Operations and maintenance planning for community-scale, off-grid wave energy devices

A. Gray
Industrial Doctoral Centre for Offshore Renewable Energy, Edinburgh, UK

D. Findlay
Albatern Ltd., Midlothian Innovation Centre, Roslin, UK

L. Johanning
University of Exeter, Penryn Campus, Cornwall, UK

ABSTRACT: An operations and maintenance (O&M) simulation tool has been developed with inputs specific to the off-grid array of wave energy converters designed by Scottish company Albatern Ltd. This paper takes the ongoing test programme of six 'Squid' wave energy devices as a case study for analysing several aspects of the O&M strategy for an off-grid wave energy array. The study demonstrates how the O&M simulation model can be a useful tool to inform contractual negotiations during the development phase of a wave energy array. Uncertainty in the model inputs is addressed by presenting the results of three different input scenarios.

1 INTRODUCTION

1.1 *Wave Energy Technology*

There is huge potential for wave energy to be a significant contributor to clean, renewable electricity production worldwide. It has been estimated that up to 13GW of wave energy converters (WECs) could eventually be installed in UK waters (Boud, 2012). However, the wave energy sector has so far struggled to gain a foothold in the commercial offshore renewable energy market dominated by the offshore wind industry. There have been several high profile casualties on the route to developing a grid-connected WEC, such as the demise of Scottish wave energy developers Pelamis Wave Power (BBC, 2014) and Aquamarine Power (BBC, 2015). The Scottish Government reaffirmed its commitment to the sector with the creation of funding body Wave Energy Scotland (WES) in 2015. The WES programme seeks to build upon past experience and address the challenges facing the sector in order to de-risk WEC technology and attract private investment, paving the way for commercial development.

One area being investigated by Wave Energy Scotland is the development of off-grid wave energy converters to provide power to fish farms or island communities. The argument is that there is a large amount of risk in deploying large devices with ratings of over 750kW, due to the steep learning curve seen when carrying out real sea testing. The development focus has previously been on these larger devices due to the perceived need to mitigate large capital expenditure (CAPEX), incurred by equipment such as subsea power cables, by building at 'economies of scale'. Whilst that viewpoint is entirely justified, the vast number of unexpected challenges faced when testing WECs offshore has proved to be a stumbling block for the wave energy sector. In deploying and testing much smaller devices, it may be possible to learn vital lessons before building at larger scales for commercial, grid-connected projects. In addition, these smaller devices can generate an income by providing electricity to fish farms or isolated island communities as an alternative to expensive and unsustainable diesel generators.

One aspect of WEC technology with high risk and uncertainty is operations and maintenance (O&M). Estimating the lifetime operational expenditure (OPEX) of wave energy array projects is vital as these costs are significant in calculating the Levelised Cost of Energy (LCOE) of devices. LCOE is one of the metrics used to determine the economic viability of a WEC. Therefore, careful planning of O&M strategies is required to minimise these costs and make the technology attractive to private investors. Research implemented within the Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE) seeks to address the issue of uncertainty surrounding lifetime costs and maintenance planning of off-grid wave energy arrays. As part of the project, this study takes Albatern's WEC technology as a case study to analyse several aspects of their O&M strategy using a Monte Carlo based simulation tool.

1.2 *O&M Models*

Many studies have been carried out analysing the O&M strategies for offshore renewable energy projects. The offshore wind industry is at a much more advanced stage than the wave energy sector and, as such, there are countless O&M models which have been developed over the years to analyse offshore wind farms. Hofmann (2011) carried out a review of 49 decision support tools for offshore wind farms, such as that created by Poole & Walford (2008), finding that many of the tools have been created using spreadsheet based software. Hofmann's own model, described by Hofmann & Sperstad (2013), uses a Monte Carlo approach and takes uncertainty due to weather and failure rates into account. More recent studies have begun to use the vast experience built up by the global offshore wind industry to assess the sensitivity of O&M tools, e.g. Martin et al. (2016). This experience is also being used to validate O&M models, as described by Dinwoodie et al. (2014). These studies generally agree that further operational experience will increase confidence in inputs to O&M models, such as failure rates, thereby increasing the reliability of the outputs, e.g. OPEX costs.

In contrast, there have been very few attempts at creating O&M models for wave energy arrays. A study by Abdulla et al. (2011) used a statistical model to assess the availability of Aquamarine Power's second generation Oyster device, a flap-type WEC, rated at 800kW per device. The Monte Carlo-based functionality of the model is similar to an O&M tool developed by Pelamis Wave Power, as described by Gray et al. (2014). That study focused on an array of Pelamis' 750kW attenuator-type WECs. Ambühl et al. (2015) use an O&M tool to explore several different O&M strategies for the WaveStar device, a fixed offshore structure with 'floater' arms to generate electricity, developed in Denmark. The tool used is slightly different in that it incorporates a damage model to simulate fatigue of two components within the device, rather than assuming constant failure rates over the array lifetime. The O&M tool methodologies described in these publications are still useful and relevant, despite the difficulties faced by developers of grid-connected wave energy technology. To the authors' knowledge, there have been no previous studies analysing O&M aspects of off-grid wave energy arrays.

It is clear that O&M simulations tools can be extremely useful for estimating OPEX and availability of wave energy arrays, analysing different O&M strategies, and assessing component reliability targets. If sufficiently realistic data is provided, this bottom-up approach can improve confidence for investors, thereby paving the way for commercial development.

1.3 *Case Study*

Albatern Ltd. is a developer of wave energy technology based in Midlothian, Scotland. The company is the manufacturer and operator of its Squid technology, a form of articulated WEC, several units of which can be connected together and deployed in a WaveNET array. Sheltered-sea trials of their 6-series 'Squid' WEC, rated at 7.5kW (see figure 1), have been carried out, including at the Isle of Muck in 2014 (see figure 2). Further testing is ongoing at Mingary Bay on the Ardnamurchan Peninsula in Scotland.

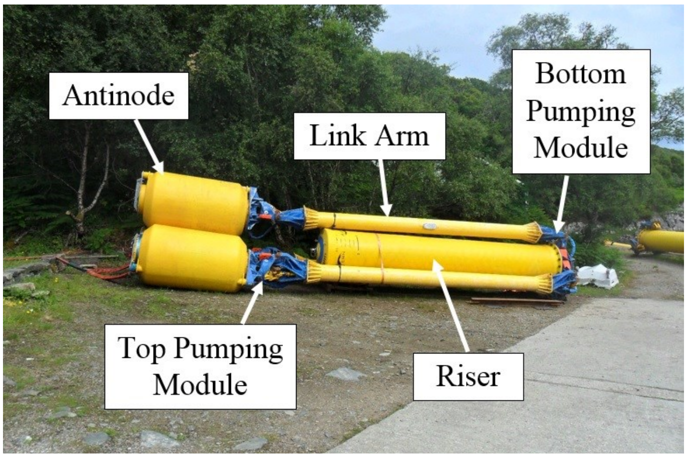

Figure 1. Albatern's 6-series Squid device in transport mode

Figure 2. Albatern's 6-series WaveNET array being tested at the Isle of Muck, 2014.

The devices are intended to supply clean energy to fish farms and off grid communities as a replacement for diesel generated power. The modular nature of the Squid devices means that the main electrical and mechanical components are accessible. The power take-off unit (PTO) is located inside one of the anti-nodes and can therefore be replaced without having to retrieve the entire Squid device. Other components, such as the instrumentation box, are also easily accessible. However, Squid retrieval is required for some faults and for routine inspections. When a Squid is retrieved, it can be towed using low cost vessel into the safety of a sheltered harbor, where maintenance can take place independent of adverse weather conditions. The moorings and electrical connections within the WaveNET array have been designed so that a single Squid can be manually disconnected and rapidly placed in transport mode (with the arms folded in) without affecting the other devices in the array. Three vessels are available for the testing programme at Mingary Bay, identified as the 'slow boat', the 'fast boat' and a Rigid Inflatable Boat, the 'rib'. These vessels are low-cost and are readily available at fish farms and island communities.

2 METHODOLOGY

2.1 *Model Functionality*

This study makes use of an O&M simulation model created with inputs specific to Albatern's WaveNET array being tested at Mingary Bay. It is a Monte-Carlo based tool, built using spreadsheet software, whereby estimated failures rates of all the components within each Squid are taken into account. This enables a reactive maintenance strategy to be modelled, where simulated faults can either require onsite (offshore) repair/replacement or can mean that the entire Squid device must be retrieved and repaired offsite (at the O&M base). In addition, each Squid is scheduled to undergo a routine service (offsite) once every two years during the summer months. This proactive maintenance activity will involve non-destructive testing of components and the WEC structure, removal of biofouling and other routine maintenance checks. The model runs for every three hours over the course of the array lifetime of 20 years. At each interval, the model runs through the processes seen in figure 3.

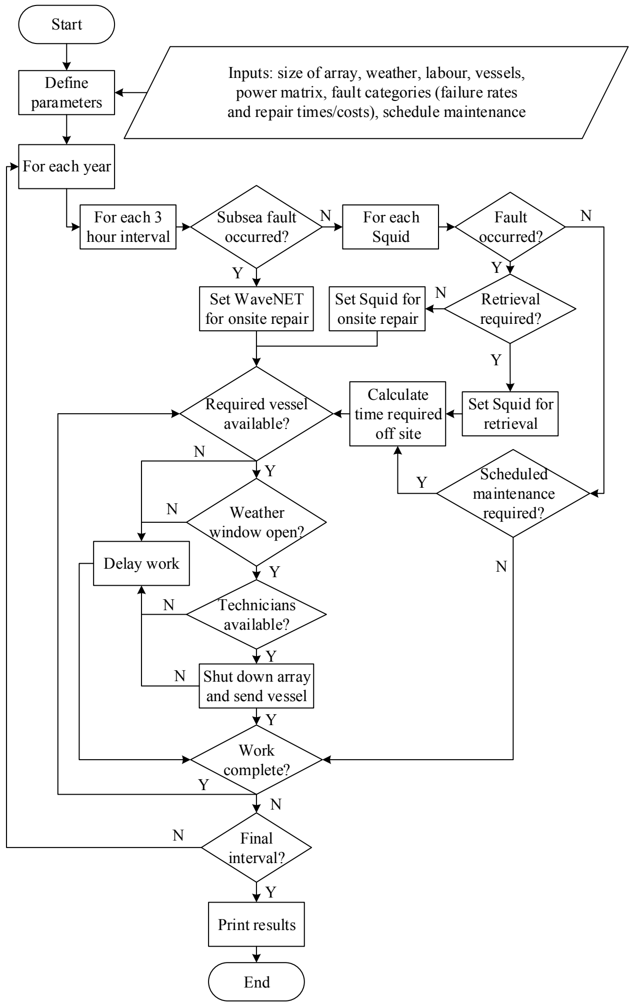

Figure 3. Flowchart of O&M model functionality

2.2 *Model Inputs*

All failures modes have been identified through a Failure Modes and Effects Analysis (FMEA), providing estimations of failures rates and repair parameters, such as parts cost, incurred power loss and time to fix. To speed up the O&M tool simulation, all failure modes have been placed into one of thirteen categories seen in Table 1.

Table 1. Fault categories in O&M model

Fault Category	Relevance	Action
Major mooring	Array	Subsea work
Major structure	Squid	Retrieve Squid
Major hydraulic	Squid	Retrieve Squid
Major electrical	Array	Subsea work
Intermediate mooring	Array	Subsea work
Intermediate structure	Squid	Retrieve Squid
Intermediate hydraulic	Squid	Replace PTO
Intermediate instrumentation	Squid	Replace ins. box
Minor mooring	Squid	Retrieve Squid
Minor structure	Squid	Retrieve Squid
Minor hydraulic	Squid	Replace PTO
Minor electrical	Squid	Replace PTO
Minor instrumentation	Squid	Replace ins. box

The Monte Carlo analysis operates by generating a random number and comparing it to the failure rates stated in each category. Limited real-sea testing of the WaveNET array makes obtaining accurate failure rates difficult. Thus, the failure rate estimations have primarily been obtained from the expert judgement of the engineers involved in designing and manufacturing the Squid units, although values have been inferred from handbooks such as OREDA (Offshore and Onshore Reliability Data) where possible. Several installation and retrieval operations have been carried out on the Squid 6-s units in recent years. This experience, albeit somewhat limited, feeds into the assumptions made for maintenance parameters such as repair times, site travel times, parts costs and vessel fuel costs. The 'slow boat' is the only vessel used for retrieval of Squid devices. The 'fast boat' is used for carrying out subsea work or onsite PTO replacements. The instrumentation box is much smaller and can therefore be replaced using the 'rib'.

A hindcast dataset for Mingary Bay containing significant wave height (Hs) and wave period (Tp), built using a SWAN (Simulating WAves Nearshore) model by Metocean Solutions Ltd, is provided to the O&M tool. These values are matched to a power matrix for the WaveNET array, created using ANSYS Aqwa, in order to calculate energy produced at 100% availability. Revenue is then calculated by applying an assumed sale price of electricity.

Constraints are applied to the model to enhance its realism. The routine service phase is limited to two Squid devices offsite at any one time, ensuring a staggered approach. In addition, repairs and marine operations are limited by the number of technicians available at the O&M base at any given time. However, the model user can choose to allow contractors to be hired on a short term basis. This might involve bringing in staff from the fish farm or locals from the island community, depending on where the array is deployed. This is a likely scenario, given that a study by Gray et al. (2016) found that availability of a wave farm can be increased significantly when short term contractors are used. In this study, it is assumed that two technicians are permanently employed at the O&M base, but external contractors can be brought in when required. It may not always be possible to hire staff at very short notice, so a 95% probability of external contractors being available is built into the model.

2.3 *Model Outputs*

The O&M tool produces a results spreadsheet containing the key information from the simulation. For each year, the availability, parts costs, inspection costs, potential revenue (at 100% availability), actual revenue earned, vessel fuel cost, technicians work time and contractors fees (if used) are produced, along with annual average values. In addition, costs are assigned to each fault category, aiding the identification of the key components that have the largest impact over the course of the array lifetime.

2.4 *Presentation of Results*

Although care has been taken to provide the O&M models with the most realistic inputs possible, there is still a significant amount of uncertainty due to the limited real-sea experience gained with the Squid devices. Therefore, three different scenarios are presented. The first scenario is where the inputs in the O&M tool are provided by the expert judgement of the engineers at Albatern. This is referred to as the ‘realistic’ scenario. The ‘optimistic’ scenario is where particular inputs, defined as ‘adjusted parameters’, are reduced by approximately 20% (or as close to 20% as possible). The adjusted parameters include all failure rates, repair & replacement times, and labour requirements. Squid installation & retrieval times are also included because, although new moorings connection techniques will be tested at Mingary Bay which aim to reduce these times, the values are still somewhat uncertain due to limited operational experience. Other inputs contain far less uncertainty, such as technicians’ salaries, parts costs, site travel times and vessel fuel costs, and are therefore not adjusted. For the third and final scenario, the adjusted parameters are increased from the ‘realistic’ case by 20%. This is labelled the ‘pessimistic’ scenario.

For each of the three scenarios, 50 simulations have been carried out using the same hindcast dataset of weather conditions, with the mean values presented. In analyses where some inputs are changed in order to compare the results, this process is carried out each time a new input case is used.

3 RESULTS

3.1 *Vessel Usage*

The outputs of the O&M model simulations can find the average number of days per year that each vessel is required. This information can be seen in figure 4 for each of the three input scenarios. Figure 5 presents the average number of days each vessel is used in years when routine service events are schedule.

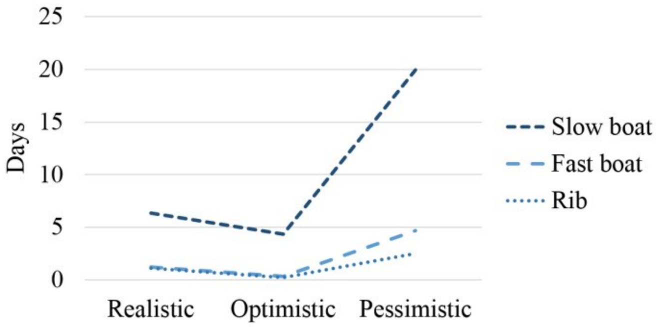

Figure 4. Average number of days per year each vessel is needed

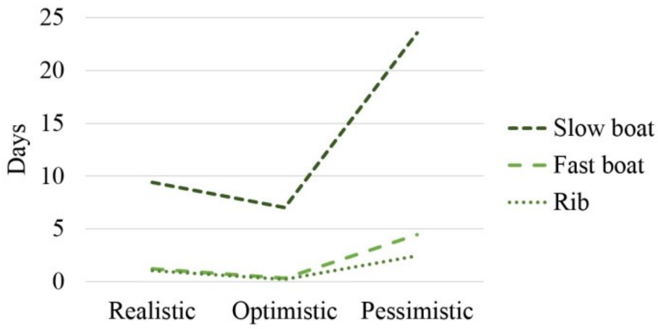

Figure 5. Average number of days per year each vessel is needed, only in years when routine service is scheduled

3.2 *Electricity Sale Price*

Electricity sale price will be subject to negotiations for future projects. Three tariffs have been analysed using the O&M model: [redacted]. Figure 6 presents the normalised ’profit’ (revenue – OPEX) for the three scenarios using each of the three different tariffs.

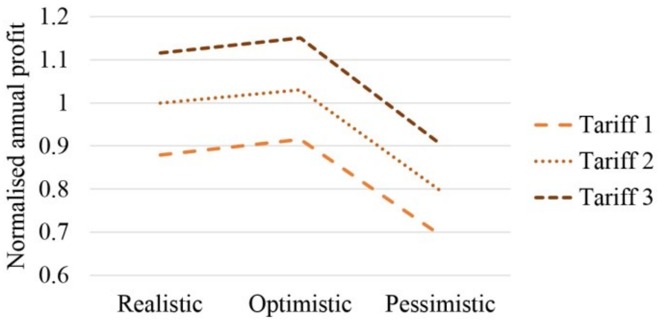

Figure 6. Mean annual 'profit' comparing three tariffs. Normalised against the 'realistic' scenario at [redacted].

3.3 *Labour*

Figure 7 shows the differences in OPEX for the three input scenarios. A breakdown of OPEX is also provided for each case.

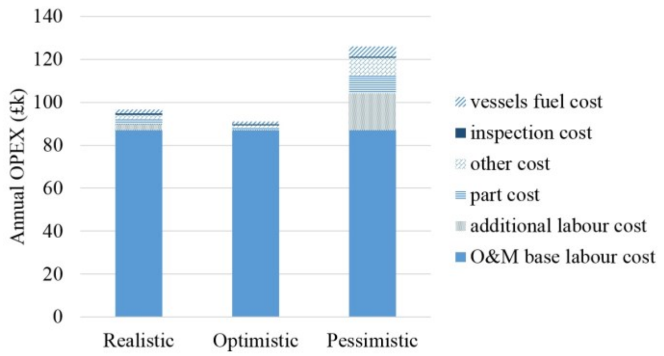

Figure 7. Annual OPEX breakdown when two technicians are employed at the O&M base

Figure 8 gives the total OPEX incurred when 1, 2, 3 or 4 technicians are permanently employed at the O&M base, in conjunction with hiring contractors when required.

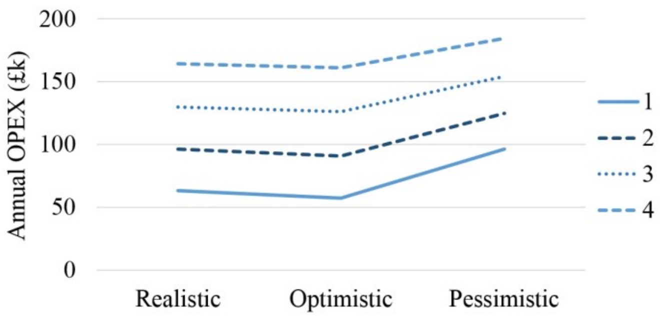

Figure 8. Total OPEX for different numbers of permanently employed technicians

3.4 *Base Development*

In the previous model simulations, the only constraint on the number of Squids at the O&M base at any one time has been applied during routine servicing. Figure 9 presents the results, in terms of array availability, when space at the O&M base is limited for all onshore work. The original labour case is used, where two technicians are permanently employed at the O&M base.

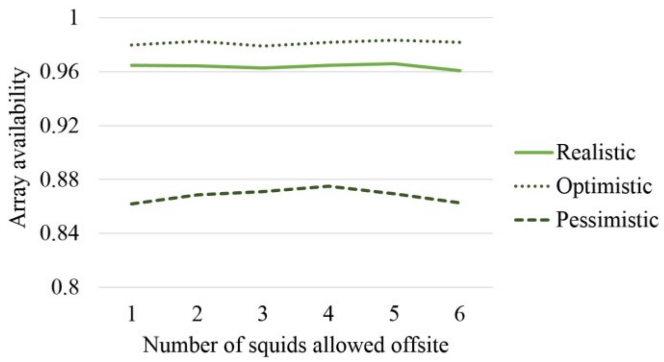

Figure 9. Array availability for different O&M base constraints

4 DISCUSSION

4.1 *Informing Decisions*

The results presented in this study can act as a guide for informing decisions about the operational logistics of an off-grid wave energy array project. Figure 4 demonstrates that the outputs of an O&M simulation model can include the number of days per year particular types of vessels will be required. It can be seen that the six device WaveNET array analysed in this study will need a vessel capable of towing a Squid WEC for approximately 6 days per year, given the 'realistic' scenario of inputs provided by Albatern engineers. However, when certain inputs are increased in the 'pessimistic' scenario, this value rises to approximately 20 days per year. As the routine service has been assumed to take place every two years on each Squid, it is expected that such a vessel would be in even higher demand in these years. This is confirmed in figure 5, where the average number of days the 'slow boat' is used is close to 10 for the 'realistic' scenario, and approximately 24 for the 'pessimistic' case. The other two boats are used for far fewer days per year than the 'slow boat'. In the 'optimistic' scenario, when certain inputs are decreased (such as failure rates), these two vessels are hardly used at all. This indicates that if reliability of devices is improved and maintenance tasks are streamlined, then only one vessel would be required for all repairs and onsite replacements on the array, thereby making contract negotiations slightly easier.

A key area for negotiation during the project development phase of an off-grid wave energy array will be the sale price of electricity. Most off-grid energy users, such as fish farms and island communities, require diesel generators. The price of diesel fluctuates, the same as with all fossil fuels, making it difficult to select a base case for the price of electricity. The three tariffs used to create figure 6 were selected based on the assumption that an off-grid community would pay [redacted] for a renewable source of electricity. It can be seen that the annual profit earned by the array decreased by over 20% when the 'pessimistic' inputs are used compared to the 'realistic' scenario. This is true for all three tariffs. When the base [redacted] tariff is increased or decreased by [redacted], the annual profit changes by 11% accordingly. Further analysis of capital expenditure, combined with these outputs of the O&M tool, would be able to provide a holistic means of assessing the economic viability of a WaveNET array. An informed decision could then be taken by all parties involved in the project as to what the sale price of electricity should be.

The breakdown of annual operational expenditure (OPEX) given in figure 7 shows that the primary expense for a WaveNET array will be labour costs. In the 'realistic' scenario, over 90% of annual OPEX is spent on labour. This includes approximately £2.7k spent on bringing in external contractors. This cost increases to £17k in the 'pessimistic' scenario due to the increased number of failures and the higher number of technicians required for maintenance tasks. In the 'optimistic' case, the amount spent on external contractors is minimal, though the cost of permanently employing two technicians at the O&M base accounts for 96% of total OPEX. In such a small scale wave energy array as assessed in this study, such high labour costs have significant impacts on the economic viability of the project. Total annual OPEX is reduced significantly when only one technician is permanently employed at the O&M base, as shown in figure 8. This would mean bringing in external contractors regularly when any maintenance tasks or marine operations are required. Such a strategy would need careful assessment, as there may be unacceptable health and safety risks involved when only one staff member is permanently employed at the O&M base. The analysis presented in this study does not take into account the fact that there may be a limited number of external contractors available to the WaveNET array. Further work is needed to incorporate all aspects of array O&M workforce into the analysis, including staff holidays and working hours, health and safety regulations, contractor travel times and technician expertise.

Selecting a site suitable as an operations base is a vital part of wave energy project development. The initial analysis presented in this study (figure 9) shows that there is little impact on WaveNET availability when the number of Squids that can be kept offsite (i.e. onshore) at any one time is constrained. This is due to fact that the array assessed in this study only contains six WECs and some key components can be replaced onsite (i.e. offshore) if required. The number of Squids in an array is not limited by engineering, due to the modular design of the devices. Therefore, further analysis is required to assess at what point the amount of space available at the O&M base becomes a limiting factor for a larger WaveNET array.

4.2 *Model Uncertainty*

There are significant differences between the results of the three scenarios ('realistic', 'optimistic' and 'pessimistic') in each graph presented in this study. One example is the 10-12% difference in annual availability seen between the 'optimistic' and 'pessimistic' scenarios in figure 9. This shows that the results of the O&M model are highly sensitive to the inputs. It is therefore vital to obtain the most realistic inputs possible in order to minimise the uncertainty within the tool, and thus obtain the most useful outputs possible. Further confidence in the model inputs, such as repair times and failure rates, will be obtained during the Mingary Bay testing programme.

5 CONCLUSIONS

This study has focused on operations and maintenance (O&M) planning for off-grid wave energy devices. Inputs to a Monte-Carlo based O&M simulation tool include failure rates of components and subsystems, obtained from a Failure Modes and Effects Analysis (FMEA). Previous testing of the Squid devices has shown that replacement of certain key parts, such as the power take-off unit, can be undertaken whilst the WEC is still offshore at the array site. Other repairs, as well as a two-yearly routine service on each device, require the Squid to be removed from site and taken to the safety of a sheltered O&M base. This study has described the functionality of the O&M tool and used the model to analyse particular aspects of operational logistics.

It has been demonstrated that the O&M tool can be used to inform contractual negotiations with customers, such as a fish farm or an island community where diesel-powered electricity generation would be replaced by clean energy. The analysis presented has shown that the economic viability of off-grid wave energy projects are highly sensitive to aspects such as labour requirements and electricity sale price. It is therefore vital to reduce capital expenditure (CAPEX) and OPEX wherever possible, whilst maximizing revenue.

The limited amount of real-sea testing gained with the Squid devices means that many of the inputs to the O&M tool contain a large amount of uncertainty. For example, it is unclear exactly how many technicians would be required to undertake a routine service of the WEC and how long the task would take. More confidence in these inputs, and particularly with component failure rates, will be obtained through further testing of arrays and implementation of condition monitoring systems. The information gained from the current testing programme will inform the design of grid-connected WECs and move the wave energy sector further towards commercialisation.

6 FURTHER WORK

Further work in the project will explore additional modifications that could be made to the O&M simulation tool. The power matrix used in this study is specific to the six Squid array. ANSYS Aqwa will be used to create a power matrix for a WaveNET array containing a greater number of Squids. This will enable much larger arrays to be modelled using the O&M tool.

The failure rates currently in the model are constant values and therefore do not account for component fatigue, which is of particular relevance to structural parts. It will be possible to incorporate a damage model into the O&M tool, as described by Ambühl et al. (2015). However, realistic data on how components within the Squid WEC are affected over time will not be obtained until the condition monitoring system, as detailed by Kenny et al. (2016), has been in place for some time. This will enable more realistic inputs to be provided to the O&M tool, which will increase confidence in the outputs. Following the Mingary Bay test programme, realistic outputs of the O&M tool will be combined with a detailed assessment of CAPEX in order to calculate Levelised Cost of Energy (LCOE). This is a vital process in order to build investor confidence and move towards the design and deployment of grid-connected wave energy converters.

7 ACKNOWLEDGEMENTS

The lead author would like to thank the academic supervisors of this IDCORE project for their contributions, advice and support. Similar thanks must go to the engineers involved in developing the Squid devices at Albatern Ltd. The author would also like to thank Wave Energy Scotland, the IDCORE programme and their funding bodies, in particular the ETP (Energy Technology Partnership), for their support. IDCORE is funded by the Energy Technology Partnership and the RCUK Energy Programme; Grant number EP/J500847/1.

8 REFERENCES

Abdulla, K., Skelton, J., Doherty, K., O’Kane, P., Doherty, R. & Bryans, G. 2011. Statistical Availability Analysis of Wave Energy Converters. *Aquamarine Power Ltd. In Proc. 21st International Offshore & Polar Engineering*. Maui, Hawaii. 1, 572-577.

Ambühl, S., Marquis, L., Kofoed, J. & Sørensen, J. 2015. Operation and maintenance strategies for wave energy converters. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, 1-25.

BBC. 9 Dec 2014. Deadline passes for wave power firm Pelamis offers. [Online]. Available at: *http://www.bbc.co.uk/news/uk-scotland-scotland-business-30391102*. Accessed: 14/6/16.

BBC. 28 Oct 2015. Aquamarine Power calls in administrators. [Online]. Available at: *http://www.bbc.co.uk/news/uk-scotland-scotland-business-34659324*. Accessed 14/6/16.

Boud, R. 2012. UK wave energy resource. *AMEC Environment & Infrastructure UK Limited, OBO Carbon Trust*.

Dinwoodie, I., Endrerud, O., Hofmann, M., Martin, R. & Sperstad, I. 2014. Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms. *Wind Engineering*. 39, 1–14.

Gray, A., Dickens, B., & Johanning, L. 2014. The Modelling of Pelamis Wave Power's Operations and Maintenance Strategy. *ASRANet International Conference on Offshore Renewable Energy. 15-17 September 2014*. Glasgow, UK.

Gray, A., Dickens, B., & Johanning, L. 2016. Identifying key O&M strategy considerations for a wave energy array – a case study on Pelamis. *ICOE: International Conference on Ocean Energy. 23-25 February 2016*. Edinburgh, UK.

Hofmann, M. 2011. A Review of Decision Support Models for Offshore Wind Farms with an Emphasis on Operation and Maintenance Strategies. *SINTEF Energi AS. Wind Engineering*. 35, 1–16.

Hofmann, M. & Sperstad, I. 2013. NOWIcob – A tool for reducing the maintenance costs of offshore wind farms. *SINTEF Energy Research*. *In DeepWind. 24-25 January 2013*. Trondheim, Norway. *Energy Procedia*. 35, 177-186.

Kenny, CJ., Findlay, D., Lazakis, I., Shek, J. & Thies, PR. [Awaiting publication] 2016. Proposed Control and Instrumentation Topologies for an Integrated Wave Energy. *In RENEW2016. 24-28 October 2016*. Lisbon, Portugal.

Martin, R., Lazakis, I., Barbouchi, S. & Johanning, L. 2016. Sensitivity analysis of offshore wind farm operation and maintenance cost and availability. *Renewable Energy*. 85, 1226-1236.

Poore, R. & Walford, C. 2008. Development of an Operations and Maintenance Cost Model to Identify Cost of Energy Savings for Low Wind Speed Turbines. *Global Energy Concepts, LLC. NREL, National Renewable Energy Laboratory*. Seattle, Washington. NREL/SR-500-40581.