Ocean Engineering xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ocean Engineering

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

Reliability and O & M sensitivity analysis as a consequence of site specific characteristics for wave energy converters

Anthony Gray[a,*], Beth Dickens[b], Tom Bruce[c], Ian Ashton[d], Lars Johanning[d]

[a] Industrial Doctoral Centre for Offshore Renewable Energy, Edinburgh EH9 3JG, UK
[b] Quoceant Ltd., Edinburgh EH6 5NP, UK
[c] The University of Edinburgh, Edinburgh EH9 3JG, UK
[d] University of Exeter, Penryn Campus, Cornwall TR10 9FE, UK

ARTICLE INFO

Keywords:
Wave energy
Failure rates
O & M
Reliability
Wave farms

ABSTRACT

Estimates for lifetime costs of wave energy arrays are difficult to obtain due to the uncertainty surrounding weather windows and failure rates for wave energy converters (WECs). An operations & maintenance (O & M) simulation tool has been used to assess the sensitivity of WEC failure rates on the profitability of a wave farm, with the Pelamis P2 device used as a case study. Two offshore wave energy sites in the UK have been characterised and presented in terms of accessibility for marine operations and power generation. It was found that a wave farm at one site would incur higher costs due to vessels having to wait longer for suitable weather windows. This was balanced by higher generated revenue, showing how the tool can be used to support strategic planning and site selection. The results identify the sensitivity to failure rate estimations for different components, helping target future work to reduce uncertainties and costs. The results highlight the need for WEC developers to collaborate closely with component manufacturers in order to design the best device possible for the challenging marine environment. Collaboration enables more realistic failure rate estimates to be obtained, leading to better understanding of the operational costs for commercial wave energy farms.

1. Introduction

The wave power sector has potential to be a major contributor to global renewable energy generation. At a national level, the total power capacity of wave energy projects in UK waters could potentially reach 13 GW in the future (Boud, 2012). Globally, up to 95 GW of wave energy devices could be installed in the world's seas and oceans (Gunn and Stock-Williams, 2012). However, the wave energy sector has not yet seen the development of commercial-scale arrays. Several different device concepts have been considered since the 1970s. This includes seabed-fixed devices (e.g. ‘Oyster’, ‘Wavestar’), as well as floating designs (e.g. ‘Edinburgh Duck’, ‘Pelamis’). Significant advances have been made in terms of understanding the hydrodynamic behaviour of wave energy devices in the marine environment, as well as in other areas such as estimating power capture (Borthwick, 2016). However, the early part of this decade has seen several of the major companies in the sector go out of business. Interest in tackling the wave energy challenge is still strong, with governments around the world funding initiatives such as Wave Energy Scotland (Highlands and Islands Enterprise, 2016) and the Wave Energy Prize (EERE, 2017). A recent report by the European Commission (Magagna et al., 2016) states that up to 37 MW of wave energy projects could be operational within the European Union (including the United Kingdom) by 2020.

One of the key barriers to commercialisation of the wave energy sector is the high cost of energy relative to other forms of renewables. Wave energy is estimated to cost up to $500US/MWh (£380/MWh) at present, compared to approximately $200US/MWh (£150/MWh) for offshore wind (World Energy Council, 2013). For the developers of wave energy converter (WEC) technology to attract private investment, it is vital that they obtain realistic estimates for the levelised cost of energy (LCOE) based on a holistic engineering approach.

Operations and maintenance (O & M) will account for a significant

Abbreviations: CBA, Cost-Benefit Analysis; CCO, Channel Coastal Observatory; EMEC, European Marine Energy Centre; FMEA, Failure Modes and Effects Analysis; Hs, Significant Wave Height; LCOE, Levelised Cost of Energy; MTBF, Mean Time Between Failure; O & M, Operations and Maintenance; OPEX, Operational Expenditure; OREDA, Offshore and Onshore Reliability Data; P2, second generation Pelamis wave energy device; P_{fail}, probability of failure (per year); PRIMaRE, Partnership for Research In Marine Renewable Energy; SPARTA, System Performance, Availability and Reliability Trend Analysis; Te, Wave Energy Period; VBA, Visual Basic for Applications; WEC, Wave Energy Converter; WES, Wave Energy Scotland

* Correspondence to: University of Edinburgh, Room 1.A123/4, Alrick Building, King's Buildings, West Mains Road, Edinburgh EH9 3JG, UK.
E-mail address: anthony.gray@ed.ac.uk (A. Gray).

http://dx.doi.org/10.1016/j.oceaneng.2017.06.043
Received 15 December 2016; Received in revised form 15 June 2017; Accepted 17 June 2017

amount of the total costs of any offshore renewable energy development. In the offshore wind industry, O & M costs account for approximately 20% of the total costs of wind farms (BVG Associates, 2013). Estimates for this operational expenditure (OPEX) are difficult for WECs due to the relatively small amount of experience gained in the sector. However, estimates can be obtained through the use of O & M simulation tools. These have been used widely in the offshore wind industry over the years for both cost estimation and operations planning (Hofmann, 2011; Pahlke, 2007). They can also provide a clear picture of the O & M strategy considerations necessary to ensure smooth operation of wind farms, as demonstrated by Scheu et al. (2012) and Douard et al. (2012). Building O & M simulation tools for wave energy has significant potential in developing wave energy projects (Walker et al., 2013) and providing feedback into the design of devices (Martin et al., 2016).

The limited operational experience of wave energy converters in comparison to offshore wind turbines means that some estimates of wave energy OPEX simply assume a percentage of capital expenditure (CAPEX), as demonstrated by O'Connor et al. (2013). Very few examples of simulation tools modelling detailed O & M strategies of wave energy arrays have been published. One model presented by Abdulla et al. (2011) takes the case study of Aquamarine Power's 'Oyster' WEC and uses a Monte Carlo approach to simulate the occurrence of faults on the device. The study assesses the availability of the WEC but does not analyse costs. Another example is the model representing the Wavestar device, presented by Ambühl et al. (2015), where failure rate data from the offshore wind industry is translated to the WEC. A 'damage model' is included to account for fatigue of structural components. Commercially-available simulation tools for wave energy arrays, such as ForeCoast Marine (JBA Consulting, 2015) and MERMaid (Mojo Maritime, 2016), are focussed on accessibility and marine operations planning at present, rather than on obtaining estimates of OPEX. A European funded project, DTOcean, has produced an open-source suite of tools to allow developers of WEC technology to begin planning arrays (Weller et al., 2015). The project includes a lifecycle logistics work package which may help assess the O & M strategy of a wave energy farm, if adequate inputs to the tool can be provided (Teillant et al., 2014).

One of the key inputs required to obtain realistic estimates and scenarios from an O & M simulation tool is failure rate data. This is becoming less of a problem in the offshore wind industry due to the relatively large amount of operational data available to both academics and industrial researchers. Carroll et al. (2015) draw on a population of over 2000 wind turbines to undertake an analysis on reliability of different generator types. The significant amount of available data for offshore wind turbines has led to the creation of the SPARTA (System Performance, Availability and Reliability Trend Analysis) project; "*a database for sharing anonymised offshore wind farm performance and maintenance data*" (ORE Catapult, 2016). SPARTA was inspired by the OREDA handbook, first created in 1981, which has contributed to improved safety and cost effectiveness in the oil and gas industry (OREDA, 2015). A similar reliability database for wave energy is not possible at present, in part due to the large variety of WEC concepts currently being explored.

Obtaining reliability data for WECs is particularly challenging due to the paucity of full scale testing in open sea conditions (Thies et al., 2012). Destructive testing on generic components such as mooring lines is an extremely useful activity for reducing the uncertainty for failure rates (Weller et al., 2014). Any other WEC components are device-specific, however, and therefore require testing to be undertaken by the developer themselves. Such testing can be time consuming and expensive, making it unattractive to WEC developers with tight financial constraints (Wolfram, 2006). As a result, destructive testing is usually only considered necessary for key components such as hydraulic ram cylinders (Rühlicke and Haag, 2013).

Many off-the-shelf components such as hydraulic seals are supplied by the manufacturer accompanied by expected failure rates (Voith, 2016). This data may not be accurate for WECs, however, as the components are being used in a different way and in a different environment than their design specifications (Thies et al., 2012). In reality, the best source of reliability information at this early stage of the wave energy sector's development is the expert judgement of the engineers involved. There is a significant amount of uncertainty surrounding failure rates obtained in this manner and this needs to be accounted for when used in O & M tools for estimating OPEX and availability of a wave farm.

Weather data is also a key requirement of an O & M model in order to evaluate so called 'weather windows'; periods when the devices can be accessed by vessels and maintenance crew. The weather conditions defining these windows generally come through operator experience as well as vessel specifications (O'Connor et al., 2013). O & M tasks for a wave farm should be scheduled for periods when accessibility is highest and expected revenue is at a minimum (Walker et al., 2013), though this may not always be possible due to unexpected failures. Weather data is also required for yield estimation. Higher temporal and spatial resolution, as well as the proximity of source weather data to a proposed site, will improve the accuracy with which an O & M tool can represent weather conditions, resulting in a more robust estimation of OPEX costs and farm availability.

This study addresses site characteristics affecting accessibility and power performance, and uncertainty surrounding failure rate estimates for wave energy converters. The study makes use of a Monte Carlo-based O & M simulation tool, whereby failure rates are used to simulate the occurrence of faults on a machine. A case study based on the second-generation Pelamis WEC has been used due to the significant amount of experience gained during a testing programme achieving over 11,000 grid connected hours. The study aims to demonstrate the model as an effective tool for budgeting and planning of a wave energy array. It also highlights the ability of the tool to support targeting work priorities for developing wave energy technologies.

The methodology of this study, including the model inputs and functionality, is described in Section 2. The model's base case scenario is detailed in Section 3, along with the characteristics of two selected sites. The results of the sensitivity analysis are presented and discussed in Section 4. The main conclusions of the study are highlighted in Section 5, before further work is suggested in Section 6.

2. Methodology

The O & M tool used in this study is focused on the Pelamis P2 device (Fig. 1), rated at 750 kW. The tool was developed initially in 2007 by Pelamis Wave Power. The software has since been upgraded over the course of a partnership with the Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE).

2.1. Pelamis O & M strategy

The operations and maintenance phase of wave energy converters needs careful consideration for arrays of the devices to become economically viable. Lessons can be learnt from the more advanced

Fig. 1. One of the two Pelamis P2 machines operating at EMEC in 2012 (Pelamis Wave Power).