Renewable Energy 52 (2013) 99–110

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A methodology for equitable performance assessment and presentation of wave energy converters based on sea trials

J.P. Kofoed [a], A. Pecher [a,*], L. Margheritini [a], M. Antonishen [a], C. Bittencourt [b], B. Holmes [c], C. Retzler [c], K. Berthelsen [d], I. Le Crom [e], F. Neumann [e], C. Johnstone [f], T. McCombes [f], L.E. Myers [g]

[a] Aalborg University, Department of Civil Engineering, Sohngaardsholmsvej 57, 9000 Aalborg, Denmark
[b] Det Norske Veritas BV, The Netherlands
[c] University College Cork, Ireland
[d] Aalborg University, Denmark
[e] Wave Energy Centre, Portugal
[f] University of Strathclyde, UK
[g] University of Southampton, UK

ARTICLE INFO

Article history:
Received 14 June 2011
Accepted 28 October 2012
Available online 22 November 2012

Keywords:
Wave energy converters
Performance assessment
Annual energy production
Wave to wire
Sea trials

ABSTRACT

A general and widely applicable methodology to assess and present the performance of wave energy converters (WEC) based on sea trials is presented. It is meant to encourage WEC developers to present the performance of their WEC prototypes, on a transparent and equitable way while taking care of possible discrepancy in the observed performance of the WEC. Due to the harsh uncontrollable conditions of the sea that is encountered by WECs during sea trials, some of the performance of the WECs might be sub optimal and the data sets not fully complete. The methodology enables to filter the data by applying a selection criterion on the performance data that was obtained for a certain range of wave conditions. This selection criteria result in a subset of performance data representing the performance of the WEC for specific wave conditions, from which an average value an appreciation of the related uncertainty can be derived. This can lead to the estimation of the annual energy output of the WEC at its test location, while it also provides a method to estimate its annual energy output for another location of interest and possibly also at another scaling ratio. The same methodology can also be used to perform parametric studies with environmental or device dependent parameters and to analyse the power conversion chain from wave to wire, which both could lead to an enhanced understanding of the performance and behaviour of the WEC.

The same methodology is also applicable to tidal devices or any other developing technologies that are used in an uncontrollable environment.

1. Introduction

Numerous documents have been published by different research entities in various countries regarding the development and performance analysis of wave energy converters (WEC) based on tank testing and sea trials. However, it has been shown that there is a need of having even more developed standards in ocean energy as standards are expected to contribute positively to the development of the industry [1,2]. Existing literature on the presentation and analysis of WEC sea trial performance data focuses primarily on commercially ready or well-established devices rather than those under development. Some of these related documents are [3–7].

This paper provides a methodology for the analysis and presentation of data obtained from sea trials of wave energy converters and is an expansion of the related EquiMar protocols [8]. The equitable aspect of this methodology lies in its wide application, as any WEC at any scale or stage of development can be considered as long as the tests are performed in real sea conditions, and that the results contain statistical information concerning the

* Corresponding author. Tel.: +45 99 40 84 74; fax: +45 99 40 85 52.
E-mail addresses: jpk@civil.aau.dk (J.P. Kofoed), afsp@civil.aau.dk (A. Pecher), lm@civil.aau.dk (L. Margheritini), michael.antonishen@gmail.com (M. Antonishen), Claudio.Bittencourt.Ferreira@dnv.com (C. Bittencourt), B.Holmes@ucc.ie (B. Holmes), c.retzler@pelamiswave.com (C. Retzler), kkb@math.aau.dk (K. Berthelsen), izan@wave-energy-centre.org (I. Le Crom), frank@wave-energy-centre.org (F. Neumann), cameron.johnstone@strath.ac.uk (C. Johnstone), tom.mccombes@strath.ac.uk (T. McCombes), l.e.myers@soton.ac.uk (L.E. Myers).

0960-1481/$ – see front matter
http://dx.doi.org/10.1016/j.renene.2012.10.040

Nomenclature

AEP	annual energy production [Wh]
Contrib	contribution to the available wave energy resource [-]
CI	confidence interval
CL	confidence level
H_{mo}	estimate of the significant wave height derived from spectral moment, $4\sqrt{m_0}$ [m]
g	gravitational acceleration [m/s^2]
n	number of data points
m_n	spectral moment of the nth order [m^{2}f^n]
L	dimension, e.g. length [m]
LF	load factor [-]
P	power output [W]
Prob	probability of occurrence [-]
$P_{average}$	average power output [W]
P_{wave}	wave power [W/m]
s	sample standard deviation
t^*	statistical parameter representing the confidence level of the confidence interval
T_e	wave energy period (m_{-1}/m_0) [s]
v	characteristic velocity [m/s]
η	non-dimensional power performance (also referred to as efficiency) [-]
η_{zone}	non-dimensional power performance for the wave conditions of a zone [-]
η_i	non-dimensional power performance of a performance data point [-]
λ	scaling ratio, requiring geometrical similarity = L_f/L_m [-]
WEC	wave energy converter

stated performance of the WEC. This will allow the estimation of the annual energy production (AEP) of the WEC at any scaling ratio and location of interest. The representation of the performance will be better resolved when more performance data has been gathered and consequently its statistical reliability will be increased.

The harsh environmental conditions in which sea trials are performed involve a large range of engineering development and device monitoring challenges, since the offshore environment is by nature uncontrollable and only predictable to a certain extent. Unfortunately this can incur significant costs during device development and, even with heavy investment, some WEC components or measurements can still perform poorly. In addition, having the WEC tested in every possible sea state can require very long trials, since some conditions occur only very infrequently. This often leads to testing campaigns that are not as extensive as desired. Therefore, the performance analysis should be robust enough to allow using suboptimal performance data that are obtained from sea trials that are not fully completed. In other words, this methodology is focused at retrieving the maximum amount of useful information out of incomplete data sets.

This methodology presents means to assess the performance of a WEC, tested in real sea conditions, by evaluating its performance (in a first approach) separately for different wave conditions. These "different wave conditions" are defined as zones and the range of their corresponding wave parameters is defined in accordance with the availability of data and resolution of the scatter diagram [9]. For each of these zones, the performance of the WEC will be stated together with a statistical parameter describing the reliability of the stated performance. Based on the performance of each zone, an overall appraisal of the performance can then be created. Once the non-dimensional performance is characterised for the specific wave parameters of each zone, it can be translated to scatter diagrams of other locations of interest or used for different scales of the device. The methodology facilitates as well parametric studies, as the performance data can be chosen accordingly.

The uncertainty of the performance for a zone is based on the selected performance data that are chosen to represent the sea conditions. A minimum number of data points must be considered for each range of zones in order to ensure that the results are both repeatable and reproducible, and a limit is set regarding the maximum range of a sea state. Although the representation of the environmental conditions in which the tests occur will be reduced to the bi-variate $H_{m0} - T_e$ scatter diagram, the influence of other environmental parameters is still expected to be present in the representation of the performance by the inclusion of different data points for each sea state. The extent to which other environmental parameters or even device dependent parameters influence the performance of the WEC can also be investigated using this methodology.

2. Overview of the methodology

A schematic overview of the different steps and possible applications of this methodology are given in Fig. 1. The arrows surrounding the figure indicate that the process can be repeated throughout the sea trials, especially when more data becomes available.

In general, while the same methodology can be used at any stage of development of a WEC as long as the tests are performed in real sea conditions, there are three principal applications:

- The assessment of the AEP of the WEC at its test location. The results of this analysis can subsequently be used to estimate the performance of the same WEC at another location of interest. In the case that the device is to be scaled or used at another location, the data can be scaled correspondingly and the results can be used to validate a numerical data model.
- The assessment of the available energy at various stages of the energy conversion chain from wave-to-wire. This offers an individual view on specific energy conversion steps, allowing characterisation of each steps behavioural trend relative to the wave conditions.
- The assessment of the influence of a specific environmental or device dependent parameter on the performance of the WEC, possibly at various energy conversion steps.

Irrespective of the eventual application of the method, the procedure consists of three main parts. The first part intends to pre-process the environmental data (e.g. waves, tides, wind, etc.) and the performance data (e.g. mechanical power, electricity transmitted to the grid, etc.). This consists of establishing the environmental matrix that contains all parameters used to characterise the environmental climate at the test site. This environmental matrix has to be based on long term data, typically 10 years or more for wave data [10], in order to cover all the long and short term variability of the individual parameters. This can then be simplified into the scatter diagram, determined by H_{m0} and T_e. The performance of the WEC at the conversion stage of interest – in terms of power output (P) or available power – is processed relative to its corresponding environmental conditions in order to obtain the non-dimensional performance values of the WEC, and forms the basis of the procedure. In cases where various energy conversion steps or other device dependent or environmental parameters are investigated, then they must also be included in the data at the beginning.