Operations and maintenance optimisation for a 100 MW wave energy farm in Ireland

S. Giorgi, A. Henry, B. Kennedy, J. van ' t Hoff, R. Costello, P. Lourdais, H. Gaviglio, M. Dickson

Abstract—**Marine operations that are required for the development and service of offshore wave energy farms represent a significant proportion of the total project costs. These operations can be optimised through design and innovation to improve the LCOE of the project. This paper presents an analysis of marine operations in offshore renewable energy projects and shows the importance of early, detailed analysis and optimisation of these activities. The analysis uses general-purpose techno-economic analysis software developed by Wave Venture. The software provides an integrated engineering and financial simulation specifically designed for the needs of offshore renewable energy technology. A 100 MW wave energy farm, made up of 250 CorPower devices, off the west coast of Ireland is defined and analysed to demonstrate the capabilities of the techno-economic analysis incorporating a marine operations logistics model. The results demonstrate the strength of integrated logistics and finance software in the analysis and design of wave farms, and how these simulations can lead to significant improvements in the LCOE of offshore renewable energy projects.**

Keywords—**Wave energy converter, Wave farm, Techno-economic model, Operations and maintenance, OPEX, LCOE, CorPower Ocean.**

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I. Introduction

THIS work has been undertaken as part of the WEC.0 project, which is an Ocean Energy ERA-NET funded project seeking to develop tools for early-stage performance and cost design. The WEC.0 project is led by Rockall Research with partners Wave Venture, Mocean Energy and CorPower Ocean.

In this paper, the use of the techno-economic tool *TE™*, developed within the project by Wave Venture, is presented.

The software is used to develop a model of a 100 MW wave farm at the Atlantic Marine Energy Test Site (AMETS) off the coast of Mayo, Ireland. The wave energy converters (WECs) used for the farm are CorPower’s device [1], which is currently in the early stages of development, however, for the purpose of this study, it is assumed that it is a mature technology. The farm is made up of 250 individual WECs. The model is used to optimise the operations and maintenance (O&M) element of the project, including parameters such as the number of vessels and number of onshore teams.

The principal metric used for the optimisation is the levelised cost of energy (LCOE) but other factors, such as time to install the farm and availability, are considered. It is worth emphasising that, although LCOE is used as a metric to compare alternative scenarios, the figures are not accurate forecasts of overall project costs due to the early stage of development of the CorPower WEC and the assumptions that have been made to formulate a future scenario, in which a mature version of the WEC is installed in a large farm. The LCOE metric is simply used to compare scenarios highlighting the importance of early-stage O&M modelling and the effectiveness of the software. Moreover, it will be shown that the results of this modelling activity may have a considerable influence on the WEC farm design.

The LCOE is a well-established techno-economic metric having a standard practice within the energy generation sector, used to compare different energy production projects. [2] shows a reversed LCOE calculation procedure, by initially setting a LCOE target and successively calculating the corresponding average energy production, capital expenditure (CAPEX) and operational expenditure (OPEX); different WEC technologies are taken into consideration. In [3] and [4], Giassi presents an economical model (both CAPEX and OPEX are taken into consideration) for large-scale wave energy systems, with the objective of finding optimal configurations with minimal LCOE. In [5], the National Renewable Energy Laboratory (NREL) presents future possible economic trajectories of wave energy harvesting, by collecting and analysing the technical views of experts in the wave energy field. In [6] Castro-Santos proposes a wave energy techno-economic model based on Geographical Information System (GIS), utilised to estimate the most advantageous areas around the coasts of Portugal for the deployment of WECs, adopting LCOE as comparison metrics. Another study regarding the economic feasibility of the deployment of WECs around the Portuguese coasts is presented in [7], where the LCOE is calculated in the case of three different technologies (Pelamis, AquaBuOY and Wave Dragon). [8] investigates the impact on LCOE by changing the WEC development and design strategies. In [9], a wave energy techno-economic study is presented, where the LCOE of different WECs, based on a variety of technologies, is calculated in different regions of the North Sea (coasts of Germany, Netherlands, Belgium and France); the metocean data from the NSWD database is used for the calculation of power production. The Carbon Trust and NREL both recommend Monte Carlo simulation as a tool for quantification of uncertainty in the LCOE. The use of Monte Carlo simulation in the economic assessment of energy projects has been demonstrated by Short [10] for wind energy and Farrell [11] for wave energy. Weber et. al. [12] anticipate that techno-economic optimisation will form a crucial part of a successful structured innovation and performance-before-readiness WEC development.

The holistic nature of the *Wave Venture TE™* analysis tool means that the economic or financial consequences of technical design choices can be assessed rapidly. Without integrated software, this evaluation is only available through a long process involving multiple software packages, bespoke spreadsheets and fragile data translation and transfer. Integrated software aims to put the important metrics at the hands of decision makers and designers every step of the way, from concept initiation through R&D all the way to large project planning.

II. METHODOLOGY

The *Wave Venture TE™* software is an integrated engineering and financial analysis package, specifically designed for the needs of wave energy technology development. The software combines:

- Wave-to-wire simulation
- Logistics & operational model
- Cost model & simulated cash flow model
- Financial analytics
- Numerical optimisation

The outline structure of the integrated techno-economic optimisation is shown in Fig. 1. The components of the integrated analysis utilised for this study are the operational model, cost model and the financial cash-flow model.

The operational model simulates the logistics of wave farm installation, operation and maintenance and ultimately decommissioning. The main inputs of the operational model are the WEC power characterisation, environmental data (necessary to calculate weather windows and the system energy productivity) and a characterisation of system reliability in the form of a failure mode effects analysis (FMEA). The main outputs are estimates of the availability, energy production and operational resource usage such as vessels, ports and maintenance teams. The advantages of this approach are that the availability and the operational expenditure are calculated by the simulation based on verifiable inputs, such as the number of utilised vessels or maintenance teams, instead of arbitrary availability percentage and arbitrary operational cost assumptions.

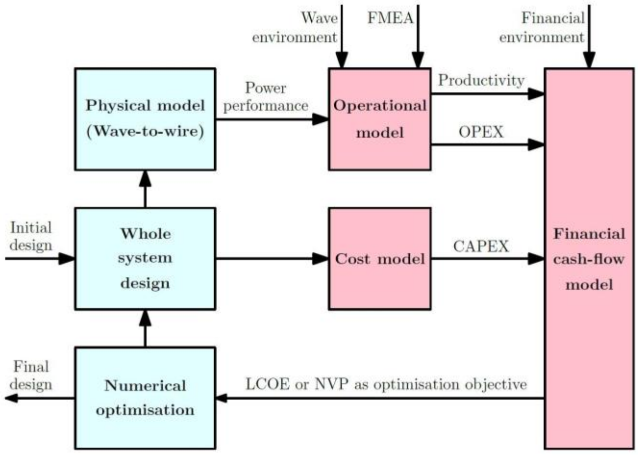

Fig. 1. Structure of the integrated techno-economic optimization software (in red the components utilised for the current work).

The operational simulation follows the discrete-event simulation paradigm [13] [14], as previously used in [15], it is focused on simulating the lifecycle of any machine population. The simulation tracks the state of a population of machines given a set of possible states and a set of possible state transitions. In the ideal progression, each machine would go through a sequence of pre-operational states related to manufacture, transport, final assembly, installation, then enter its operational state for its operational life, then go through a sequence of post-operational states related to decommissioning. However, in reality, it is unlikely that a machine will operate uninterrupted for the duration of its operational life, random breakdowns and scheduled and unscheduled maintenance will inevitably occur. Fig. 2 shows the state block diagram, made up of states and transitions, used to implement the O&M components of the model for the current case study. Tables I and II provide descriptions of the states and transitions, respectively. Transitions (Tr#) represent an internal leg of work that is done, moving the WEC from one state to the next.

The cost model is designed to allow a hierarchical cost breakdown structure, which allows a versatile and flexible representation of the costs required by any particular technology and project, while also facilitating a high amount of automatic processing.

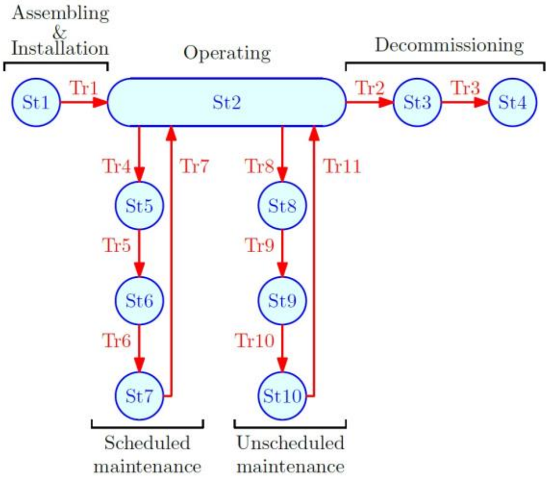

Fig. 2. WEC state block diagram.

TABLE I
WEC STATES

State	Description
St1	Ready for assembling & installation
St2	Operating
St3	Ready for decommissioning
St4	Decommissioned
St5	Ready for scheduled maintenance (no energy production)
St6	Device onshore for scheduled maintenance
St7	Ready for reinstallation after scheduled maintenance
St8	Device failed (no energy production)
St9	Device onshore for unscheduled maintenance
St10	Ready for reinstallation after unscheduled maintenance

Fig. 3 shows an overview of the *Wave Venture TE*™ integrated engineering and financial simulation. The weather resource data, input as a time series, is processed in order to generate output time series, such as energy yield and cash flow. The simulation includes a Monte Carlo analysis, which allows the uncertainty of output data to be quantified.

TABLE II
WEC TRANSITIONS

State	Description
Tr1	WEC assembled and towed from the port to the offshore farm and connected to mooring and electrical cable.
Tr2	WEC passes from operating state to ready for decommissioning.
Tr3	WEC towed to the port and dismissed.
Tr4	WEC passes from operating state to ready for scheduled maintenance.
Tr5	WEC disconnected from mooring and electrical cable and towed to the port.
Tr6	WEC undergoes scheduled maintenance by an onshore maintenance team.
Tr7	After scheduled maintenance, WEC is towed from the port to the offshore farm and connected to mooring and electrical cable.
Tr8	WEC passes from operative state to failed state.
Tr9	WEC disconnected from mooring and electrical cable and towed to the port.
Tr10	WEC repaired by an onshore maintenance team (unscheduled maintenance).
Tr11	After unscheduled maintenance, WEC is towed from the port to the offshore farm and connected to mooring and electrical cable.

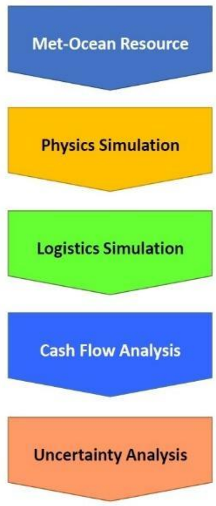

Fig. 3. Overview of the *Wave Venture TE*™ software.

Fig. 4 shows a generic work sequence example used in the logistics simulation. In response to events in the wave farm lifecycle, including the install program, random failures, scheduled maintenance and decommissioning program, sequences such as these are triggered and are actioned by vessels and other resources in the context of weather windows and other constraints. This approach gives a bottom-up assessment of operational costs and durations without making untestable high level assumptions, which may result in suboptimal O&M resources and/or inaccurate cost predictions.

Fig. 4. Work sequence example.

III. SIMULATION INPUT DATA

The following subsections present the input data used to build the techno-economic model.

A. *Basic assumptions*

A series of basic assumptions have been made to construct the model of the wave farm and its O&M tasks and infrastructure. The wave farm has an operational lifetime of 20 years and the simulation, incorporating installation and decommissioning, is typically several years longer than the device lifetime. In this case, using historical wave resource data, the simulation starts on the 1st of May 1980 and each WEC stops production after 20 years, on the 1st of May 2000.

It is assumed that the onshore substation and export cable are already available at the site (with no additional costs to the farm project) and that the offshore substation, inter-array cables and moorings are already installed prior to the project start date (with these costs included in the farm project costs).

It is assumed that all onshore and offshore operations may be undertaken 24 hours per day. This includes shift work by 3 onshore maintenance teams and the assumption that offshore operations can be conducted regardless of daylight hours, in this future scenario with an assumed mature technology.

B. *Offshore farm and wave climate*

The simulated 100 MW farm is located at the AMETS Test Area A, which is located 16 km west of Belderra Strand on the Belmullet Peninsula, Co. Mayo, Ireland, as shown in Fig. 5. The site is fully exposed to the Atlantic Ocean and has a water depth of 100 m.

The wave climate, significant wave height, *Hs*, and peak period, *Tp*, in hourly time steps has been obtained from the ECMWF ERA5 model [16] for the location of the wave farm. This data is used together with the WEC's power matrix to determine the power production and with the operational permits (see Table III) to determine if operations can be undertaken at each time step.

It is worth noting that AMETS is a highly energetic site with average incident wave power of approximately 60 kW/m and a mean significant wave height of 3 m [17], which reduces to 2 m in summer months. While these substantial wave power levels are beneficial in terms of energy production, they put significant pressure on offshore operations due to the offshore permit restrictions.

To date CorPower have focused development of the WEC for sites in Portugal which have much more favourable weather windows. Therefore, it should be noted that the cost of energy production at this site for the G12 device may be higher as the WEC and its supporting operations have not been optimised for a highly energetic site such as AMETS. The LCOE values presented in this paper are not intended to be indicative of real costs, but simply used as a metric to compare and optimise various O&M parameters for the farm to highlight their influence.

The seasonal probability density function (PDF) and cumulative distribution function (CDF) of significant wave height, *Hs*, are presented in Fig. 6. The plots highlight that periods with wave heights less than 1 m are relatively rare (about 220 hr/year), and opportunities for offshore repair requiring crew transfer to the WEC, likely limited to $Hs <$ 0.5 m, are extremely rare, even in the summer months. It is also worth noting that the limitation of only conducting operations in daylight hours has not been considered in this analysis and would bring further restriction to access. However, this would have less of an impact in the long days of the summer months when the majority of the weather windows are likely to occur.

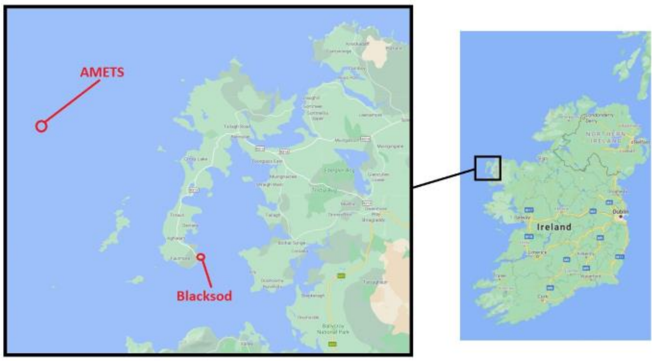

Fig. 5. Locations of Blacksod port and offshore wave farm at AMETS.

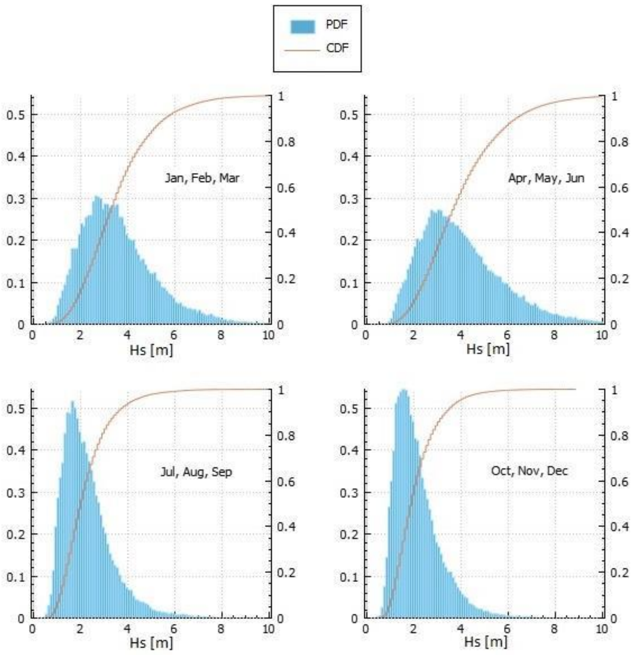

Fig. 6. Seasonal distribution of significant wave height at AMETS.

C. *Port and infrastructure*

Blacksod Harbour is the port used as the base for installation, maintenance and decommissioning operations. Blacksod is a small harbour on the Belmullet peninsula (see Fig. 5), which has plans to expand its infrastructure to provide support services for offshore renewables. The distance of Blacksod port to the AMETS site is 35 km. In the simulations of this work, no limit to the port capacity is applied to the Blacksod port.

D. *CorPower WEC*

The 100 MW wave farm consists of 250 CorPower's G12 devices, each with a nominal power rating of 0.4 MW. The CorPower WEC is a point absorber type, with a heaving buoy on the surface absorbing energy from ocean waves.

The buoy is connected to the seabed using a tensioned mooring system (see Fig. 7). Novel phase control technology makes the compact devices oscillate in resonance with the incoming waves, strongly amplifying the motion and power capture. The system has improved survivability in storms, thanks to its inherent transparency to incoming wave energy in long storm waves. The high structural efficiency allows for a large amount of energy to be harvested using a relatively small and low-cost device, reducing the equipment cost per MW capacity. Generators and power electronics are standard components known from the wind industry, enabling well known grid connection architecture to be employed. Each WEC operates autonomously by a programmable logic controller located inside the device [1]. Fig. 8 shows an artist's impression of the CorPower's array.

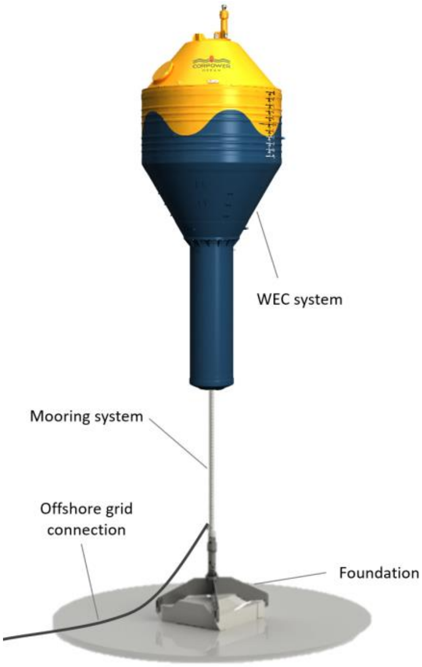

Fig. 7. CorPower's WEC concept.

CorPower provided a confidential power matrix for the G12 WEC which is utilised, together with the wave climate time series from the ECMWF ERA5 model, for the power production calculation. Furthermore, a FMEA has been developed for the subassemblies of the CorPower WEC (see Section F).

Fig. 8. Artist's impression of CorPower's array.

E. *Maintenance strategy*

Both scheduled and unscheduled maintenance are utilised in the simulations. Considering the long waiting time due to the few and narrow available weather windows throughout the year, it is preferable to mitigate the impact of failures of the WEC, which could be inaccessible for months, losing a significant portion of the potential energy production. Therefore, scheduled maintenance is carried out after the WEC has been operating for 5, 10 and 15 years, at which point the WEC is towed back to port and a preventive service is carried out. This would involve carrying out visual inspections and diagnostics, where some repair or replacements can be made even if a component has not technically failed. Note that in the simulations it is assumed that no power is produced when the WEC is waiting for the scheduled maintenance (see state 5 in Table I). This is a conservative assumption used in the simulations and is independent of the CorPower WEC characteristics.

Scheduled maintenance takes 24 hours once the WEC is at port and costs an average of €5000 is attributed for replaced hardware costs. Towing the WEC at 6 kn (11.11 Km/h), the 35 km from the farm to port takes approximately 3.15 hr and, therefore, without delays due to the weather conditions, the whole scheduled maintenance operation is carried out in approximately 1.5 days.

Unscheduled maintenance is undertaken if a fault occurs on the WEC (the faults occur based on the parameters within the FMEA, as shown in Section F). Due to the highly energetic sea conditions and lack of available weather windows at the AMETS site, see Fig. 6, the offshore maintenance service with a likely maximum allowed *Hs* of 0.5 m for crew transfer is considered to be prohibitive. Therefore, the WEC maintenance, due to either minor or major faults, requires the WEC to be towed to shore for onshore repair (both scheduled and unscheduled maintenance).

In the simulations, it is assumed that each WEC is connected to and disconnected from the mooring and the electrical cable utilising quick connectors, in order to reduce time associated with the associated O&M tasks.

Different connection/disconnection (c/d) times are considered in the simulations (1, 1.5, 2 and 2.5 hours) and their effects on the farm performance are analysed.

F. *Reliability and FMEA*

The system reliability is defined as the probability of the components working together, in order to deliver a specified performance. A component is said to fail when it is no longer capable of functioning as it should. The failure of one of the components may compromise partially, or totally, the functionality of the system [18]. The occurrence of a failure is a probabilistic event, whose likelihood depends on many factors.

The life length, *T*, is the period of time during which a component or system works within its specified parameters. At the end of its life, the component or system changes from proper function to failure. Across a population of identical devices, the life length can be described as a random variable [19] [20]. The CDF of *T* is represented by:

$$F_T(t) = prob\{T \leq t\} \tag{1}$$

which is the probability that the life length is in a time interval [0,*t*]. The PDF is given by:

$$f_T(t) = dF_T(t)/dt \tag{2}$$

$f_T(t)dt$ represents the probability that the life length is in the time period [*t*, *t*+*dt*]:

$$f_T(t)dt = prob\{t \leq T < t + dt\} \tag{3}$$

An important function to describe the reliability of a component is the failure rate (also called hazard rate), *h(t)*, which is the instantaneous conditional probability of failure, given survival to any time. Therefore, *h(t)dt* is the probability that component fails in time period [*t*, *t*+*dt*], given that it has not failed in [0,*t*] (*h(t)dt* describes the chances of failure of an operable object in the next infinitesimal interval of time).

The failure rate of any component varies with age and follows the well-known bathtub shape, shown in Fig. 9 [19], which can be considered in three distinct parts. The first part is characterised by a decreasing failure rate and represents the infant mortality or debugging period. This could be due to a combination of design errors, substandard material, inaccurate manufacturing methods, imprecise quality control, assembly faults or human errors. The second portion of the curve, which exhibits a constant failure rate, corresponds to the useful life of a component. Finally, in the third portion of the curve, the wear-out stage sets in and the component failures become more frequent. Failures in this stage can result from such things as corrosion, oxidation, friction, wear, and fatigue.

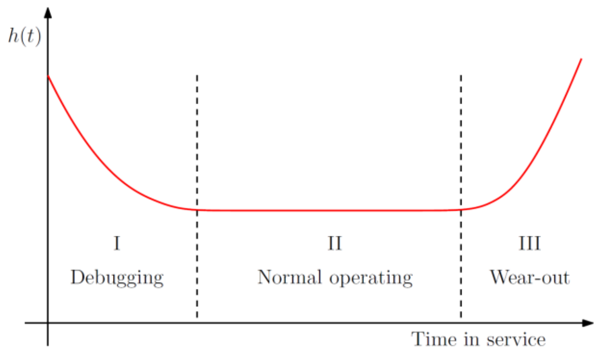

Fig. 9. Component failure rate versus time in service (bathtub curve).

An important reliability measure is the mean time to failure (MTTF), which represents the length of time that an item is expected to last in operation until it fails, which is given by [21]:

$$MTTF = E[T] = \int_0^{\infty} t\, f_T(t)dt \tag{4}$$

The most widely used distribution function for modelling reliability is the exponential distribution, and it is based on the hypothesis [19] [20]:

$$h(t) = \lambda \tag{5}$$

$$F_T(t) = 1 - exp\{-\lambda t\} \tag{6}$$

For an exponential distribution, MTTF = $1/\lambda$.

CorPower provided a confidential FMEA for the G12 WEC including a list of subcomponents, each with failure rate λ and a cost for its replacement. In the simulations, the *Wave Venture TE™* software generates random failures of the subcomponents, by following exponential distributions having the failure rates provided by CorPower. In the simulations, the failure rates are assumed constant over the WEC's lifetime and independent from the weather conditions.

Furthermore, the different WECs are assumed to be electrically connected in a parallel configuration, therefore, the failure of a device does not compromise the energy production of any other WEC in the farm.

G. *Vessels and teams*

Three team types are utilised to perform the operation and tasks included in the simulations:

- The onshore assembly team assembles the WEC at the port, in order to prepare the WEC for its first installation in the farm.
- The installation, maintenance & decommission vessel team, which uses a tug to deploy and recover the WEC during its life.
- The onshore service team, which carries out the scheduled and unscheduled maintenance tasks on one WEC in the port.

Each onshore assembly team consists of three working shifts to enable a 24-hour work schedule. Since the WEC assembly is carried out only at the beginning of the life of each WEC, the amount of work carried out by the onshore assembly team is limited, therefore, the onshore assembly team has a daily contract. The total cost of each assembly team to cover 24 hour of work is 2500€/day.

The key characteristics of the vessel and the associated permits based on the significant wave height, *Hs*, are presented in Table III.

Vessel costs are presented in Table IV. The tugs are hired through a long-term farm maintenance contract on a fixed annual rate with additional costs associated with vessel usage.

TABLE III
VESSEL CHARACTERISTICS AND PERMITS

Characteristic/permit	Value
Vessel speed [kn]	12
WEC tow speed [kn]	6
Hs vessel tow permit [m]	2
Hs vessel travel permit [m]	3
Hs vessel work-connect permit [m]	1.5
Hs vessel work-disconnect permit [m]	2
Hs vessel onsite permit [m]	3.5

TABLE IV
VESSEL COSTS

Cost type	Value
Mobilisation cost	€ 24,000
Fuel hourly	€ 1,300
Daily hire	€ 6,000
Annual cost	€ 2,190,000

A maintenance team can only work on one WEC at a time. Each onshore maintenance team consists of three working shifts to enable a 24-hour work schedule. The onshore maintenance teams are hired through a long-term farm maintenance contract on a fixed annual rate of €600k per year (€200k per shift).

H. *Costs and cash flow hierarchy*

The *TE*™ software calculates the costs and other cash flows associated with a wave farm using a hierarchical cash flow model. Fig. 10 shows the cash flow hierarchy utilised for the current study. In the analysis, each of the nodes in the cash flow tree structure is available as a time series. This approach is both highly structured and highly versatile. The LCOE is calculated using (7), as presented in [22],

$$LCOE = \frac{DEVEX + \sum_{n=0}^{N} PV(CAPEX_n) + \sum_{n=0}^{N} PV(OPEX_n) + PV(DECEX_n)}{\sum_{n=0}^{N} PV(AEP_n)} \quad (7)$$

where *AEP* is annual energy production (measured in MWh), *n* is the year and *PV* is the present value (also called present discounted value) as defined in [22],

$$PV(X) = \frac{X}{(1+d)^n} \quad (8)$$

where *d* is the discount rate.

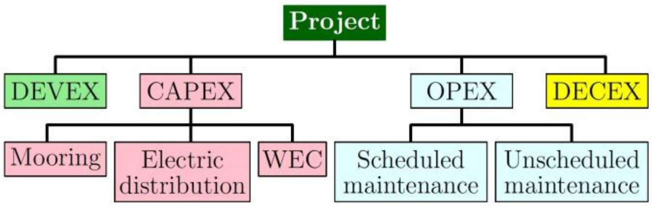

Fig. 10. Cash flow hierarchy.

DEVEX - the project development costs have been set to €15M, which includes pre-FEED engineering, environmental surveys, project management, legal and consenting costs.

CAPEX includes the cost of the CorPower WEC (€0.36M per unit), its assembling/installation, the mooring and the electrical infrastructure. It is assumed that the onshore substation and export cable are already available at no cost to the project. It is assumed that the offshore substation, inter-array cables and moorings are already constructed and paid for at the beginning of the simulation. The total electrical infrastructure cost, including hardware and installation, is €72.65M and the total mooring cost, including hardware and installation, is €16M.

OPEX - operating and maintenance cost includes the cost of servicing and maintaining the farm (the vessel cost for maintenance, see Table IV, the cost of the onshore maintenance team and hardware replacement related to failures based on the FMEA).

DECEX - the decommissioning costs based on vessel usage from the simulations. Scrappage is not included here, due to the lack of information, however, this would be a fixed cost and will not change for any of the simulated scenarios.

It is worth noting again that the LCOE is not fully representative of a real project due to lack of specific and accurate information in areas such as project development costs, specific onshore and substation requirements and inter array cables. The CAPEX of the WEC is also based on an early-stage assessment of a future design with high volume production. The LCOE is based on the best available information and is simply used here as a benchmark metric to compare alternative scenarios relating to O&M tasks.

Project financing strategies are out of the scope of this analysis and, therefore, a fixed 10% discount rate has been used in the simulations, which is in line with typical values from other similar projects.

IV. RESULTS

Using the model described in Sections II and III, the O&M elements of the wave farm have been modelled in a wide range of scenarios with alternative configurations, in order to determine the most influential parameters and their optimum values. The following subsections present the results of varying these parameters on key metrics such as time to install the farm, availability and LCOE.

I. *Installation time analysis*

The objective of the installation time analysis is to avoid a selection of O&M parameters that would lead to excessively long installation times, in the order of years, for the 250-unit wave farm. The simulation begins on the 1st May 1980 and the *time to install* is measured from this point to when all 250 WEC have been installed.

In the simulations, the complete WEC installation is realised by carrying out, in sequence, the following tasks:

- WEC assembling at port by an assembly team (WEC assembly time is 5*24 hours).
- WEC towed to the wave energy site by a vessel.
- WEC connection to moorings and electrical cable.

For the installation time analysis, three different O&M variables are considered:

- Time to connect/disconnect the WEC to the moorings and electrical cables: 1, 1.5, 2 and 2.5 hours.
- Number of vessels: 1, 2, 3 and 4.
- Number of assembly teams: 1, 2, 3, 4 and 8.

Fig. 11 and Table V show the time necessary to install 250 WECs, in the case of a connection/disconnection time of 1 hour. In the analysis, different numbers of assembling teams are considered (1, 2, 3, 4 and 8) and different numbers of vessels are considered (1, 2, 3 and 4).

TABLE V
INSTALLATION TIME (1 HOUR CONNECTION/DISCONNECTION TIME)

Assembly teams	1 vessel	2 vessels	3 vessels	4 vessels
1	1289	1289	1289	1289
2	809	750	745	742
3	784	457	420	420
4	769	450	416	391
8	717	385	356	352

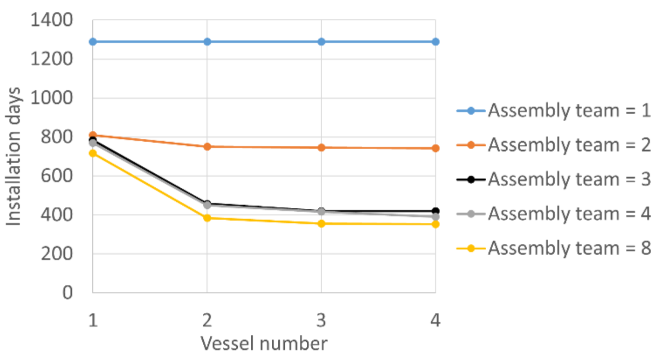

Fig. 11. Installation time against number of vessels for various numbers of assembly teams, in the case of c/d time 1 hr.

With just 1 assembly team the installation of the farm would take 1289 days (about 3.5 years), no matter how many vessels are used. The bottleneck here is the slow rate of 'production' of the WECs and clearly this is too long. Increasing to 2 assembly teams reduces the installation time to between 742 days (by using 4 vessels) and 809 days (by using 1 vessel), which is still an excessive time (>2 years) to build out the farm.

The most marked improvement or step change is seen when moving to 3 assembly teams, with at least 2 vessels, which takes no more than 457 days. Further increases to 4 assembly teams and/or 4 vessels does not show any marked improvement.

With 8 assembly teams, there is a reduction of the installation time of approximately 50 to 60 days, but this is not deemed significant considering that the workforce is doubled.

In summary, there is a significant impact on installation time in using 1 or 2 or 3 assembly teams but, for assembly teams greater than 3, there is no significant advantage. Similarly, 2 vessels are better than 1 but any more only offer marginal gains.

A similar analysis can be carried out in the case of connection/disconnection times of 1.5, 2 and 2.5 hours, which are shown in Figs. 12, 13, 14, respectively. The plots show the connection/disconnection time has little effect on the time of install the farm, with only a small number of additional days required.

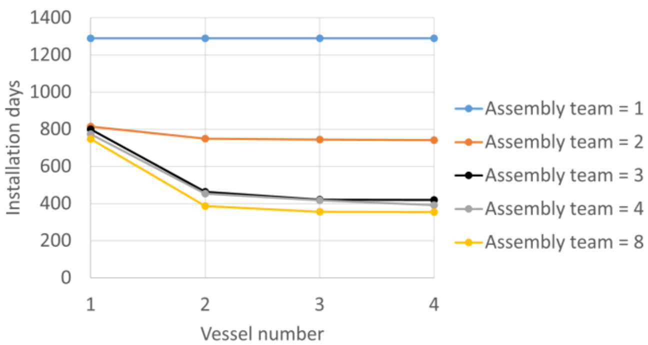

Fig. 12. Installation time against number of vessels for various numbers of assembly teams, in the case of c/d time 1.5 hr.

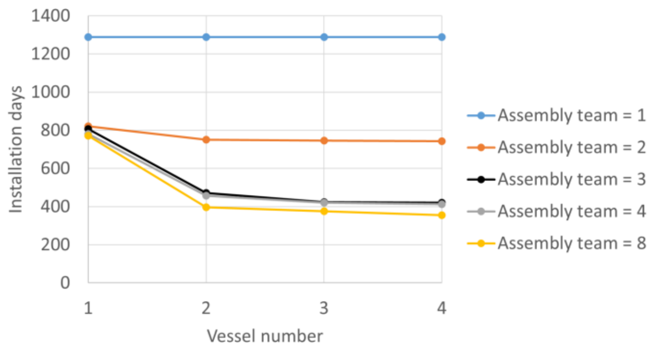

Fig. 13. Installation time against number of vessels for various numbers of assembly teams, in the case of c/d time 2 hr.

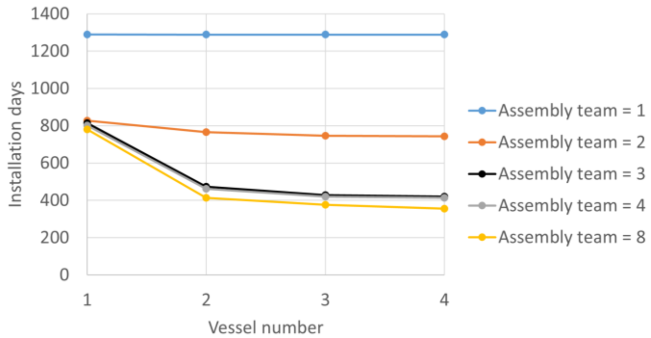

Fig. 14. Installation time against number of vessels for various numbers of assembly teams, in the case of c/d time 2.5 hr.

From the previous analysis, it is possible to see that a good compromise appears to be using 3 assembly teams. Fig. 15 compares the installation time, using 3 assembly teams, for the various connection/disconnection times. Again, it is clear that the connection/disconnection time has no significant impact on the time to install the farm.

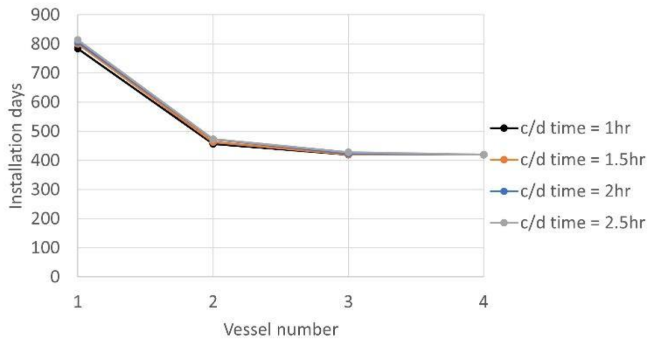

Fig. 15. Installation time against number of vessels for various connection/disconnection times, in the case of assembly team = 3.

Lastly, Fig. 16 shows the time series of the installed WECs in the optimum case with 3 assembly teams and a c/d time of 1 hour. The plot shows that during the 'winter' months, October to February, the installation curve is nearly flat, showing that very few WECs are installed in this period, due to the lack of weather windows that permit the installation tasks. Conversely, the curve is steep in the 'summer' months (from March to August) when the majority of the WEC installations take place.

Fig. 16 shows that in the case of using 1 vessel, the farm installation period spans two winters (two flat areas), which largely delays the completion of the farm installation. With 2 vessels, the build out of the farm spans one winter, which represents a large improvement. Further increases to 3 and 4 vessels reduces the installation time but not by a large amount. Therefore, from the point of view of the farm installation time, it appears that using 2 vessels is a good compromise.

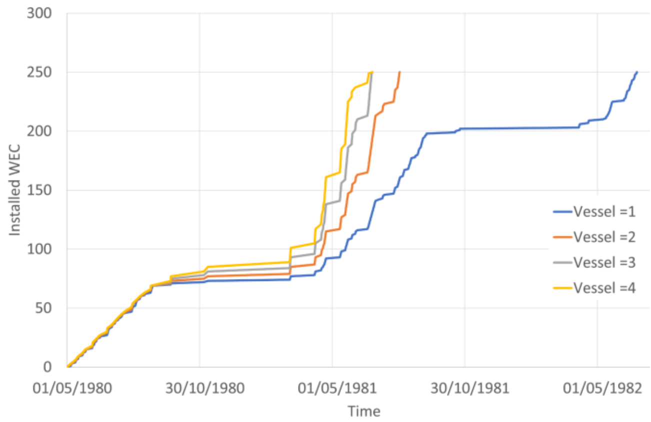

Fig. 16. Time series of WECs installed, where connection/ disconnection time is 1 hr and 3 assembly teams, and 2 onshore teams are utilised.

It is also worth noting that the build of the farm could have been started earlier than the 1st of May and this would likely have resulted in more WECs installed in the first year, as many WECs are installed in April of the second year. However, it is unlikely that this change would have allowed all 250 WECs to be installed before the winter in the same year.

Furthermore, another bottleneck exists in the first year and can be identified by the fact that all four curves in Fig. 16 lie almost on top of one another, meaning that extra vessels do not lead to many more installed WECs in the first year. For vessels > 1, approximately 75 WECs are installed in the first summer period, while 175 are installed in the second year (albeit this is a slightly longer period). This is due to WEC assembly starting with the simulation on the 1st of May 1980 and as it takes the 3 assembly teams 5 days to produce the first 3 WECs the vessels have little work to do and, essentially, they are constantly waiting for WECs to be produced, at a rate of 3 WECs every 5 days. In the second year, the assembly teams have been working throughout the winter months to produce WECs and, therefore, the vessels do not have to wait, and more additional vessels have the advantage of installing more WECs in a short time. In summary, the simulations suggest that the WEC assembly should have started earlier than vessel hire, in order to build up supply and avoid this bottleneck.

Finally, it is worth noting that the wave resource and thus the weather windows vary from year to year which could impact the installation time, but a sensitivity analysis across many years is beyond the scope of the present work.

J. *Availability analysis*

This section focuses on the effect of the O&M parameters (number of vessels, number of onshore teams and c/d time) on the availability of the farm. The availability of the farm is reduced from 100% by failures of the WECs based on the reliability described in Section F and by the recovery of each WEC every 5 years for scheduled maintenance. The recovery and redeployment of WECs is also constrained by the limited weather windows at the farm location, meaning that failed WECs may remain on site for some time, while repaired or serviced WECs may also be stuck in port.

Following the analysis of the time to install the farm in Section I, the number of assembly teams has been selected as 3 for the farm. Figs. 17 to 20 show the total mean availability of the farm, in the case of c/d time equal to 1, 1.5, 2 and 2.5 hours, respectively. The four plots show that, irrespective of c/d time, there is a substantial improvement in farm availability when moving from 1 to 2 vessels. For more than 2 vessels there is a monotonic but less pronounced improvement.

Similarly, there is a significant improvement in moving from just 1 onshore maintenance team to 2. There is no significant improvement with more than 2 maintenance teams and, therefore, 2 maintenance teams is seen as the best compromise.

Fig. 21 shows that the c/d time has a significant impact on availability if only 1 vessel is used, resulting in an availability of 62% with a c/d time of 1 hr and an availability of 50% with a c/d time of 2.5 hr. However, with 2 or more vessels the c/d time does not have a large impact. Increased number of vessels does increase availability up to 90%.

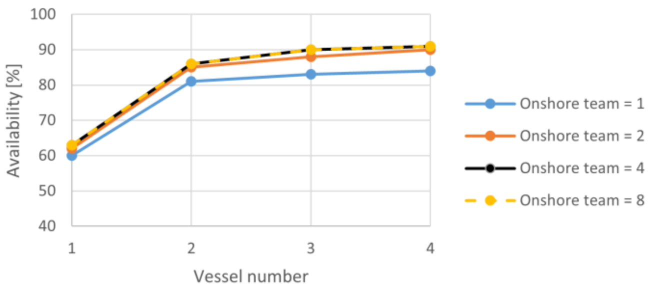

Fig. 17. Farm availability versus vessel number for various numbers of onshore teams, in the case of c/d time=1 hr and assembly team=3.

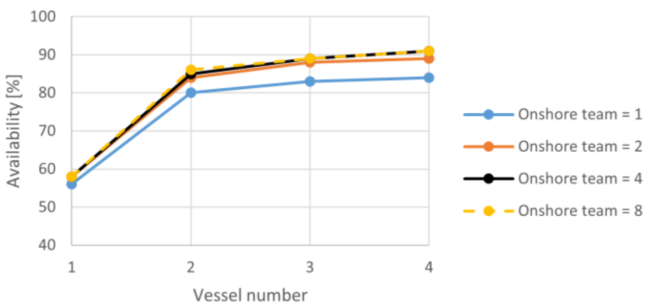

Fig. 18. Farm availability versus vessel number for various numbers of onshore teams, in the case of c/d time=1.5 hr and assembly team=3.

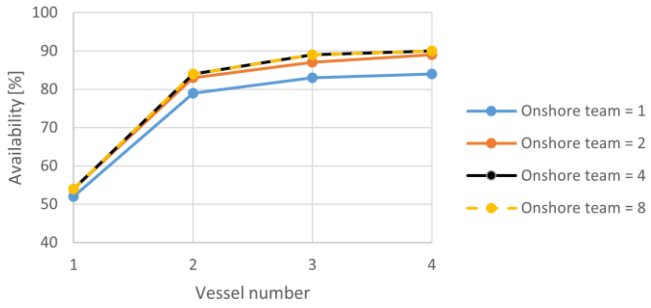

Fig. 19. Farm availability versus vessel number for various numbers of onshore teams, in the case of c/d time=2 hr and assembly team=3.

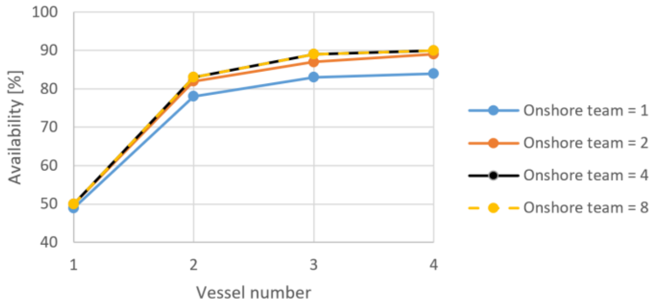

Fig. 20. Farm availability versus vessel number for various numbers of onshore teams, in the case of c/d time=2.5 hr and assembly team=3.

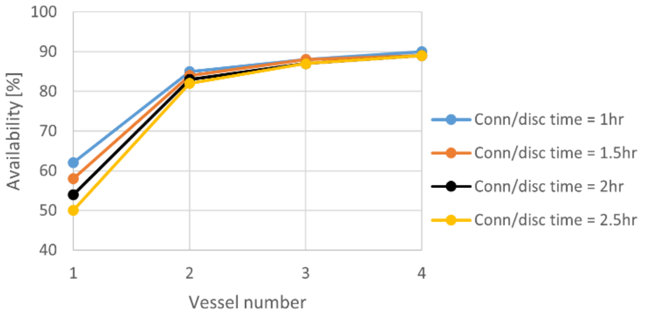

Fig. 21. Farm availability versus vessel number for various connection/disconnection times, in the case of assembly team=3 and onshore team=2.

It is important to underline that a larger availability does not necessarily represent an improvement of the economic performance of the farm. Indeed, if the costs incurred to increase the availability, for example by increasing the number of vessels or onshore maintenance teams, are too onerous, the augmented energy produced is not sufficient to compensate for the enlarged costs. The undesired result is that the LCOE may augment, instead of reducing, with increased farm availability. This will be addressed further in Section K.

After considering the mean availability of the farm, it is possible to analyse more in detail how the availability of the farm changes over time. Fig. 22 shows the availability time series starting from the farm installation all the way through to the decommissioning. The plot shows three troughs, every five years, due to the scheduled maintenance and an annual fluctuation due to the failure of WECs and the lack of opportunity to recover, repair and redeploy them during the winter months, reducing the availability of the farm. Note that the three evident troughs are also a consequence of the conservative simulation assumption, which states that there is no power production when the WEC is waiting for the scheduled maintenance, as explained in Section E.

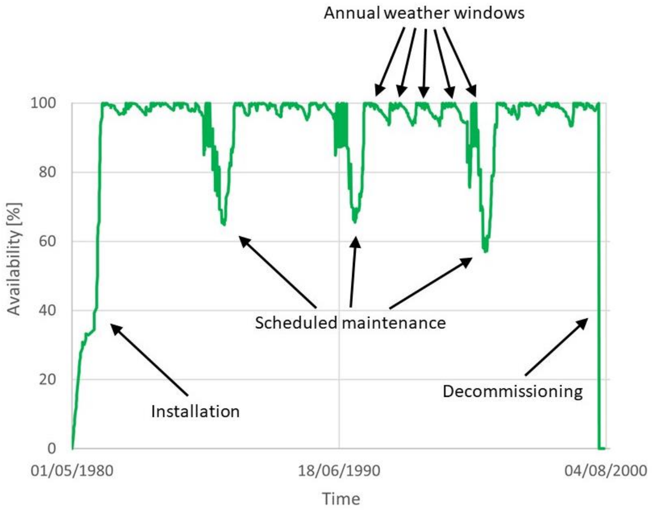

Fig. 22. Time series of availability over the life of the farm and its main characteristics.

Fig. 23 compares the farm availability in the case of three different O&M scenarios:

A) Onshore team number = 1, vessel number = 1.

B) Onshore team number = 2, vessel number = 2.

C) Onshore team number = 8, vessel number = 4.

Scenarios A, B and C also assumed a c/d time of 1 hr and use 3 assembly teams.

Scenario A represents the most reduced effort for the O&M tasks and in this case the mean availability is just 60%. Note the deep troughs related to the scheduled maintenance. Clearly, in this scenario the O&M resources are not sufficient to carry out the necessary tasks and several years pass before all WECs are reinstalled after their scheduled maintenance.

Conversely, scenario C represents the most intense effort for the O&M tasks and results in a mean availability of 91%. In this case, the drop in availability due to the scheduled maintenance is recovered in a few months. In the periods between two consecutive scheduled maintenance, the availability clearly shows the fluctuation due to the annual weather windows, with availability being high in summer and reduced in winter months.

Finally, scenario B is the techno-economically optimal O&M configuration (as will be shown in Section K). Of course, the curve sits between scenarios A and C, and the mean availability is 85%. In this case, the depth of the trough availability is reduced and the drop due to the scheduled maintenance is recovered fast enough, even if it is slower than scenario C.

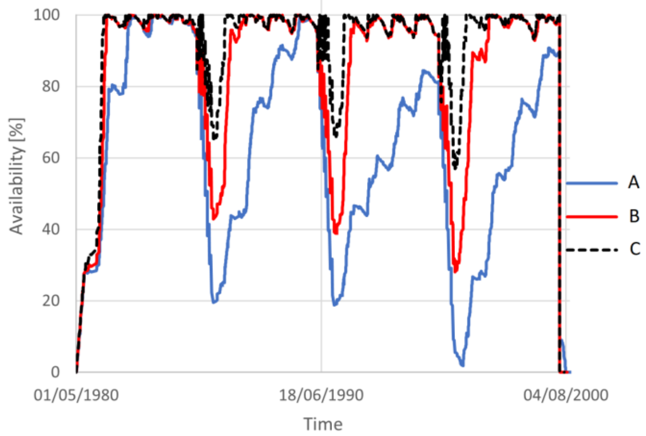

Fig. 23. Time series of availability over the life of the farm with c/d time=1 hr, assembly team=3. Scenario A: onshore teams=1, vessels=1. Scenario B: onshore teams=2, vessels=2. Scenario C: onshore teams=8, vessels=4.

It is worth noting that the drop in availability due to the 5-year scheduled maintenance program, with availability dropping below 50% for several months (see Fig. 23) has a significant effect on the power output of the farm, as shown in Fig. 24 in the case of scenario B.

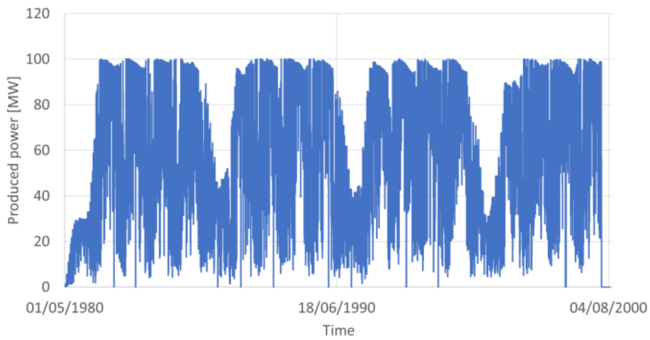

Fig. 24. Time series of produced power over the life of the farm with c/d time=1 hr, in the case of scenario B (onshore teams=2, vessels=2).

K. LCOE analysis

In this section, the number of vessels and onshore maintenance team is optimised to minimise LCOE. From time to install analysis in Section I, 3 assembly teams was found to be optimal. In this analysis, c/d time, number of vessels and number of onshore teams are changed and their effect compared.

Results are presented in Figs. 25 to 28, which show that lowest LCOE is always when 2 vessels are used. As shown in the availability analysis in Section J, in cases with more than 2 vessels the availability is increased, but the plots in this section highlight the higher costs incurred, and so these cases are not optimal from the point of view of the farm economics. Since the overarching objective is the LCOE reduction, from the plots it is very clear that 2 vessels should be chosen.

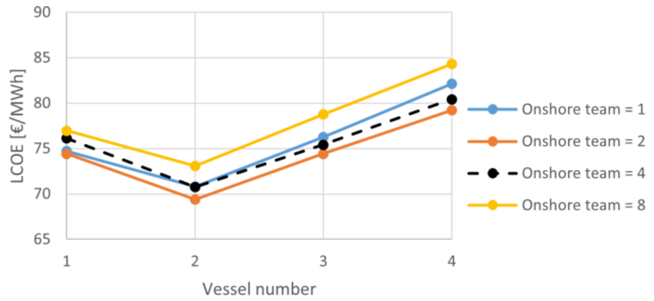

Fig. 25. LCOE versus vessel number for various numbers of onshore teams, in the case of c/d time=1 hr and assembly team=3.

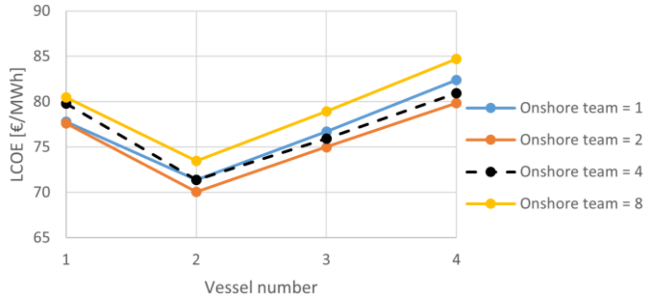

Fig. 26. LCOE versus vessel number for various numbers of onshore teams, in the case of c/d time=1.5 hr and assembly team=3.

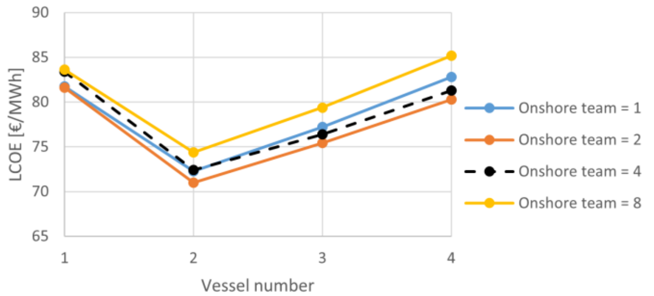

Fig. 27. LCOE versus vessel number for various numbers of onshore teams, in the case of c/d time=2 hr and assembly team=3.

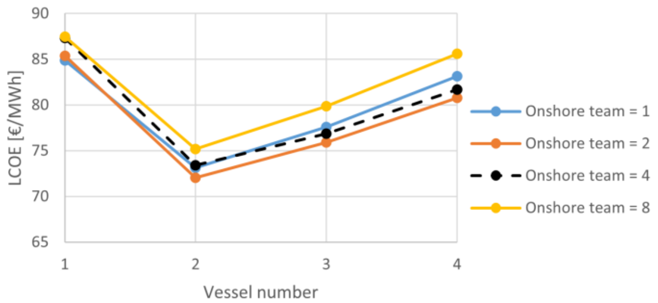

Fig. 28. LCOE versus vessel number for various numbers of onshore teams, in the case of c/d time=2.5 hr and assembly team=3.

Fig. 29 shows the dependency of LCOE on c/d time and the number of onshore maintenance teams (in the case of 3 assembly teams and 2 vessels, as shown to be optimal previously). For the various c/d times, the lowest LCOE is consistently attributed to the use of 2 onshore maintenance teams. This confirms the availability analysis results in Section J, showing that, for greater than 2 onshore teams, the availability does not increase large enough to justify the additional costs associated with the extra teams. Therefore, in terms of availability and LCOE, 2 onshore maintenance teams should be utilised.

Fig. 29 also shows that by reducing the c/d time, it is possible to reduce the LCOE. This is intuitive since a reduction of c/d time brings a reduction of working hours (costs reduction) and a faster maintenance cycle (higher availability).

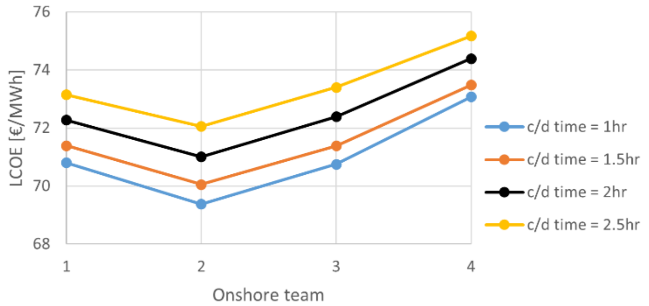

Fig. 29. LCOE versus number of onshore teams (vessels = 2, assembly team = 3).

In order to better understand the dependency of LCOE on the c/d time, Fig. 30 shows the case of 3 assembly teams, 2 onshore teams and 2 vessels. It is shown that the LCOE increases monotonically with c/d time, but the impact is less than 5%, increasing from approximately 69 to 72 €/MWh.

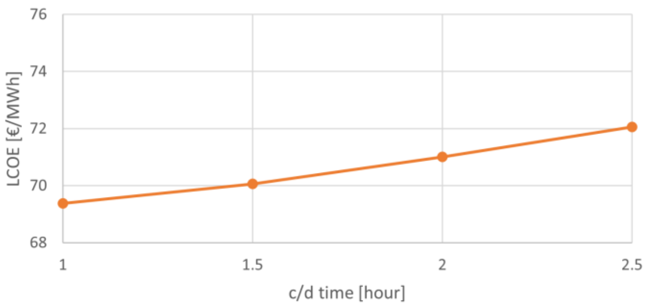

Fig. 30. LCOE versus connection/disconnection time (assembly team=3, onshore team=2 and vessels=2).

Fig. 31 shows the results on the plane Availability - LCOE, in the cases of c/d time of 1 and 2.5 hours. Ideally, on this plane, the solution should lie on the right bottom corner, having high availability and low LCOE. Note that each line shows an LCOE minimum for 2 onshore teams, as already observed in Fig. 25 to 29. Furthermore, Fig. 31 shows that by passing from a c/d time of 2.5 to 1 hour, the curves move towards the bottom right corner, improving the farm performance. Fig. 31 also distinctly shows that the using only 1 vessel results in a significant reduction of the availability (as the corresponding blue curves are not clustered with the other curves). The plot also shows that an increase in the availability does not necessarily correspond to a reduction of the LCOE, as in each line where the number of onshore teams increases from 2 to 4 both availability and LCOE increase.

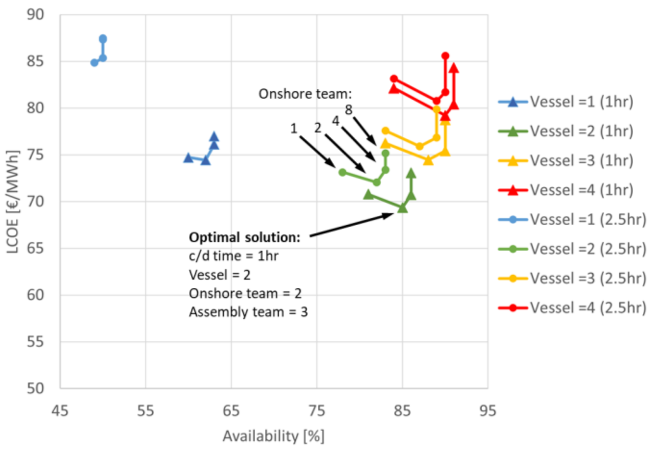

Fig. 31. LCOE versus availability, with various numbers of vessels and 2 alternative c/d times. In each coloured line, four different numbers of onshore teams are considered (=1,2,4,8).

The optimal configuration obtained from the simulations is highlighted in Fig. 30, with an LCOE of 69.4 €/MWh and an availability of 85%. This case has the following parameters:

- 1 hour connection/disconnection time
- 2 vessels
- 2 onshore maintenance teams
- 3 WEC assembly teams.

Again, it is worth stressing that the G12 WEC and its supporting operations have not been designed or optimised for a highly energetic site such as AMETS. Therefore, while energy production may be greater, there are significant additional costs associated with operating the farm in this wave climate. The LCOE values produced by these simulations are not representative of future values and are predicted to be significantly lower at other sites such as off the Coast of Portugal. LCOE values in this paper are simply used to compare alternative O&M parameters to highlight their influence.

The breakdown of costs is presented in Fig. 32, which shows an increase in OPEX relative to the CAPEX as the number of vessels is increased. For the best-case scenario, the CAPEX and OPEX make up 43% and 53% of the total project costs, respectively.

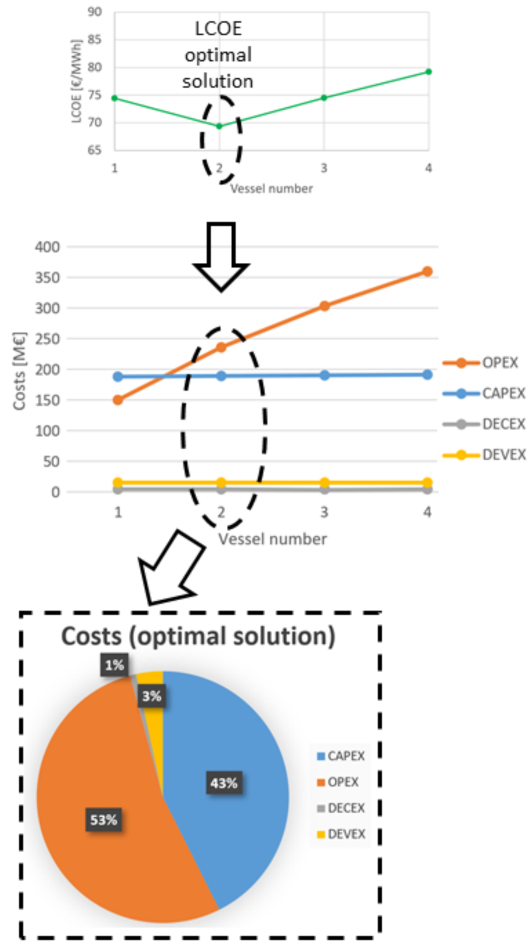

Fig. 32. Cost breakdown for the optimal O&M configuration.

It is worth noting that the percentage of the project costs associated with OPEX may be seen as higher than that usually predicted for WECs. However, OPEX is often the late element of the cost breakdown to receive significant attention, as WEC developers often focus much of their efforts on better understanding CAPEX costs, especially in the early stages of development. Therefore, this more detailed assessment of OPEX may seem higher as it is likely to be more accurate.

Conversely, the CAPEX value used here is for a WEC that has not been designed for the highly energetic climate of AMETS, and therefore the CAPEX may be somewhat underestimated. Lastly, consider that this location is very challenging for the O&M of a wave farm, requiring large vessels, with the ability to operate in more energetic seas, and meanwhile the lack of weather windows leads to lower availability, due to the restricted access to recover and redeploy WECs.

V. Conclusions

A techno-economic model has been developed of a future scenario of a 100 MW wave farm at AMETS off the west coast of Ireland. The farm consists of 250 WECs representing a mature version of CorPower Oceans's G12 WEC. The techno-economic model has been used to identify pain points and optimal parameters relating to the operations and maintenance activities, with the ultimate goal of lowering the overall LCOE of the project. It is worth noting that this is the subject of ongoing research and based on many early-stage cost assumptions. The LCOE results presented here are purely used to compare alternative O&M configuration, such as number vessels, and are in no way intended to be a prediction of the LCOE of CorPower's WEC, which has not been designed for AMETS. The goal of the work is to highlight the need for O&M modelling through the insight and cost savings that it can provide.

The key findings of this work are:

- AMETS is a highly energetic but challenging environment for the O&M component of a wave farm development. The lack of weather windows severely limits marine operations, impacting time to install the farm and farm availability due to limited access to recover failed WECs and redeploy repaired units.
- The time to install the farm is an important and much overlooked parameter. Various factors contribute here and could lead to several years to complete the installation. It was found challenging to install the 250 devices in one year, without unduly increasing LCOE. The analysis showed that the use of two 'summer' install periods is optimal for the current project.
- Bottlenecks were identified in the simulation, which reduced the advantage associated with using multiple vessels during the installation phase. The largest issue here is that WEC assembly started on day one and as there were no reserves, the vessels spent much of the first year waiting for WECs to install. The rate of installation in the second year was vastly different, as many WECs had been assembled throughout the winter months meaning that there was a store of WECs ready for installation.
- The configuration with the highest availability does not always produce the lowest LCOE. Achieving high average farm availability means increasing staff and vessel numbers to maintain the farm, which incurs significant costs. If the costs are too onerous, the augmented energy produced is not sufficient to compensate for the higher costs.
- OPEX costs for the optimal configuration simulated represent 53% of the total project costs, whereas CAPEX is 43%. This ratio could be deemed somewhat higher than other works but this is likely due to the higher level of detail included in these simulations and the accommodation nature of the wave climate at AMETS. Further work in optimising the O&M elements of the farm could reduce the OPEX proportion.

In conclusion, this paper has shown the utility of O&M modelling in terms of more accurately quantifying OPEX costs, identifying bottlenecks and optimising parameters. Ultimately, this modelling approach can be used within a full techno-economic model to identify opportunities to drive down the LCOE of wave farms.

ACKNOWLEDGEMENT

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