Mapped economic modelling of wave energy

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ABSTRACT: A high level economic model has been developed to map wave energy performance and level-ised cost of energy (LCOE). It takes time-series, gridded hindcast wave data, for example generated by SWAN (Simulating WAves Nearshore) software. Interpolating this data against a device power matrix, the wave conditions are converted to power, and then to LCOE using a discounting method and considering capital and operational costs. The results are presented as maps, which serve as high level site assessment tools and allow the most cost-competitive sites to be established.

Initial results have been generated for Albatern Ltd, a Scottish wave energy developer and industrial partner of the research project. Their technology is the WaveNET, a small-scale array based device which is constructed from 7.5 kW rated modular units (known as "Squids"). LCOE Maps have been created for a domain covering the Scottish Western Isles, as well as for NOAA hindcast datasets for regions around the world. This paper includes a sample case study, comparing the LCOE for a device concept at two different scales. The results found that, while the larger device performs better over the majority of the area, there are places where the smaller device has a better LCOE, sometimes by as much as 20-30 p/kWh. These are in the more sheltered regions, and imply both that there is not a one fit all solution to wave energy, and that device scale is a parameter which could be tuned for location.

1 INTRODUCTION

1.1 *Motivation*

With the threat of large scale climate change from global warming, worldwide there is a significant need to transition to a low carbon economy. Over the last twenty years, there has been increasingly interest in renewable energy as a way to reduce greenhouse gas emissions from electricity production. Some of these technologies, for example wind power and solar power, have been the subjects of decades of research and are beginning to reach cost parity with fossil fuels. Wave energy, by comparison, is a less mature technology and is yet to see a commercial breakthrough. However, it sustains interest due to the sheer size of the resource, in theoretical terms estimated to be two to four terawatts globally (Mørk 2010, Gunn 2012). It also has a number of potential advantages over other renewables: being less localized than tidal energy, more predictable and without the visual or environmental impact of wind energy, and not constrained to daylight hours like solar energy. It also follows seasonal demand well, with higher energy demand in winter being matched by stormier seas.

Despite these characteristics, there are also significant challenges that need to be overcome in order for wave energy to move from a solely R&D activity to a commercial industry. Currently, the main barrier is cost. The marine environment is a harsh one, and a high level of engineering is required for a device to survive while articulating enough to produce sufficient electricity. Because the concept is so novel, bespoke components and design methodologies are required, adding both cost and complexity. This, coupled with unknowns in operation and maintenance (O&M) costs due to lack of operating experience in the sector, means that costs and uncertainties in wave energy are high.

For any energy system, understanding the costs is crucial in order to secure a return for investors and to make sure that it is competitive with alternative solutions. For emerging renewable technologies like wave energy, where costs are still relatively high and not fully understood, research in this area allows cost reduction strategies to be formulated, improving investor confidence in the business approach.

This work presents a model which has been designed to counteract economic uncertainty, by predicting and assessing the levelised cost of energy (LCOE) of wave energy projects. The work was conducted as part of a collaboration with Albatern Ltd, a small scale wave energy developer based in Midlothian, Scotland. Some sample results from the model are also presented: a case study showing the effect of device scale on LCOE.

1.2 *LCOE and discounting*

In the energy industry, LCOE is the most common metric used to compare the relative cost between different technologies. It can be defined as:
"The constant price at which electricity would have to be sold for the production facility to break even over its lifetime, assuming it operates at full capacity." (Heal, 2009)
Mathematically, this can be expressed as:

$$\text{LCOE} = \frac{C\,(\text{PV})}{E\,(\text{PV})} \quad , \tag{1}$$

where C and E are the total project costs and energy produced, discounted to present values. Discounting is the process of reducing cash flows (or occasionally other quantities like power) that occur in the future. This is carried out to reflect the time preference of money, namely that cash flows in the present are worth more than those in the future as they can be invested sooner and are subject to less uncertainty. Future values are discounted by multiplying them by a discount rate, D:

$$D = \frac{1}{(1+r)^t} \quad , \tag{2}$$

where t is the time period that the cash flow occurs in (commonly the year or the month) and r is the discount factor. This is an arbitrary quantity, which represents the level of risk concerned with the investment. For an emerging technology like wave energy, typically the value used is between 6% and 15%.
Considering the discount factor for each cost and energy contribution, the LCOE can hence be represented with summations of these quantities, with each discounted to the present:

$$\text{LCOE} = \frac{\sum_{t=0}^{n} C(t)/(1+r)^t}{\sum_{t=0}^{n} E(t)/(1+r)^t} \quad . \tag{3}$$

1.3 *Related literature*

As wave energy is an emerging technology, with device performance and cost competitiveness still to be proved, there have been a number of studies focused on economic evaluation.

There are several studies which analyse and compare different device concepts. One example, Thorpe (1999), reviews shoreline, nearshore and offshore devices. Mainly considering device arrays at MW scale, analysis of LCOE is performed using a mixture of data from developers and estimations where data were not available. A study by Dalton and Lewis (2011), assessed the performance and economic potential of five more modern device concepts. Power was calculated using a joint occurrence matrix at a test location, which was considered for both the nearshore and offshore devices. Several cost metrics were analysed using a bespoke Microsoft Excel based model (NAVITAS). While it was found that higher rated devices had lower costs, in general the economic performance of all the devices analysed was poor, due to high capital costs.

Other economic studies have been performed, using models to focus on different cost aspects. Previsic (2004) conducted an economic feasibility study for a specific wave energy project: a Pelamis wave farm off the coast of California. This included obtaining quotes from local suppliers to construct the devices near to site, and performing Monte Carlo analysis on the different costs to examine uncertainty (which has also been conducted for more contemporary studies, for example Farrell, 2015). By examining learning rates, the author concluded that wave energy could be competitive with wind into the future, but high O&M costs meant that government support was important. Allan et al. (2011) calculated the LCOE for a wave energy farm, again made up of Pelamis type devices, and compared this to LCOE values for more traditional forms of energy. Wave energy was found to be considerably more expensive than the other systems, although this was somewhat offset when considering subsidies, namely Renewable Obligation certificates (ROCs), which helped bring it closer to other renewable sources. Several studies have included reliability analysis into wave LCOE calculation, for example Teillant et al. (2012), which also includes analysis of weather windows for operations.

Lastly, while all of the previous studies only calculate LCOE at single points, there are several studies which deal directly with mapping of LCOE. Castro-Santos et al. (2015) used GIS to map the LCOE for an oscillating water column type device around the coast of Portugal. The authors filtered out restricted areas, for example environmental protected areas and areas with rocky bathymetry where wave energy could not be deployed. Vazquez and Iglesias (2016) created a Matlab model to calculate spatial

capital costs for a tidal stream device. They use these costs to map levelised capital cost of energy, demonstrating that the spatial costs have a significant impact on the suitability of certain sites.

1.4 Devices

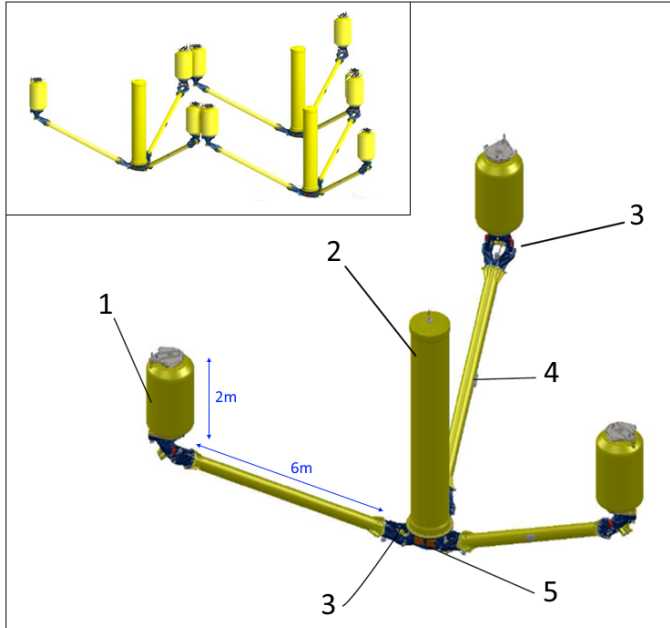The devices that are considered to demonstrate the capability of the model are both part of the Wave-

Figure 1: The WaveNET Series-6 wave energy device. Top left: A WaveNET array of three Squid modules. Bottom: A single Squid unit. Main components are the anti-nodes (1), riser (2), pumping modules (3), link arms (4) and central node (5). The PTO module is enclosed in an Anti-node.

NET family of devices, being developed by Albatern. The WaveNET is an array based device, made up of interconnected modular units called Squids. The array floats on the surface and effectively acts as a multi-point absorber. Energy from the waves creates movement between the device joints, which contain hydraulic pumping modules and create electricity via a hydraulic power take off (PTO) system.

There are two main classes of WaveNET which have been considered for this paper. The Series-6, shown in Figure 1, is a small scale device, currently in the technology demonstration phase. Each Squid module is rated at 7.5 kW, allowing arrays of tens to hundreds of kW to be deployed. So far, six Squids have been produced. The Series-12 is a larger scale device concept. The design, while in the process of being finalized, is approximately twice the physical size of the Series-6 and is rated at ten times the power, 75 kW per Squid.

Data for both of these devices, namely costs and power matrices, have been provided by Albatern in order to develop the model. The inputs that were used to generate the sample results presented in this paper are described in Section 2.2

2 METHODOLOGY

2.1 The model

2.1.1 Structure

The economic model has been coded in Matlab, and is made up of three modules.

The first module loads the wave data into Matlab, which are stored locally as NetCDF files. Each file corresponds to a year of hindcast data for a particular domain, and contains time series of significant wave height, Hs, and peak wave period, Tp. The domain is defined by a grid of points, each corresponding to a location in latitude and longitude. Currently, results have been generated for two different sources of hindcast data: a dataset covering North West Scotland, provided by Albatern, and various datasets created by NOAA and freely available online. For the case study in this paper, the Scotland data set is used and is described in more detail in Section 2.2.

Once the data are loaded into Matlab, the second module converts the sea state at each time step and location into power. This is achieved by using a 2D device power matrix as a lookup table, interpolating the Hs and Tp for each sea state into a power value. The result is a power time series for each grid location in the domain. By summing the powers for each time series, the annual power is calculated. The rated power of the system can be set, which has the effect of limiting values in the power matrix to this maximum value.

The final module calculates the LCOE, by using the power output data from the previous module along with the discounting method described in Section 1.2. The device costs are stored as Matlab data structures, and are currently treated as static across the model domain. In this stage, different cost scenarios can be examined by the user, to consider uncertainty and the range of costs which might be seen. The results can be exported into kml files, to be visualized in Google Earth.

2.1.2 Assumptions and simplifications

As the model is in an early stage of development, a number of simplifications are made.

Firstly, it was assumed that the annual wave conditions are seen for every year of the project. This means that the power is replicated in every years of the project, so that the only difference in power between years is due to discounting. This decision was taken to avoid the issues regarding computer memory and performance, from having to load and store multiple years of data and arrange them consecutively.

Additionally, as already mentioned, the costs in this version of the model are independent of loca-

tion. This is a significant simplification, as in reality the cost of components such as the export cable, mooring system and O&M will have high dependence on factors such as the water depth, distance to shore and distance to the port of operations. This means that the LCOE calculated at each location is directly linked to the energy at that location. Hence, rather than comparing relative LCOE across the domain, the model is better used to inform about the relative differences in costs brought about under different sensitivities.

Finally, there is a limitation in the treatment of availability. Currently, the model assumes 100% availability, so there is no power loss associated with downtime. In reality, there will be periods where the device is not generating power due to reliability issues and scheduled maintenance, which will be closely related to the maturity of the technology. There were two reasons why this was not considered at this stage. Firstly, due to limited operating experience, reliability data and operating schedules are not well understood, although there is significant research in this area (Gray et al, in press). Also, such analysis would also add great complexity, as availability will also have a high spatial dependence. This is outside the scope of this work, but is a consideration for future model versions.

2.2 Wave data

The North West Scotland dataset covers an area of approximately 90 by 200 miles, including Skye and the Outer Hebrides. The wave data, hindcast time series for the years 2000 to 2009, was purchased by Albatern from MetOcean Solutions Ltd, a consultancy who specialize in generating oceanography data. The data variables, most importantly Hs and Tp, are given at three hour time steps, with a spatial resolution of 0.0167° in both latitude and longitude. They were produced using a custom SWAN (Simulating WAves Nearshore) model, created using input wind and wave spectral data from larger scale wave models ran by NOAA. This data was internally validated, using well established processes which are described in other studies, for example Huckerby & Johnson (2008).

2.3 Case study 1: Scale comparison

The model was ran for the Series-6 and Series-12

Device	Series-6	Series-12
No. of Squids	6	6
Rated power (kW)	45	450
Efficiency (%)	100	100
Cut-out Hs (m)	6	12
Min Water depth (m)	20	30
Lifetime (y)	20	20
Discount rate (%)	8	8

Table 1: Input parameters used to calculate LCOE for two different device scales.

devices over the North West Scotland domain for the year 2005. The model input parameters are displayed in Table 1. Power matrices for both devices were provided, but are not reproduced due to commercial sensitivity. They had been determined from simulations in the frequency domain, using RAOs from simulations in Ansys Awqa at a range of sea states to determine the response of the PTO and limiting the torque. Each matrix were capped at the rated power for that device.

Both devices were considered to be triangular six Squid arrays, with rated powers of 45 kW and 450 kW. The conversion efficiencies were both assumed to be 100%. This value was chosen to allow the analysis to be conducted on a purely hydrodynamic level. In reality, efficiency values depend heavily on the nature of the PTO. This is very device specific and unique to the two systems, which would make the impact of scale alone less clear.

A cut-out Hs was added for each device, based on the design specifications. This is to represent the fact that, in extreme sea conditions, the device will go into a survival mode and not produce power.

Minimum water depths of 20m for the Series-6 and 30m for the Series-12 were also considered. This constraint occurs from the fact that the devices, with a relatively large draft, need a level of clearance to prevent collision with the seabed.

For the LCOE calculation, the discount rate and project lifetime values represent devices at an early, commercial level of maturity.

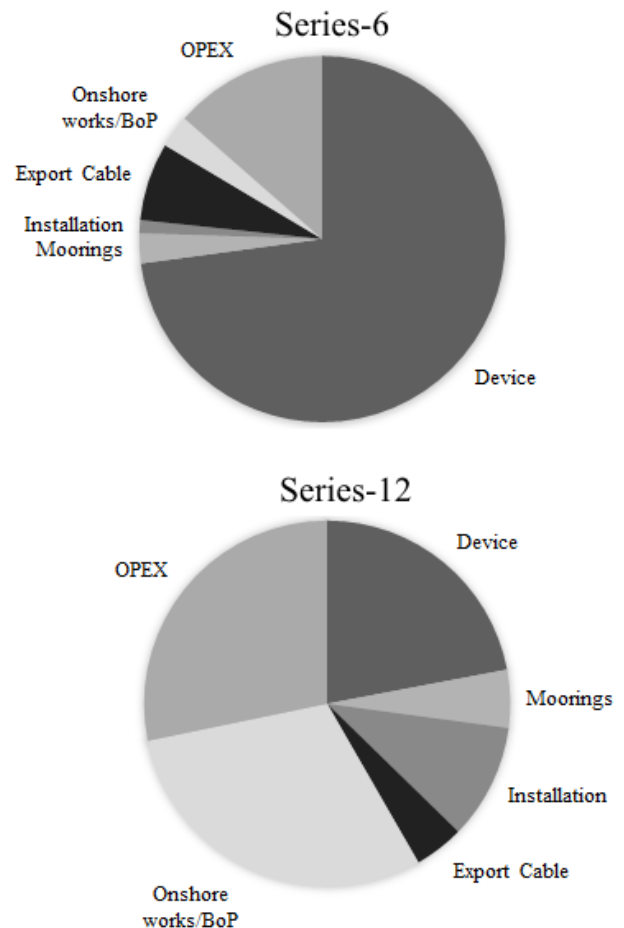The costs were obtained from data provided by

Figure 2: Breakdown of costs for the two devices exam

the manufacturer. In the case of the Series-6, capital costs were taken from actual bills of materials, while operational costs were estimated on a per Squid, per year basis from past operating experience. As the Series-12 concept is still in the design phase, the costs were

Figure 3: The effect of design on LCOE. Top left: LCOE for the Albatern Series-6 device
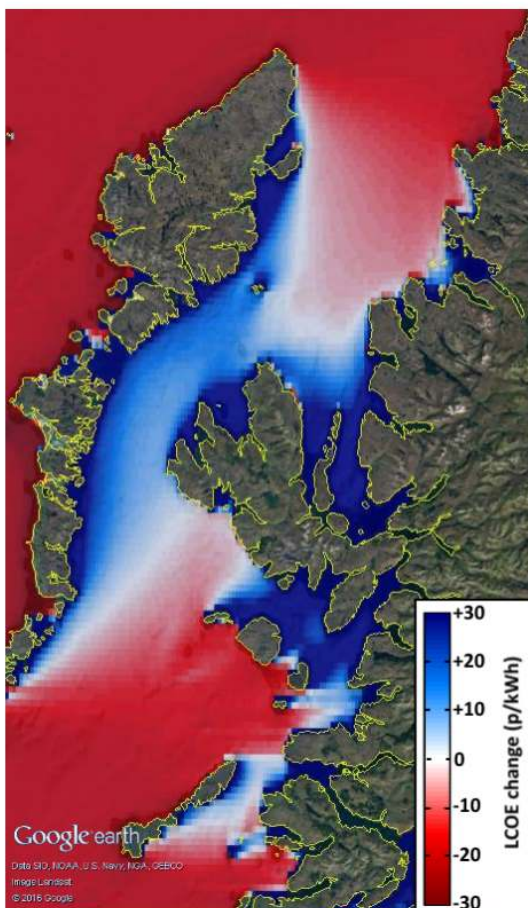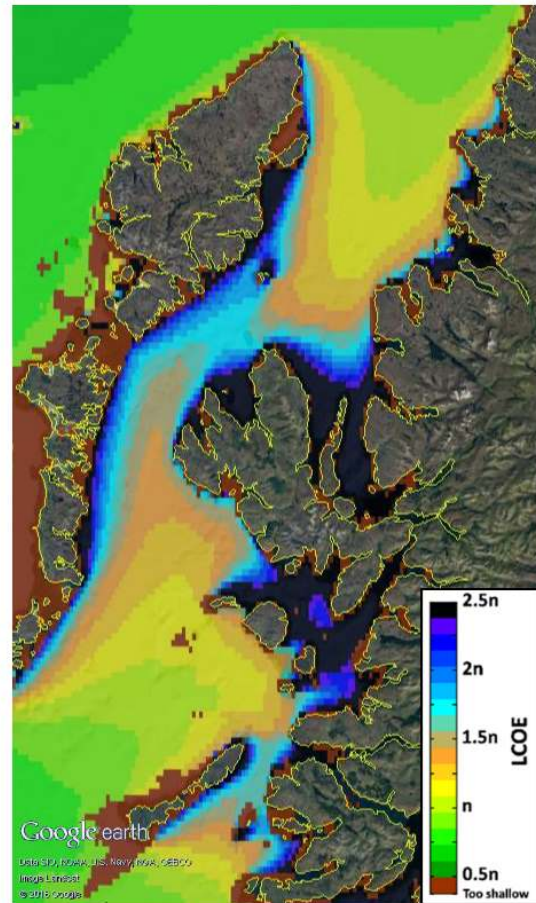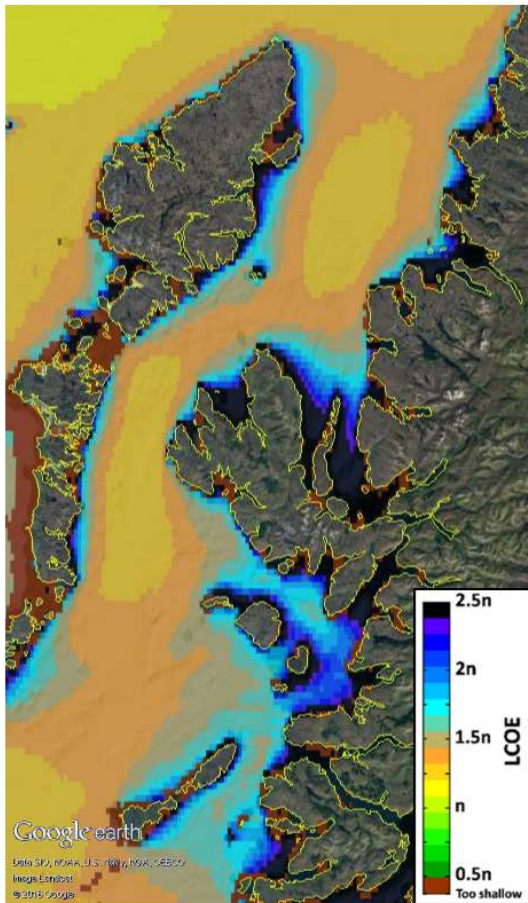
estimated from experience of the Series-6 and material quantities. Figure 2 shows the cost breakdown for each device, however absolute costs cannot be provided due to commercial sensitivity. Something to note is that there are significant differences between the two cost profiles, particularly with respect to the device cost. This falls from 72% of the total cost for Series-6 to 22% for Series-12. The main reason for this is due to design improvements and economy of scale, which means that the relative increase between scales is fairly low. This is in contrast to the relative costs of OPEX, onshore works/BoP (balance of plant) and installation, which all greatly increase due to the need for larger, more expensive vessels, onshore infrastructure and ancillary equipment.

3 RESULTS AND DISCUSSION

Figure 3 shows the LCOE for the Series-6 and Series-12 devices, as well as the relative difference between them. Interestingly, while the Series-12 is more cost competitive over the majority of the domain, the smaller device has a lower LCOE in some areas. These can be seen to be the more sheltered areas, where the conditions are more benign. This implies that there is not necessarily a one fit all solution to this device concept, and that device scale could be somewhat tuned for location. It is true that many of these sheltered locations, while better for the smaller scale device, are still greatly in excess of the lowest costs achievable elsewhere. This indicates that they would probably be overlooked for some of the better looking sites, without significant reductions in cost or changes to the device design to target these conditions.

The larger Series-12 device performs much better in more exposed locations. This is due, not only to relative cost reduction due to economy of scale, but also improved power capture. As the device is longer, the joints are more responsive in the longer period swell waves which arrive from the west. For Albatern's particular device concepts, the relative movement between the joints is what drives the power capture. The smaller device is less able to harness these swell waves, as it is more prone to heave motion as a whole unit rather than the different parts articulating independently.

Something else to note is that, because the majority of the Series-6 cost is in the device itself (Figure 2), the uncertainty in LCOE is likely to be lower. This is because the device costs are unlikely to vary spatially. Because a significant proportion of the Series-12 costs are in OPEX and installation, which have a high spatial dependence, the uncertainty in the results is higher. For both devices, locations very far offshore will have much higher LCOE in reality, due to increased costs associated with ac-cessing and maintaining the device and in the length of export cable to the shore.

3.1 *Future work*

There are several ways in which the model that has been presented could be enhanced into the future. The main improvement would be to include spatially dependent costs. This would allow remote locations, which look good by virtue of their wave climate, to be screened out. By using path finding algorithms, for example the A* or Dijkstra's algorithm, the distances between locations of the map could be estimated, as well as the optimal paths to link them. Applications for this could include calculating export cable lengths from the grid points to a landing point, or the distance from site to port to inform O&M scheduling.

The effects of scaling could be examined further by analysing the LCOE for devices of the same class, but with different link arm lengths between Squid components. While a longer link arm might incur a higher manufacturing cost, this could potentially be offset by better performance in higher period sea conditions.

4 CONCLUSION

This paper has described an economic model which allows LCOE of wave energy to be calculated and mapped over large regions. It does this by using hindcast wave data time series, generated using numerical wave models, to obtain power at each grid location. These are combined with costs, and both discounted to present values.

The model has great potential as a site assessment tool, to inform device design. This is demonstrated in the sample results, which indicate that, despite economies of scale associated with larger devices, there is potentially still a market for smaller devices. While the model is competent at examining sensitivities in the modelling assumptions, there is large uncertainty in the relative results in a single results set due to the fact that costs are fixed and not spatially dependent. The real value of this model will be when these costs are included, currently the subject of further research, which will allow the lowest cost regions for a particular project specification to be quantified.

5 ACKNOWLEDGEMENTS

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