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A Markovian approach to power generation capacity assessment of floating wave energy converters

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ABSTRACT

The significant cost required for implementation of WEC sites and the uncertainty associated with their performance, due to the randomness of the marine environment, can bring critical challenges to the industry. This paper presents a probabilistic methodology for predicting the long-term power generation of WECs. The developed method can be used by the operators and designers to optimize the performance of WECs by improving the design or in selecting optimum site locations. A Markov Chain model is constructed to estimate the stationary distribution of output power based on the results of hydrodynamic analyses on a point absorber WEC. To illustrate the application of the method, the performance of a point absorber is assessed in three locations in the south of Tasmania by considering their actual long-term sea state data. It is observed that location 3 provides the highest potential for energy extraction with a mean value for absorbed power of approximately 0.54 MW, while the value for locations 1 and 2 is 0.33 MW and 0.43 MW respectively. The model estimated that location 3 has the capacity to satisfy industry requirement with probability 0.72, assuming that the production goal is to generate at least 0.5 MW power.

1. Introduction

Over the past few decades, the significant increase in global energy demand and the environmental concerns due to fossil fuel emissions have generated a great interest for researchers to investigate the development of renewable energy technologies. Among all available resources, the marine environment, with an abundant capacity and high spatial concentration, provides outstanding potential for harvesting power from ocean waves while occupying no land. Previous researches show that the world's largest waves, with an average wave height of 6 m, occur frequently in the Southern Ocean including the southern and western coastal regions of Australia [1,2]. According to Harries et al. [3]; the mean power in wave fronts in these regions varies between 30 and 70 kW/m and may peak at 100 kW/m. To extract the available power, a number of technologies for wave energy converters (WECs) are proposed, a review of which has been provided by Antonio [4]. Point absorbers are one of the major types of WECs where the horizontal extension of the device is very small compared to the typical wavelength. Through the wave-excited resonance, the periodic motion of a point absorber buoy drives a hydraulic power take-off (PTO) system or a linear generator to produce electricity [5]. Other types of WEC are attenuators and overtopping systems with larger horizontal extensions.

Despite the large effort made by researchers and industry stakeholders, WECs are currently at the prototype stage with only a few of them being tested in an open sea environment [4,6]. This results in the scarcity of available data such as actual power generation rates measuring the performance of WECs. The Development of WEC technologies is considered to be in a critical stage requiring research to focus on the techno-economic solutions [7]. In

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this process, several elements such as wave energy potential in the area of interest and energy occurrence and its distribution among various sea states should be extensively investigated [8,9].

Several researchers have investigated WEC performance and power absorption potentials, most of which neglect the randomness of the sea environment, focusing on the design improvement possibilities. Some of the conducted studies have adopted statistical approaches for producing wave power atlases in specific locations [10–12] or generated a wave characteristic profile with a spatio-temporal resolution using numerical modelling approaches [13]). Bhinder et al. [14] developed a numerical hydrodynamic model to evaluate the efficiency of a WEC located near the coast of western France. Considering the sea states in this location, their model was tested for a wide range of significant wave heights and wave periods. Despite the efficiency of the method in estimating the power output, the study has failed to take into account the occurrence probability of each sea state.

Bozzi et al. [9] investigated the feasibility of wave energy exploitation near the Italian coast by estimating the energy production of hypothetical wave farms. Based on the performance matrices of studied WEC and 21 years recorded sea state data for a specific location, this research estimated the power generation capacity factor as a percentage of those in other assessed locations. Abaei et al. [15] also developed a risk-based methodology for WEC site implementation in Tasmanian waters. In their work, Bayesian methods were adopted to select the optimum WEC site location based on actual sea environment data. The developed method, provides a sound tool for probabilistic analysis and Multi Criteria Decision Making (MCDM) in marine renewable energy applications. The former research makes some recommendation for improving the capacity factors, while the latter predicts the expected utility of installing WEC devices in a specific location. However, these methods do not necessarily provide a solution for predicting the long-term probability of achieving the desired level of power in a given location.

This paper presents a probabilistic methodology for estimating the energy production performance of WEC devices. For this purpose, a Markov Chain (MC) model is developed to predict the long-term power generation of floating WECs with respect to a wide range of sea states. It should be noted that this study does not consider the long-term variations of sea states. The long-term fluctuations or changes in the environmental condition due to climate change effects are out of the scope of this paper. Moreover, the extreme values are not included in the prediction of power generation. The scope of this study excludes analyzing the effect halting production due to extreme conditions or facility downtime due to maintenance and operation. This methodology considers the uncertainty of the marine environment by adopting the actual occurrence probability of each operational sea state for a specific location. Based on these probabilities and the results of numerical hydrodynamic simulations, a Continuous-Time Markov Chain (CTMC) is developed for WEC performance estimations. A case study illustrates the application of methodology through predicting power generation capacity of a point absorber WEC in three locations in the south of Tasmania.

1.1. *Continuous-time Markov Chain (CTMC)*

A continuous-time Markov Chain (CTMC) is a random process $\{X(t): t \geq 0\}$ with state space$S$forming a family of random variables $X(t)$ indexed by some set T [16]. The state of the process, $X(t)$, takes value from S for all time $t \geq 0$. That is, $X(t) = i$ expresses that the process at time t is in state i. Note that $X(t) = i$ implies that $X(u) = i$ for all $u \in [t; t + \varepsilon)$, for some $\varepsilon > 0$. A process must satisfy the following Markovian property, or memoryless property, to be called a CTMC

$$P(X(t+s) = j | X(u) = x(u), 0 \leq u < s, X(s) = i) = P(X(t+s) = j | X(s) = i),\\ for\ all\ s, t \geq 0\ ,\ \ i, j, x(u) \in S. \tag{1}$$

Eq. (1) states that in a Markovian process, the future evolution of the process depends on its history only through the present state. A CTMC is said to be time-homogenous if the probabilities $P(X(t+s) = j | X(s) = i)$ are independent of s for all s, $t \geq 0$, and all s, $t \geq 0$, in which it can be written

$$P(X(t+s) = j | X(s) = i) = P_{ij}(t), \tag{2}$$

where $P_{ij}(t)$ is the transition probability from state i to j in time interval t. The generator matrix $\mathrm{Q} = [q_{ij}]$, which includes the transition rates from each state of the process to another, is given by

$$q_{ij} = \lim_{h \to 0^+} \frac{P_{ij}(h) - P_{ij}(0)}{h} = P'_{ij}(0) = \frac{d}{dh} P_{ij}(0)|_{h=0}, \tag{3}$$

Or equivalently, in matrix notations, by

$$\mathrm{Q} = \lim_{h \to 0^+} \frac{\mathrm{P}(h) - \mathrm{P}(0)}{h} = \mathrm{P}'(0) = \frac{d}{dh} \mathrm{P}(0)|_{h=0}. \tag{4}$$

An accurate estimation of the generator matrix Q requires enough samples of the process in which the property of the system under analysis is divided into m states. This statistical result of the analysis, based on Q, will approach its true value when the number of samples reaches infinity. The generator matrix can be used to conduct probabilistic modelling of the system, such as the long term distribution of the process, as discussed later in the paper.

MC models have been widely used by researchers in various engineering applications such as maintenance and integrity management of wind turbines [17], failure assessment of oil and gas pipelines [18] and optimization of monitoring processes in nuclear power plants [19]. Given the successful use of this technique in different research areas, we adopt it in the present study for evaluating the long-term energy absorption of WECs in a specific offshore location considering its sea state characteristics.

2. Wave power absorption methodology

The proposed methodology aims at providing a tool for predicting the power generation performance of WECs in particular offshore locations. This tool will enable the operators and designers to determine whether the site of interest for establishing the WEC farm will provide the potential for achieving a desired level of power output. Consequently, the economic risk associated with establishing a WEC farm can be decreased while the methodology also assists in improving the design for a higher energy production

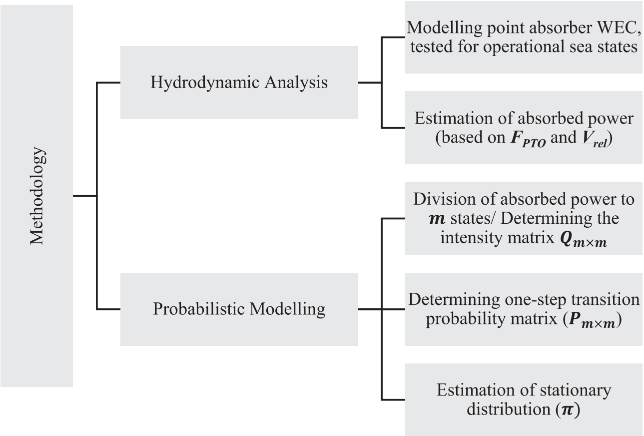

Fig. 1. Developed methodology for probabilistic estimation of WEC power generation capacity.

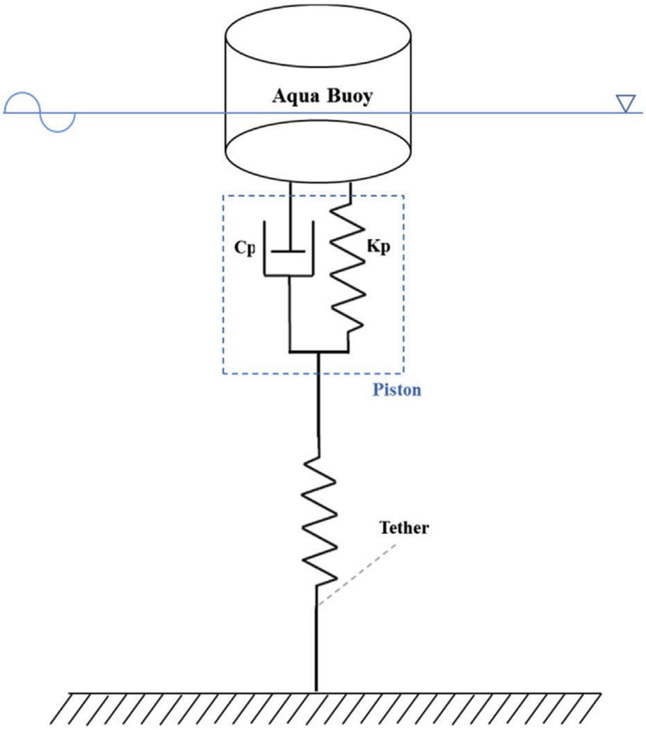

Fig. 2. Schematic representation of the point absorber WEC with a hydraulic power take-power take-off (PTO).

rate. Fig. 1 illustrates the stages of the proposed methodology and the key elements covered in each stage.

2.1. Hydrodynamic analysis

In order to predict the performance of a WEC in the open sea, the responses of the structure that represent the power generation should be analyzed. Aiming at the economic aspect of performance, the operational sea states in the location of interest must be considered in the analysis. Moreover, the operational details of energy production, which depend on the type of WEC, must be evaluated. This study focuses on a point absorber WEC with a hydraulic PTO system, as illustrated in Fig. 2. The spring-damper system shown in Fig. 2 represents the hydraulic piston attached with a tether (shown with a spring) to the sea bed.

In these structures, the heave motion of the floating buoy causes a piston (shown in the figure) to drive a pump attached to the sea floor. The hydraulic pump in turn delivers high pressure water to hydro-electric turbines located in an onshore plant. The PTO mechanism is modelled by So et al. [20]; where the power absorbed by the hydraulic PTO is given by

$$P_{PTO} = -\overrightarrow{F_{PTO}}\overrightarrow{V_{rel}}, \tag{5}$$

where the V_{rel} is the relative velocity between the piston and its cylinder and F_{PTO} is the reaction force, calculated by

$$F_{PTO} = \varDelta p_{piston} A_{piston}, \tag{6}$$

where $\varDelta p_{piston}$ is the differential pressure of hydraulic piston and A_{piston} is the piston area.

The model in Fig. 2 was adopted for the hydrodynamic analysis based on Boundary Element Method (BEM) in OrcaFlex software [21]. The mooring line of the model consists of two sections replicating the tether as well as the hydraulic piston. A non-linear stiffness profile is considered for the piston section, ensuring that the displacement of the piston rod is limited to a desired range.

The structure's responses are simulated by a wide range of sea states that cover the operational conditions. The time histories of axial force and relative velocity are obtained from the piston section. The product of these parameters is calculated for each time step of the simulation, based on Eq. (5), providing the power absorbed by the PTO. Absorbed power data is produced to conduct the probabilistic analysis and establish the MC model of power generation.

2.2. Markov Chain model

Based on the acquired data, a multi-state Markov model is developed for prediction of the long-term energy production of WECs. In order to establish the model, it is necessary to divide the entire range of absorbed power into a number of power states, where the bounds of this division are determined based on the expected power for each sea state (with a joint probability distribution of $H_s$and T_z). For instance the i^{th} power state bound which is the expected power from the i^{th} sea state can be calculated by:

$$P^i_{H_s} = \frac{\rho g^2}{64\pi}\left(H^i_s\right)^2 T^i_z, \tag{7}$$

where ρ is sea water density, g is acceleration due to gravity, H^i_s and T^i_z are the significant wave height and zero crossing wave period of the relative sea state. It should be noted that by considering m sea states, the entire range of absorbed power will be divided into m states with the following bounds,

$$\begin{cases} Power\ State\ 1 & 0 \le P < P^1_{H_S} \\ Power\ State\ i, \quad i \ne 1, m & P^i_{H_S} \le P < P^{i+1}_{H_S} \\ Power\ State\ m & P^m_{H_S} \le P. \end{cases} \tag{8}$$

Fig. 3 illustrates the MC with m states (each represented by a circle), where any of the shown arcs represent the transition from one state to another.

By comparing the absorbed power in each time-step with the bounds of each power state, the residence accumulated time in each state, $T_{\sum i}$, is estimated. Next, to establish the intensity matrix, Q , the transition rates of the system from the ith to the j^h power state is [22]. These rates, denoted as λ_{ij}, are the ratio between the

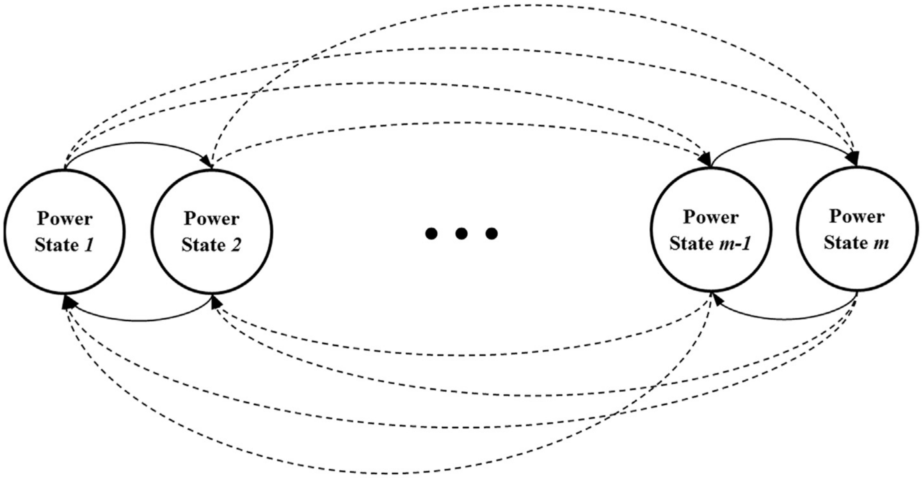

Fig. 3. Generic Markov Chain for predicting WEC power generation. The entire range of output power is divided into m states (in circles) and the arcs represent transitions from one state to another.

number of time steps in which the system is observed to transit from $i$to j, T_{ij}, and the total residence accumulated in each state. That is, for$j \neq i$,

$$\lambda_{ij} = \frac{T_{ij}}{T_{\sum i}}. \tag{9}$$

To account for the randomness of sea environment in WEC performance predictions, the occurrence probability of each adopted sea state is incorporated in the analysis and the transition rates are updated using

$$\begin{aligned} \bar{\lambda}_{ij} &= \lambda_{ij} p\left(H_s^i\right), \quad j \neq i, \\ \bar{\lambda}_{ii} &= -\sum_{j \neq i} \bar{\lambda}_{ij}\,, \qquad j = i, \end{aligned} \tag{10}$$

where $p(H_s^i)$ is the occurrence probability of ith sea state. The intensity matrix Q is then given by

$$\mathrm{Q} = [\bar{\lambda}_{ij}\,] = \begin{bmatrix} \bar{\lambda}_{11} & \bar{\lambda}_{12} & \cdots & \bar{\lambda}_{1m} \\ \bar{\lambda}_{21} & \bar{\lambda}_{22} & \cdots & \bar{\lambda}_{2m} \\ \vdots & & & \\ \bar{\lambda}_{m1} & \bar{\lambda}_{m2} & \cdots & \bar{\lambda}_{mm} \end{bmatrix}. \tag{11}$$

The stochastic matrix P, which includes transition probabilities between the states of the model is constructed based on:

$$\mathrm{P}(t) = e^{\mathrm{Q}t}, \tag{12}$$

where t is the time step. The probability distribution of CTMC for WEC system at time t is the row vector $\mathrm{q}(t)$ defined as

$$\mathrm{q}(t) = \left[q_j(t)\right] = \left[q_1(t) \quad q_2(t) \quad \cdots \quad q_m(t)\right], \tag{13}$$

where $q_i(t)$ is the unconditional probability of the WEC system to be in state i at time t. Given that the initial distribution of the system, $\mathrm{q}(0)$, and the one-step transition matrix P are known, the distribution of the system at time t can be calculated using

$$\mathrm{q}(t) = \mathrm{q}(0)e^{\mathrm{Q}t}. \tag{14}$$

When the number of intervals approaches infinity ($n \to \infty$), the power generation state of WEC system approaches a certain steady value, defined as the stationary probability vector of power generation using

$$\pi = [\pi_j] = \lim_{n \to \infty} \mathrm{q}(t) = \lim_{t \to \infty} \mathrm{q}(0)e^{\mathrm{Q}t}. \tag{15}$$

Eq. (15) suggests that the long-term state probabilities of WEC power output will approach π_j after a sufficient length of time, regardless of the initial state of the system. In the proposed methodology, assuming that the stationary distribution exists, it is obtained by solving the system of equations

$$\begin{cases} \pi \mathrm{Q} = 0 \\ \pi \mathrm{e} = 1, \end{cases} \tag{16}$$

where e is a (column) vector of ones of appropriate size. Estimation of the power state probabilities enables the evaluation of WEC performance for a given design and sea environment characteristics.

3. Methodology application: case study of WEC sites in Tasmanian waters

To demonstrate the application of the developed MC model in this paper, power generation performance of a point absorber WEC is probabilistically assessed. The structure is modelled in OrcaFlex software with the geometric details listed in Table 1. As discussed in Section 2.1, a non-linear stiffness profile is applied on the piston section to limit the displacement of the piston rod to the desired range. This has been neglected by some of the previous studies [5,12] and reported to be a possible way to improve power

Table 1
Geometry details of simulated point absorber WEC.

Variable	Value	Unit
Water Depth	50.0	m
Buoy Maximum Diameter	5.0	m
Buoy Maximum Height	10.0	m
Tether Length	33.95	m
Tether stiffness	628×10^3	kN
Piston Length	10.0	m

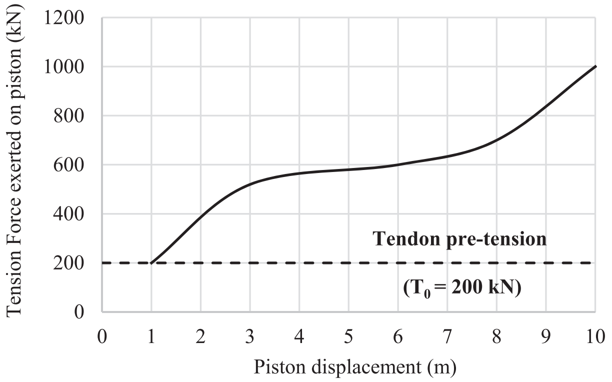

Fig. 4. Non-linear stiffness profile used for piston section of point absorber mooring, considered to limit the range of piston displacement.

generation modelling of such structures. Li et al. [12] suggested that including a nonlinear characteristic of the pumping and mooring system may result in prediction of higher power outputs. This stiffness profile is presented in Fig. 4.

Three sites in the south of Tasmania are considered for output power estimations of the point absorber. Research has shown that the world's biggest waves occur most frequently in the Southern Ocean including the region south of Australia from the southwest of Western Australia to the southern coastline of Victoria and Tasmania. Fig. 5 illustrates the location of studied sites along the southern coast of Tasmania. According to Gadonneix et al. [23] and Harries et al. [3]; Tasmanian waters have one of the greatest wave energy potentials in the world. Actual sea state data from Ref. [24] incorporating a joint distribution of significant wave height H_S and zero-crossing wave period T_Z for each location is adopted. The occurrence probability of the sea states are established from the data. Fig. 6 presents a comparison of sea state probability

Fig. 5. Three site locations in south coast of Tasmania considered in the case study.

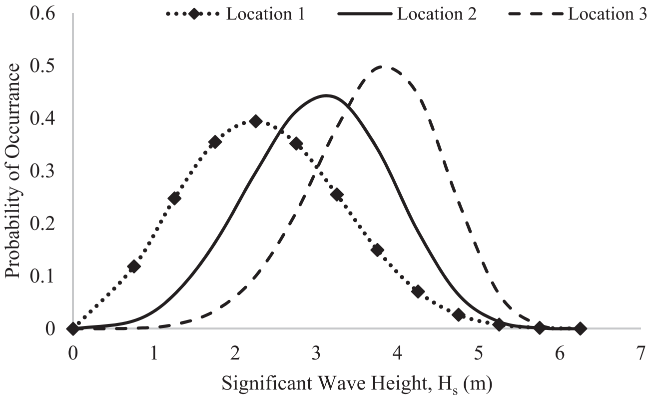

Fig. 6. Comparison of sea state probability distributions for three WEC site locations in the south of Tasmania.

distributions amongst the studied locations. It can be seen that in location 3, waves with significant wave heights of approximately 4 m occur with highest probabilities, $p(H_s = 4) = 0.5$. However the most probable wave heights occurring at location 1 and 2 will be around 2 and 3 m. The hydrodynamic analyses are carried out for 12 sea states ensuring that the operational conditions in these locations were comprehensively simulated. That is, numerical simulations were conducted for the range of sea states, while the probability of occurrence of each state will be different amongst the three locations of the case study. Table 2 lists the joint sea states adopted in this study. It should be noted that the extreme sea states were not considered in the present research, since analysis of the structure's safety is out of its scope.

The response of the structure, including the power take-off force and relative velocity of the piston section, are acquired from the results of numerical simulations. This is necessary for estimating the time-series of the absorbed power for each sea state using Eq. (5). Using the state ranges in Table 3, the level of output power is divided into 12 states (see Fig. 7) enabling the calculation of total residence time in each state. Moreover, it is required that the number of time steps in which the WEC system transits from each power state to another are counted and recorded. This is essential for establishing the Markov chain model and calculation of the probabilities.

Based on the concepts presented in Section 2.2, the transition rates were computed for every site while accounting for the occurrence probability of sea states in that location, shown in Fig. 6. This results in obtaining the intensity matrix Q for each location based on the mathematical relationships explained earlier in the paper. The intensity matrix for location 1, $Q^{(1)}$, including the transition rates between any of the absorbed power states, is shown in Eq. (17). It should be noted that each array of $Q^{(1)}$ has the unit of $\frac{1}{T}$. For instance, the array$\lambda_{12} = 0.0557$ has the physical interpretation that the system will move to power state 2 at this rate, when leaving state 1. Thus, an array with a larger value indicates that once the process leaves one state, it is more likely to enter this state compared to one with a lower value.

$$Q^{(1)} = [\bar{\lambda}_{ij}] = \begin{bmatrix} -0.0557 & 0.0557 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0492 & -0.0723 & 0.0231 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0464 & 0.0221 & -0.0821 & 0.0136 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0482 & 0.0232 & 0.0119 & -0.1082 & 0.0250 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0465 & 0.0248 & 0.0109 & 0.0079 & -0.0965 & 0.0064 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0414 & 0.0318 & 0.0124 & 0.0078 & 0.0051 & -0.1035 & 0.0049 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0366 & 0.0328 & 0.0192 & 0.0078 & 0.0053 & 0.0040 & -0.1096 & 0.0039 & 0.0000 & 0.0000 & 0.0000 \\ 0.0336 & 0.0298 & 0.0232 & 0.0104 & 0.0049 & 0.0037 & 0.0034 & -0.1122 & 0.0033 & 0.0000 & 0.0000 \\ 0.0341 & 0.0384 & 0.0252 & 0.0122 & 0.0050 & 0.0025 & 0.0020 & 0.0019 & -0.1251 & 0.0019 & 0.0019 \\ 0.0374 & 0.0318 & 0.0240 & 0.0128 & 0.0048 & 0.0023 & 0.0021 & 0.0021 & 0.0020 & -0.1214 & 0.0020 \\ 0.0334 & 0.0325 & 0.0235 & 0.0141 & 0.0080 & 0.0026 & 0.0021 & 0.0020 & 0.0019 & 0.0019 & -0.1219 \end{bmatrix} \tag{17}$$

The negative elements in the main diagonal of this matrix highlight that the rates within all the state of the process are conserved i.e. in a Markov model the process should enter other states once it leaves one state. This is shown by the sum of arrays in each row of the intensity matrix equalling zero. These elements of

Table 2
Sea state parameters used in the hydrodynamic analysis of point absorber WEC.

Sea state Number	1	2	3	4	5	6	7	8	9	10	11	12
Significant Wave Height, H_s (m)	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	5.25	5.75	6.25
Zero Crossing Wave Period, T_z (s)	4.0	5.0	6.0	7.0	7.0	8.0	9.0	9.0	9.0	10.0	11.0	12.0

Table 3
Lower bounds of absorbed power states considered for Markov Chain model.

State Number	1	2	3	4	5	6	7	8	9	10	11	12
Absorbed power (MW)	0	0.125	0.25	0.375	0.5	0.625	0.75	0.875	1	1.125	1.25	1.375

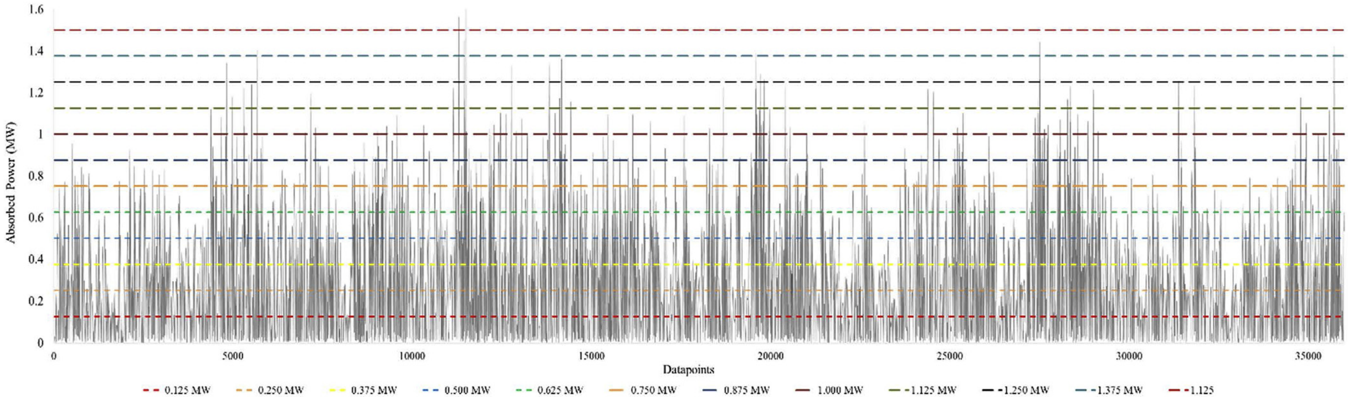

Fig. 7. Estimated absorbed power by point absorber in sea state 12 and location 2, dashed lines illustrate the range of each power state in MC model.

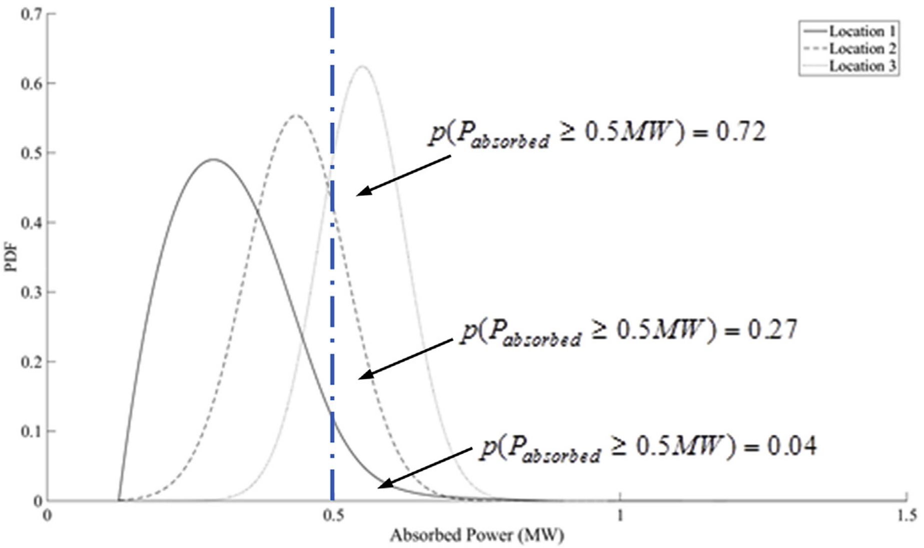

Fig. 8. Comparison of predicted absorbed power from waves in three locations south of Tasmania, the probability of obtaining at least $p(p_{absorbed} \geq 0.5\text{ MW})$ is also determined for each location.

the main diagonal can also be used to determine the mean time that the process was in each state before leaving it.

Upon constructing the one-step transition matrix, the probabilistic analysis yielded a stationary distribution for absorbed power from three locations. This is interpreted as the long-term power generation indicating the probability of extracting different levels of energy (i.e. divided into discrete numbers of states) from a specific location. That is, a probability value will be obtained for each state of power which shows the likelihood of generating the amount in the long run.

In order to show the advantages of the proposed method, a comparison of predicted output power is conducted between the three locations. For this purpose, probability density functions (PDFs) of produced power are developed using the stationary matrices, as illustrated in Fig. 8. It can be seen in that figure that location 3 has a generated power mean value of approximately 0.54 MW, while this value for locations 1 and 2 is around 0.33 MW and 0.43 MW, respectively. Moreover, the resulting PDFs suggest that in location 3 the mean output power is expected to be produced with probability 0.63. These probabilities are 0.55 and 0.46 for location 1 and location 2, respectively. This model can also be used for determining the level of certainty in extracting a desired amount of energy from a given environment. Assuming that the production goal in industry is 0.50 MW, it is predicted that location 3 has the potential to satisfy this requirement with 0.72 probability, however, this value is significantly lower for other locations (0.04 for location 1 and 0.27 for location 2). The presented results highlight that the proposed model can efficiently predict the long-term performance of WEC devices considering the uncertainty associated with waves in the marine environment. This model can be used by the stakeholders of the industry should there be a need for evaluating the potential of a specific site location or comparing or performing an optimization of the operation. The method can be readily used by the designers to optimize the performance of the systems by improving the design or selecting more suitable site locations.

4. Conclusion

The present paper proposes a methodology for predicting the long-term performance of WECs in power generation. The developed method integrates hydrodynamic analysis of marine floating structures with probability models to estimate the power absorbed by a WEC in the long run considering the uncertainty associated with the sea states in an environment. For this purpose, a point absorber WEC is numerically analyzed where the resultant responses of the simulations are adopted to develop a continuous-time Markov chain model with 12 states. The model is adopted to estimate the stationary probability distribution of output power for all the power states. As a case study, the structure's performance is assessed in three locations in the south of Tasmania considering their actual long-term sea state data. It is observed that location 3 provides the highest potential for energy extraction with a mean value for absorbed power of approximately 0.54 MW 0.54 MW while this value for locations 1 and 2 is around 0.33 MW and 0.43 MW, respectively. The results also suggest that in location 3 the mean output power may be produced with probability 0.63. The importance of this method is that it can be used to determine the level of certainty in producing a desired amount of power in a given WEC site location. The model estimated that location 3 has the capacity to satisfy the industry requirement with probability 0.72, assuming that the production goal is 0.5 MW. It is seen that the proposed methodology can efficiently predict the long-term performance of WEC devices and be readily used by the operators and designers to optimize WEC performance by improving the design or in selecting more suitable site locations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2019.08.099.

References

[1] O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, IPCC special report on renewable energy sources and climate change mitigation, in: Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 2011.

[2] G. Mork, S. Barstow, A. Kabuth, M.T. Pontes, Assessing the global wave energy potential, in: Paper Presented at the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering, 2010.

[3] D. Harries, M. McHenry, P. Jennings, C. Thomas, Hydro, tidal and wave energy in Australia, Int. J. Environ. Stud. 63 (6) (2006) 803–814.

[4] F. Antonio, Wave energy utilization: a review of the technologies, Renew. Sustain. Energy Rev. 14 (3) (2010) 899–918.

[5] Z. Cheng, J. Yang, Z. Hu, L. Xiao, Frequency/time domain modeling of a direct drive point absorber wave energy converter, Sci. China Phys. Mech. Astron. 57 (2) (2014) 311–320.

[6] A. De Andrés, R. Guanche, J. Weber, R. Costello, Finding gaps on power production assessment on WECs: wave definition analysis, Renew. Energy 83 (2015) 171–187.

[7] V. Franzitta, P. Catrini, D. Curto, Wave energy assessment along Sicilian coastline, based on DEIM point absorber, Energies 10 (3) (2017) 376.

[8] R.J. McCarthy, E. Arzaghi, M.M. Abaei, R. Abbassi, V. Garaniya, I. Penesis, A risk-based approach to layout implementation of WEC array by addressing accidental constraints, Ocean Eng. Mar. Energy 5 (1) (2019) 73–84.

[9] S. Bozzi, R. Archetti, G. Passoni, Wave electricity production in Italian offshore: a preliminary investigation, Renew. Energy 62 (2014) 407–416.

[10] N. Jadidoleslam, M. Özger, N. Ağıralioğlu, Wave power potential assessment of Aegean Sea with an integrated 15-year data, Renew. Energy 86 (2016) 1045–1059.

[11] F. Kara, Time domain prediction of power absorption from ocean waves with wave energy converter arrays, Renew. Energy 92 (2016) 30–46.

[12] W. Li, J. Isberg, J. Engström, R. Waters, M. Leijon, Parametric study of the power absorption for a linear generator wave energy converter, J. Ocean Wind Energy 2 (2015) 248–252.

[13] S.H. Ahn, Y. Xiao, Z. Wang, X. Zhou, Y. Luo, Performance prediction of a prototype tidal power turbine by using a suitable numerical model, Renew. Energy 113 (2017) 293–302.

[14] M.A. Bhinder, A. Babarit, L. Gentaz, P. Ferrant, Potential time domain model with viscous correction and CFD analysis of a generic surging floating wave energy converter, Int. J. Mar. Energy 10 (2015) 70–96.

[15] M.M. Abaei, E. Arzaghi, R. Abbassi, V. Garaniya, I. Penesis, Developing a novel risk-based methodology for multi-criteria decision making in marine renewable energy applications, Renew. Energy 102 (2017) 341–348.

[16] S.M. Ross, A First Course in Probability, Pearson Prentice Hall, 2010.

[17] C.I. Ossai, B. Boswell, I.J. Davies, A Markovian approach for modelling the effects of maintenance on downtime and failure risk of wind turbine components, Renew. Energy 96 (2016b) 775–783.

[18] C.I. Ossai, B. Boswell, I.J. Davies, Application of Markov modelling and Monte Carlo simulation technique in failure probability estimation—a consideration of corrosion defects of internally corroded pipelines, Eng. Fail. Anal. 68 (2016a) 159–171.

[19] J.-j. Jiang, L. Zhang, Y.-q. Wang, Y.-y. Peng, K. Zhang, W. He, Markov reliability model research of monitoring process in digital main control room of nuclear power plant, Saf. Sci. 49 (6) (2011) 843–851.

[20] R. So, A. Simmons, T. Brekken, K. Ruehl, C. Michelen, Development of pto-sim: a power performance module for the open-source wave energy converter code wec-sim, in: Proceedings of OMAE 2015, 2015.

[21] Manual, O. (2006). Orcina Ltd. Daltongate, UK.

[22] A. Lisnianski, D. Elmakias, D. Laredo, H.B. Haim, A multi-state Markov model for a short-term reliability analysis of a power generating unit, Reliab. Eng. Syst. Saf. 98 (1) (2012) 1–6.

[23] P. Gadonneix, F.B. de Castro, N.F. de Medeiros, R. Drouin, C. Jain, Y.D. Kim, J. Ferioli, M.-J. Nadeau, A. Sambo, J. Teyssen, Survey of Energy Resources: Focus on Shale Gas, World Energy Council, 2010.

[24] A.R.E.A. CSIRO, Australian wave energy atlas, Retrieved from, http://nationalmap.gov.au/renewables/, 2017.