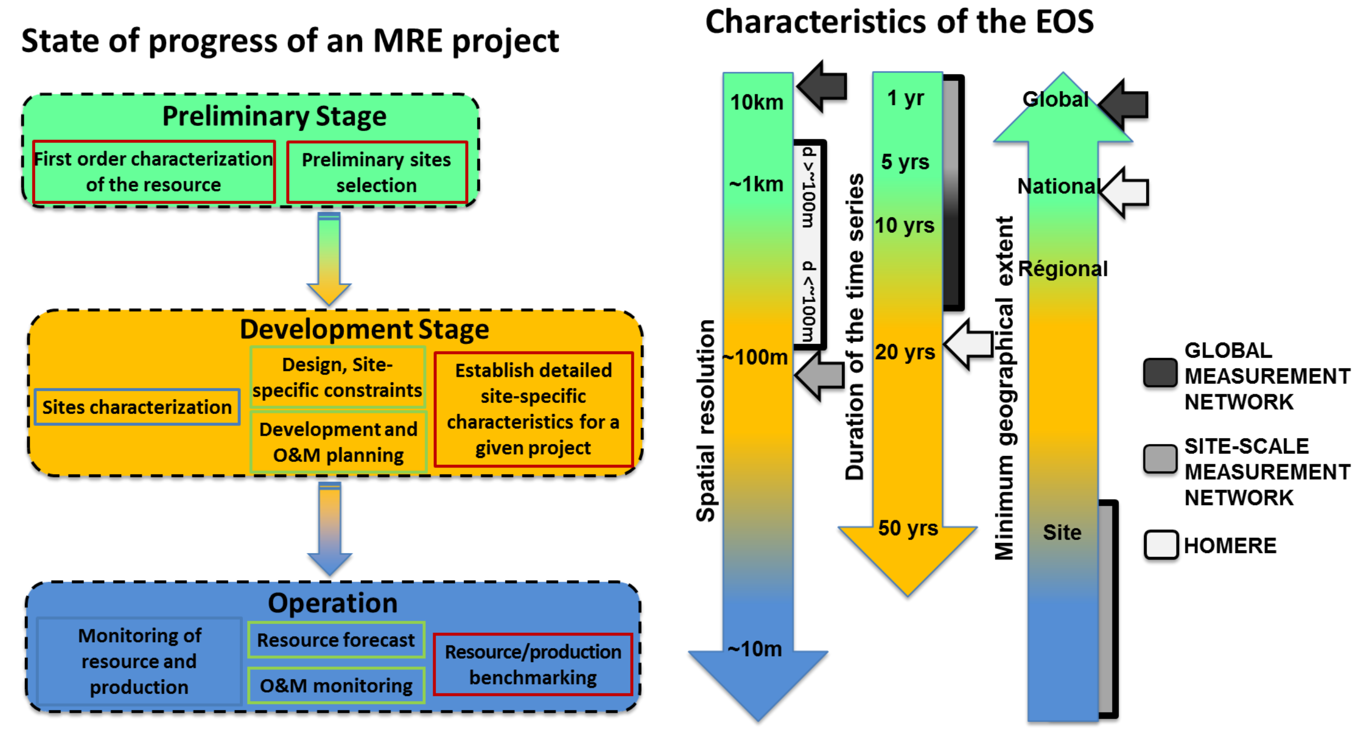

Fig. 7: Relevance of EOS time series for appropriate resource characterization depending on the state of progress of an MRE project. The properties of Homere as well as global and site-scale measurement networks are reported on the 'Characteristics of the EOS' arrows, with closer to the tip of the arrow meaning better characteristic. For instance, coarse spatial resolution (~10 km), 1 year time series over a global geographical extent is sufficient for very early preliminary stage, but advanced development stage requires spatial resolution of about 100 m, and longer time series over a geographical coverage that can be below the regional scale but should be wider than the site-scale. This figure was realized based on the recommendations provided by the EquiMar project ([11]).

VII. Prospects

A. *Resource Characterization*

The work carried out has proven that Homere's design is suitable to characterize the marine energy resource from a national down to a site scale provided that the set of variables it is delivering is appropriately processed. For instance, wave power density precisely informs about available power for wave energy extraction and, in a GCOS-like sense, could be considered as an essential variable for wave resource assessment [20]. So far, the scripts, algorithms and dissemination methods have been developed for a limited geographic area and a rather short duration (5 years out of 19 years available) compared to the total length of the time series. The extension of this work to the entire geographic area and time period covered by Homere is in progress.

B. *Dissemination Tool*

Resource assessment is intended to inform about both the energy available to a device and the conditions under which the energy farm will operate. The combination of both information is critical when deciding how and where to site a marine energy device, and provides essential insight for planning, operations and construction. The information our project is producing is targeting both aspects of the resource, and the dissemination tool we are developing is intended to provide the users with a "one-stop shop" for collecting that information from a national down to a site scale, in a format that is suitable for a wide range of down the line applications. Information about energy resource is necessary to device developers, investors, utilities and government. Information for wave and current loadings, on a site basis, is likely to be dimensioning parameters or at least, will impact the final design of a device. This information is useful for designers, insurers and classifiers. Finally, statistics about accessibility to the site, for a fully operating project, helps defining the installation and maintenance strategy. This information is required for designers, marine contractors, insurers and classifiers. Further stakeholders consultation is in progress in order to precisely meet their expectations in terms of resource characterization. Considering the wide range of potential users, a flexible, adaptive and user-oriented dissemination tool is being designed. Focus has been brought on:

1 – Interoperability: Resource mapping is one of the many parameters that come into consideration when bringing together multiple users of the sea to make informed and coordinated decisions about how to sustainably use maritime area, which is referred to as Marine Spatial Planning (MSP). Interoperability fully complies with the integrative role of MSP, which is an initiative adopted by the European Union. It dramatically increases the capacity of the information produced by the current work to be integrated into MSP or any GIS-type tool, efficiently providing MRE stakeholders with comprehensive description of marine energy resource characteristics at all scales from site to national.

2 – Open and easy access: The dissemination tool is being designed keeping in mind that maps, graphs and, most of all, corresponding numerical values are intended to be downloaded by the users for a more personalized processing of the information delivered. This ensures that the information can be reused for user-specific applications, such as modelling early insight into the economics of a marine energy project. This is an essential aspect that most of the dissemination platforms do not offer so far.

ACKNOWLEDGEMENT

The authors are grateful to Ifremer for giving full access to Homere database. Access can be requested through the PREVIMER website (http://www.previmer.org/).

REFERENCES

[1] International Renewable Energy Agency (IRENA), "Ocean Energy Technology Readiness, Patents, Deployment Status and Outlook," 2014.

[2] UICN, "Développement des énergies marines renouvelables et préservation de la biodiversité," 2014.

[3] H. Smith, E. C. Maisondieu, I. With, and E. A. Bouferrouk, "Resource Assessment for Cornwall , Isles of Scilly and PNMI," 2014.

[4] F. O. Rourke, F. Boyle, and A. Reynolds, "Renewable energy resources and technologies applicable to Ireland," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 1975–1984, Oct. 2009.

[5] F. O Rourke, F. Boyle, and A. Reynolds, "Tidal energy update 2009," *Applied Energy*, vol. 87, no. 2, pp. 398–409, Feb. 2010.

[6] H. Smith and C. Maisondieu, "Best Practice Guidelines for Wave and Current Resource Assessment Task 1 . 6 of WP3 from the MERiFIC Project," no. June, pp. 1–16, 2014.

[7] E. Boudière, C. Maisondieu, F. Ardhuin, M. Accensi, L. Pineau-Guillou, and J. Lepesqueur, "A suitable metocean hindcast database for the design of Marine energy converters," *International Journal of Marine Energy*, vol. 3–4, pp. e40–e52, Dec. 2013.

[8] H.-Y. Chong and W.-H. Lam, "Ocean renewable energy in Malaysia: The potential of the Straits of Malacca," *Renewable and Sustainable Energy Reviews*, vol. 23, pp. 169–178, Jul. 2013.

[9] International Renewable Energy Agency (IRENA), "Wave Energy Technology Brief," 2014.

[10] A. F. D. O. Falcão, "Wave energy utilization: A review of the technologies," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 3, pp. 899–918, Apr. 2010.

[11] D. Ingram, G. Smith, C. Bittencourt-Ferreira, and H. Smith, *Protocols for the Equitable Assessment of Marine Energy Converters*, no. 213380. 2011.

[12] International Renewable Energy Agency (IRENA), "Tidal Energy Technology Brief," 2014.

[13] V. Venugopal, T. Davey, H. Smith, G. Smith, B. Holmes, S. Barrett, M. Prevosto, C. Maisondieu, L. Cavaleri, L. Bertotti, J. Lawrence, and F. Girard, "Wave and Tidal Resource Characterisation," 2011.

[14] C. Guedes Soares, a. R. Bento, M. Gonçalves, D. Silva, and P. Martinho, "Numerical evaluation of the wave energy resource along the Atlantic European coast," *Computers & Geosciences*, pp. 1–13, Mar. 2014.

[15] G. García-Medina, H. T. Özkan-Haller, and P. Ruggiero, "Wave resource assessment in Oregon and southwest Washington, USA," *Renewable Energy*, vol. 64, pp. 203–214, Apr. 2014.

[16] M. G. Hughes and A. D. Heap, "National-scale wave energy resource assessment for Australia," *Renewable Energy*, vol. 35, no. 8, pp. 1783–1791, Aug. 2010.

[17] G. Mattarolo, F. Lafon, and M. Benoit, "Wave energy resource off the French coasts : the ANEMOC database applied to the energy yield evaluation of Wave Energy Converters," in *Proceedings of the 8th European Wave and Tidal Energy Conference*, 2009, pp. 247–255.

[18] E. Boudière and C. Maisondieu, "Manuel de l'utilisateur de la base de données HOMERE," 2014.

[19] A. Babarit, J. Hals, M. J. Muliawan, A. Kurniawan, T. Moan, and J. Krokstad, "Numerical benchmarking study of a selection of wave energy converters," *Renewable Energy*, vol. 41, pp. 44–63, May 2012.

[20] GCOS, "The second report on the adequacy of the global observing systems for climate in support of the UNFCCC," 2003.