Capability Assessment of DTOcean Array Design Tool for Ocean Energy

Tianna Bloise Thomaz, Leonore van Velzen, Henry Jeffrey, Encarni Medina Lopez, and Tom Wills

***Abstract*—There are several tools to assist in the development of ocean energy technologies. DTOcean (Optimal Design Tools for Ocean Arrays) is the first open-source tool that enables all stakeholders to investigate the optimal design of an ocean energy array, combining different disciplines together. DTOcean is a collaborative project funded by the European Commission under the H2020 LCE-15-2016 call.**

The present work assesses the applicability of DTOcean to design an ocean energy array by comparing the results of DTOcean with design choices made by a team of expert engineers for an existing array of three tidal devices. This paper compares DTOcean design choices and the design choices made for the existing array regarding Hydrodynamics, Electrical Sub-systems, Moorings & Foundations, Installation, and O&M. Limitations of the current version of DTOcean are identified, and improvements suggested. Some limitations can be attributed to DTOcean's focus on the optimisation of a large scale commercial farm, such as the requirement of an offshore substation. Other limitations are not related to the size of the array but to assumptions on specific approaches - such as the need for a specialist cable laying vessel - which differ from practical experience. Such limitations can lead DTOcean to make different design choices. Nonetheless, with appropriate assumptions, DTOcean estimates of Levelised Cost of Energy (LCOE), capital and operational costs and Annual Energy Production (AEP) agree broadly with experience from a real-world tidal array. Learning from the DTOcean project is now supporting the development of an improved DTOcean+ tool.

***Keywords*— DTOcean, Demonstration Project, Optimisation Tool, Tidal Energy Array.**

I. Introduction

OCEAN energy can help meet renewable energy targets, with the overall aim to reduce carbon emissions to tackle climate change and provide security of energy supply. The industry association, Ocean Energy Europe, estimates that 100 GW of installed wave and tidal energy capacity could be installed in Europe by 2050 [1]. Ocean energy deployments also bring socio-economic benefits: jobs, investments and reduction of carbon footprint [2].

At present, the ocean energy sector is focussed on the development of technologies from demonstration projects to the market. Comparing wave and tidal energy, the latter is at a further stage in the path to market. Tidal energy has progressed to technology convergence around horizontal axis turbines, as witnessed in the wind industry. Whereas the wave energy sector is currently focussed on single device demonstrations, tidal energy devices have moved towards multi-device demonstration arrays. A range of challenges need to be tackled to move the ocean energy sector from demonstration to commercial stage.

The European funded ETIP Ocean project [3] has identified technology, finance, environmental and socio-economic challenges encountered in the ocean energy sector. A set of fourteen priority challenges were selected, of which 'developing and implementing optimisation tools' is one. There is a range of different tools to assist in the development of ocean energy technologies. The EU-funded project Optimal Design Tools for Ocean Arrays, DTOcean [4] (ID: 608597), which ran between 2013 and 2016 under the 7th Framework Programme, developed a software tool to assist in the industrial development of ocean energy arrays. This open-source tool enables all stakeholders, from industry to governments, to investigate the optimal design of ocean energy arrays.

To reach the development targets of ocean energy deployment, European policies support the progress of the sector through funding programs. EnFAIT, "Enabling Future Arrays in Tidal" [5], is an R&D and technology demonstration project which received Horizon 2020 funding in 2017. The tidal energy developer, Nova Innovation Ltd, is the lead partner on this project (ID: 745862) which runs until 2022, demonstrating a grid-connected tidal energy array. EnFAIT explores the layout of tidal turbines in an array to investigate the interactions

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and optimisation of a real tidal energy site. An additional three turbines will be installed and subsequently relocated, to better understand wake effects. It aims to build investor's confidence to move the sector forward to commercial projects.

This paper evaluates the application of DTOcean for the design of a tidal array and identifies improvements to the tool through a comparison with the design choices made for the EnFAIT tidal array.

The paper presents potential tools to support ocean energy deployment in Section II. The methodology of DTOcean, and a comparison analysis follow in Section III. Section IV determines the case study, of which results are presented and discussed in Section V. The overall conclusions are presented in Section VI.

II. Background

Designing a tidal energy array is a complex process, similar to those of offshore wind energy farms, where the primary focus is on maximising profits through optimising the Annual Energy Production (AEP) [6] and reducing operating costs. In a tightly packed array of many devices, production losses from wake interactions an electrical effects must be minimised.

There are many hydrodynamic models and studies that consider array interactions and wake effects by modelling the environmental conditions and device characteristics [7, 8, 9], however the EnFAIT project will be the first time that these effects are quantified at full scale on a grid-connected array of so many turbines.

The electrical design involves electrical layout decisions and calculation of electrical losses. Power World [10] is a tool used by academia to define power losses of a pre-defined electrical system.

The design of mooring and foundations involves the definition of optimal foundation type to minimise costs. There is commercial software in industry, such as Orcaflex [11], to define mooring design loads.

Installation models consider installation procedures and calculate their time and cost. Software like Mermaid [12] assists with the definition of optimal weather windows to reduce costs. The required operations are specified, for example the installation order and vessel data, and Mermaid works out the optimum way to carry out these operations based on input time series Metocean data. In the same way, Mermaid can also be used to plan maintenance interventions.

O&M models are also developed for the definition of a maintenance strategy, calculation of availability, costs and fuel consumption that feeds environmental studies. Wave Energy Scotland (WES) [13] developed an open-source O&M tool for the estimation of OPEX, which assists in the definition of the Levelised Cost of Energy (LCOE). Due to the current stage of the sector, many projects adopt a simplified estimation of these metrics. In these cases, costs are estimated as a percentage of CAPEX [14]. O&M models should be linked to reliability evaluation, in order to define the maintenance plan [15]. Tools like AvSim and RCM (Isograph) are used to plan and predict maintenance polices, for example by the use of logical interaction of failures.

Once the aforementioned cost centres are defined and the AEP is calculated, the economic assessment can be performed. Normally, projects define their own tool for the economic estimations of a project. Some projects also evaluate environmental and social impacts along with socio-economic benefits. The environmental assessment, such as Life-Cycle Assessment (LCA), can be used to estimate and compare carbon emissions of a project when compared to fossil fuel generation sources [16]. Positive externalities for a society are highlighted in Socio-Economic Cost of Energy (SCOE) studies, showing the social benefits, such as the number of jobs supported [2].

The aim of DTOcean is to combine aspects of all of these disciplines and develop an open-source tool to assist ocean technology developers and investors to make smart and cost-effective design choices for ocean energy arrays.

III. Methodology

DTOcean was a European funded project, which ran between 2013 and 2016 with eighteen partners throughout Europe, providing a base of expertise in the relevant areas for the development of this suite of tools. DTOcean designs an ocean energy array at a certain location for a chosen technology type, going through the following stages: Hydrodynamics; Electrical Sub-Systems; Mooring and Foundations; Installation; and Operations & Maintenance. These stages are defined as "*Modules*". Each of these *Modules* can be assessed by three *Assessments*, namely Economics, Reliability, and Environmental. The software architecture is shown in Fig. 1.

This paper does not analyse the choices for the computational modules or the thematic algorithms, but investigates the DTOcean results for a certain case study. A general overview of the *Modules* and *Assessments* is given in the following subsections, with examples of algorithms and/or design structures [17, 18].

A. Hydrodynamics

This stage calculates the power output of the energy converters, providing an array layout based on the optimal power generation or Annual Energy Production (AEP). The q-factor (1) indicates the hydrodynamic interaction between the turbines in the array; it is an index for the energy loss. The user provides a threshold, indicating the minimum q-factor.

$$q - factor = \frac{AEP}{AEP_{array\ without\ interaction}} \quad (1)$$

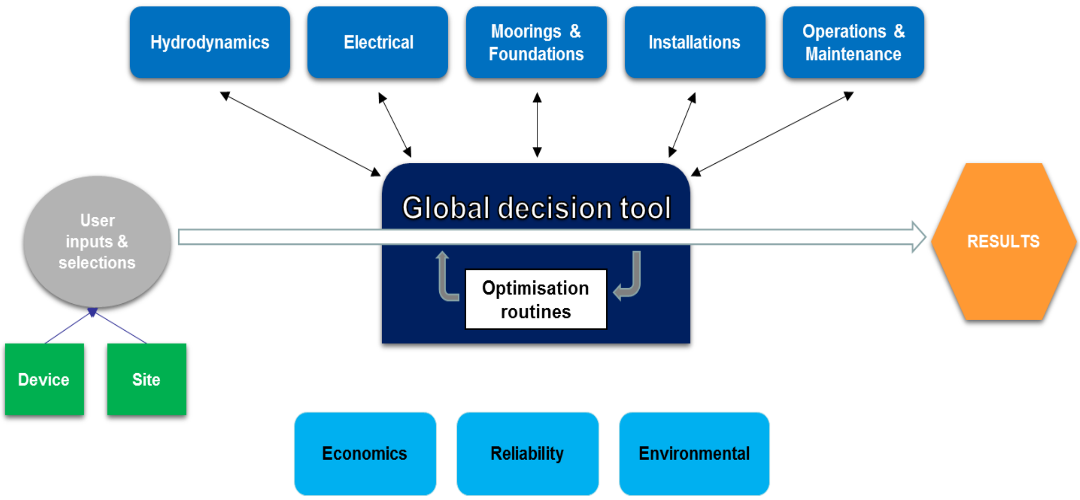

Fig. 1. Architecture of DTOcean, Design Tool for Ocean Energy Arrays. The image illustrates all the *Modules* and *Assessments* of DTOcean, as well as the representation of inputs, outputs and optimization process.

The determination of the turbine locations is restricted by the no-go areas, the minimum distance between the turbines, the maximum number of turbines, and the q-factor.

B. *Electrical sub-systems*

The Electrical Module designs the electrical layout for the array as determined in the previous Hydrodynamics Module. It considers all electrical sub-systems, such as the umbilical cable, the electrical connectors and the offshore collection points. The network relies on the transmission voltage, capacity and number of the transmission cables; number, location and type of offshore collection points; the intra-array network topology; and the optimal cable routing. The architecture of this module is shown in Fig. 2.

The restrictions to the design of the electrical network are formed by the physical environment, power flow constraints and available components.

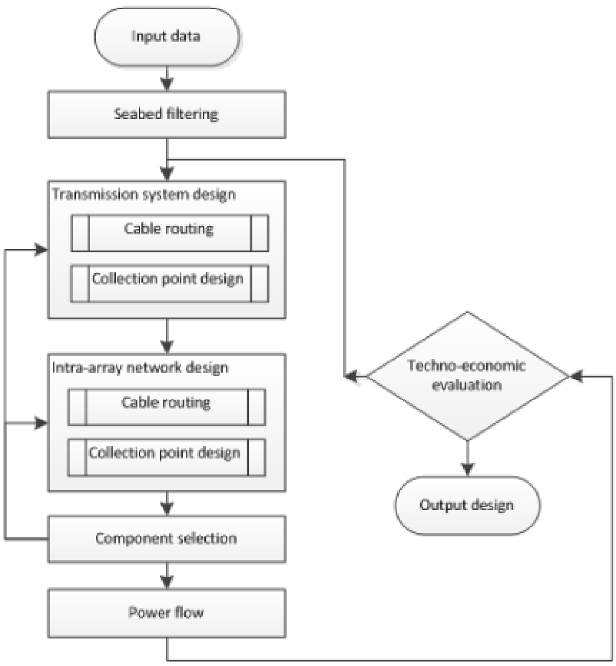

Fig. 2. Top-level overview of the architecture of the Electrical Sub-Systems Module of DTOcean [15].

C. *Mooring and foundations*

This module evaluates the optimal types of mooring and foundations for the array, based on the lowest capital cost. This is established through static and quasi-static analysis to determine suitable moorings and foundations for the investigated scenario, to retain the integrity of the electrical umbilical cable. The constraints of this module are determined based on reliability and environmental data provided by the user. As the module searches for the lowest capital cost, this is also a constraint. This module provides the user with the option to pre-select the mooring or foundation type, and locations.

D. *Installation*

In this module, the installation procedure of the array design as determined in the previous modules is proposed based on the lowest cost. This module consists of nine different logistic phase options, namely installation of ocean energy converter devices, driven pile foundations, gravity based structures, mooring systems, static export power cables, static inter-array power cables, dynamic power cables, offshore collection points, and external cable protection. These logistic phases are combined through the external logistic phase sub-module. This is followed by the installation procedure definition sub-module, which determines the sequence of the logistic phases and the base installation port. In the next sub-module, the logistic functions assessment sub-module, assesses all marine operations for operation. The installation module is completed with an optimisation routine to find the lowest cost solution.

E. *Operation and maintenance*

Based on the reliability of the sub-systems, the maintenance activities are determined. This module, as for Mooring and Foundations and Installation, searches for the O&M plan with the lowest impact on LCOE. The user indicates the maintenance approaches, namely corrective, calendar/time based, condition based maintenance, or a combination of these. The latter two are preventive measures (Fig. 3).

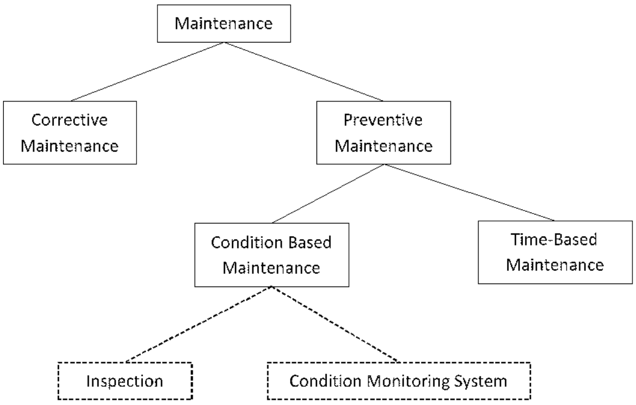

Fig. 3. Maintenance strategies adopted in DTOcean [15].

F. *Assessments*

1) *Economics*

The economic assessment is based on a set of functions used to calculate the LCOE (2), which follow from the results from the *Modules* as well as the user input. Of the set of functions within the economic assessment, the main inputs can be divided in the 'bill of materials', the 'energy output table' and the user-defined discount rate.

$$LCOE = \frac{\sum_{i=1}^{n} \frac{CAPEX_i + OPEX_i}{(1+r)^i}}{\sum_{i=1}^{n} \frac{AEP_i}{(1+r)^i}} \qquad (2)$$

2) *Reliability*

The Reliability Assessment Module (RAM) constructs the reliability of the sub-systems, which are given as user outputs, as well as feedback into the O&M module to be able to determine the required activities. The RAM was not a focus point in this study.

3) *Environmental*

The Environmental Impact Assessment (EIA) provides a qualification and quantification of the potential pressure of the design choices on the environment. This is done by giving an Environmental Impact Score (EIS). The EIA was not a focus point in this study.

This paper was written based on the application of DTOcean to a real tidal energy case study in which three devices have been deployed. As this tidal array is one of the first of its kind, the knowledge of this project can be of significant use to the sector and the development of DTOcean. The comparison between the existing array and DTOcean results gives recommendations for the further development of the suite of DTOcean software tools.

IV. Case Study

This section presents a case study that demonstrates the methodology that discussed in Section III, which was used to design an optimal system for ocean energy arrays. The case study of the existing array located in Bluemull Sound, in Shetland in the north of Scotland, is taken as the input scenario for DTOcean to be able to make the comparison of the numerical results and the deployed devices.

DTOcean contains an internal database with reference data. Some examples of the main items are vessels, equipment, ports and Failure Rates (FRs). DTOcean does not use the library for all input values, but additional input data is required to determine the specific scenario. Examples of this are environmental data, type of turbine, and bathymetry of the lease area and cable corridor.

The environmental data at Bluemull Sound was collected with three Acoustic Doppler Current Profilers (ADCPs), followed by an extrapolation of these points to arrive to an hourly average velocity Fig. 4. shows the Nova innovation tidal turbine M100 with 100kW rated capacity.

Other assumptions of the case study are a discount rate of 10%, a project lifetime of 20 years and a project start date on the 1st June 2020. The start date has an impact on the weather windows and therefore on the offshore activities.

Fig. 4. Nova Innovation tidal turbine M100 bi-directional turbine with 100kW rated capacity.

The DTOcean database can be altered, adjusting values and adding new items to it. DTOcean contains a list of fifty vessels, which are divided in different classes, such as heavy lift installation and offshore support & maintenance. For this scenario, the type of vessel used by Nova Innovation for the offshore activities (a Multi-category workboat) was added.

The library provides FRs for components of the ocean energy system. The FRs of the device, however, need to be specified as additional input data. The list of ports was also altered for this case study, and closer ports to the deployment site (ports of Cullivoe and Belmont) were added.

V. Results and Discussion

This section compares the results presented by DTOcean and the design choices made by the existing array deployed at the Bluemull Sound. This section discusses the reason for different design choices and highlights areas with similar choices.

G. *Hydrodynamic*

Fig. 5 shows the array layout defined by the DTOcean Hydrodynamic Module and the existing array layout. The figures show the complete lease area. The cable corridor is not shown in these figures. For the same lease area, there is a difference between the two cases among the placement of the turbines' layout and a difference regarding the turbine's orientation. Still, there is a similarity in the AEP produced in both scenarios.

DTOcean results consider the turbines distributed across the lease area, whereas on the existing array the were placed in the southern end of the lease area. The chosen arrangement of the existing array was based partyly on the minimisation of subsea export cable length and the ability to carry out offshore activities on more than one turbine with the same mooring spread whilst having enough lateral space between the turbines to avoid risking collisions, to improve reliability and minimise cost and environmental impact. DTOcean, however, places the devices as far apart as possible. In the Hydrodynamic Module, DTOcean does not take the next stages (such as the cost of O&M, installation, environmental or reliability impacts) into account. The Hydrodynamic Module considers the optimization of AEP to define the location and orientation of turbines.

There is also a difference between the two cases when considering turbine orientation. The design of the existing array considers the direction of each turbine individually, to minimise the interaction between turbines and avoiding wake effects having a negative impact on the annual energy production. DTOcean does not allow different orientations for each device. The DTOcean case presents one orientation for the entire array. Due to the large distance between turbines, there is no interaction between them and thus no reduction of AEP due to the wake effects.

Therefore, although the turbine's layout and orientation are different for each case, the AEP is similar for both scenarios.

H. *Electrical*

Fig. 6 shows the electrical infrastructure presented by the DTOcean Electrical Module and the existing array layout. The bathymetry image shows the complete lease area and cable corridor.For the same cable corridor and lease area, a number of differences are observed.

The existing array has three export cables, through the licensed cable corridor, connected to an onshore substation. The DTOcean Electrical Module provides an offshore substation, which is a requirement of the tool. Therefore, only one export cable is needed, combined with intra-array cabling. The placement of an offshore substation is a requirement of DTOcean, this could be a logical choice for a commercial array (i.e. a larger array) but was not necessary in the case of the Shetland Tidal Array.

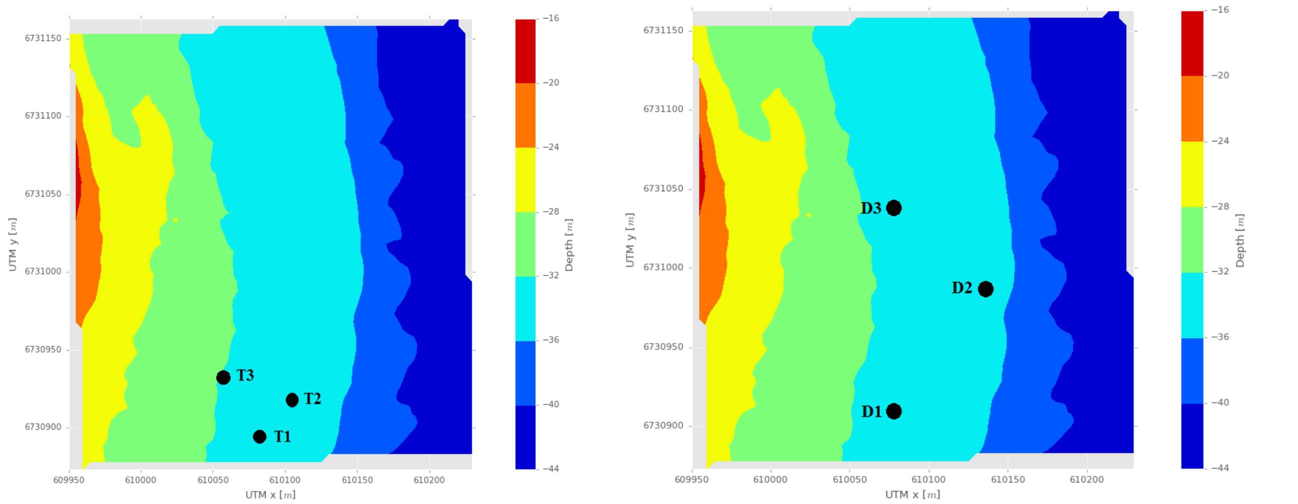

Fig. 5. Array layout for three turbines. The left image shows the design choice made by the existing array and the right one shows the results from DTOcean Hydrodynamic module.

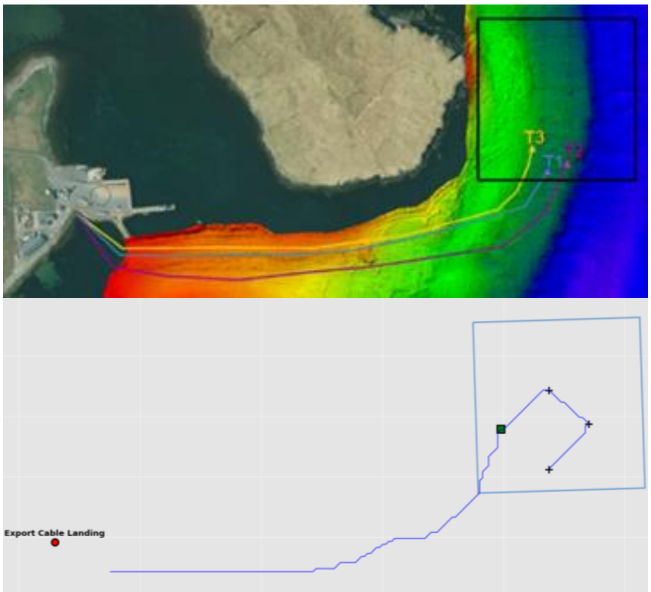

Fig. 6. Electrical design for an array of three turbines. The upper image shows the design choice made by the existing array and the bottom one shows the results from DTOcean Electrical Module.

There is also a difference between the two cases when considering the cable installation technique. DTOcean defines cutting as the cable installation technique, whereas the existing array installs the cables by laying them directly on the seabed. This laying method is not available within DTOcean. The tool options are jetting, ploughing, cutting and dredging

I. Foundations

Fig. 7 shows the design choice made by DTOcean Foundation Module for the three tidal turbines and for the substation.

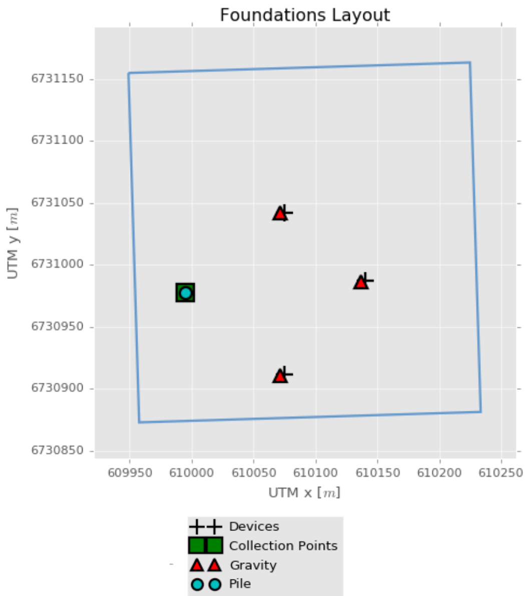

Fig. 7. Foundation design for an array of three turbines and one offshore substation. The image shows the design choice made by DTOcean Moorings and Foundations Module.

The design choices of the DTOcean Foundation Module and the existing array is similar for the device foundation mass, but different for the substation foundation type (in that no offshore substation was required on the Shetland Tidal Array). For this case study, the foundation was provided as input to DTOcean as gravity bases. This choice was made for this project, as it is a reliable and cost-effective method. In addition, retrieving the complete structure at the end of life is relatively easy with minimal environmental impact. DTOcean defines the mass of the gravity foundation, which is similar to the mass defined by the design of the existing array. The existing array gravity bases were constructed with a slightly higher mass compared to the DTOcean designs. This could be attributed to a higher safety factor for the real case demonstration project, or to the fact that the real foundations were designed to a higher level of detail using validated site data.

J. Installation

The DTOcean Installation Module provides five different stages to install the system as designed in the previous modules, namely installation of driven piles/foundations, collection point, static export cables, static array cables, and devices. To perform the different tasks of the installation plan, the installation plan includes a selection of a port, vessels and equipment.

There are a number of differences between the choices made by the DTOcean Installation Module and the choices made for the installation of the existing array, regarding port, vessel and equipment selection. However, there are also similarities when considering the installation plan and certain time slots.

DTOcean allows the selection of only one port to perform the activities. However, with the real case study, two different ports were selected for logistical reasons.

The order of the DTOcean installation plan is similar with the deployed project, excluding the installation of the offshore substation. However, a point where the existing and DTOcean array differ is the potential for executing certain activities concurrently, such as onshore preparation activities and offshore deployment operations: DTOcean does not allow this.

DTOcean’s procedure time slots (preparation time, departure delay and transit time) are dependent on the start date and the weather limit. The comparison between the existing array and the DTOcean results showed a significant difference in departure delays, with these being longer in the DTOcean analysis than witnessed on the Shetland Tidal Array. This was attributed primarily to the resolution of the metocean data used as a DTOcean input. A higher resolution is required to accurately represent the slack water periods during which most offshore operations take place.

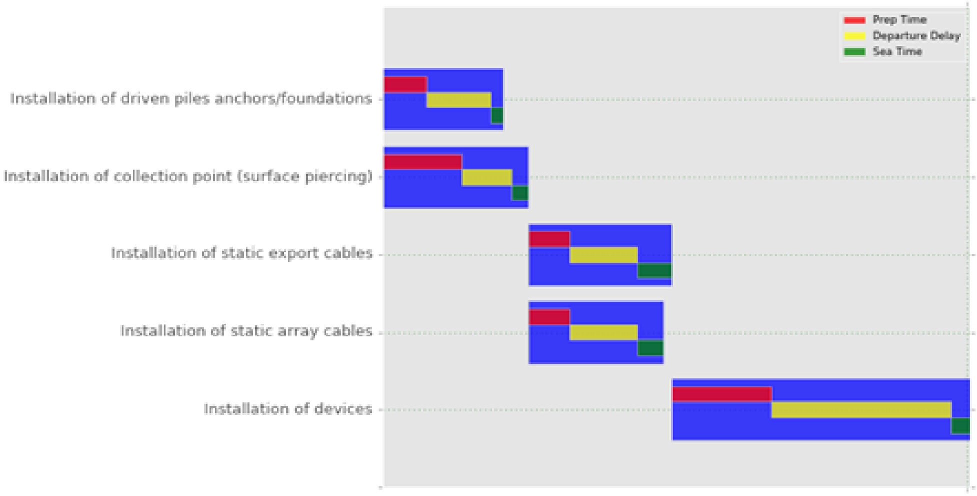

Fig. 8. Installation plan for an array of three turbines, one offshore substation, three gravity foundations, one pile foundation, one export cable and intra-array cablings. The image shows the installation steps made by DTOcean Installation Module.

K. *Operation and maintenance*

The Operation and Maintenance Module provides an O&M strategy over the lifetime of the project that minimizes the impact on LCOE. The strategy is based on a combination of corrective and preventive activities. Evidently, there is a relation between the number of preventive procedures and the need for corrective maintenance activities. DTOcean can accounts for this. Fig. 9 shows the share of costs spent with preventive and corrective activities defined by DTOcean O&M Module for this case study.

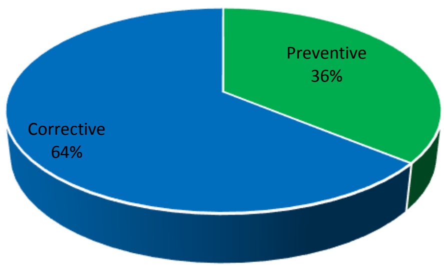

Fig. 9. Share of preventive and corrective activities provided for an array of three turbines. The image shows the results provided by DTOcean O&M Module.

The interval of planned O&M activities is defined as an input of DTOcean. As a result, DTOcean defines the number of unexpected activities, downtime of devices, costs and ultimate AEP (e.g. considering electrical losses and availability).

The maintenance strategy of the DTOcean O&M Module and the existing array have a certain similarity; the highest percentage of time and costs are associated with unexpected operations rather than planned ones. There is also a similarity regarding the downtime of devices, and the ultimate AEP.

L. *Economic*

Within DTOcean, the economic assessment is determined through the calculation of the LCOE. As already explained, LCOE is calculated using estimates for CAPEX, OPEX and AEP (2). Fig. 10 shows a comparison between the DTOcean cost centres and AEP and those of the existing array. DTOcean values are normalised with values based on the existing array.

Breaking down the LCOE cost components, there is reasonable consistency between the values from the existing array and the DTOcean results. The main differences in CAPEX can be found in the substructure cost (due to the difference in mass of the foundation as discussed in the Foundation section) and in installation costs (as Nova use a single, relatively low-cost vessel). For a reasonable comparison of OPEX, more data on the operation time of the existing array is required. Therefore, apart from a couple of design differences, cost and AEP are relatively similar.

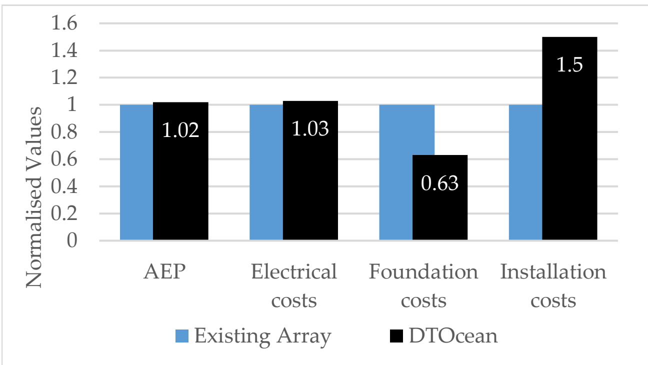

Fig. 10. Normalised values of AEP, electrical, foundation and installation costs, between results of the Existing Array and the DTOcean Scenario.

Although the input data for the LCOE calculation presents high similarity between scenarios, the LCOE values provided by the DTOcean Economic Assessment are quite different of the LCOE estimations of the existing array. It is important to note that, a sense-check of the DTOcean calculations led to the discovery of a miscalculation in the discounted values.

M. *Reliability and environmental assessments*

Both the reliability and environmental DTOcean assessments are difficult to compare with the existing array. A more accurate comparison can only be made based on extended experience with the deployed array.

N. *Further discussion*

In addition to the improvements identified with the comparison between DTOcean scenarios and the existing array, there are some other suggestions made for the improvement of the tool. The socio-economic impact evaluation as well as the decommissioning stage are not included within the first generation of DTOcean. The latter is an essential stage of a project, but when considering discounted values, it does not affect significantly the cost of energy. The SCOE is an additional evaluation to support the sector, it is a useful evaluation but not essential.

VI. CONCLUSION

This study shows DTOcean design choices for an array of three tidal devices and compares these with the choices made for the Nova Innovation Shetland Tidal Array, in Scotland. DTOcean is a tool developed to assist ocean energy stakeholders to make economic and environmental predictions for ocean energy arrays. These predictions are based on optimal design choices. There are other design tools in literature that can be applied in wave and tidal energy projects, but DTOcean is the first tool, which attempts to tie together all these different areas. The tools suggested in literature are normally focused on specific areas of the design process and limited to certain applications. DTOcean assesses the hydrodynamic, electrical, moorings and foundations, installation and O&M stages. DTOcean also provides an economic evaluation as well as reliability and environmental impact assessments.

It was found that the tool has certain limitations that require improvements. Several of these limitations can be attributed to DTOcean's aim of optimising a commercial farm (i.e. larger array), such as the requirement of an offshore substation, the restriction of only one orientation for the entire array and the obligatory selection of multiple vessels and equipment for marine operations. Other limitations do not relate to the size of the array, such as the consideration of AEP maximization only for the definition of array layout, the lack of a 'direct cable laying' option and restrictions in DTOcean's ability to model the detail of environmental condition to marine operations. These limitations resulted in several differences in design choices between the two cases. However, by making appropriate assumptions, the final economic results (e.g. LCOE, costs and AEP) can be made to align reasonably well with experience on an operational tidal energy project.

In conclusion, DTOcean is a tool that can be used to estimate the economic indicators of ocean energy arrays, based on a holistic design approach. The results of this study suggest that DTOcean may fit better when applied at an appropriate level of detail to commercial scale projects (larger arrays), which is not yet compatible with the status of the sector. Nevertheless, it can be useful to make predictions and assess cost reduction opportunities.

ACKNOWLEDGEMENT

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