The O&M driven design of a multi-row platform tidal project

Giovanni Rinaldi, George Crossley, Richard Parkinson, and Lars Johanning

Abstract— **A number of tidal projects with different design, sizes and conceptual approaches, have been developed in recent years. While the technology has proven to be effective in converting tidal streams into electric energy, the economic viability is still far from being achieved due to unforeseen complications following the installation of the devices.**

In this paper, the authors provide an overview of the major challenges tidal energy developers should consider in order to design a viable tidal energy device. In addition, based on past field experiences, the typical issues encountered by offshore contractors during the deployment of one or an array of devices are presented. Therefore, paying special attention to the operational requirements of the devices, the solutions to these offshore challenges are proposed. Hence, a novel tidal concept is presented, using lifecycle O&M costs as a top driver for the development of the device. Subsequently, the iterative improvement of the project is achieved by means of a verified and calibrated integrated framework, based on Monte Carlo simulation and evolutionary algorithms, in order to support the decision-making process and management of the assets. Thus, the pivotal role of computational tools to improve the profitability of the project while ensuring satisfactory levels of availability and reliability is highlighted, and the potential for cost reduction in the design of a tidal energy project, in order to achieve financial viability, is shown.

Keywords—**O&M, Assets management, optimization, tidal energy, decision making.**

I. INTRODUCTION

THE quest for novel ways of extracting energy from the oceans is still ongoing and at a very active stage.

Ocean energy, considered as a green and renewable source of energy, has in fact a huge potential, linked to the successful conversion of the energy of waves and tides into electricity. Tidal energy in particular, caused by the cyclical gravitational forces exerted by sun and moon, has been indicated as a powerful, reliable and predictable renewable energy source. A large range of concepts exploiting tidal streams have been proposed in the past [1–5], with various technologies currently at different stages of development. Novel ideas are still being evaluated with the intent of obtaining a winning design in the competition for the most cost effective device. More in general, due to the high costs related to the manufacture, installation and operation of the devices, the lesson learnt with past experiences is used in order to propose new solutions that can reduce the final cost of energy. In other words, the final objective is the achievement of the economic viability at every stage of the project, starting from the pre-engineering till the decommissioning phase.

To this end, a new methodology for the exploitation of tidal energy on commercial scale with a focus on efficiency and cost reduction, is presented in this paper. The main key drivers of the proposed design, which led to the selected choices based on past experiences, were:

- The need to reduce complexity thereby reducing costs, improving reliability and improving availability;
- Creating a competitive market for original equipment manufacturers (OEMs)/ Turbine manufacturers;
- The need to reduce installation and operation and maintenance (O&M) costs (especially lifecycle O&M costs);
- The need to reduce balance of plant costs;
- Better understand the commercial drivers for commercial arrays;
- Achieving cost reduction and optimisation through weight reduction.

Thus, once the device is presented, a concept and feasibility study, including a techno-economic analysis of this innovation in the context of a commercial array, is carried out to assess and challenge the effectiveness of the design process. The remaining part of the paper is structured as follows. In section II the proposed device is presented, highlighting the factors that were taken into account to ensure a successful design. In section III, the methodology used to test the effectiveness of the proposed

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device and assess its commercial viability, as well as to obtain important indications that allowed to further improve the initial design, is described. The input data gathered to achieve this objective are reported in the same section. Thus, the results depicting the performance of the tidal concept reached across the different stages of an iterative improvement procedure are provided. These results, together with the finally selected configuration and proposals for future work, are then discussed in section IV, before conclusions on the overall study are drawn in section VI.

II. DEVICE

The patent-pending tidal energy device presented in this paper is proposed and being developed by the Cornwall-based company Inyanga-Tech [6]. The project is focused on a holistically integrated solution, considering all aspects with equal importance from the outset rather than developing a solution around a particular turbine or technology.

Firstly, leading current turbines weigh around 150t to 200t, causing major knock-on effects in increased fatigue and complexity, reduced reliability, complex and heavy foundations, expensive installation and unsustainable O&M costs. Secondly, despite promising results being recently obtained [7], floating devices have several challenges related to moorings and power cables, array exploitation, and survivability due to being in the most energetic and corrosive section of the water column. Addiotionally floating tidal technologies create a major navigational hazard and allow for a very low packing density in the most energetic parts of a given site. Thirdly, big offshore construction and support vessels, specialised or adaptable to the installation and the maintenance of tidal devices respectively, are difficult to procure, especially during summer months, and expensive to contract. Under these circumstances, a new tidal concept called "HydroWing" is proposed, aiming at addressing these fundamental issues that have delayed the industrialisation of the tidal sector. Hence, the project focuses on a design characterized by modularisation and reduced weight, based on tested and well-established operation and construction methods.

The invention consists of a staggered frame arrangement onto which a number of "wings" (2 to 3) is lowered. Each wing is a cluster of turbines (3 to 5) grouped onto a structure similar to an aircraft wing. Vertical corridors are integrated for a quick and easy launch and recovery of each wing, during both the installation and operation phases. Horizontal corridors are allowed between two consecutive turbines in order to guarantee a smooth tidal flow.

Two renders of the device, demonstrating the concept, are shown in Fig. 1 and Fig. 2.

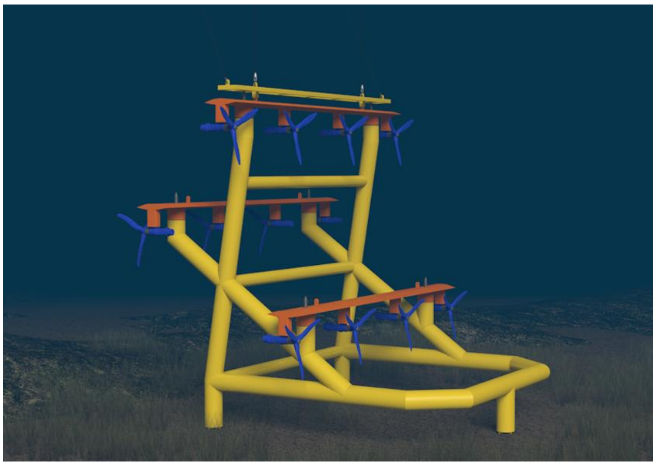

Fig. 1. Rendering of the Inyanga-Tech's HydroWing concept.

The individual wing target weight is 10t to 15t (including turbines). Each wing is lowered (or raised) for installation and maintenance purposes by means of a couple of heave compensated davits, which can be fitted to any workboat, multi-cat, barge or support vessel. The target weight of the main support structure is 120t, with an additional 250t of ballast weights for an estimated number of 9 to 15 tidal turbines.

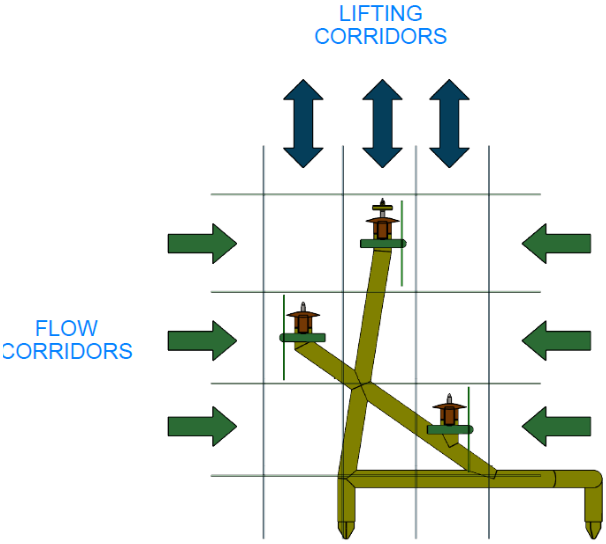

Fig. 2. Rendering of the Inyanga-Tech's HydroWing concept. Side view.

The HydroWing installation, operation and maintenance approaches are modelled around a number of innovative measures aiming at facilitating the management of the device at all stages:

- Integrated wing structure with wet mate connected to turbine support structure;
- Installation using a standard workboat, barge or supply vessel;
- Twin davits, skid mounted, to install and maintain via a controlled tandem lift;
- Fully integral launch and recovery beam with integrated instrumentation;
- No requirement for remote operated vehicles (ROVs) nor cranes;

- Minimal manpower requirement for launch and recovery.

These ideas are summarised and graphically represented in the render in Fig. 3.

Fig. 3. Rendering of a generic operation with one of the wings of the HydroWing concept.

These objectives are achieved through:

- Development of a cost optimised multi-turbine foundation structure;
- Lower balance of costs by integrating several turbines as a single unit;
- Spread fatigue load into the base structure in a balanced manner (over wings and support structure connection points) in such a way to increase fatigue life of the overall support structure;
- Development of a robust O&M strategy eliminating the dependency on big offshore vessels;
- Use of tried and tested subsea operation hook-up methodologies;
- Development of a purpose built fully integrated Launch and Recovery system (LARS) that can be easily integrated on any flat deck work vessel, removing the need for cranes;
- Creation of an intelligent business model able to exploit tidal energy on a commercial scale.

III. ASSESSMENT AND IMPROVEMENT METHODOLOGY

The University of Exeter supported the development of the HydroWing technology through a feasibility study of the device, with particular emphasis towards the O&M related strategic decision. More specifically, a study aimed at providing an effective O&M strategy, able to maximize availability while reducing through life operational expenses (OPEX), was carried out in order to assess the preliminary feasibility of the concept.

In order to do so, a set of computational tools developed at the university was employed. This set is constituted by a model for the estimation of the key performance indicators (KPIs) of an offshore renewable farm, and another for the methodical and automated proposal of ameliorating alternatives. Both models are integrated in an individual framework for the strategic improvement of the O&M assets and logistics of an offshore energy farm.

The first model [8] is based on a discreet-time Markov Chain Monte Carlo simulation, which is a common approach in this area, for the prediction of the performance parameters of the simulated array of devices. For this reason, it is indicated in this work as "characterization model". This exploits the metocean data of the location where the offshore farm is or will be located, together with all the specifications of the projects in terms of devices, vessels and maintenance strategies. Hence, a large number of inputs, mechanisms and constraints are considered in order to obtain a series of outcomes that depict the offshore farm in terms of its reliability, availability, maintainability and profitability.

The second model [8–10] is used in order to automate the optimization procedure needed to improve the technical and economic viability of the devices. For this reason, it is indicated in this work as "optimization model". This is achieved by exploiting a novel approach that applies evolutionary algorithms to the ocean renewables context. This approach explores a high number of candidate solution to the problem of managing the maintenance assets for an offshore renewable farm. Thus, it provides a series of optimised trade-off solutions in terms of cost, reliability and availability generated as a result of the choice of each solution. As a result, once the favourite trade-off among these objectives (minimize costs, maximize availability, maximize reliability) is chosen, the procedure permits to make decisions regarding the two fundamentals aspects of the farm from an O&M point of view, namely the maintenance vessels and the properties of the device components. The strategic decisions which characterize these aspects can be defined in terms of [10]: the number of units for each maintenance vessel; the possibility of performing maintenance interventions overnight; whether to charter or purchase the maintenance vessel; whether to limit the use of the vessels to specific periods of the year (e.g. summer months); whether for each component of the devices redundant elements should be installed (compatibly to technical constraints); whether for each component of the turbines, a more reliable alternative should be installed (i.e. with a reduced failure rate); and whether for each component of the device there should always be an immediate availability of spare parts.

Each of these decision will affect, to different extents: the reliability of the devices, the availability of the tidal farm and the overall O&M costs. The final objective is finding the optimal value of each decision variable in the problem of optimizing O&M and logistics for offshore renewable devices.

Both models are fully described, together with exemplificative case studies, in references [8–12]. This combination of tools provides a comprehensive characterization and optimization methodology, useful to evaluate the effectiveness of an offshore renewable project, suggest suitable improvements, and as a result reduce its costs and increase its economic viability. A simplified flowchart of this integrated framework is shown in Fig. 4.

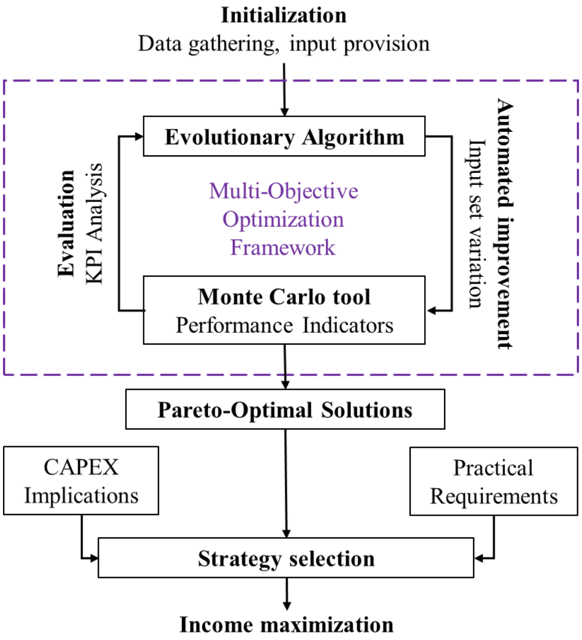

Fig. 4. Simplified Flowchart of the implemented optimization methodology

A. Input data

Following the preliminary considerations presented in sections I and II, a first simulation is run using the characterization model in order to achieve a base case scenario. As mentioned in previous section III, In order to characterize the project a series of input data need to be gathered. These are: metocean data of the selected location, reliability data of the device (in terms of its subsystems and components), capabilities of suitable maintenance vessel(s) to be tested for maintenance activities, strike price for the electricity produced, and eventual modifications that have an effect on capital expenditures (CAPEX). The sources and considerations on the selected input data are hereinafter reported.

Metocean data: Skerries, in North Wales, is selected as a suitable location for this study. ADCP measurements are used to obtain the current speed data, whereas the wind and wave are downloaded by the open-access platform SOWFIA [13,14]. The total simulated period is 10 years, with a timestep of 1 hour.

Tidal turbine: Several turbines and models were initially considered for this study. However, after an analysis of the available metocean resource, especially the current speed distribution, the selected turbine is the Tocardo T100 with a rotor diameter of 6.3m [15]. The rated power of this turbine is 42kW. Thus, the rated capacity of one device is 0.63MW (assuming 15 turbines are mounted on each device, 5 per wing) and 16 HydroWing devices are needed to get a farm of 10MW of installed capacity.

Reliability and other components' data: Due to the novelty of the tidal sector and the scarcity of open source repositories, retrieving reliability data extracted from operational experience is extremely challenging. As a consequence, reliability data are estimated based on specifically adapted databases, extracted from existing information regarding the same components, but used in different environments, and properly adjusted with correction factors in a procedure called Reliability Assessment. In this case, both taxonomy (subsystem and components) of the tidal turbines and failure rates have been extracted from [16]. Procurement and repair times, as well as repair and replacement costs, are assumed on the basis of research in the market, previous works [8], and experts' opinion. The number of spare parts in stock is decided according to the failure rates of each component and repair price.

Maintenance vessel: the installation and maintenance philosophy for this device contemplate the use of an individual vessel for all kinds of operations, in order to decrease expenses as a consequence of long term charters or, possibly, the purchase of a dedicated vessel. According to dimensions and weight of the turbines and the support structure, a small/medium size vessel with dedicated launch and recovery system (LARS) is expected. Thus, a dynamic positioning (DP) Multicat type vessel is initially selected for the study. The related capabilities, used to calculate transit times from the maintenance port located in Holyhead using Mermaid [17], are extracted from previous works [8,18] and existing database [19]. The crew working shift is fixed to 12 hours.

Economics: the electricity strike price is initially set to 305£/MWh according to the prices for tidal energy generation in 2018/19 set in [20].

IV. RESULTS

A. Base case

Once that the initial input data are gathered, a simulation using the O&M models is run and a series of key performance indicators for the farm obtained. The results are not encouraging, due to the high number of failures and the limits in reparability using only one vessel, which in turn leads to high downtimes. In summary, the theoretical maximum (without any failure) annual energy produced by the entire farm is 40722.04 MWh/Year, corresponding to a capacity factor of 46.12% or 4039.89 equivalent hours. However, when the failures and consequent downtimes due to maintenance interventions are considered, these values drop to 4793 MWh/Year, corresponding to a capacity factor of 5.43 % or 475.54 equivalent hours. In terms of availability, this corresponds to 11.84% of energy-based availability. These values lead to serious consequences in terms of economic performance of the project, with lost production due to downtime of £108m and, adding direct O&M cost (sum of repair costs, crew cost and vessel costs) of £20.55m, a negative final generated income of £-5.93m.

Looking at the results of the simulation, the main reason for these outcomes is the insufficient number of vessels (only 1), which is not capable of satisfying the maintenance demands of the whole farm. This happens because, due to either unavailability of suitable weather windows or the insufficient speed in performing maintenance operations, too many devices enter in downtime as a result of the failure of one of their components at the same time. In other words, when there is a problem with one of the devices, if contemporarily another problem arises in another device, this has to stay in downtime until when the vessel has finished with the repair of the first device and is ready for the following intervention after having returned to port. This can be seen in Fig. 5, in which the proportion between operating and not operating time for each of the devices in the farm during the simulated period is shown.

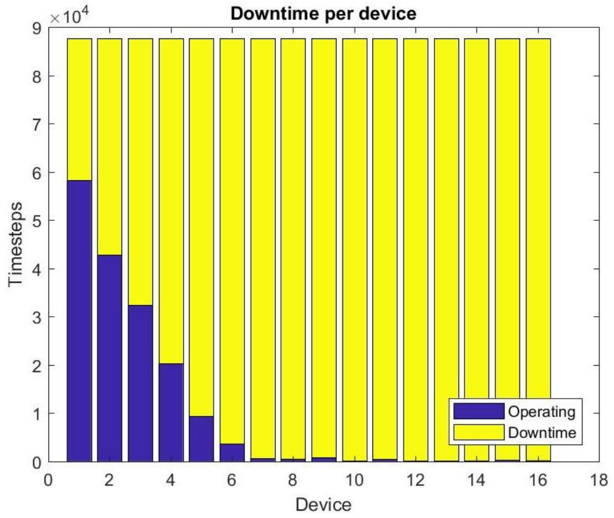

Fig. 5. Operating and not operating time for each of the HydroWing devices during the simulated period

Hence, the fundamental issue in this base case is the combination of insufficient number (or capability) of the maintenance vessel together with low reliability of the device. Regarding this last point, as shown in Fig. 6, the most sensitive component is the generator of the device, which contributes to most of the failure (up to a quarter of the total number of failures), followed by the blades and the inverter.

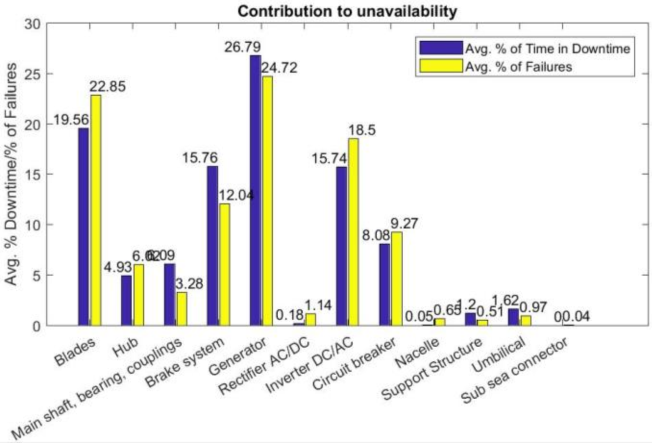

Fig. 6. Percentage contribution (average through simulations) to total number of failures and total downtime caused by each component.

Something important to notice is that, for this simulation, all components are considered critical for the whole device, meaning that if one of the components fails, the entire device will enter in downtime as a consequence of that failure. However, this is a conservative hypothesis which is not necessarily representative of the investigated concept, because since a multiple number of turbines (15) are installed on the same support structure, if one of these turbines fails nothing prevents the others from producing (unless one of the shared components, e.g. the transmission cable, fails). Another relevant observation is that the failure distributions for all the considered components are exponential, which translates into a constant failure rate, and therefore prevents the assumption of an improvement in reliability over the years as a result of a plausible learning process with the device. On top of this, since the number of spare parts is limited for all components, there is a procurement time to be added to the total repair time when the failure happens.

B. *Improved scenario*

Following the results of the base case, a number of input parameters are modified with the intent of improving the outputs of the simulation. These modifications consisted of:

Reducing the number of components: based on the assumption that integrating components would reduce balance of plant costs and improve the reliability of the device, three of the previous components (rectifier AC/DC, inverter DC/AC and circuit breaker) are clustered into an equivalent component, i.e. the converter;

Redundancy of components: the number of subsea connectors is increased from one (for the whole device) to three (for each of the wings of the support structure). This allows the remaining wings to operate if one of the connectors fails;

Maintenance vessel: a different type of maintenance vessel is considered for the simulation. A platform supply vessel (PSV) is considered due to having charter costs and fuel consumption rate similar to those of the previously considered Multicat type vessel, but higher operation limits, extra space on the deck and easy adjustability for external components, e.g. the launch and recovery system (LARS) needed for the maintenance of the devices. In addition, a long term charter, in order to have the vessel permanently on location, is now assumed as the charter strategy;

Computational model: the capability of modelling a partial functioning of the device is now added to the characterization model, in order to allow the use for a multi-turbine device. In this way, if one of the turbines enters in downtime, the rest of the device will keep producing at a proportionally decreased capacity;

Total installed capacity: the project is extended to a 30MW farm, in order to justify both the permanent charter of the PSV onsite and the use of an onshore warehouse to be used as a spare parts storage and maintenance facility (therefore removing the waiting times due to procurement of spares in case of replacement);

Turbine model: an updated (with higher rated power) version of the turbine, the Tocardo T200 (9m diameter) [21], is selected in order to achieve the adjusted installed capacity with a lower number of devices.

Economics: The strike price for electricity is decreased to 150 £/MWh in order to consider a more realistic estimate for the contract for difference (CfD) in the UK.

Most importantly, after these manual changes in the inputs set, the optimization model is used in order to establish the ideal value of these decision variables in a bottom-up procedure. However, for this case study, the capabilities of the algorithm are only partially exploited because several constraints are imposed in order to limit the search procedure, according to the preliminary considerations stated in previous sections. In other words, the choice on number of units for the maintenance vessel is limited to one, the possible reduction in failure rate is not contemplated because only off the shelf components are considered, and eventual redundancy is allowed only for umbilical and subsea connector. According to these restrictions, the outcomes of the optimization framework suggest to: use the PSV rather than the DP Multicat, have it available for maintenance throughout the year (purchase (new or second hand), bareboat charter or similar arrangement), enable overnight maintenance interventions, apply redundancy on the subsea connectors (keep three instead of one), have at least a spare part always available for all components.

Once that the ideal values for each decision variable are established, compatibly with engineering constraints, the simulation with the characterization model is repeated and new results are obtained. This time the results are significantly more promising than in the previous simulated case, estimating the energy produced by the entire farm as 1154233.36 MWh/Year, corresponding to a capacity factor of 43.9% or 3845.52 equivalent hours. In terms of availability, this corresponds to 93.93% of energy-based availability. The lost production due to downtime is £11.19m and, adding the direct O&M cost (sum of repair costs, crew cost and vessel costs) of £31.33m, the final generated income is £141.8m over the 10 simulated years.

Preliminary calculations on capital expenditures have been made in collaboration with marine services providers, taking into account design and consent, survey preplanning, foundations design and build, substations and cables procurement, turbines purchase, offshore installation and onshore works. For a project of 30MW, CAPEX resulted in estimated figures of around £120m. Hence, deducting these figures from the generated income estimated above, a reasonable margin of around £20m profit is obtained over the 10 years simulated period. This bodes well for the viability of the project, especially if a longer payback period over which the initial costs can be spread, e.g. 20 years, is considered.

With regards to the other results, this time the most sensitive components (contributing to almost one third of the total number of failures and of the total downtime of the offshore farm) is the converter. This could be somehow expected because now it groups three of the components considered in the previous cases (inverter, rectifier and circuit breaker). The generator is the second component with most failures over the simulated period, followed by the blades. This is shown in Fig. 7.

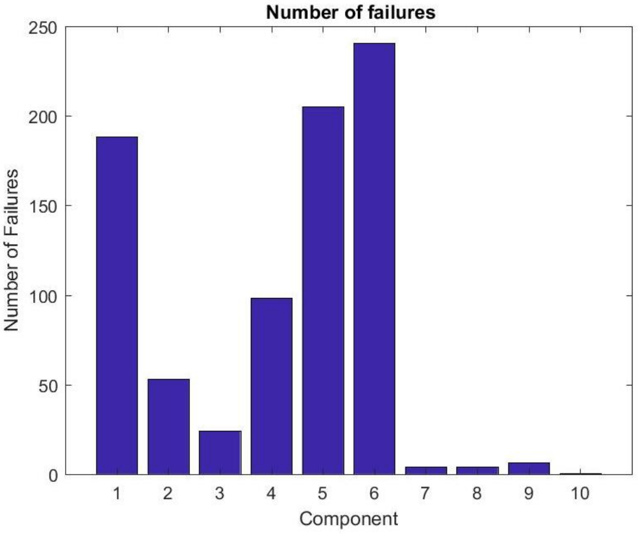

Fig. 7. Number of failures for all devices (average through simulations) over the simulated period, per component[1].

However, as shown in, the component that causes by far most of the maintenance costs due to repair/replacement actions is the generator of the device, accounting for around 60% of the total spare parts cost. Also the repairs

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[1] List of components: 1 = Blades; 2 = Hub; 3= Main shaft, bearing, couplings; 4 = Brake system; 5 = Generator; 6 = Converter; 7 = Nacelle; 8 = Support Structure; 9 = Umbilical; 10 = Subsea connector.

of the brake system contribute significantly, reaching around 22% of the total spare parts cost.

When all the maintenance costs are analysed, the long term charter of the vessel results in being the highest cost driver, followed by the production losses. Curiously, the cost of the maintenance crew are more than those of repairs/replacement. In this regard, it must be noticed that the cost for each crew technician is set to 250£ per day, without making an eventual distinction between project crew and vessel crew.

An ulterior important result is that related to the utilization of the maintenance vessel, the PSV. This, has been used for 824 corrective maintenance operations, allowing the entire farm to operate at full capacity (all components of all devices operational) for only 12% of the simulated time.

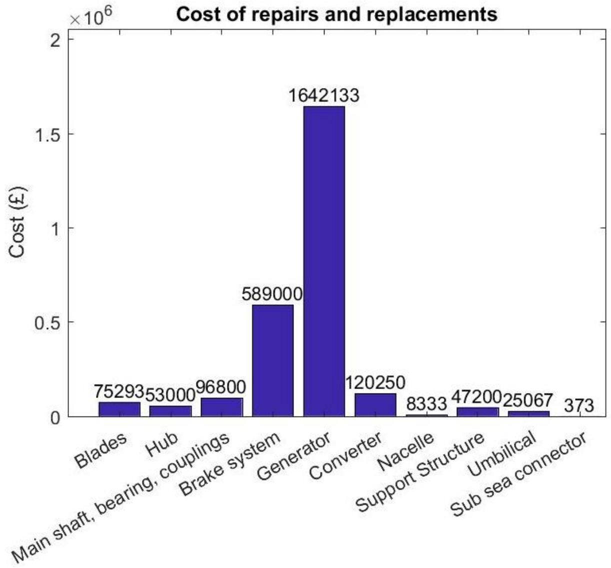

Fig. 8. Cost of repairs and replacement (average through simulations) over the simulated period, per component.

Considering the repair times during each intervention, as well as the transit times between the maintenance port and the offshore location, the total utilization time of the vessels corresponds to an amount of hours close to the entirety of the simulated period. In other words, this means that the maintenance vessel has been used for almost every day of operation, certainly justifying the long term charter or purchase of the vessel but also opening to the possibility of chartering another one in addition, with reduced or similar capabilities, to support maintenance.

Finally, further considerations can be made by superposing the probability distribution of the current speed and the power curve of the selected device, as shown in Fig. 9. Here it can be seen how despite a significant part of the resource is exploited by the devices, either at full or reduced capacity, there is still a consistent amount which is not fully exploited due to the lower yield site. Thus, a more energetic location or a turbine capable of producing more at lower current speeds could be considered to fully exploit the energy extraction.

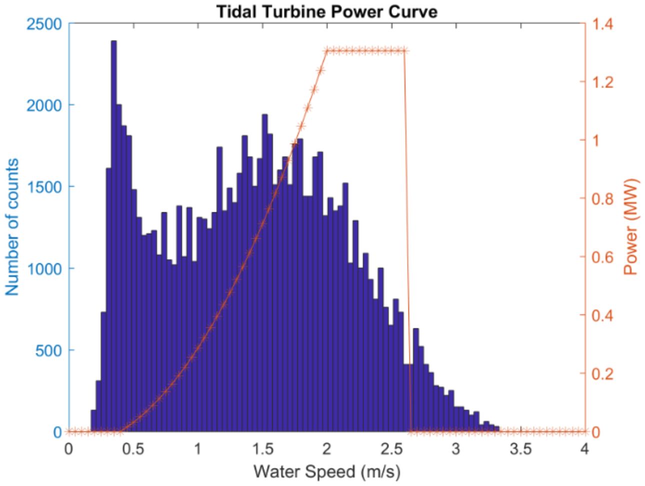

Fig. 9. Current speed distribution of the selected location and tidal turbine power curve.

V. DISCUSSION

The results provided in this study permit to identify the areas for improvement in the current concept of the project, as well as allowing for the proposal of ameliorating ideas in the project planning. Among possibilities for the manual improvement of the O&M strategy and offshore farm's performance, which would translate in further variation of the inputs set, it is worth considering:

- the use of a refined taxonomy (list of components) and reliability data, following discussion with the manufacturer of the selected tidal turbine;
- the option of simulating the servicing of the turbines onshore, as opposed to the current in situ repair strategy;
- the evaluation of a bigger project, e.g. 100MW, with a view to techno-economic scaling. This would further justify the possible use of more than one maintenance vessels, not necessarily of the same kind;
- the introduction of a batch repair threshold considering the number of components of the same kind that have to fail before starting a repair operation, and the consequent introduction of a group maintenance policy (group more maintenance interventions in the same event in order to save costs);
- a baseline study against conventional devices in order to further demonstrate the viability of the project especially from a logistics and asset management perspective.

Similarly, among ameliorating alternatives of a more generic nature, it is worth mentioning:

- the evaluation of a different location, with higher average flow speeds, for the development of the project;
- the inclusion of a storage system, in order to remedy to the intermittency of the energy delivery due to the very nature of the tidal resource. Besides, this would allow to provide regular base load power to the grid and store excess energy for limited grid connections;
- take advantage of the modularity of the support structure by installing bigger turbines, for slower flows, at

the bottom wing and smaller turbines at the top where the tidal flow is fully developed.

VI. CONCLUSIONS

In this study, a lifecycle analysis of a novel tidal energy concept, as a means to improve its design using the O&M planning and assets management as a key driver, is conducted. Combining preliminary considerations, based on previous experiences with tidal stream devices, to the information gained through computational simulation, the guidelines for a viable and remunerable tidal energy project are obtained. Notwithstanding a number of restrictions, due to design and engineering requirements, this work highlights the added value computational tools can provide in improving the performance of a project and assist in the decision-making process. In fact, the use of such tools permits to identify the major cost drivers and areas of improvement, propose suitable remedies and alternatives in a methodical way, and obtain improved solutions for the amelioration of the assets management. In this way the availability and remunerability of the project are maximized, while the operational expenses through life minimized.

On the other hand, the computational tools can be also further improved as a consequence of their use with novel tidal concepts, requiring ad hoc modelling capabilities in order to realistically capture their dynamics.

Despite further analysis is needed in order to fully include all the implications of capital expenditures, the preliminary results indicate that the project is commercially viable and there is a suitable margin for economic return. The approach proves to be fundamental in order to assess the feasibility of a project, understand limitations and challenges for its management, advance strategies for the mitigation of the criticalities and, most importantly, support the concept development.

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