EMACOP Project: Assessment of Wave Energy Resource Along France's Coastlines

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Summary
The research objectives of the french project EMACOP are to estimate the available marine energy and to study the efficiency and sustainability of systems and their morphodynamic impacts. This paper focus on the assessment of wave energy resource on existing structures along France's coastlines. Methodology through analytical calculations leading to select the most energetic sites, example case and results are described.

Introduction
The French research project EMACOP (Energies MArines, COtières et Portuaires) aims to study and promote the development of marine energy systems in ports or coastal structures in France.

This article fits in the framework of the task "wave power devices on existing structures" of the EMACOP project. Its objective is to identify and characterise the wave energy potential of 22 sites along France's coastlines in order to select the most relevant sites which could be equipped with Wave Energy Converters (WEC).

This work was done from the statistical analysis of the numerical wave database ANEMOC, built from 23 years hindcast, developed by CETMEF and EDF R&D LNHE (Benoit *et al.*, 2008), and in-situ measurements from french buoys network CANDHIS (CETMEF). For each site, analytical calculations based on theory of wave propagation were used to characterise wave climates and wave power levels. Particular attention should be paid to this approach: indeed, this work is about preliminary wave energy resource assessment of 22 identified sites (Figure 1). Hence, a simple analytical method of wave propagation from open sea to near-shore (Goda, 2000) was used as an indicator of the near-shore wave energy potential.

Background Literature

Wave Power Level
Real seas contain waves that vary considerably in height, period and direction. However, real seas remain relatively constant over the period of a few hours thereby comprising a sea state than can be described by a directional spectrum $E(f,\theta)$. The established convention is to describe the spectrum in non-directional form $S(f)$ which is expanded by a directional distribution $D(f,\theta)$:

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

The wave power level is a measure of the power available per unit of crest length in a unidirectional sea. It is expressed as:

$$P_w=\rho.g\int S(f).c_g df$$

where ρ is the water density, c_g the wave group velocity and c_p the wave phase velocity:

$$c_g=\frac{1}{2}c_p\left(1+\frac{2kh}{\sinh(2kh)}\right) \quad , \quad c_p=\left(\frac{g}{k}\tanh(kh)\right)^{\frac{1}{2}}$$

k is the wave number corresponding to the energy period T_e, $k=\frac{2\pi}{L}$,

with L the wavelength: $L=\frac{gT^2}{2\pi}.\tanh\left(\frac{2\pi h}{L}\right)$, h is the water depth and T the wave period (EQUIMAR, 2011).

In deep water (i.e., when the wavelength is smaller than twice the water depth), the wave power level may be calculated directly from H_{m0} (measure of significant wave height calculated through spectral analysis) and T_e:

$$P_w=\frac{\rho g^2}{64\pi}H_{m0}{}^2.T_e \tag{1}$$

Wave Propagation

As waves approach the shore through waters of decreasing depth, waves are modified by a number of phenomena such as refraction, shoaling, wave breaking and diffraction. As a result, the wave energy resource can vary significantly depending on the local bathymetry.

Introducing the concept of Equivalent Deepwater Wave (EDW), the height and period of this EDW can be defined as (Goda, 2000):

$$H'_0=K_d K_r (H_{1/3})_0 , T_{1/3}=(T_{1/3})_0$$

where H'_0 is the EDW height, $(H_{1/3})_0$ is the deepwater significant wave height and $(T_{1/3})_0$ the significant wave period of deepwater waves. For the purpose of the study, diffraction influence was ruled out hence K_d =1.

Given deepwater wave direction α_0, in shallower water (h) the refraction wave phenomenon shifts the direction of wave propagation. The h-depth wave direction is defined as:

$$\alpha_1=\arcsin\left(\sin(\alpha_0)\tanh\left(\frac{2\pi h}{L}\right)\right)$$

and the refraction coefficient K_r as:

$$K_r=\sqrt{\cos\alpha_0/\cos\alpha_1}$$

For small amplitude waves with a single period, the variation in wave height due to the wave shoaling effect is taken into account via the shoaling coefficient Ks:

$$K_s=\sqrt{\frac{(c_g)_0}{c_g}}=\frac{1}{\sqrt{\left[1+\frac{4\pi h/L}{\sinh(4\pi h/L)}\tanh\left(\frac{2\pi h}{L}\right)\right]}}$$

The wave height within the surf zone (H_c) is then described following approximation:

$$H_c=H_{1/3}=\begin{cases} K_s H'_0 & h/L_0 \geqslant 0{,}2 \\ min[(\beta_0 K_r H_0+\beta_1 h),(\beta_{max} H'_0), K_s H'_0] & h/L_0 < 0{,}2 \end{cases}$$

where L_0 denotes the wavelength in deepwater. Coefficients β_0, β_1 and β_{max}, for approximate estimation of wave heights, integrate the sea bottom slope (Goda, 1975).

Due to wave breaking, limiting height of individual wave breaking waves (H_b) is introduced following the formula:

$$H_b=A.L_0\{1-\exp[-1{,}5\frac{\pi h}{L_0}(1+15\tan^{4/3}\theta)]\}$$

θ is the bottom slope, and the coefficient A takes the value 0.17 for regular waves.

Localisation Along France's Coasts

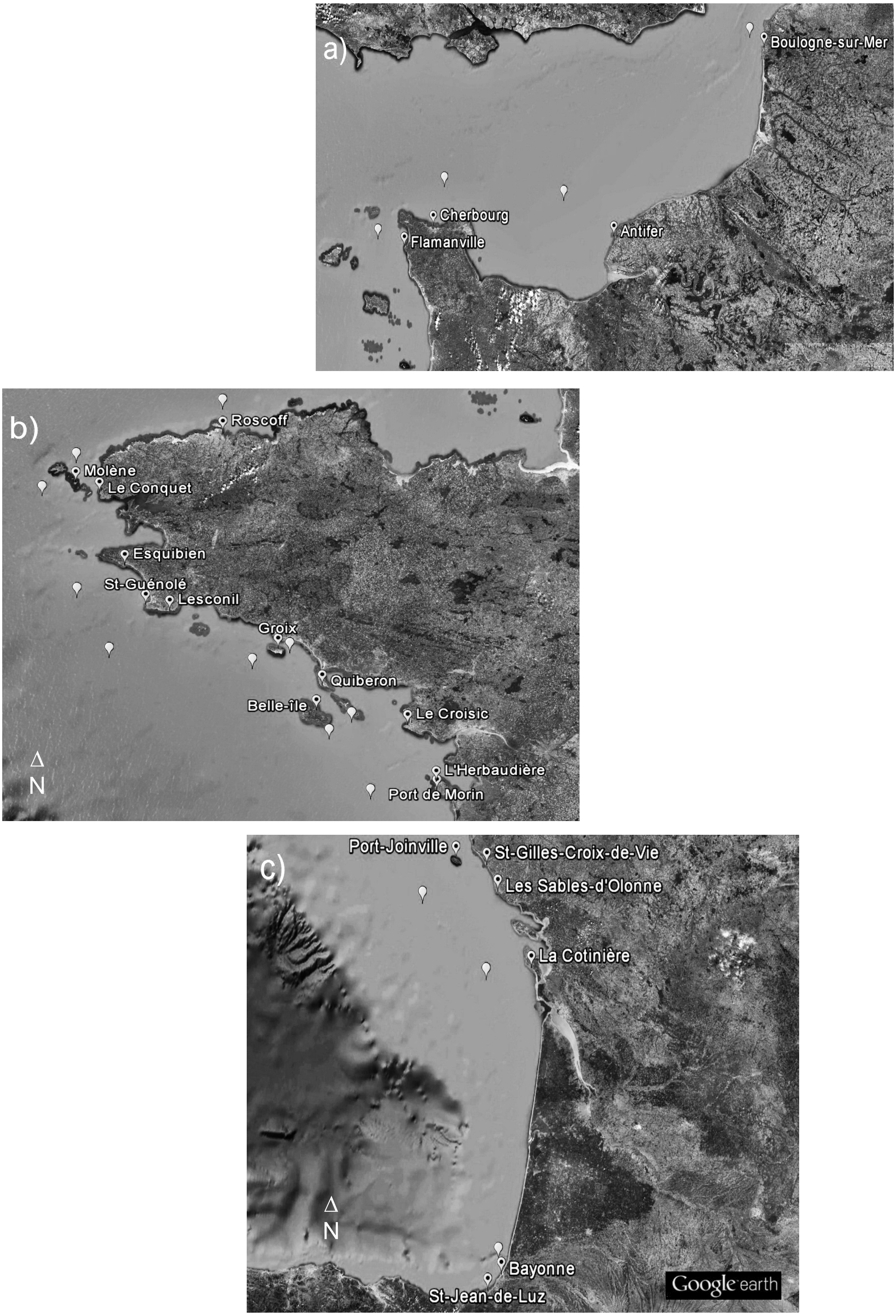

Figure 1: Sites localisation and corresponding deepwater ANEMOC points:
a) English Channel coast, b) Britanny and West coast, c) South-West coast.

Study Methodology

Estimation of Wave Climate

Offshore Wave Climate

Offshore wave climate is assessed from the numerical wave database ANEMOC. This database is built from hindcast simulations from 1979 to 2002 using the software TOMAWAC coupled with the wind database ERA-40, and validated with in-situ buoys.

For the purpose of this study, only deep-water wave data (depth over 50 meters) from ANEMOC have been selected. Data analysis calculations and graphic representations were made using the software Scilab (http://www.scilab.org). For each deepwater ANEMOC point (200 000 sea states), parameters such as spectral significant wave height H_{m0} (m), mean energy period T_e (s) and mean wave direction (°) were calculated.

Seasonal differences led to study separately 3 wave climates (Table 1): a winter one (from October to March), a summer one (from April to September) and, for better comprehension and comparisons, an annual climate was kept. Then, the wave power level (in kW/m) is known for each sea state by applying the deepwater formula (1).

Table 1: Offshore results.

Site	N° Point ANEMOC	Depth (m CD)	Distance to shore (km)	Annual wave power Pw (kW/m)	Winter wave power (kW/m)	Summer wave power (kW/m)	Annual wave height Hs (m)	Energy period Te (s)	Mean wave direction (° / North)
Boulogne-sur-Mer	1341	58	10	2.9	4.4	1.4	0.8	5.7	250
Antifer	1890	43	40	4.9	7.8	2.2	1	6.2	280
Cherbourg	1154	64	24	9.3	14.5	4.1	1.3	6.8	270 ; 50
Flamanville	2291	35	20	14.2	23.2	5.4	1.5	7.8	270
Roscoff	1080	66	10	27.7	43.8	12	2	8.8	285
Molène	0730	80	10	20.1	30.6	9.8	1.8	8.3	300
Le Conquet	0398	97	30	54.1	88	20.8	2.6	9.1	285
Esquibien Saint-Guénolé	1232	60	30	44.3	71.1	18	2.4	9	285
Lesconil	0281	100	40	44.2	70.6	18.3	2.4	9.1	280
Groix	4150	11	5	12.2	19.8	3.5	1.2	9.6	225
Quiberon	0874	72	36	23.5	38.1	9.2	1.7	9	260
Belle-île	2421	32	12	11.2	18.4	4.1	0.9	9	250
Le Croisic	1499	50	38	20.6	33.1	8.3	1.6	9.1	260
Port de Morin L'Herbaudière Port-Joinville	1544	51	35	29	46.9	11.5	1.9	9.4	275
St-Gilles-Croix-de-Vie Les Sables d'Olonne	0315	103	65	34.6	55.1	14,4	2.1	9.3	275
La Cotinière	1105	65	44	28.3	44.8	12.1	1.9	9.2	275
Bayonne Saint-Jean-de-Luz	0016	198	8	25.8	40.4	11.4	1.8	10.1	300

Site Wave Climate

Wave climate on the 22 sites is assessed from the offshore wave parameters propagated to the sites by the analytic method presented previously. For each propagated sea state, new spectral parameters (significant wave height (H_c), energy period (T_e) and mean wave direction) allow the calculation of the near-shore power level (P_c): $P_c = \frac{\rho g}{8} H_c^{\,2} . c_g$ with c_g , the group velocity described previously.

Sites Assessment

First Assessment

Firstly, sites were characterised with the following parameters:

- bathymetry (m CD);
- mean sea level: for the calculation of wave parameters, on site, the mean sea level was considered (SHOM, 2011);
- wave parameters: significant wave height (H_c), energy period (T_e), wave direction and wave power levels for annual (P_c), winter and summer climates (Table 2);
- length of coastal structure: the wave power level being a measure of the power available per unit of crest length, the length of the structure influences directly the wave energy potential of a site;
- sea-bottom nature;
- environmental and socio-economic constraints.

Table 2: Results on sites.

Site	Bathyme-try (m CD)	Mean Sea Level (m)	Annual wave power Pc (kW/m)	Winter wave power (kW/m)	Summer wave power (kW/m)	Annual wave height Hc (m)	Mean wave direction (° / North)	Length of useful structure (m)
Boulogne-sur-Mer	3	4.9	2.8	4.2	1.3	0.7	260	1600
Antifer	16	4.9	5.1	8.2	2.2	0.9	280	1900
Cherbourg	10	3.8	4.4	6.3	2.5	1	300 ; 60	4000
Flamanville	3	5.4	13.6	22.2	5.4	1.4	270	700
Roscoff	2	5.3	7.8	10.8	4.9	1.2	0 ; 40	300
Molène	0	4.3	7.9	11.6	4.8	1.3	345	60
Le Conquet	1	4.0	21.1	30.2	11.8	2.1	250	140
Esquibien	2	3.1	6.9	8.4	3.4	1.3	140	340
Saint-Guénolé	2	3.0	21.1	30.2	12.6	2.1	285	250
Lesconil	0	3.1	8.1	9.7	5.2	1.5	190	200
Groix	1	3.1	x	x	x	x	x	200
Quiberon	0	3.1	5.8	8.2	3.2	1.1	210	350
Belle-Ile	2	3.1	0.9	1	0.7	0.5	25 ; 100	200
Le Croisic	-2	3.3	1.6	1.9	1.4	0.8	315	450
Port de Morin	-2	3.4	2.1	2.4	1.8	0.9	235	400
L'Herbaudière	-2	3.4	1.8	2.1	1.6	0.9	325	100
Port-Joinville	0	3.1	1.8	2.3	1.3	0.7	10	100
St-Gilles-Croix-de-Vie	1	3.2	12.2	17.9	6.6	1.6	240	250
Les Sables d'Olonne	1	3.2	10.3	13.4	5.1	1.4	210	100
La Cotinière	-2	3.6	2.5	3.1	1.9	1	225	150
Bayonne	7	2.5	24.3	37.8	11.1	1.8	300	500
Saint-Jean-de-Luz	10	2.5	21.8	33.8	10.1	1.6	315	500

Following this first assessment, 8 sites, characterised by low wave power level and short structure, were ruled out (Molène, Groix, Belle-Ile, Le Croisic, Port de Morin, L'Herbaudière, Port-Joinville and La Cotinière) (Table 2).

Second Assessment

The 14 remaining sites have been reviewed based on the detailed analysis of statistical parameters previously described (Lenee-Bluhm, 2011):

- Bivariate distribution of energy for sea states defined by wave height H_c and energy period T_e (Figure 3);
- Cumulative distribution of occurrence (annual, winter, summer) and energy of wave parameters P_c, H_c, T_e and mean wave direction α (Figure 4);
- Monthly evolution of offshore and nearshore wave power levels, P_w and P_c respectively (Figure 5).

Following this second assessment, 5 sites, with an insufficient wave energy potential, were ruled out (Boulogne-sur-Mer, Roscoff, Lesconil, Quiberon and Les Sables d'Olonne).

Example Case: Bayonne

Port Structure

The Port of Bayonne, in southwestern France, contains two rubble-mound breakwaters built in the early 1970s (Figure 2). The main breakwater is 870 meters long and is highly exposed to waves. The second breakwater is 100 meters long and is less exposed to waves.

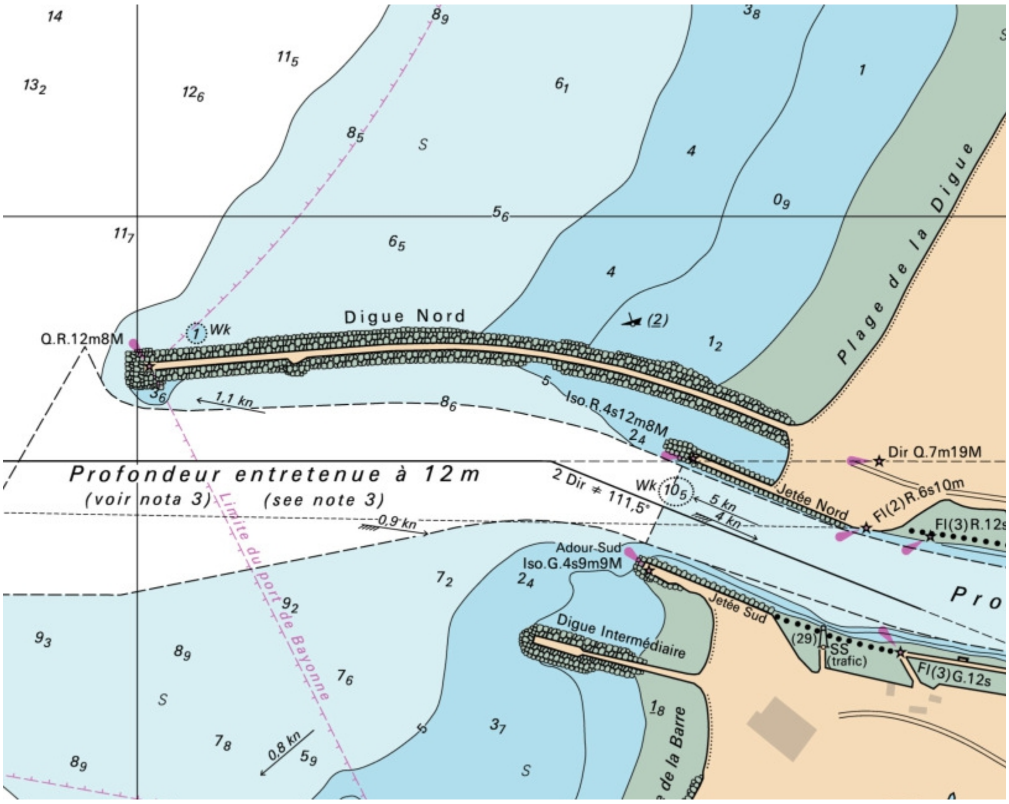

Figure 2: Coastal structure localisation (© SHOM).

Along the Digue Nord breakwater, the bottom slope remains constant (1°), and the bathymetry ranges from 0 to 10 m (at chart datum, CD). In this case, ruling out the section between 0 and 2 m (CD), a 500 m-length part of the structure, where occurrence of wave breaking is limited, can be used for WEC. Sea bottom consists in coarse grained sand.

Results

Wave Climate

From ANEMOC and the wave propagation method described previously, the 3 wave climates (annual, winter and summer), in deepwater and in situ, can be characterised (Table 3).

The wave energy potential in Bayonne provides a good resource for wave conversion with a mean annual wave power of 24.3 kW/m (37.8 kW/m in winter). Indeed, this region is directly exposed to large swell with mean wave direction around 300°N.

Table 3: Wave climates in deepwater and site – Bayonne.

Bayonne	Annual		Winter		Summer	
	Deepwater	Site	Deepwater	Site	Deepwater	Site
Wave height (m)	1.8	1.8	2.2	2.3	1.3	1.3
Energy period T_e (s)	10.1	10.1	11.3	11.3	8.9	8.9
Wave power level (kW/m)	25.8	24.3	40.4	37.8	11.4	11.1

Wave Energy Potential Statistics (ANEMOC Database)

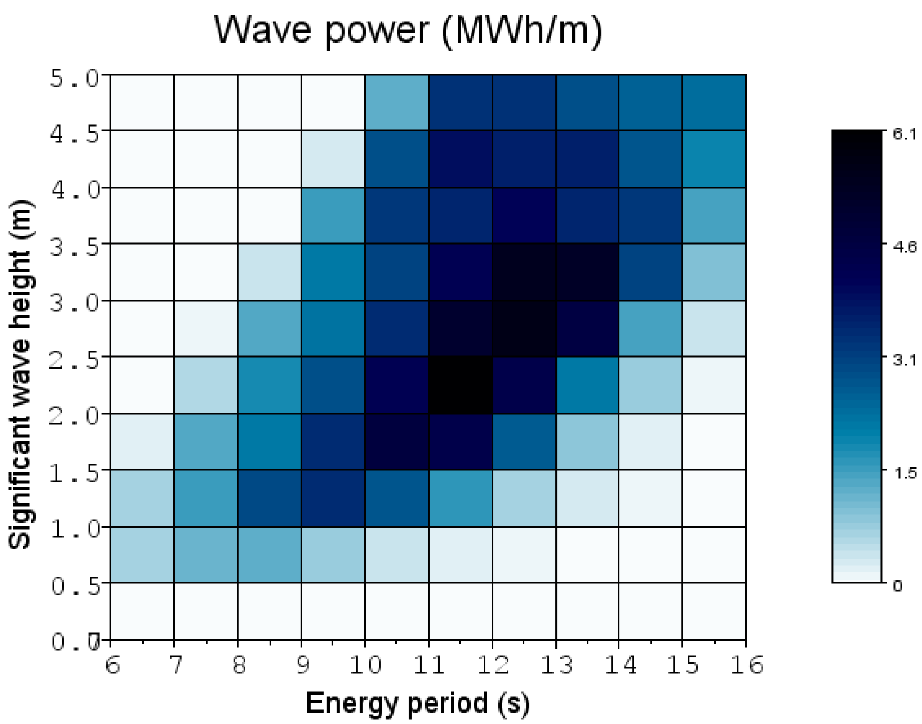

Figure 3: Bivariate distribution of energy (MWh/m) for sea states defined by wave height and energy period

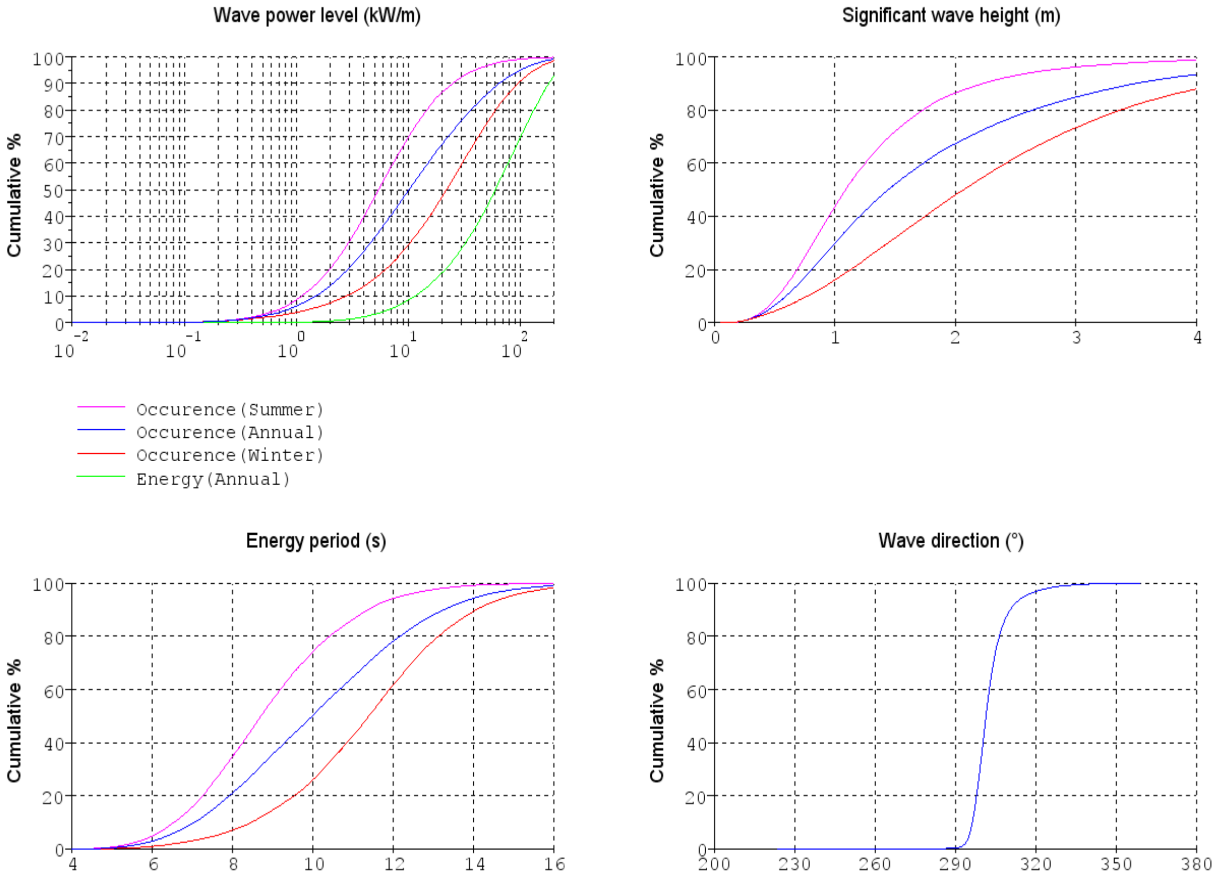

Figure 4: Cumulative distribution occurrence and energy of P_c, H_c, T_e and α.

The wave power level beyond the average annual power (24.3 kW/m) represents 25% of annual time, i.e. 90 days per year, and accounts for 75% of the annual energy. During winter, the wave power level is greater than 24.3 kW/m for 47% of the time, i.e. 85 days. The wave power level is less than 10 kW/m for 50% of annual time and accounts for only 10% of the annual energy, i.e. 182 days per year.

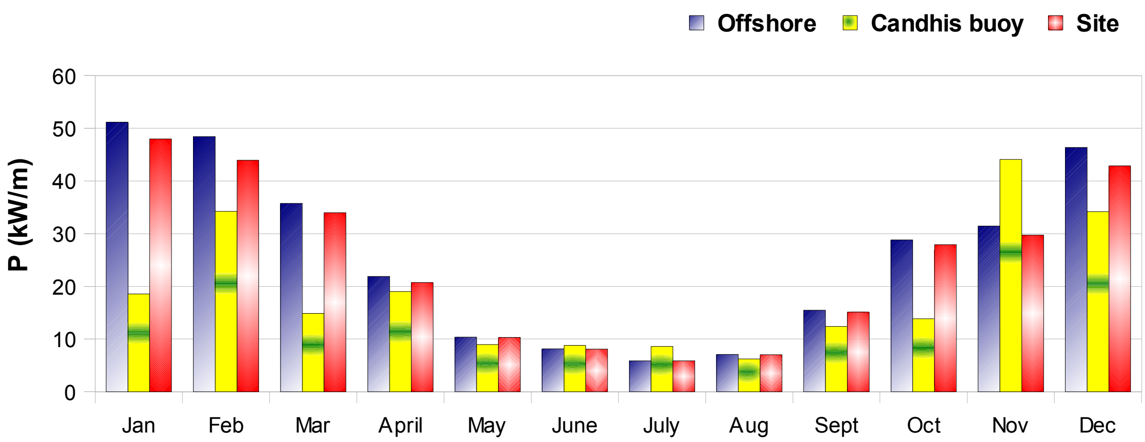

Figure 5: Monthly evolutions of offshore and site wave power levels.

The results of the study are significantly higher than the values of the directional buoy CANDHIS. Monthly variability and different time scales (more than 23 years for ANEMOC and 1.8 year for CANDHIS) could explained the discrepancy mainly observed during the winter period.

Final Classification of Sites

The study methodology, applied to 22 sites along France's coastlines, enables to extract the most energetic sites:

- Antifer (Seine-Maritime);
- Cherbourg, Flamanville (Manche);
- Le Conquet, Esquibien, Saint-Guénolé (Finistère);
- Saint-Gilles-Croix-de-Vie (Vendée);
- Bayonne, Saint-Jean-de-Luz (Pyrénées-Atlantiques).

From this result, it emerges that sites with the highest wave power levels are located in Brittany and in Basque-Country, which is consistent with the results obtained by Mattarolo *et al.* (2009).

The energy level undergoes an important decrease as arriving close to shore in Brittany (e.g. 44.3 kW/m offshore and 21.1 kW/m at Saint-Guénolé site), while, in Basque-Country, a lower reduction is noticed (e.g. 25.8 kW/m offshore and 21.8 kW/m at Saint-Jean-de-Luz site).

Both types of transfer could be explained by the different bathymetric configurations of these areas. The Britanny's coast is very indented and sites are in shallow waters. While the Basque-Country's coast is regular and sites are in intermediate water.

Discussion

Limitations of the Methodology

Results presented here must be considered with caution. Indeed, the aim of this work was to assess a large number of sites in order to extract those with good wave energy potential that will be studied in greater detail in a second step. So, this assessment method presents validity limits.

Simplified Formulation

This wave propagation by analytical method should be applied to sites with straight, parallel depth-contours and constant slope. In a water area where the average slope of the sea bottom is very gentle and in which the zone of shallow depth continues for a great distance (e.g. continental shelf offshore Brittany), wave attenuation due to bottom friction may not be negligible. It should be noted that diffraction has not been taken into account.

Sites Particularities

Typically, sites in Brittany are particularly complex compared to other sites. Presence of islands and shoals significantly attenuates deepwater waves (e.g. Cherbourg, Roscoff, Le Conquet) so wave power level can be overestimated. On the contrary, Esquibien is protected by the Lervilly Cape. Diffraction phenomenon in this area is important thus wave power level in Esquibien may be underestimated.

Prospects

Numerical models of wave propagation (TOMAWAC, SWAN and WAVE WATCH III) and wave database PREVIMER, build from hindcast simulations from 1996 to 2012 using WAVE WATCH III model, will be used in order to know more precisely the wave climate of sites (EPRI, 2011).

Furthermore, a few pilot sites will be instrumented (with pressure sensors, wave-buoys, ADCP...) in order to confirm the results of the study, calibrate the numerical models and refine the wave energy potential of those sites.

References

M. Benoit, F. Lafon & G. Goasguen (2008) *Constitution et exploitation d'une base de données d'états de mer le long des côtes françaises par simulation numérique sur 23 ans. Base ANEMOC en Atlantique, Manche et Mer du Nord,* European Journal of Environmental and Civil Engineering, Volume 12/1-2, pp 35-50.

ANEMOC, Atlas Numérique d'Etats de Mer Océanique et Côtier, CETMEF, EDF R&D-LNHE (2011), available at: http://anemoc.cetmef.developpement-durable.gouv.fr

CANDHIS, Centre d'Archivage National de Données de Houle In Situ, CETMEF (2012), available at: http://candhis.cetmef.developpement-durable.gouv.fr

EPRI, Electric Power Research Institute (2011) Technical Report *Mapping and assessment of the United States Ocean Wave Energy Resource*, Palo Alto, CA: 2011.1024637. 176 p.

EQUIMAR, Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Coast and Environmental Impact (2011) Deliverable D2.2: Wave and Tidal Resource Characterisation, 83 p.

Y. Goda (1975) *Deformation of irregular waves due to depth-controlled wave breaking,* Rept. Port and Harbour Res. Inst., 14(3), pp 59-106.

Y. Goda (2000) *Random seas and design of maritime structures*, Advanced series on Ocean Engineering, Vol. 15, World Scientific, Singapore, 443 p.

PREVIMER, Coastal observations et forecast wave database products, IFREMER, SHOM, Météo-France (2008), available at: http://www.previmer.org

P. Lenee-Bluhm, R. Paasch & H. Tuba Özkan-Haller (2011) *Characterizing the wave energy resource of the US Pacific Northwest*, Renewable Energy, Volume 36, pp 2106-2119.

G. Mattarolo, M. Benoit & F. Lafon (2009) *Wave energy resource off the French coasts: the ANEMOC database applied to the energy yield evaluation of Wave Energy Converters*, 8th European Wave and Tidal Energy Conference Series, Uppsala, Sweden.

SHOM (2011) *Ouvrage de marée, Références altimétriques maritimes, Cotes du zéro hydrographique et niveaux caractéristiques de la marée,* 98 p.