Modeling of vessel and equipment cost for the maintenance activities of an offshore tidal energy array

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Abstract

Tidal energy is one of the most promising sectors of energy conversion that can be extracted from renewable sources, taking into account the uninterrupted flow of tidal currents regardless of the surrounding environmental conditions. In this case, a detailed analysis of the planned and unplanned maintenance attributes has been developed in order to examine the various O&M parameters influencing the cost elements. Major features for both planned and unplanned maintenance include the identification of the transportation, labor, workshop and equipment/tools cost. The above are estimated for different operational scenarios as well as for the maintenance of a single device per day. Overall, the O&M cost per device is estimated as well as the cost per MW (gross and net) and the cost/kWhr. The results show that the overall O&M cost is not prohibitive compared to other renewable energy applications while it may vary according to the initially selected O&M scenario.

Keywords

Tidal energy device, planned/unplanned maintenance, cost of equipment, vessel cost, full-scale tidal park

Introduction

Tidal energy is one of the most promising sectors in terms of harnessing marine power. Research studies in this field have recently expanded considerably, especially in the UK, while initial studies on the design, installation, operation and maintenance (O&M) activities have already been originated. Indicatively mentioned are the studies by Mueller and Wallace (2008), Douglas et al (2008), Hameed et al (2010) and the UK Carbon Trust (2006a, 2006b). However, the majority of the tidal energy concepts are founded on considerations of the effect of high speed tidal currents in different areas around the world, not acknowledging the potential of extracting power from low speed tidal areas. This is the case of the Deep Green project involving the Seakite device, which is designed as a moving underwater power plant, optimized to produce energy from low-speed tidal streams. However as with any type of marine energy converter, the full-scale installation and activation of Seakite induces a cost related to the actual operation and maintenance activities of the device and accordingly of the full-scale deployment of the Deep Green project of a tidal park array. Various studies have been performed in this field including the works of Dinwoodie et al (2013), Li et al (2011) also considering other renewable energy resources (Nielsen and Sørensen, 2011, van Bussel, and Zaaijer, 2003).

In this respect, a methodology for arriving at the estimation of the O&M cost of the full scale project is carried out in the study herein, taking into account a number of attributes of the planned, unplanned and total maintenance cost of the full-scale tidal park such as the transportation, labor, workshop and equipment/tools cost. In this respect, the O&M cost per device is estimated as well as the cost per MW (gross and net) and kWhr.

The initial section of the present paper introduces the concept of the Seakite device and its operational characteristics while the next section describes the O&M modeling performed in terms of the planned and unplanned costs involved. Following the above, an application of the mentioned methodology is demonstrated including different operational scenarios. Having performed that, the overall O&M cost for different parameters is shown while the last section of the paper presents the findings and conclusions of this study.

Methodology

Deep Green tidal energy device

As mentioned above, the Seakite device is designed as a moving underwater power plant, optimized to produce energy from low-speed tidal streams. In this case, Seakite employs a control system in order to move on an eight-shaped trajectory of about 300m length. The lift produced by the wing and its movement drives the turbine, which powers the generator in the Seakite. With a tidal current speed of 1.6 m /s, the wing will move with a speed up to 16 m/s. The power is transmitted through a cable integrated in the wire to a terminal at the seabed, which is connected to the shore. The overall weight of the device is expected to be around 7 tons. The main parts of the Deep Green device include the wing [1], rotor [2], nacelle [3] and tethering system [4] (Fig. 1).

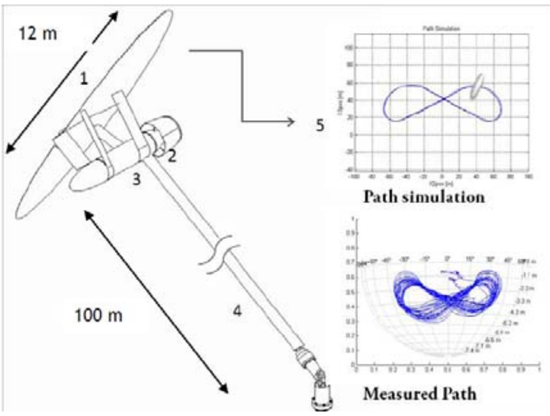

Fig. 1:Seakite device initial design concept and main parts

As is shown, the wing includes a set of equipment and parts such as a set of batteries for redundancy control, the buoyancy system as well as the struts that connect the wing with nacelle. The nacelle houses a turbine and a 0.5 MW-generator used to produce the power required. It also includes a rotor, which has a diameter of 1.0 meters and rotates at 600 rpm. Behind the rod, a rudder is mounted. The device will be connected to the ground by a tethering system and a swivel as part of the seabed foundation. A Quick Release Mechanism (QRM) is used as the connecting point between the two main struts supporting the wing and the tethering system. It is placed at a distance of about 10m from the top of the wing providing a safe and a secure point in case the device needs to be detached from the tethering system for retrieval and maintenance. The Deep Green device will be able to operate in water depths of 60-120m with a water depth clearance of 15m from the surface of the sea when in operational condition.

In order to perform the study for the development of methods for handling of the full-scale Deep Green device during service & maintenance operations, the main particulars of the device are needed (including the height of the device down to the Quick release mechanism). This will facilitate the specification of the vessels and carnage systems needed so as to perform the transportation of a spare full-scale device to the tidal park location, enable the retrieval of an existing one out of the water, which will then be replaced by the spare device which is carried onboard the vessel. In this respect, the following dimensions for the full-scale device are specified as wing span (12.0m), wing breadth (2.6m) and device height (7.0m) from top of wing to Quick release mechanism.

Planned maintenance cost model

In this section, the various attributes of the Planned maintenance cost are examined. These include the Transportation, Labor, Workshop and Equipment cost as shown in Eq. 1:

$$CPL = Ctran + Cla + Cwork + Ceq \tag{1}$$

C_{PL} Planned maintenance cost (£)
C_{tran} Transportation cost (£)
C_{la} Labour cost (£)
C_{work} Workshop cost (£)
C_{eq} Equipment cost (£)

The associated transportation cost (C_{tran}) is the outcome of two attributes; that is the hired vessel cost and the new-built vessel cost (C_{nb}). Moreover, in case two maintenance vessels are employed, the hire vessel cost can be the combination of vessel 1 hire cost (C_{vh1}) and vessel 2 hire cost (C_{vh2}) as shown in the following equations:

$$C_{tran} = C_{vh1} + C_{vh2} \tag{2}$$
$$C_{tran} = C_{nb} \tag{3}$$

C_{tran} Transportation cost (£)
C_{vh1} Vessel 1 hire cost (£)
C_{vh2} Vessel 2 hire cost (£)
C_{nb} Vessel new built-capital cost (£)

Following the above, vessel 1 hire cost is given by:

$$C_{vh1} = t_1 * R_1 * (1 + f_{ves}) + (Cf / 2) \tag{4}$$

C_{vh1} Vessel 1 hire cost (£)
t_1 Time vessel 1 is hired (days)
R_1 Daily rate for vessel 1 (£)
f_{ves} Vessel contingency factor for delays due to weather conditions (%)
Cf Annual Cost of fuel

On the other hand, the time that the maintenance vessel 1 is hired is equal to:

$$t_1 = t_{tp1} + t_{tp2} + t_{tp3} + t_{ins} \tag{5}$$

t_{tp1} Time to tidal park (hours)
t_{tp2} Time in tidal park (hours)
t_{tp3} Time to detach/attach one Seakite (hours)
t_{ins} Inspection time per Seakite

Time to the tidal park is equal to:

$$t_{tp1} = [2 * Dist1 / (V_{sp1} * 1.852)] * (1 + f_{ves}) \tag{6}$$

Dist1 Distance to the tidal park (km)
V_{sp1} Vessel speed to reach tidal park (knots)
f_{ves} Vessel contingency factor for delays due to weather conditions (%)

Time in the tidal park is equal to:

$$t_{tp2} = Dist2 + [2 * Dist1 / (V_{sp2} * 1.852)] * (1 + f_{ves}) \tag{7}$$

Dist2 Distance to the tidal park (km)
V_{sp2} Vessel speed in the tidal park (knots)

The time to detach the old Seakite and attach the new Seakite in place is calculated as:

$$t_{tp3} = (T_{rov} + T_{other}) * (1 + f_{ves}) \quad (8)$$

T_{rov} Time to mob/demob ROV from vessel (hours)
T_{other} Time other than ROV-bring Seakite onboard (hours)

Moreover, inspection time (t_{ins}) may vary depending on the time of the initial examination of the Seakite. In this case, it may be considered on an hourly basis per device.

In addition to the above, the cost of fuel needed for a single vessel in order to perform the planned maintenance tasks is given by the following:

$$Cf = DFC * Dsea * Prfuel * Nmain * Oilcorr \quad (9)$$

DFC Daily fuel consumption (tons of fuel)
Dsea Days at sea
Prfuel Price of fuel (£)
Nmain Number of main engines (constant)
Oilcorr Lube & Diesel oil correction factor set as 1.15 (constant)

The DFC is calculated as follows:

$$DFC = EPmax * SFOC * Fmean * 10^{-8} \quad (10)$$

EPmax Engine power max (KW)
SFOC Specific fuel oil consumption (gr/KW*h)
Fmean (%) of main power output

On top of the above, in case the cost of the crew that will be employed onboard the maintenance vessel is also needed, it is estimated as follows:

$$C_{cr} = \sum_{n}^{i=1} Ccr_i = Ccr_1 + Ccr_2 + ... + Ccr_n \quad (11)$$

$\sum_{n}^{i=1} Ccr_i$ Cumulative crew cost (£)
Ccr_i The cost of each crew member employed onboard the vessel (£)

Moreover, the cost of each crewmember is estimated according to number of crew needed onboard the vessel employed (smaller barge type of vessel or bigger DP vessel) multiplied by a factor of two as the crew members employed onboard any vessels are working on an on-off rota throughout the year. Furthermore, in case of a second maintenance vessel needed to work in tandem with the first maintenance vessel, the following equation applies:

$$C_{vh2} = t_2 * R_2 * f_{ves} \quad (12)$$

C_{vh2} Vessel 2 hire cost (£)
t_2 Time vessel 2 is hired (days)
R_2 Daily rate for vessel 2 (£)
f_{ves} Vessel contingency factor for delays due to weather conditions (%)

The time that vessel 2 is hired is estimated in a similar way as for the one suggested for the first maintenance vessel (vessel 1). Moreover, the Labour cost (C_{la}) can be estimated as follows:

$$C_{la} = N_{tech} * t_{wves} * t_{tot} * R_{ves} \quad (13)$$

C_{la} Labour cost (£)
N_{tech} Number of technicians (onboard the vessel)
t_{wves} Time working/vessel operation time (hours per day)
t_{tot} Total working time (days)
R_{ves} Rate/hour on vessel (£)

In this case, t_{tot} is the total working time spent for repairing all the devices in the tidal park (which may be equal to the time (in days) that the maintenance vessel 1 is hired ($t_{tot} = t_1$)).

On top of the above, the Workshop cost (C_{work}) is given by:

$$C_{work} = C_{wla} + C_{sp} \quad (14)$$

C_{work} Workshop cost (£)
C_{wla} Workshop labour cost (£)
C_{sp} Spare parts cost (£)

The workshop labour cost (C_{work}) is specified by:

$$C_{wla} = N_{wtech} * t_{work} * t_{tot} * R_w \quad (15)$$

C_{work} Workshop cost (£)
N_{wtech} Number of technicians (at the workshop)
t_{work} Workshop time (hours)
t_{tot} Total working time (days/year)
R_w Workshop rate/hour (£)

Additionally, the workshop spare parts cost (C_{sp}) is given by:

$$C_{sp} = \sum_{n}^{i=1} Csp_i = Csp_1 + Csp_2 + ... + Csp_n \quad (16)$$

$\sum_{n}^{i=1} Csp_i$ Cumulative spare parts cost (£)
Csp_i The cost of each spare part used for the device (£)

At this point, it needs to be mentioned that the cost for having an operational spare Seakite is estimated in the capital expenditure of the project. In this respect, it is assumed that three spare Seakites (5% of the total number of Seakites deployed in the full-scale tidal park) will be available at the project hub port at any time for quick transportation and installation offshore for replacing an existing mal-functioning Seakite. In this case, the mal-functioning Seakite will be removed from the tidal park and transported onshore in order to perform the maintenance tasks required.

Moreover, the equipment and tools cost (C_{eq}) needed to perform the planned maintenance tasks is given by:

$$C_{eq} = C_{rov1} + C_{rov2} + C_{other} \quad (17)$$

C_{eq} Equipment cost (£)
C_{rov1} Cost for using ROV 1-inspection ROV (£)
C_{rov2} Cost for using ROV 2-working ROV (£)
C_{other} Other equipment cost including tools etc. (£)

In this case, the cost for employing ROV 1 and ROV 2 are calculated as shown next:

$$C_{rov1}= t_{rov1} * f_{rov1} * + R_{rov1} \quad (18)$$

t_{rov1} Time ROV 1 is working, equal to vessel 1 operation time (days /year)
f_{rov1} Contingency factor for not using ROV 1 due to weather conditions
R_{rov1} ROV 1 rate/day (£)

Similarly, the cost for employing ROV 2 (working ROV) is provided by the following formula:

$$C_{rov2}= t_{rov2} * f_{rov2} * + R_{rov2} \quad (19)$$

t_{rov2} Time ROV 2 is working, equal to vessel 1 operation time (days /year)
f_{rov2} Contingency factor for not using ROV 2 due to weather conditions
R_{rov2} ROV 2 rate/day (£)

The cost for any other equipment/tools that will be used onboard the vessel for the service and maintenance operations of the tidal energy device is specified by:

$$C_{other}= \sum_{n}^{i=1} Cother_i = Cother_1 + Cother_2 + ... + Cother_n \quad (20)$$

$\sum_{n}^{i=1} Cother_i$ Cumulative cost for any other equipment/tools used onboard the maintenance vessel (£)
$Cother_i$ The cost for any other equipment/tools used onboard the maintenance vessel (£)

Having examined the cost parameters for the planned maintenance sequence, the corresponding calculations are carried out for the unplanned maintenance tasks in the following section.

Unplanned maintenance cost model

In general terms, the unplanned maintenance cost follows a similar way of calculation as with the planned maintenance parameters. However, there are certain differences, especially in the case of estimating the failure rates and consequently the downtime caused by unexpected failures of different components of the device. In this respect, the unplanned maintenance cost is a derivative of the following:

$$C_{UPL} = C_{tran} + C_{la} + C_{work} + C_{eq} \quad (21)$$

C_{UPL} Unplanned maintenance cost (£)
C_{tran} Transportation cost (£)
C_{la} Labour cost (£)
C_{work} Workshop cost (£)
C_{eq} Equipment cost (£)

As mentioned before, all the various parameters of the unplanned maintenance cost are similar to the ones used for the estimation of the planned maintenance cost. However, the unexpected failures of the different components of the device need to be accounted for in this case. The latter is calculated by considering the failure rates of the individual components, which will affect the annual availability of the overall device. This is performed as follows:

At first, the failure rates for different components of the Seakite are taken into account. At this point, it needs to be mentioned that the full-scale application of tidal energy devices is not at a mature stage in order to recuperate actual failure rates for the different modules of the device. A valid alternative to this is the use of actual failure rates from other related fields of research and application in the renewables sector (e.g. wind turbines, other renewable energy devices) adjusted to the subject case study by employing certain adjustment factors. In this case, two factors are used; namely factor f_1 for the naval underwater environment and factor f_2 for the data uncertainty origination (data compiled from various sources such as research papers and other project reports). This leads to the calculation of the failure rate for component n as shown next:

$$\lambda_n= \lambda_{orig} * f_1 * f_2 \quad (22)$$

λ_n Failure rate for n component
λ_{orig} Original failure rate
f_1 Adjustment factor for naval underwater environment
f_2 Adjustment factor for data uncertainty origination

Combining the individual failure rates for each device component, the overall device failure rate is estimated. Then, the device availability A_d is calculated by using the exponential distribution in order to provide the operational period during which the device may operate free of failures. That is:

$$A_d = 1- e^{-\lambda t} \quad (23)$$

A_d Device availability per year (%)
λ Overall device failure rate
t Time for which availability is accounted for

In this respect, the estimation of the overall annual availability of the device will enable the determination of the time that the vessels and equipment for the unexpected maintenance tasks will be needed as well. Then, the total maintenance cost can be calculated as shown in the following section.

Total maintenance cost

The total maintenance cost is derived as the summation of the planned and unplanned maintenance costs; that is:

$$C_{TOT} = C_{PL} + C_{UPL} \quad (24)$$

C_{TOT} Total maintenance cost (£)
C_{PL} Planned maintenance cost (£)
C_{UPL} Unplanned maintenance cost (£)

Moreover, in terms of the determination of other attributes of the overall tidal park, the following need to be estimated regarding planned maintenance. This is the planned maintenance cost per device (C_1), planned maintenance cost per MW (gross: C_2, and net: C_3,) and the planned maintenance cost per kWhr (C_4) as described next:

$$C_1 = C_{PL} / N_{dev} \quad (25)$$

C_1 planned maintenance cost per device
C_{PL} Planned maintenance cost (£)
N_{dev} Number of devices used in the full-scale tidal park

$$C_2 = C_{PL} / Cap_{tpgr} \quad (26)$$

C_2 planned maintenance cost per MW (gross)
C_{PL} Planned maintenance cost (£)
Cap_{tpgr} Tidal park gross capacity

Accordingly:

$$Cap_{tpgr} = Cap_{sgr} * N_{dev} \quad (27)$$

Cap_{sgr} Single device output capacity gross (MW)

$$C_3 = C_{PL} / Cap_{tpnet} \quad (28)$$

C_3 planned maintenance cost per MW (net)
C_{PL} Planned maintenance cost (£)
Cap_{net} Tidal park net capacity

$$Cap_{net} = Cap_{snet} * Cap_{tpgr} \quad (29)$$

Cap_{snet} Single device output capacity net (MW)

$$Cap_{snet} = Cap_{sgr} * f_{cap} * f_p \quad (30)$$

Cap_{sgr} Single device output capacity gross (MW)
f_{cap} Capacity factor (%)
f_p Power generation availability (%)

$$C_4 = C_{PL} *10^2 / Cap_{tot} * 10^6 \quad (31)$$

C_4 planned maintenance cost per kWhr
C_{PL} Planned maintenance cost (£)
Cap_{tot} Total tidal park net capacity (output) (GWhr/year)

Moreover:

$$Cap_{tot} = Cap_{net} * N_{dev} \quad (32)$$

Accordingly, similar attributes are estimated for the unplanned maintenance cost; that is the unplanned maintenance cost per device (C_1), unplanned maintenance cost per MW (gross: C_2, and net: C_3,) and the unplanned maintenance cost per kWhr (C_4). The equations described above are the same with the only difference of using the unplanned maintenance cost in the place of the planned maintenance cost respectively. What follows next is the application of the above maintenance models in the case study of the full scale Deep Green project as shown in the next section.

Application of maintenance models

In this section, the application of the maintenance modeling methodology developed herein is demonstrated in the deployment of the full-scale tidal park. Following the above, the attributes used for the calculation of the planned maintenance cost together with the day rates of different types of vessels used in the maintenance operations and the cost of the crew employed on the maintenance vessels are given in Appendix A. For the unplanned maintenance cost, the main attributes remain the same for all different sub-cost elements (transportation, labor, workshop and equipment/tools). However, there is an additional feature regarding the failure rates of the various components of the Seakite. These are given in Table 1.

Table 1: Unplanned maintenance cost attributes

Failure rate	Component	Original failure rate	Final failure rate
$\lambda 1$	shaft	0.0070	0.0485
$\lambda 2$	brake	0.0325	0.2252
$\lambda 3$	electrical system	0.0925	0.6408
$\lambda 4$	blade	0.0273	0.1892
$\lambda 5$	generator	0.0545	0.3777
$\lambda 6$	control system	0.1000	0.6930
$\lambda 7$	miscellaneous	0.0299	0.2072

Moreover, failure rate adjustment factors are also considered as shown in Table 2.

Table 2: Unplanned maintenance failure rate adjustment factors

λ factor	Explanation	Value
f_1	naval underwater environment	6.30
f_2	data uncertainty origination +-10%	1.10

Given the above data, the planned and unplanned maintenance cost for the full-scale device and tidal park can be estimated accordingly. Hence, planned maintenance cost is estimated as: C_{PL} = £2,080,237 annually when using one vessel, including two planned maintenance intervals annually (maintenance occurring every six months). In this case, the maintenance works are carried out continuously (24hours/7 days). In case a single device is maintained per day, the planned maintenance cost rises to C_{PL} = £2,505,837 annually.

If there is a need to employ a second bigger vessel for this sort of maintenance tasks (especially in the case of inspecting and maintaining the foundations), the overall planned maintenance cost is in the range of £7,545,837 annually. In this second case, an inspection as well a working ROV are employed.

For the estimation of the unplanned maintenance cost C_{UPL}, the cost for the deployment of a vessel should be considered as well as the overall availability of the device per year. In this regard, the provided failure rates suggest that the device will need unplanned maintenance of its components to be carried out every three months, thus four times annually. The latter multiplied by the cost of employing a vessel, labour and equipment/tools to carry out the maintenance tasks provides the annual unplanned maintenance cost for the full-scale tidal park. In this case, the cost will be C_{UPL} = £2,550,355 for continuous maintenance of the devices (continuous work throughout the day for 7 days a week). In the case that one single device is maintained per day, the unplanned maintenance cost rises to C_{UPL} = £3,720,355. The above are summarized in Table 3.

Table 3: Maintenance scenarios

Maintenance type	***Multiple devices/day (£)***	***One device/day (£)***
Planned		
One vessel	2,080,237	2,505,837
Two vessels	5,944,237	7,545,837
Unplanned		
One vessel	2,550,355	3,720,355
Two vessels	6,855,355	11,100,355

Having estimated all the above, it is now feasible to calculate the following planned and unplanned maintenance parameters:

- cost/device (£)
- cost/MW (gross) (£)
- cost/MW (net) (£)
- cost/kWhr (£pence)

These parameters are examined regarding four different scenarios as mentioned below:

- Scenario 1: One vessel, continuous maintenance operation
- Scenario 2: One vessel, maintenance of one device/day
- Scenario 3: Two vessels, continuous maintenance operation
- Scenario 4: Two vessels, maintenance of one device/day

The overall results for the planned/unplanned and total maintenance cost are shown in Fig. 2,3 and Appendix B.

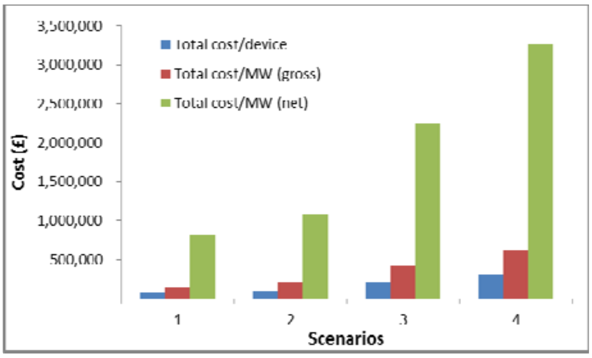

Fig. 2: Total maintenance cost for various scenarios

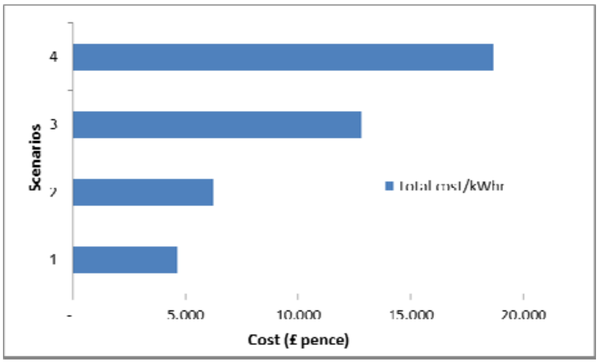

Fig. 3: Total maintenance cost per kWhr

As can be seen in Figure 2, the total maintenance cost is influenced by the number of vessels involved in the maintenance operations. More specifically, it increases compared to the original condition (Scenario 1) when two vessels are employed (Sscenario 3 - One vessel, continuous maintenance operation and Scenario 4 - Two vessels, maintenance of one device/day). Moreover, the total cost is also increased when a single device is maintained per day of operation, as shown in scenario 2 (One vessel, maintenance of one device/day) and Scenario 4 (Two vessels, maintenance of one device/day) as well.

Additionally, as shown in Fig. 3, the total maintenance cost per kWhr increases as more vessels are employed and as more time is dedicated per device (in this case, one device is maintained per day). On the other hand, the total cost per kWhr drops significantly if a single vessel, appropriately equipped, operates continuously to service the tidal park.

Conclusions

The present paper presents a study on the maintenance cost of the equipment and vessels to be used in the full-scale tidal park of the Deep Green project. In this respect, the following have been considered and further examined:

- The various attributes of the planned maintenance cost have been established taking into account various sub-elements such as the transportation, labor, workshop and equipment/tools cost. The transportation sub-category may involve the use of either a single vessel or the combination of two vessels. The first one may be used for usual service activities of the Seakite while the second vessel can be employed when more demanding maintenance activities are required. However, given the appropriate specifications and onboard equipment of the vessel, a single one can be also engaged in the maintenance operations of the full-scale Deep Green tidal park.

- When examining the different parameters of the planned maintenance sequence, the transportation cost occupies the main part of it. This is the reason why stringent examination of the specific transportation characteristics needs to be carried out in terms of which vessel to use, by either hiring or building a brand new one, which will eventually accommodate the full-scale tidal park best. In this respect, it is shown that by hiring a single vessel to work continuously onsite (Scenario 1) is a more cost-effective option.
- Regarding the Unplanned maintenance cost, the same attributes are also examined (transportation, labor, workshop and equipment/tools cost). In addition to the above, the overall failure rate of a single device is also examined in order to study the effect of unexpected failures to the overall device availability. This is performed by studying the individual failure rates of the specific components of the Seakite and adjusting them to the specific operating conditions (e.g. underwater marine environment). In this way, the overall Seakite availability was determined. It was found that unexpected failures might occur every $3^{1/2}$ months, which means that additional maintenance effort needs to be concentrated on specific components of the Seakite. However, because of the scarcity of actual failure data for tidal energy converters, the initial failure data used for the present study were taken from similar components in the renewable sector and adjusted to the subject conditions. In this respect, it is advised to further validate the current results and re-evaluate the existing unplanned maintenance model when the model Seakite test results will be generated.
- Moreover, having performed the assessment of the planned and unplanned maintenance cost elements, the total maintenance cost is studied as well. The attributes examined in this case include the cost/device, cost/MW (gross and net) as well as the cost/kWhr for the full-scale project. Four different scenarios are investigated. These are the use of either one vessel with continuous maintenance operation (Scenario 1) and the use of one vessel with maintenance of one device/day (Scenario 2). Scenario 3 involves the employment of two vessels in continuous maintenance operation while Scenario 4 mentions the use of two vessels with maintenance tasks of one device/day. As expected, Scenario 1 provides the best option for the achievement of the total maintenance activities. It is also important to highlight that the total cost/kWhr is comparable with similar studies performed in the renewable sector.
- Further scenarios and different options can be also analyzed in terms of the capital cost and relevant expenditure needed (e.g. crew cost, fuel cost, etc.) when a new-building vessel is used for the maintenance operations for the full-scale Deep Green project

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Appendix A

Table 1: Planned maintenance cost attributes

Attribute	Value
Seakite gross output capacity/device	0.5 MW
Number of devices operating (N_{dev})	60
Capacity factor (f_{cap})	40%
Power generation availability (f_p)	95%
Transportation cost total	
Distance to tidal park (dist1)	20 km
Vessel speed	10 knots

Contingency factor (bad weather)	20%
Distance in tidal park	1 km
Vessel speed in tidal park	5 knots
ROV mob/demob time	0.5 hrs
Time other than ROV (bring Seakite onboard)	0.5 hrs
Inspection time / device	2 hrs
Rate/day vessel 1	£10,000
Rate/day vessel 2	£30,000
Vessel newbuilding cost	£1,500,000
Crew cost 1 (captain)	£30,000
Crew cost 2 (engineer)	£27,000
Crew cost 3 (deck crew)	£20,000
Crew cost 4 (deck crew)	£20,000
Engine power max	2,000 KW
Specific FOC (gr/KW*h)	175
% of max speed	80
Days at sea	120
Price of fuel	£630
No of main engines	1
Lub & Diesel oil correction factor	1.15
Labour cost	
Number of technicians (onboard)	2
Time working = vessel operation time	8 hrs
Rate/hour on vessel	£50
Workshop cost	
Number of technicians (workshop)	2
Workshop time	8 hrs
Workshop rate/hour	£50
Cost spare parts	£6,000
Cost per spare Seakite	£500,000
Number of fully assembled spare Seakites	3
Equipment/tools cost	
ROV contingency factor (weather conditions)	20%
ROV 1 rate/day	£2,000
ROV 2 rate/day	£5,000
Tools cost	£6,000

Table 2: Indicative cost/day for different types of vessels-2 (compilation of data acquired from various sources available in the public domain)

Vessel Type	Daily cost/day
Multicat	£3-5 k
Anchor Handling Tug Supply Vessel	£15-45 k
Offshore Inspection, Maintenance, Repair vessel	£31 k
Multipurpose Supply Vessel	£19 k
Tugboat	£4-5 k

For small O&M vessels with a skipper and maybe one or two crew the salaries for the Skipper would be around 18k and the crew around 15k per annum. For large DP vessels The following would be indicative:

- Master 65K
- C/Eng 62.5K
- Other officers between 55k and 30k
- Ratings between 23k and 30k

Supply vessel crew would typically be on between 10 and 20 % less than DP vessels depending upon individual owners. Salary also commensurate with experience, qualifications and prior experience, plus benefits. The salary range also depends on the working vessel categories. There are also some vessel owners who employ third world ratings at considerably lower salaries than those defined above. However, the officers' salaries should be the same.

Appendix B

Table 1: Planned maintenance cost parameters for different scenarios

Attributes		unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Planned cost/device	C1	£	24,933	34,671	41,764	99,071
Planned cost/MW (gross)	C2	£	49,867	69,341	83,528	198,141
Planned cost/MW (net)	C3	£	262,456	364,954	439,620	1,042,849
Planned cost/kWhr	C4	pence	1.498	2.083	2.509	5.952

Table 2: Unplanned maintenance cost parameters for different scenarios

Attributes		unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Unplanned cost/device	C1	£	32,533	42,506	62,006	114,256
Unplanned cost/MW (gross)	C2	£	65,067	85,012	124,012	228,512
Unplanned cost/MW (net)	C3	£	342,456	447,431	652,694	1,202,694
Unplanned cost/kWhr	C4	pence	1.955	2.554	3.725	6.865

Table 3: Total maintenance cost parameters for different scenarios

Attributes		unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total cost/device	C1	£	77,177	103,770	213,327	310,770
Total cost/MW (gross)	C2	£	154,353	207,540	426,653	621,540
Total cost/MW (net)	C3	£	812,385	1,092,314	2,245,542	3,271,262
Total cost/kWhr	C4	pence	4.637	6.235	12.817	18.672