Wave Energy Resource

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Advanced assessment of the wave energy resource is fundamental to guarantee the implementation of energy converters in the marine environment, thus capturing the available power with maximum efficiency, reduced costs, and minimum environmental impacts. We review here the most recent resource characterizations encompassing a panel of approaches and techniques applied to available observations (in situ and satellite), hindcast and reanalysis archives, and refined numerical simulations specifically dedicated to wave power assessments. After a description of formulations adopted to characterize the wave energy flux, the review exhibits a series of energy metrics and selection indexes considered to refine the analysis. Benefits, limitations and potential of the different methods were discussed with respect to different applications in the most energetic locations around the world.

Keywords: wave energy metrics ; numerical spectral wave models ; wave energy converters ; wave-current interactions ; marine renewable energy ; wave energy flux ; coastal shelf seas ; inter-annual and inter-seasonal variability

1. Introduction

The exploitation of ocean renewable energy is currently recognized as an potential alternative to the reduction of fossil fuels resources consumption. One of the main advantage is the high power density of the wave resource in coastal waters, thus providing a great number of potential locations for energy exploitation[1]. Over the last decades, a wide range of technologies were therefore tested and deployed in real sea conditions to convert wave energy into electricity, the great part of these applications being dedicated to the European shelf seas. The exploitation of the wave resource may especially be valuable for marine regions with high energy costs such as island territories by complementing other forms of renewable resources (such as solar, wind and tidal stream energies) and leading to lower energy infrastructure costs and reduced energy storage requirements[2]. However, the development of the wave energy sector requires to guarantee the capital investment and the economical return of next-generation projects. And these objectives involve refined assessments of available resource and expected generated power. We conducted here an up-to-date review of the basic preliminary investigations of a wave energy project that may pave the way for refined design and advanced testing of full-scale devices. This review encompasses different approaches and techniques applied to available observations (in situ and satellite), hindcast and reanalysis archives, and refined simulations specifically dedicated to wave power assessments. Further details are available in the review entitled "**Wave Energy Assessment for Exploitation**" and published in open access in the Special Issue of the Journal of Marine Science and Engineering dedicated to "Numerical Assessments of Tidal Stream and Wave Energy in Coastal Shelf Seas": https://www.mdpi.com/2077-1312/8/9/705[3]

2. Wave Energy Characterization

2.1. Wave Power Computation

Wave resource assessments aim primary at characterizing the available wave energy flux (also denominated the wave power density or wave energy potential per unit crest, in W m^{-1}), defined as the integral of the wave energy spectrum

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} c_g(\sigma) E(\sigma, \theta) d\sigma d\theta$$

where ρ is the density of seawater, g is the acceleration due to gravity, E is the wave energy density distributed over intrinsic frequencies σ and propagation directions θ, and c_g is the group velocity.

However, simplified formulations are adopted to approach the wave power density, mainly as the distribution of *E* over frequencies and directions is not always available. Regional offshore assessments rely thus on the deep-water formulation obtained by adopting the approximation of the group velocity in deep waters ($c_g = g/(4\pi f)$ with f the wave frequency), and the available wave energy flux expresses as

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e$$

with $H_s = 4\sqrt{m_0}$ the significant wave height, $T_e = m_{-1}/m_0$ the wave energy period and m_n the n$^{\text{th}}$ order spectral moment. As available numerical hindcast databases and reanalysis archives set aside the energy period, this parameter is generally approximated by relying on available periods such as the mean or peak wave periods, and a calibration coefficient is introduced. For the peak period, this calibration coefficient α is defined such as $T_e = \alpha T_p$. It is generally estimated by assuming standard shapes of the wave energy spectrum, but may present increased differences in combined sea states including long-crested swell and short-crested wind-sea waves with two energy maxima, in high and low frequencies, respectively. This results in a wide range of values for the assessment of the wave energy resource (Table 1).

Table 1. Estimations of the calibration coefficient α between the peak period T_p and the energy period T_e ($T_e = \alpha T_p$)[3].

Estimations of α	Methods	References
0.9	**Analytical derivation of a JONSWAP spectrum (peak enhancement $\gamma = 3.3$)**	[4][5]
0.86	**Analytical derivation of a Pierson-Moskowitz spectrum**	[6]
0.8	**Exploitation of observations in the Alantic Marine Energy Test Site (Ireland)**	[7]
0.86 for wind sea /1.0 for swell	**Analytical derivations of Pierson-Moskowitz spectrum and Gaussian spectrum**	[8]
$\in$ **[0.29;1.5]**	**Exploitation of NOAA observations in the North-West Atlantic**	[9]

2.2. Wave Energy Metrics

Resource assessments rely furthermore on a series of metrics and selection indexes that may be applied to the different stages of a wave energy project including the available resource (pre-production metrics) and the power generated by wave energy converters (WEC) (post-production metrics).

Pre-production metrics aim to characterize the temporal variability of the wave climate at different time scales (monthly, seasonal and annual). The coefficient of variation is thus considered to evaluate, at different time scales, the amount of variability with respect to the mean value

$$\mathrm{CoV} = \frac{\sigma_P}{P_{mean}}$$

with σ_p the standard deviation of P and P_{mean} the mean available wave power over the period considered. The intra-annual differentiations in the resource is characterized by the annual variability index

$$\mathrm{AVI} = \frac{P_{A1} - P_{A2}}{P_{year}}$$

with P_{year} the annual mean wave power, and P_{A1} and P_{A2} the mean available wave powers for the most and the least energetic years, respectively. This formulation is adapted to approach the seasonal and monthly variability indexes of the available resource with the two following expressions $\mathrm{SVI} = (P_{S1} - P_{S2})/P_{year}$ and $\mathrm{MVI} = (P_{M1} - P_{M2})/P_{year}$ where P_{S1} and P_{S2} are the mean powers for the most and the least energetic seasons, respectively; and P_{M1} and P_{M2} are the mean powers for the most and the least energetic months, respectively.

Post-production metrics focus on the evaluation of WEC generated power and performance. The capture width, expressed in m and defined as $\mathrm{CW} = P_{gen}/P$ with P_{gen} the generated power (kW), is generally considered to assess the ability of a device to absorb the available wave energy flux. However, given the wide range of WEC technologies, CW was adapted to represent the diverse solutions resulting in the Cross Width Ratio (CWR) expressed as

$$\mathrm{CWR} = \frac{\mathrm{CW}}{\mathrm{B}}$$

with B the device characteristic dimension[10]. The adaptability of a given technology to specific environmental conditions may furthermore be assessed by relying on the capacity factor that accounts for the fraction of the time the energy converter is operating at full capacity. It is defined as the ratio between the energy output E_o and the rated energy from rated power P_o with ΔT the time period considered for resource assessment

$$\mathrm{CF} = \frac{E_o}{P_o \cdot \Delta T}.$$

The Levelized Cost of Energy (LCoE) (expressed in €/Mwh) is another post-production metrics that can be exploited to evaluate the economic cost of a power generation system during its lifespan[11].

Selection indexes are suggested to reduce the uncertainties in wave energy resource assessments, and may be classified into (i) **resource-based indices** dedicated to resource classification and (ii) **hybrid approaches** dedicated to quantification of both resource and WECs generated powers. Resource-based indices include a series of parameters such as the Wave Energy Development Index (WEDI) defined as the ratio between the mean annual energy flux P_{year} to the highest (storm) energy flux J_p potential[12]

$$\mathrm{WEDI} = \frac{P_{year}}{J_P}.$$

Higher WEDI accounts for severe design penalty. Other resource-based indices may be exploited such as the Optimum Hotspot Identifier (OHI)[13] or the inter-annual variability index[14]. Among hybrid method based indices, we may also refer to two major parameters: (i) the Mutli-Criteria Approach retained to refine the selection of state-of-the-art WECs[15] and the Selection Index for Wave Energy Deployments (SIWED) exploited for an unbiased selection of technologies[16].

3. Exploitation of Available Data

Different data may be exploited to characterize the wave energy in the marine environment. This includes (i) observations from in situ wave buoys, (ii) remote sensing measurements from satellite altimeters, and (iii) hindcast and reanalysis archives primary implemented to characterize the wave climate over the past decades.

Observations are, most the time, not available in locations retained for wave energy exploitation. However, the exploitation of these data may provide valuable information to characterize the available resource. In situ observations were thus exploited in a number of resource assessments, especially off the coast of U.S.A covered by a high density of NDBC wave buoys (National Data Buoy Center – National Oceanic and Atmospheric Administration – NOAA)[17][18]. But the exploitation of in situ observations was also particularly useful to refine the estimation of the calibration coefficient between the energy period and default statistical periods (such as T_p or the mean wave period T_m), thus improving assessment of offshore available wave power density with the deep-water formulation[9].

Satellite observations are characterized by important spatial and temporal limitations for assessing the available wave energy resource. Nevertheless, these measurements were able to image through clouds and provide day-and-night data, thus resulting in a long-term and extensive monitoring of the sea state. Satellite observations constitute therefore a promising alternative to local in situ wave buoys or time-consuming complex numerical modelling. The exploitation of multi-satellite altimeters provided thus cartographies of areas with the highest energy, but also a preliminary assessment of the temporal variability of the wave resource at seasonal and monthly time scales[19][20]. However, these exploitations for wave energy resource assessment require (i) to derive the wave period with a series of inversion models and (ii) further assumptions about the relationship between the energy period and statistical wave periods.

Hindcast Databases and Reanalysis Archives may provide valuable information in the reconnaissance stage of a wave energy project saving time in the implementation, computation and validation of numerical simulations. These databases were thus exploited to (i) investigate the temporal variability of the wave energy resource, and (ii) exhibit the long-term evolutions by identifying decadal changes in wave power density[21][22][23]. Considering the offshore applications of these databases, the available wave energy resource was estimated by relying on the deep-water formulation and adopting a constant calibration coefficient between the energy period and the peak or mean periods. Most of hindcast databases rely furthermore on oceanic wave models with limitations for the resolution of wave coastal processes. These numerical simulations were also conducted with coarse spatial resolutions, insufficient to capture coastlines topography and water depths variability in nearshore waters, as well as to approach processes at refined spatial scales. Hindcast data tend therefore to be less reliable in the coastal area primary targeted for WEC implementation.

4. Numerical Simulations

Numerical wave models may offer a wide range of spectral information, reducing the uncertainties in resource assessments associated with the exploitation of the deep-water formulation and/or databases with reduced spatial and temporal resolutions, and a coarse definition of physical processes impacting wave propagation. Simulations specifically dedicated to wave power assessments may be classified into (i) basic modelling implemented for preliminary evaluation of the power density from the distribution of energy spectrum over frequencies and directions, and (ii) more complex approaches integrating wave-current interactions or energy extraction.

Wave energy simulations are conducted with phase-averaged spectral wave models that resolve the evolution of the wave energy density by taking into account the processes of generation, dissipation and nonlinear wave-wave interactions. These numerical investigations may be classified with respect to the spatial scales covered, thus considering (i) continental shelf scale applications, (ii) regional assessments along the coastline of a marine country, and (iii) local study on a targeted wave farm. Complementing resource assessments based on the exploitation of hindcast databases and reanalysis archives, shelf-scale investigations cover several decades by adopting, most of the time, coarse spatial resolutions between 1/10 and 1/5 °. In spite of increased spatial resolutions – between 0.01 and 0.05 °, regional scale investigations may also cover several decades. But these refined simulations integrate shallow-water processes (such as bottom friction and depth-induced refraction) and rely on the spectral formulation to compute the wave power density, thus providing a refined assessment of the available resource in comparison with shelf-scale applications. Coastal investigations require, however, spatial resolutions of few hundreds of meter reached with embedded simulations or unstructured computational grids, and this restricts the period of time covered. Nevertheless, simulations succeed in simulating a minimum period of 10 years following IEC technical specifications, thus characterizing the temporal evolution of the wave energy over the area targeted for energy exploitation[24].

More complex numerical resource assessments may be adopted to reduce uncertainties associated with the modelling setup, the method retained to compute wave power or the physical processes considered. Particular attention may therefore be dedicated to wave and current interactions. Indeed, in locations with strong wave and tide regimes, tidal currents may impact wave propagation through a series of mechanisms including flattening/steepening, refraction, blocking or breaking. And these effects may result in important variations of the wave energy flux over 60 %[25]. Current-induced refraction appears as one of the major mechanisms leading to these modulations of the wave energy in coastal shelf seas. However, numerical simulations require (i) refined spatial resolutions to approach the spatial variations of tidal current magnitudes and directions, and (ii) advanced coupling between the wave and tidal circulation models. For these reasons, resource assessments with tidal effects are restricted to short simulation periods. Refined simulations may also consider WEC effects (especially energy extraction) on the available resource and the generated power. However, state-of-the-art phase averaged models are not adapted to approach the complex interactions between operating devices and hydrodynamics, and these effects are, most of the time, disregarded estimating the generated power from the combination of wave scatter diagrams and WEC power matrices[26].

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