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Biofouling on mooring lines and power cables used in wave energy converter systems—analysis of fatigue life and energy performance

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Abstract

This study presents an analysis of a wave energy converter (WEC) system consisting of a buoy, a mooring system, and a power cable connected to a hub. The investigated WEC system is currently under full-scale testing near Runde in Norway. The purpose of the study was to investigate the characteristics of the entire system, primarily with regard to energy performance and the fatigue life of the mooring lines and power cable, considering the effects of marine biofouling and its growth on the system's components. By means of parametric study, the energy performance and fatigue life of the mooring lines and power cable were investigated considering two mooring configurations, three biofouling conditions, four sea states in a scatter diagram, and three wave and current directions. Hydrodynamic and structural response simulations were conducted in a coupled response analysis using the DNV-GL software SESAM. Energy performance analyses and stress-based rainflow counting fatigue calculations were performed separately using an in-house code. The results show that, for a WEC system which has been deployed for 25 years, biofouling can reduce the total power absorption by up to 10% and decrease the fatigue life of the mooring lines by approximately 20%.

Keywords: biofouling, catenary mooring chain, fatigue, power absorption, power cable, wave energy converter

1 Introduction

Among renewable energy sources, ocean energy has received considerable attention in recent years. A commercial breakthrough in wave energy converters (WECs), however, still requires an increase in the service life of the entire WEC system. In particular, the mooring lines and power cables used in the WEC system (hereafter referred to simply as moorings and cables) must be improved to match the service life of the other components of the WEC system. It has been found that fatigue is an important mechanism in determining service life [1-4]. However, because of biological activity in the water, marine biofouling will also influence the service life of these components.

Marine biofouling (a.k.a. marine growth) is a collective term for the settlement and growth of sedentary and semi-sedentary organisms on artificial structures situated in marine and estuarine environments [5]. The process begins as soon as the structure comes into contact with the seawater. Tiron et al. [6] discussed the environmental challenges faced by a WEC system after its deployment, with a particular focus on two types of environmental challenges: static marine biofouling and other marine bio-inhabitants. Given its expected years of service, a WEC system will inevitably act as an artificial reef, and the resulting

population of bio-inhabitants could impede its power production or cause an unexpected decrease in durability. Biofouling could affect the energy harvesting performance or even the normal functioning of the device by imposing an additional weight, limiting the movements of the WEC system parts.

Langhamer et al. [7] investigated the fouling assemblages on WEC buoys in the field. After field measurements, the WEC dynamics was analysed with the measured marine growth included. The study concluded that marine growth is negligible with regard to the dynamic behaviour of WEC buoys. Carswell [8] investigated the effect of marine growth on monopile-supported offshore wind turbines. In that study, the effect of marine growth was assessed by increasing the mass, surface roughness and effective diameter of the substructure of the wind turbine. Numerical calculations indicated that the changes in natural frequency and hydrodynamic loading induced by biofouling are negligible. This led to the conclusion that it is probably unnecessary to remove biofouling for reasons related to wind turbine functionality.

However, opposite conclusions have been drawn by other researchers. Tiron et al. [9] quantified marine growth on WECs using numerical population-dynamic models. Given that the predicted biofouling accounted for approximately 10% of the total mass of the WEC, they concluded that biofouling could have an important effect on its energy-absorption capabilities. Furthermore, Tiron et al. [10] also experimentally investigated the effects of algal growth on a scale model of the Oyster 800 WEC. Their results indicated a considerable drop in optimal power, by approximately 15%, in all four tested sea states.

Studies have also shown that marine biofouling has a negative impact on the structural integrity of submerged ocean structures. Heaf [11] conducted extensive parametric studies and demonstrated an increased load and a reduction in the fatigue life of a fixed offshore platform with increasing marine growth thickness. Edyvean [12] reviewed several ways in which marine fouling may affect offshore structures: by obscuring the substratum, leading to increased costs for inspection; by enhancing corrosion and corrosion fatigue; and by increasing the hydrodynamic loading due to the additional layers of fouling and its higher roughness compared with the original surface. Titah-Benbouzid and Benbouzid [13] surveyed both coated and uncoated coupons made of five different materials in a field test. Metallic materials (aluminium, stainless, and carbon steel) were found to suffer more extensively from biofouling than non-metallic materials, such as fibre composites and bearing materials. Their results also show that the level of effectiveness of an anti-fouling coating differs from one material to another. Among all tested materials, the carbon steel benefitted the most from the applied anti-fouling coating.

With regard to the financial risk involved in a marine energy project (including wave and tidal), Gueguen [14] pointed out biofouling as one cause of mooring rupture, leading to the loss of marine energy systems. Johanning et al. [15] developed a test facility for the reliability assessment of the cables and moorings used for marine energy devices. According to their studies, both biofouling and fatigue were identified as critical failure modes. However, few studies have addressed the potential implication of biofouling on the fatigue life of moorings and cables, especially when they are used in WEC systems. Thus, the objective of the current study is to numerically investigate the potential impact of biofouling on WEC systems with respect to energy absorption by the WEC, and fatigue lives of the cables and moorings. The hydrodynamic and structural simulation procedures used to perform the numerical experiment, including coupled response analysis, fatigue damage analysis, and energy response analysis, are presented. The results are presented in the form of a simulation matrix, in which the influences of the mooring configuration, biofouling conditions, and ocean environment (current and sea state conditions) are considered. The primary contribution

of this study is the presentation of a numerical assessment of both the energy performance of the system and the fatigue life of the moorings and cable under the influence of biofouling.

2 Models and methodology

This section presents the simulation models and methodology used in this study. The models used for the WEC system, the biofouling process, and the ocean environment are described in Section 2.1. The methodologies used to analyse the energy performance of the WEC and the fatigue damage of its components are presented in Section 2.2. Finally, Section 2.3 introduces the simulation matrix adopted in our study for the presentation of the results in Section 3.

2.1 Models

2.1.1 WEC system models

A WEC system is defined as the basic unit of a WEC array farm. The WEC system modelled in the current study consists of a buoy (*i.e.*, the WEC device), a mooring system, and a free-hanging cable that is connected to a stationary hub; see Fig. 1. A Cartesian coordinate system is used, with the origin located in the plane of the water surface at the geometric centre of the WEC buoy under still-water conditions. The WEC system model has been presented in greater detail by Yang et al. [4,16].

Fig. 1. Illustrations of the investigated WEC systems, with (a) the three-mooring configuration and (b) the four-mooring configuration.

The WEC buoy is a point absorber developed by the company Waves4Power [17], and it generates power from the movement of water inside its central tube. In this study, it is simplified as a closed buoy with the properties reported in Table 1. The WEC device is assumed to have a linear power take-off (PTO) system for power production. This is modelled as a constant damping in the heave degree of freedom (DOF) [18].

Table 1. Properties of the WEC buoy.

Draft, D_w [m]	27.8
Centre of buoyancy (COB) (x, y, z) [m]	(0, 0, -10.9)
Mass, M_w [metric tonnes]	353.8
Centre of gravity (COG) (x, y, z) [m]	(0, 0, -11.8)
PTO damping in heave DOF, B_{33}^{PTO} [kNs/m]	197.1

Two catenary mooring chain systems are investigated in this study, one with a three-mooring configuration and the other with a four-mooring configuration (hereafter referred to as mooring configurations M1 and M2, as shown in Fig. 1(a) and 1(b), respectively). Identical moorings are used in both configurations. The only difference is the number of moorings. The mooring chains (moorings) are symmetrically attached around the outer rim of the WEC buoy (to fairleads on the buoy) at a depth of 5 metres below the surface of the water. The moorings are anchored to the seabed at a horizontal distance of 181.83 metres from the fairleads on the buoy and at a depth of 50 metres under water. The main properties of the moorings are presented in Table 2.

Table 2. Properties of the moorings.

Length, L_M [m]	200.0
Nominal diameter, d_M [m]	0.048
Axial stiffness, EA_M [MN]	193
Mass, M_M [kg/m]	45.0
Submerged weight, W_M [N/m]	423.3
Normal flow added mass coefficient, C_{MnM} [-]	3.8
Normal flow drag coefficient, C_{DnM} [-]	2.5
Tangential flow drag coefficient, C_{DtM} [-]	0.5
Structural damping coefficient, β_M [-]	0.025
Pretension force in M1 configuration, PF_{M1} [kN]	101.0
Pretension force in M2 configuration, PF_{M2} [kN]	135.0

The power cable is modelled as a circular tube. Table 3 presents the properties of the cable. The properties were selected based on the recommendations in [4] to increase the fatigue life and reduce the risk of contact between the cable and the WEC buoy.

Table 3. Properties of the power cable.

Length, L_C [m]	70.0
Outer diameter, d_{out} [m]	0.040
Inner diameter, d_{in} [m]	0.020
Axial stiffness, EA_C [kN]	94.3
Bending stiffness, EI_C [Nm ²]	50.0
Torsional stiffness, GK_C [Nm ² /rad]	7.85
Mass, M_C [kg/m]	2.0
Submerged weight, W_C [N/m]	7.0
Normal flow added mass coefficient, C_{MnC} [-]	1.0
Normal flow drag coefficient, C_{DnC} [-]	1.2
Tangential flow drag coefficient, C_{DtC} [-]	0.0
Structural damping coefficient, β_C [-]	0.025

2.1.2 Biofouling models

A precise quantitative estimate of the marine biofouling on a WEC requires detailed *in situ* measurements of the flow properties and biological activity. However, such information is typically lacking during the initial design phase and will only become available once the device has actually been deployed for a certain period of time. Similar challenges also arise in the development of offshore wind energy systems; see [8,19,20].

An anti-fouling coating is applied to the WEC buoy itself. Therefore, only the biofouling effects on the moorings and cable are considered in this study. Two fouling conditions are investigated, as defined by Tiron et al. [9] and NORSOK [21], which are hereafter referred to as fouling conditions F2 and F3, respectively. A reference case without biofouling is referred to as F1. The biofouling is modelled as an increase in the submerged weight and drag coefficients of the moorings and cable, following the recommended procedure defined in the Position Mooring standard [22]; see Appendix A for details. The largest marine growth values, representing the final stable state of fouling, from the two cited studies are used for the comparison.

Although the standard cited above is intended for mooring systems, we adopt the same principles for the cable because of its similar slender geometric characteristics in relation to the floating WEC device.

The three considered fouling cases are described as follows, and their properties are presented in Table 4:

1. F1: This is a reference case in which the WEC system is situated in a non-fouling environment.
2. F2: A fouling layer with a uniform bio-density is applied to cover the entire mooring system, with a mass density of 1325 kg/m^3 [9,22]. As determined from the total biofouling mass value reported by Tiron et al. [9] and the assumed bio-density, the fouling thickness is 25.3 mm.
3. F3: The uniform bio-density of the fouling layer covering the entire mooring system is set to 1300 kg/m^3 . In accordance with NORSOK [21], the fouling model consists of two distinct zones: From the water surface to a depth of 40 metres (first zone), a 60 mm fouling thickness is adopted. For water depths below 40 metres (second zone), a fouling thickness of 30 mm is used.

Table 4. Summary of the three fouling cases and their properties in the numerical model; see Appendix A for a definition of each property.

	F1	F2	F3
Definition of fouling condition			(first/second zone)
Mass density of fouling, ρ_{growth} [kg/m^3]	-	1325	1300/1300
Thickness of fouling, ΔT_{growth} [mm]	-	25.3	60/30
Change of model parameters due to the different fouling conditions*			
W_M [N/m]	423.3	457.6	533.1/463.0
C_{DnM} [-]	2.5	5.1	8.8/5.6
C_{DtM} [-]	0.5	1.0	1.8/1.1
W_C [N/m]	7.0	22.3	24.8/-**
C_{DnC} [-]	1.2	2.7	4.8/-**
C_{DtC} [-]	0.0	0.0	0.0/-**

* See Tables 2 and 3 for the definition of each parameter.

** The cable is located in the first zone, therefore, no value is assigned in the second zone.

The development and distribution of biofouling in different marine environments have been extensively investigated with respect to, for example, recruitment and succession of fouling organisms [23,24], composition of biofouling community [25-27], fouling assemblages on ocean energy devices [7,20], and numerical modelling of biofouling on WECs [9,21,28].

Tiron et al. [9] estimated ten years of biofouling accumulation using numerical population-dynamic models. In their predictions, the marine growth was considered to consist of a biofilm, a colony of *L. digitata*, and a colony of *M. edulis*. These predictions are considered to be relevant for the test site (Runde, Norway) because the target marine environment considered by [9] was similar to the Runde test site in terms of water temperature and water depth. However, because the cited study described the fouling development in terms of the areal bio-density (kg/m^2), whereas the Position Mooring standard [22] requires both the thickness (mm) and bio-density (kg/m^3) as calculation inputs, an assumption of a bio-density of 1325 kg/m^3 is adopted [22]. With this assumption, the thickness of the biofouling layer can be calculated; see the description of fouling condition F2 above. The sensitivity of the results to this density assumption is further discussed in Section 4.1.

The NORSOK standard [21] serves as the second core reference, used to formulate the description of fouling condition F3. This standard provides an estimation of the fouling between latitudes of 59° and 72° N, which includes the location of the test site at Runde, Norway. The NORSOK guideline was also chosen because it provides a reasonably conservative fouling prediction and therefore is commonly used in engineering design practice in the oil and gas industry [29].

2.1.3 Descriptions of wave loads and ocean currents

The ocean environment is subject to continuously changing sea states. Four sea states (S1-S4, see below) are compared, each of them characterized in terms of its significant wave height (H_s) and peak wave period (T_p). The JONSWAP spectrum is used, with a peak shape parameter estimated in accordance with [30].

1. S1: $H_s = 1.5 \text{ m}$, $T_p = 13.5 \text{ s}$. These conditions represent a sea state with a relatively long wave period.
2. S2: $H_s = 2.0 \text{ m}$, $T_p = 5.0 \text{ s}$. These are considered to be the optimal operating conditions for our WEC system because the T_p of the sea state is close to the resonant period of the WEC device. In addition, S2 is also representative of the most frequently observed sea states at the test site at Runde.
3. S3: $H_s = 3.5 \text{ m}$, $T_p = 7.5 \text{ s}$. These conditions represent a sea state with a high wave height.
4. S4: $H_s = 7.5 \text{ m}$, $T_p = 8.5 \text{ s}$. This is considered to be a critical sea state for operation.

Among different sources of ocean current [30], the wind-generated current is the dominating one at the Runde test site. Hence, this type of current is chosen for study. The speed of the current is set to 0.5 m/s at the surface of the water (based on data measured at Runde and provided by Waves4Power [17]), whereas its slab vertical profile is estimated following [30].

It has been shown in [4] that different wave and current directions can exert a significant influence on the response of the considered WEC system. Moreover, even for a given direction of the incoming waves and current, the WEC systems in a WEC array farm will be subjected to different loads depending on their relative orientations in the array. Therefore, three incoming directions of 0 , 135 , and 180 degrees (referred to as load directions D1, D2, and D3, respectively) are compared in our parametric study. Illustrations of these directions in relation to the WEC system are presented in Fig. 2.

Fig. 2. Illustrations of the (a) three-mooring and (b) four-mooring WEC systems in relation to the incoming wave and current directions.

2.2 Methodologies

This study consists of three major analyses. In the following sections, the basic information of each analysis will be elaborated; see Appendix B for a schematic flowchart.

2.2.1 Coupled response analysis

Two major approaches exist for performing numerical simulations of the dynamic behaviour of WEC systems: coupled and de-coupled analyses. It was concluded in [16] that a coupled analysis yields more reasonable results for the motion response of the WEC buoy and the structural responses of the cable and moorings, and therefore, this type of analysis was chosen for this study. The simulations were performed using the DNV-GL SESAM commercial software package. In particular, SIMO [31] was used to simulate the motion of the WEC buoy, and RIFLEX [32] was used to perform the hydrodynamic and structural analyses of the cable and moorings.

2.2.2 Fatigue damage analysis

The stress levels in the cable and moorings are typically lower than their design yield stresses. Hence, a stress-based approach to the fatigue analysis is adopted. For the fatigue analysis, the stress history of the cable and moorings was first obtained from time-domain simulations (see Section 2.2.1). Next, the rainflow counting method (RFC) was used to extract the stress cycles and the corresponding stress ranges from the stress history [33,34]. Finally, the fatigue damage was calculated based on the Palmgren-Miner cumulative rule using the S-N curve for the material under consideration. For further details of the fatigue damage analysis, see [4,16].

The fatigue properties of the moorings have been specified according to the suggested design values in the Position Mooring standard [22]. For the power cable, the experimental data from Nasution et al. [35] are adopted. These data are based on the assumption that the copper wires in a power cable carry the load of the entire cable structure. Consequently, the material parameters α and m in the S-N curve are assigned values of 6.0×10^{10} and 3, respectively, for the moorings [22] and 6.098×10^{19} and 6.238, respectively, for the cable [35].

2.2.3 Energy performance analysis

The energy performance is evaluated in terms of the time-averaged absorbed power. At every time instant t , the instantaneously absorbed wave power $P(t)$ and time-averaged absorbed power $\bar{P}(t)$ were calculated as follows [18]:

$$P(t) = B_{33}^{PTO} [\dot{\xi}(t)]^2 \quad (1)$$

$$\bar{P}(t) = \frac{1}{T} \int_0^T B_{33}^{PTO} [\dot{\xi}(t)]^2 dt \quad (2)$$

where ξ is the heave motion of the WEC buoy, as extracted from the coupled response analysis (Section 2.2.1); the dot notation represents the derivative with respect to time; and B_{33}^{PTO} is the PTO linear damping coefficient in the heave direction (see Table 1).

2.3 Simulation matrix

Because of the variety of different scenarios and configurations investigated, as introduced above, a simulation matrix is adopted for clarity in the presentation of the results. All of the different controlling factors considered are independent of each other. From the simulation matrix representation, one can identify the critical values of these factors while observing the overall trends of their impact on the WEC system.

In summary, the following controlling factors are investigated:

1. Mooring configuration: the three-mooring configuration and the four-mooring configuration, denoted by M1 and M2, respectively.
2. Biofouling conditions: three fouling conditions F1, F2, and F3, where F1 is the biofouling-free case.
3. Sea states (*i.e.*, wave properties): four sea states S1, S2, S3, and S4, where S2 is considered to represent the design operating conditions for our WEC system.
4. Wave and current direction (*i.e.*, incoming direction of waves and current): three directions D1, D2, and D3.

Figure 3 shows a schematic view of the simulation matrix that is used to present the results in Section 3. The mooring configurations (M1 and M2) and fouling conditions (F1, F2, and F3) are presented together on the horizontal axis. These two factors are compared together because they are considered to be representative of the long-term set-up and inherent characteristics of the WEC system. By contrast, the sea states (S1, S2, S3, and S4) and load directions (D1, D2, and D3) are related to the ocean environment in which the WEC system is located and are presented on the vertical axis of the matrix.

Fig. 3. Schematic view of the simulation matrix.

3 Results

The duration of a given sea state is taken to be three hours [30]. For comparison, all values are normalized with respect to the reference case, which is defined as M1-F1-S2-D3 and is indicated by the cells with grey background in Tables 5-7. The reference case is the case with the most similar settings to the operating conditions at the Runde test site.

3.1 Energy performance of the WEC system

The procedure of energy performance analysis is illustrated in Fig. 4. Figure 4(a) shows that the heave motion (ξ) and velocity ($\dot{\xi}$) of the WEC buoy are generally elevated by the waves, where the observed trend of the smaller amplitudes and phase shifts are attributed to the damping effect from the PTO system. The corresponding instantaneous and time-averaged absorbed power of the WEC buoy are presented in Fig. 4(b), which are calculated according to Eq. (1) and (2), respectively. In this study, the last value of the time-averaged absorbed power after three-hour simulation was used to compare the energy performance between various scenarios.

Fig. 4. Illustration of the energy performance analysis for the first 300 seconds of the M1-F1-S2-D3 case.

Table 5 shows the results of the energy performance analyses for the WEC device. The average absorbed power in the reference case is 18.44 kW. The mean power absorption is primarily governed by the wave height. This study does not presume an arbitrary upper bound corresponding to an extreme sea state. However, for reasons of operational safety, the WEC system will not be fully operational in such a sea state. Therefore, the real absorbed powers in sea state S4 are expected to be less than the values shown in Table 5. Changes in the load direction (D1, D2, and D3) have only a minor influence on the power performance. Based on this observation, one can exclude the orientation of the WEC system as one of the major factors influencing the absorbed power.

Table 5. Normalized average absorbed power results for the WEC, where the reference case corresponds to 18.44 kW.

Mooring configuration				Three moorings (M1)			Four moorings (M2)		
Fouling condition				F1	F2	F3	F1	F2	F3
Sea state	S1	Wave and current direction	D1	0.56	0.54	0.54	0.56	0.53	0.53
			D2	0.56	0.54	0.54	0.56	0.53	0.53
			D3	0.56	0.54	0.53	0.56	0.53	0.53
	S2		D1	1.00	0.91	0.86	0.97	0.87	0.81
			D2	1.00	0.91	0.87	0.97	0.87	0.82
			D3	1.00	0.91	0.87	0.97	0.87	0.82
	S3		D1	4.62	4.19	4.02	4.46	3.94	3.76
			D2	4.60	4.16	4.00	4.51	4.01	3.82
			D3	4.53	4.05	3.92	4.46	3.93	3.76
	S4		D1	18.34	16.80	15.90	16.84	14.89	13.96
			D2	18.07	16.40	15.48	17.58	15.62	14.60
			D3	17.08	15.29	14.54	16.81	14.85	13.92

The M1 configuration (three moorings) exhibits better power performance than does the M2 configuration (four moorings) in all simulated cases. The WEC buoy absorbs energy through the activation of linear PTO damping. The mooring system, however, also contributes with a damping effect to the WEC system as a whole, which can lead to energy dispersion and hence a reduction in power absorption [36]. Because the M2 configuration introduces higher total damping due to the presence of an additional mooring, the decrease in the absorbed power in the M2 case is expected. However, the use of more mooring chains will according to [37] be used together with smaller mooring line diameters for the particular mooring condition—which, in the current context, is defined by the WEC and the environmental loads—to achieve comparable reaction curves among different mooring configurations. Since the current investigation adopted identical mooring lines for the two configurations M1 and M2, the observed result is only useful as a demonstration of the explanation in [36]. It should therefore not be used to judge the intrinsic superiority of either of the two mooring configurations (see further discussions in Section 4.4).

The presence of biofouling (fouling conditions F2 and F3) also reduces the power absorption of the WEC, by up to 17% among the simulated cases. This decrease is more severe under F3 fouling than under F2 fouling. The average decreases in absorbed power caused by F2 and F3 fouling are 9% and 12%, respectively. In a comparison of the two mooring configurations, the M2 configuration suffers a greater reduction in absorbed power due to fouling.

With other factors set as M2-D2-S2, Fig. 5 shows the example results of motion response of the WEC buoy in three translational DOFs under various fouling conditions. In the horizontal plane (x - y plane, Fig. 5(a)), smaller motional span of the buoy is observed under the presence of the biofouling. A similar observation is made in the heave motion of the buoy (Fig. 5(b)), resulting in the lower power absorption. In the M2 configuration, the average decreases in power absorption of the WEC caused by F2 and F3 fouling are 10% and 14%, respectively. The overall results suggest that the presence of biofouling is a critical factor affecting the power absorption of a WEC.

Fig. 5. (a) Horizontal motion response, and (b) vertical motion responses with respect to time of the WEC buoy for the M2 configuration under various fouling conditions, all other factors are defined as in the S2-D2 case.

3.2 Fatigue life performance of the moorings and cable

The calculated fatigue lives of the moorings are presented in Table 6. The shortest fatigue life among all moorings is shown in each case. The predicted fatigue life in the reference case is 8 years. Similarly, Table 7 presents the fatigue life results for the cable, and the fatigue life in the reference case is predicted to be 2.0×10^{10} years. The presented fatigue lives should be interpreted as upper bounds because intrinsic failure mechanisms, such as wear and bio-corrosion, are not considered in the current study.

Table 6. Normalized results for the shortest fatigue life among all moorings, where the reference case corresponds to 8 years.

Mooring configuration				Three moorings (M1)			Four moorings (M2)		
Fouling condition				F1	F2	F3	F1	F2	F3
Sea state	S1	Wave and current direction	D1	1.26E+1	4.52E+0	3.80E+0	9.22E+1	2.80E+1	2.19E+1
			D2	1.95E+1	7.38E+0	6.93E+0	2.30E+1	8.57E+0	7.98E+0
			D3	1.18E+2	3.99E+1	3.53E+1	9.35E+1	3.02E+1	2.59E+1
	S2		D1	7.88E-2	4.63E-2	4.78E-2	8.51E-1	4.33E-1	4.21E-1
			D2	1.08E-1	6.75E-2	7.79E-2	1.28E-1	8.10E-2	9.55E-2
			D3	1.00E+0	5.64E-1	6.24E-1	8.62E-1	4.64E-1	4.96E-1
	S3		D1	6.55E-3	4.22E-3	3.96E-3	4.47E-2	2.36E-2	2.23E-2
			D2	8.06E-3	5.31E-3	5.34E-3	8.97E-3	5.95E-3	6.13E-3
			D3	5.04E-2	2.86E-2	3.01E-2	4.52E-2	2.48E-2	2.51E-2
	S4		D1	3.22E-4	3.13E-4	3.00E-4	1.62E-3	1.38E-3	1.29E-3
			D2	3.70E-4	3.55E-4	3.52E-4	3.84E-4	3.73E-4	3.78E-4
			D3	1.76E-3	1.36E-3	1.56E-3	1.63E-3	1.42E-3	1.38E-3

Table 7. Normalized fatigue life results for the cable, where the reference case corresponds to 2.0×10^{10} years.

Mooring configuration				Three moorings (M1)			Four moorings (M2)		
Fouling condition				F1	F2	F3	F1	F2	F3
Sea state	S1	Wave and current direction	D1	4.25E+4	2.94E+6	9.65E+4	4.13E+4	2.74E+6	9.08E+4
			D2	6.34E+4	6.08E+4	3.37E+3	3.54E+4	3.52E+4	2.43E+3
			D3	4.13E+3	4.97E+3	5.26E+2	3.13E+3	3.89E+3	4.78E+2
	S2		D1	2.35E+2	1.05E+5	9.02E+2	2.22E+2	1.09E+5	8.72E+2
			D2	1.35E+2	2.48E+2	4.24E+0	9.08E+1	1.64E+2	5.37E+0
			D3	1.00E+0	1.58E+1	1.26E+0	9.43E-1	1.43E+1	1.20E+0
	S3		D1	8.31E+0	3.95E+2	6.68E+0	9.56E+0	5.44E+2	1.11E+1
			D2	1.08E-1	6.77E-1	1.36E-1	1.13E-1	4.45E-1	1.16E-1
			D3	5.28E-3	6.48E-2	2.46E-2	5.12E-3	6.36E-2	2.38E-2
	S4		D1	3.37E-4	1.98E-2	4.26E-3	3.44E-4	5.17E-2	8.43E-3
			D2	1.48E-2	1.01E-2	9.55E-4	1.63E-2	7.04E-3	1.07E-3
			D3	4.44E-4	1.92E-3	4.03E-4	4.19E-4	1.92E-3	4.14E-4

The results show a quite large variation in fatigue lives in the moorings and the cable for the different sea states. The main factor behind this is related to the higher sea states (S3 and S4) where our methodology overestimates the accumulated fatigue damage in these components due to too large motions of the WEC; see Section 3.1 for a discussion. This has a

clear effect on the upper and lower boundaries of the fatigue lives for these components as presented in Tables 6 and 7.

In the M1 configuration, the shortest fatigue life of the moorings is observed for the D1 direction. In the M2 configuration, load direction D2 always results in the shortest fatigue life of the moorings. A similar trend is also observed for the cable fatigue life, where a load in the D3 direction yields the shortest fatigue life for the cable with only one exception: for the F1-S4 case, load direction D1 yields the shortest fatigue life irrespective of the mooring configuration. These results indicate that if the load is incident with a direct heading on a mooring or cable, it will cause more significant fatigue damage, resulting in the shortest fatigue life. Therefore, from a structural safety perspective, the orientation of each WEC system should be carefully designed depending on the load direction at its site of operation.

Some differences in the fatigue life of the moorings are observed between the two mooring configurations (M1 and M2). For all three load directions (D1, D2, and D3) investigated in each sea state, the M1 configuration always yields the longest fatigue life of the moorings. However, the M2 configuration results in a longer average fatigue life when averaged over all load directions.

Figure 6 shows an example of the biofouling influence on the stress response and fatigue damage of the mooring line. With all other factors set as M1-S1-D1, the results plotted are from the most critical mooring area in terms of the fatigue damage, which is the mooring aligning with the load direction D1 and first element near WEC; see Fig 2(a). The presence of biofouling leads to an increase of the mean stress and the stress amplitude (Fig. 6(a)), resulting in larger fatigue damage and lower fatigue life of mooring line (Fig. 6(b)). The effect of biofouling is found to be more evident under moderate sea states. The average decreases in fatigue life of the moorings caused by biofouling (fouling conditions F2 and F3) are 68%, 40%, 40%, and 10% under sea states S1, S2, S3, and S4, respectively. Under the severe sea state (S4), the load from the environment dominates the results of the fatigue analysis. Under the moderate sea states (S1, S2, and S3), the additional mass and drag introduced by biofouling create additional inertial and drag forces that become the major load factors in the fatigue analysis in the absence of significant sea state loading. The maximum decrease in the fatigue life of the moorings caused by biofouling is 76%, observed in the M2-F3-S1-D1 case.

Fig. 6. Example of (a) axial stress response and (b) accumulated fatigue damage of moorings under various fouling conditions. The other control factors are defined as M1-S1-D1.

The long fatigue lives of the cable indicate a need to develop a more detailed model for stress response and fatigue analysis. This study simplified the umbilical cross section of the cable to a circular tube, a simplification that was used in a previous study and was found to be useful for the identification of the cable's fatigue-critical locations [4]. The current investigation shows that this model is not sufficient for more detailed fatigue analyses, and especially not in assessments and comparisons of different failure modes such as bird caging, wear, and fretting damage between internal cable umbilicals. Nonetheless, in comparison with a fouling-free condition (*e.g.*, F1), the results indicate that minor fouling (*e.g.*, F2) can increase the fatigue life of the power cable. However, when there is more biofouling present (*e.g.*, F3), no clear trend can be observed: in some cases the fatigue life of the cable is increased while in other cases the fatigue life is reduced. Hence, the initial conclusion is that the fatigue life of the cable is not strongly influenced by biofouling.

4 Discussion

4.1 Sensitivity study regarding the fouling bio-density

As described in Section 2.1.2, an assumption regarding the bio-density must be made for fouling condition F2. However, a range of possible bio-densities is found in the literature, from 900 to 2200 kg/m³ [8,38-41]. This range was therefore chosen as the range to be considered in a sensitivity study.

The bio-density investigation was conducted for the reference case, M1-F2-S2-D3. The average power and fatigue life results for different bio-densities are shown in Fig. 7. The fatigue life of the cable is excluded from the figure and also is not discussed in the following

sections because it was observed to be essentially insensitive to biofouling; see the discussion in Section 3.2. All values are normalized with respect to the original reference case (assuming a bio-density of 1325 kg/m^3). The average absorbed power and the fatigue life of the moorings in the reference case are predicted to be 16.76 kW and 4 years , respectively. As the bio-density increases, an increase in the absorbed power and a reduction in the fatigue damage are observed. Given the same areal bio-density (kg/m^2), a higher bio-density (kg/m^3) corresponds to a smaller biofouling thickness and hence to a smaller additional drag coefficient and less additional drag force. When performing numerical analyses, if one cannot obtain the fouling bio-density, an assumption of a lower bio-density thus yields more conservative evaluation results.

Fig. 7. Correlation diagram of the power absorbed by the WEC and the fatigue life of the moorings with respect to the bio-density. It is assumed here that the value of the bio-density always gives the same total mass of the biofouling, *i.e.*, the layer thickness of the biofouling is adjusted.

4.2 Biofouling on the WEC device

The results presented in Section 3 are based on the assumption that an anti-fouling coating has been applied to the WEC buoy and that fouling therefore occurs only on the moorings and cable. However, it has also been argued by several authors that the use of anti-fouling paints on WECs may be regarded as an impractical measure [6,13,42]. Typical anti-fouling paints must be applied yearly, and the longest lasting paint technologies offer a maximum lifespan of 3-5 years. With the average expected service life of WEC systems being 25 years, the use of anti-fouling paints is therefore impractical and also unsuitable from an economic sustainability perspective.

To consider the influence of fouling also on the buoy, additional mass was added to the buoy while retaining its geometry, following the procedure described in [7,9]. The amount of fouling was predicted based on fouling condition F3 (see Section 2.1.2), resulting in an additional fouling mass on the buoy of $28.5 \text{ metric tonnes}$. For the M1 configuration, Table 8 presents the potential impact on the WEC system when the fouling accumulated on the WEC buoy is considered. All values are normalized with respect to the reference case (indicated by the cells with grey background in Table 8), in which the average absorbed power and the fatigue life of the moorings are predicted to be 18.44 kW and 8 years , respectively. It is found that although the additional mass due to biofouling accounts for only 8% of the total mass of the WEC buoy, it may lead to additional reductions in power performance and fatigue life of 13% and 21% , respectively (between fouling conditions 2 and 3, as defined in Table 8).

Table 8. Comparison between different fouling conditions: (1) no fouling on the entire WEC system, (2) fouling accumulated only on the cable and moorings, and (3) fouling accumulated on the entire WEC system.

				Average absorbed power			Mooring fatigue life		
Fouling condition				1	2	3	1	2	3
Sea state	S1	Wave and current direction	D1	0.56	0.54	0.54	1.26E+1	3.80E+0	3.33E+0
			D2	0.56	0.54	0.54	1.95E+1	6.93E+0	6.41E+0
			D3	0.56	0.53	0.54	1.18E+2	3.53E+1	3.36E+1
	S2		D1	1.00	0.86	0.73	7.88E-2	4.78E-2	4.16E-2
			D2	1.00	0.87	0.74	1.08E-1	7.79E-2	6.88E-2
			D3	1.00	0.87	0.75	1.00E+0	6.24E-1	6.12E-1
	S3		D1	4.62	4.02	3.92	6.55E-3	3.96E-3	3.14E-3
			D2	4.60	4.00	3.88	8.06E-3	5.34E-3	4.22E-3
			D3	4.53	3.92	3.82	5.04E-2	3.01E-2	2.41E-2
	S4		D1	18.34	15.90	15.45	3.22E-4	3.00E-4	2.35E-4
			D2	18.07	15.48	14.98	3.70E-4	3.52E-4	2.74E-4
			D3	17.08	14.54	13.95	1.76E-3	1.56E-3	1.27E-3

4.3 The effects of biofouling over different time durations

According to the NORSOK standard [21], biofouling growth reaches a maximum after two years. By contrast, the biofouling predictions reported by Tiron et al. [9] are provided for ten years, as presented in Table 9. Because the two cited references disagree on the time required for the fouling to reach its final stable state, the effect of the duration of fouling development is further investigated in this section. The ten-year fouling data from Tiron et al. [9] were used for these calculations, and the bio-density was set to 1325 kg/m³ [22]. All other controlling factors were defined as in the M1-S2-D3 case. Table 10 shows the corresponding changes in the numerical model's parameters due to the biofouling, and Fig. 8 shows the effects of fouling on the WEC system after various periods of operation.

Table 9. Maximum annual biofouling growth for a biofilm, a colony of *L. digitata*, and a colony of *M. edulis* (data extracted from Figures 4(b), 8(b), and 10 in [9]).

Time	[year]	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Biofilm	[kg/m ²]	0.00	0.75	1.05	1.30	1.45	1.60	1.85	2.05	2.10	2.15	2.30
<i>L. digitata</i>	[kg/m ²]	0.00	12.00	17.00	22.00	25.00	26.50	28.00	29.50	30.00	30.50	30.00
<i>M. edulis</i>	[kg/m ²]	0.00	0.00	0.04	0.18	0.33	0.50	0.82	0.95	1.07	1.08	1.20
ΔT_{growth}	[mm]	0.00	9.62	13.65	17.72	20.21	21.58	23.15	24.53	25.03	25.46	25.28

Table 10. Parameters in the numerical model that represent the biofouling condition at a specific time (year) of operation. The bio-density of the fouling is always set to 1325 kg/m³.

Time	[year]	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
ΔT_{growth}	[mm]	0.00	9.62	13.65	17.72	20.21	21.58	23.15	24.53	25.03	25.46	25.28
W_M	[N/m]	423.3	433.6	438.9	444.8	448.8	451.1	453.8	456.2	457.1	457.9	457.6
C_{DnM}	[-]	2.5	3.5	3.9	4.3	4.6	4.7	4.9	5.1	5.1	5.2	5.1
C_{DtM}	[-]	0.5	0.7	0.8	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0
W_C	[N/m]	7.0	11.4	13.8	16.5	18.3	19.3	20.5	21.6	22.1	22.4	22.3
C_{DnC}	[-]	1.2	1.8	2.0	2.3	2.4	2.5	2.6	2.7	2.7	2.7	2.7
C_{DtC}	[-]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig. 8. The effects of fouling on the WEC system after various time durations.

The values presented in Fig. 8 are normalized with respect to the biofouling-free condition, for which the average absorbed power and the fatigue life of the moorings are predicted to be 18.44 kW and 8 years. The changes in power absorption and fatigue damage are most significant during the first year, contributing 40% of the total changes observed after ten years. Over ten years of fouling development, both the power performance and the fatigue damage to the moorings reach a stable state.

4.4 Discussion of the mooring configuration and its fatigue life

A catenary mooring chain system is investigated in this study. The results show that the presence of biofouling has significant influence on the reduction of the moorings' fatigue lives. It has been shown in [13] that non-metallic materials are more resistant to biofouling, *i.e.*, less biofouling grow on non-metallic mooring line materials in seawater. This implies that if a different mooring system is used which is made of a non-metallic material, the influence of biofouling on the fatigue life may be different from the findings in the present investigation.

The expected service life of our case study WEC system is 25 years. Under this assumption, the two investigated mooring configurations satisfy expectations only under sea state S1. According to our initial investigation, the short fatigue life of the system can be primarily attributed to the load from current. With other controlling factors defined as in the M1-F1-S2-D3 case, the mooring fatigue life is predicted to be 341, 8, or 0.7 years under a current speed of 0, 0.5, or 1.0 m/s, respectively. Due to the lack of data from tank tests of the WEC buoy to estimate its current load coefficient, it was calculated according to an empirical

formula in [30]. However, it is also indicated in the same cited reference that the real current load over open sea tends to be smaller than the value estimated according to the formula. Therefore, one may expect longer fatigue lives of the moorings than what is presented herein.

The three-mooring configuration (M1) is seemingly the more attractive candidate of the two considered here, according to the presented results. However, the authors make no attempt in this study to judge the intrinsic superiority of either of the two mooring configurations. There are many other factors that contribute to a well-designed mooring system, such as material properties, stiffness characteristics, equipment and operational costs, and the feasibility of applying the mooring system in a dense array [37,43-45]. The intent of this paper is merely to present and stimulate a discussion of the differences in behaviour between the two configurations with the hope of providing insight for mooring optimization in future work. A final conclusion regarding the more suitable mooring design can only be reached after all factors have been thoroughly investigated.

4.5 Biofouling effect on the energy performance and fatigue life of mooring lines from a long term perspective

Section 3 shows that the occurrence of biofouling can reduce the energy performance and fatigue lives of the moorings up to 17% and 76%, respectively. However, one should note that this is an estimation based on one sea state condition in the scatter diagram together with a “fixed” value of biofouling with time on the cable and the moorings. Therefore, to assess the long-term effect from biofouling, one should also take the changing nature of the sea states and the development of the biofouling into account.

The long-term effect of the biofouling was studied using the three-mooring configuration (M1) together with three other assumptions. First, the growth of biofouling is assumed to follow the trend presented in Table 9 for the first ten years and then to remain constant as the 10th year of the biofouling. Second, the probabilities of occurrence of sea states S1, S2, S3, and S4 are respectively set to 2%, 53%, 37%, 8%, based on the wave scatter diagram acquired at the Runde test site (see Table 11, provided by Waves4Power [17]). Third, three wave and current directions (D1, D2, and D3) are assumed to have the same probability of occurrence.

Table 11. Wave scatter diagram at the test side Runde in Norway (Unit: 1×10^{-5}).

H_s [m]	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	Sum
12.5	0	0	0	0	0	0	0	1	2	3	0	0	0	0	6
11.5	0	0	0	0	0	0	0	2	7	0	0	0	0	0	9
10.5	0	0	0	0	0	0	0	11	10	0	0	0	0	0	21
9.5	0	0	0	0	0	0	6	42	10	0	0	0	0	0	58
8.5	0	0	0	0	0	2	29	87	2	0	0	0	0	0	120
7.5	0	0	0	0	0	14	107	103	2	0	0	0	0	0	226
6.5	0	0	0	0	0	44	267	33	5	1	0	0	0	0	350
5.5	0	0	0	0	7	166	337	37	7	2	0	1	0	0	557
4.5	0	0	0	0	43	558	136	32	14	5	1	1	0	0	790
3.5	0	0	0	1	371	563	123	48	19	6	2	1	0	0	1134
2.5	0	0	4	179	877	303	130	71	33	16	7	2	0	0	1622
1.5	0	0	221	1014	501	220	146	110	66	36	16	3	1	0	2334
0.5	644	367	684	248	107	142	162	192	117	64	19	22	3	4	2775
Sum	644	367	909	1442	1906	2012	1443	769	294	133	45	30	4	4	10002

Percentage: S1: 2% S2: 53% S3: 37% S4: 8%

Table 12 shows the total power absorption and maximum accumulated fatigue damage among all moorings after 25 years of operations. Note, however, that since the value of accumulated fatigue damage is larger than one, the mooring will fail earlier than the expected

operational period. Based on Table 12, the presence of biofouling on the cable and moorings was predicted to result in a 9% reduction in the WEC's energy performance and in a 16% increase in the fatigue damage (or an equivalent decrease of the fatigue life) of the most critical mooring line, which is the line aligning with the load direction D2; see Fig. 2(a).

Table 12. Result of power absorption and fatigue damage of moorings after 25 years of operation with consideration of the growth of the biofouling (the difference is calculated based on a biofouling-free condition "NO").

	Presence of biofouling		
	No	Yes	Difference
Power absorption [GWh]	14.8	13.5	-9%
Maximum accumulated fatigue damage among all moorings [-]	335	390	16%

4.6 Concluding remarks: verification and future work

The WEC system presented in the current study is still under development. The study contributes to both fundamental understanding and to guidelines for the future development of the actual system. The majority of the data and the parameters used have been obtained from experiments and measurements. More laboratory and full-scale tests have to be carried out to validate and verify the models and methodology. Three issues are discussed below.

Firstly, the study presented simulations of the dynamic behaviour of the WEC system using a coupled response analysis approach using the software DNV-GL SESAM. This software has been extensively verified in several studies, see *e.g.* examples in [46]. However, due to the special characteristics of each WEC system, such as the use of different PTO systems (see Section 2.1.1) and the design of optimum operation conditions under the resonant periods (see Section 2.1.3), a validation is planned for the WEC system in the current study. Model tests in a laboratory-based ocean wave test tank have been carried out and full-scale tests are currently ongoing. The results from these tests will be used in future work to validate the hydrodynamic and structural response analyses of the entire WEC system.

Secondly, the current study modelled the biofouling according to the recommended procedure in [22] by increasing both the submerged weight and the drag coefficients of the moorings and the cable. There are several ways to consider the effect of biofouling in the numerical model such as variation in: the actual mass [7,8,11,48], the submerged weight [11], the surface roughness [8,47,48], the effective diameter [8,11], the drag coefficient [11,47,48], and the added mass coefficient [11]. The biofouling composition is needed in order to judge and decide which factors can best represent its biofouling condition in a model [25]. On-site measurements of the biofouling condition are therefore needed in order to validate the model of the biofouling, and hence, the biofouling's effect on the WEC system's performance and characteristics.

Section 3.2 presents results with very long fatigue lives of the cable. The need to develop a more "suitable" local model of the cable was discussed which also can capture more failure modes than only failure due to stress-based fatigue. Structural integrity tests of the current cable in a test rig in a laboratory are ongoing. The results will assist in the development of the new cable model with regard to its characteristics and failure modes, and to calibrate its material properties to be used in the constitutive material model and in the other models used to study fatigue, wear, fretting, etc.

5 Conclusions

This study investigated the impact of the following factors on the operation of WEC systems: the mooring configuration, biofouling accumulation, and various environmental loads. The primary assessment criteria considered in this investigation were the energy performance of the system and the fatigue life of the mooring lines and power cable. The investigated WEC system is currently undergoing full-scale testing near Runde in Norway.

The results show a maximum of 17% reduction in the WEC's energy performance when biofouling is accumulated on the mooring lines and power cables. Additionally, biofouling was found to significantly reduce the fatigue life of the moorings, by up to 76% among all simulated cases. Initial improvements in the modelling and simulation approaches have been made which take into account all sea states in a scatter diagram and time variation effects from biofouling. They enabled a more realistic estimation which shows that if the WEC system is assumed to operate during 25 years, the presence of biofouling can lead to a 10% reduction of absorbed power and a 20% decrease in fatigue life of the mooring line that accumulates the most fatigue damage.

The direction of the incoming waves and current has only a negligible effect on the energy performance of the WEC. However, an incoming load with a direct heading on a mooring or cable will cause a significant decrease in fatigue life. From the structural safety perspective, the orientation of each WEC system should therefore be carefully considered with respect to the prevailing load direction at its site of operation.

The responses of different WECs vary depending on the design of the concept itself [49]. Although the results and conclusions from this study are based on a case study of a specific WEC system, they are considered to be relevant for other oscillating-body WEC systems (based on the definition of this category of WECs in [49]) due to their similarity in terms of the working principle for energy harvesting and the necessity to adopt mooring lines and power cables.

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Appendix A Modelling of the marine biofouling

Based on the recommended procedure in [22], marine biofouling on the mooring lines and the cable can be considered in a numerical model as follows:

1. Increase of the weight due to biofouling, W_{growth}

$$W_{\text{growth}} = \frac{\pi}{4} \left[(D_{\text{nom}} + 2\Delta T_{\text{growth}})^2 - D_{\text{nom}}^2 \right] \rho_{\text{growth}} \mu \left(1 - \frac{\rho_{\text{seawater}}}{\rho_{\text{growth}}} \right) g \quad (\text{A.1})$$

where ρ_{growth} is the mass density of the biofouling, ρ_{seawater} is the density of the seawater, D_{nom} is the nominal diameter of, either a mooring line, or, the outer diameter of the cable, ΔT_{growth} is the thickness of the biofouling, μ is a surface constant (2.0 for a mooring line and 1.0 for the cable), and g is the gravitational acceleration.

2. Increased drag coefficient due to biofouling, $C_{D,\text{biofouling}}$

$$C_{D,\text{biofouling}} = C_D \left(\frac{D_{\text{nom}} + 2\Delta T_{\text{growth}}}{D_{\text{nom}}} \right) \quad (\text{A.2})$$

where C_D is the drag coefficient for, either a mooring line, or, the cable.

Appendix B Schematic flowchart of the methodology applied in this study

Figure B.1 presents the schematic workflow applied in the present study, where its details are referred to [50]. The three analyses introduced in Section 2 are coloured differently in the figure: coupled response analysis (blue boxes), fatigue damage analysis (red boxes), and energy performance analysis (green box).

Fig. B.1 Schematic flowchart of the methodology applied in this study.

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Figure captions

Fig. 1. Illustrations of the investigated WEC systems, with (a) the three-mooring configuration and (b) the four-mooring configuration.

Fig. 2. Illustrations of the (a) three-mooring and (b) four-mooring WEC systems in relation to the incoming wave and current directions.

Fig. 3. Schematic view of the simulation matrix.

Fig. 4. Illustration of the energy performance analysis for the first 300 seconds of the M1-F1-S2-D3 case.

Fig. 5. (a) Horizontal motion response, and (b) vertical motion responses with respect to time of the WEC buoy for the M2 configuration under various fouling conditions, all other factors are defined as in the S2-D2 case.

Fig. 6. Example of (a) axial stress response and (b) accumulated fatigue damage of moorings under various fouling conditions. The other control factors are defined as M1-S1-D1.

Fig. 7. Correlation diagram of the power absorbed by the WEC and the fatigue life of the moorings with respect to the bio-density. It is assumed here that the value of the bio-density always gives the same total mass of the biofouling, *i.e.*, the layer thickness of the biofouling is adjusted.

Fig. 8. The effects of fouling on the WEC system after various time durations.

Figure B.1 presents the schematic workflow applied in the present study, where its details are referred to [50]. The three analyses introduced in Section 2 are coloured differently in the figure: coupled response analysis (blue boxes), fatigue damage analysis (red boxes), and energy performance analysis (green box).