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A model to map levelised cost of energy for wave energy projects

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ABSTRACT

An economic model has been developed which allows the spatial dependence of wave energy levelised cost of energy (LCOE) to be calculated and mapped in graphical information system (GIS) software. Calculation is performed across a domain of points which define hindcast wave data; these data are obtained from wave propagation models like Simulating WAves Nearshore (SWAN). Time series of metocean data are interpolated across a device power matrix, obtaining energy production at every location. Spatial costs are calculated using Dijkstra's algorithm, to find distances between points from which costs are inferred. These include the export cable and operations, the latter also calculated by statistically estimating weather window waiting time. A case study is presented, considering the Scottish Western Isles and using real data from a device developer. Results indicate that, for the small scale device examined, the lowest LCOE hotspots occur in the Minches. This area is relatively sheltered, showing that performance is device specific and does not always correspond to the areas of highest energy resource. Sensitivity studies are performed, examining the effects of cut-in and cut-out significant wave height on LCOE, and month on installation cost. The results show that the impact of these parameters is highly location-specific.

1. Introduction

With the threat of global warming, the need to transition towards a low carbon economy is gathering pace with policy makers. Many governments and institutions have adopted targets to limit carbon dioxide emissions and utilise energy from renewable sources. Examples include the Scottish government, aiming to produce 100% of gross electricity demand with renewable forms of energy (The Scottish Government, 2015) and the EU, whose Renewable Energy Directive has targeted supplying 20% of energy demand with renewables across its member states (Parliment and Council of European Union, 2009a). Wider ranging, global action is also being taken, such as the Paris Agreement which as of December 2016 has been ratified by 120 countries.

Wave energy, while in its infancy, has the potential to contribute significant renewable capacity towards both domestic and international energy markets. Studies indicate that the global theoretical resource is approximately 2 to 4 TW (Mørk et al., 2010; Cornett, 2006; Gunn and Stock-Williams, 2012). The UK has some of the best resource in the world due to strong westerly Atlantic winds: an estimated 35% of the European wave resource (House of Commons Energy and Climate Change Committee, 2009). The practical resource that could be economically extracted from UK waters has been predicted to be between 7 and 10 GW (Boud, 2012; Mackay, 2008), with a particularly strong resource off the West Coast of Scotland (Pontes, 1998). Wave energy has a number of potential advantages over other renewables: being more predictable than wind (Reikard et al., 2015) and available at night unlike solar. However it is yet to break through into the commercial marketplace, with cost currently a major barrier. The highest energy waves are found in extremely harsh marine environments, which devices must not only survive in but also produce energy in. This throws up a number of unique engineering challenges, which require bespoke, and hence expensive technology.

Understanding the cost of any energy technology is crucial, to make sure that it is competitive in the market and allow appropriate business decisions to be made. For an expensive pre-commercial industry like wave energy it is also important as it allows the pathway for future technology development to be planned and cost reductions targeted. The future of wave energy is highly dependent on its commercial viability and

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the extent to which it can compete with other sources of energy in the wider market. Economic modelling gives a way of quantifying this competitiveness, and thus designing robust models is of significant interest to the industry in the immediate term.

Economic modelling is a wide ranging topic, with a huge number of potential factors which can be considered for analysis. This means that the literature for wave energy covers a broad range of aspects. One of the earlier studies, conducted by Thorpe, was produced for the UK government to advise on the various device concepts available (Thorpe, 1999). Economic assessments were conducted by using estimates of costs and energy production, obtained from correspondence from developers. A more recent comparison study by Dalton estimated the Levelised Cost of Energy (LCOE) as a function of farm size for five device concepts off the West Coast of Ireland (Dalton and Lewis, 2011).

Because of the wider availability of data, Pelamis style devices have been commonly considered for economic assessments in the literature. While this paper is concerned with a smaller scale device, such studies should be mentioned because the underlying calculation methods are the same. The devices themselves are also similar in nature, for example both are self-referencing and rely on hydraulic power take-off (PTO) systems.

Previsic examined the commercial feasibility of a farm of Pelamis devices in California, using site specific data (Previsic, 2004). This included cost estimates from local suppliers and Monte Carlo analysis of the costs to incorporate uncertainty. A result of the study was that, while the project would struggle to compete commercially in the short term, favourable LCOE could be obtained with similar investment and learning as the wind energy industry had seen. A more recent study, conducted by Dalton et al., estimated the LCOE for the Pelamis for projects in North America, Portugal and Ireland, using a Microsoft Excel-based model (Dalton et al., 2010). Other studies include Ref. Allan et al. (2011) and Farrell et al. (2015), both of which also examine the level of present subsidy levels. The latter of these extends the analysis to revenue, using statistical analysis to estimate the confidence in a project being able to provide a significant return to an investor.

The vast majority of previous studies have been performed for single locations at a time, considering point estimates of costs and using a joint occurrence matrix to estimate energy. The limitation of such an approach is that it is difficult to know whether the point chosen is representative of the wider area, and whether it would be the optimum site for the particular device being analysed. For a developer, such an analysis gives little indication of whether the specific location accurately reflects their device's potential, and what the best location might be.

An alternative way of performing economic analyses is by repeating the calculations over multiple points, allowing the results to be mapped. Simulated metocean data is required for this, typically obtained by performing hindcast simulations with numerical wave models. While spatial methods are less accurate than single point models when considering a single location (as some costs are calculated rather than directly specified by the user), they provide a powerful indication of the best areas for deploying the device and the overall trends across the region of interest.

For wave energy, previous spatial studies have been focussed on several areas. A common theme is resource assessment studies: estimating the raw energy available in the waves to make judgements on the most suitable locations for wave energy projects (for example Refs. Pontes (1998); Iglesias et al. (2009); Sierra et al. (2013)). Some of these studies also incorporate device power matrices in the analyses, to see how the device performance matches the resource (such as Ref. Gunn and Stock-Williams (2012)). Another research theme involves using graphical information system (GIS) based methods to determine viable project locations, by taking account of spatial costs and exclusion areas. An example is Ref. Prest et al. (2007), where the effect of exclusion zones on wave energy cable routing was examined. An alternative methodology is a multi-criteria based analysis, where a selection of different locational parameters are examined and assigned a score and weighting depending on the perceived positive or negative effect on a project. These are aggregated for each point across the domain, the final scores indicating the most suitable areas for deployment. Examples for wave energy include Refs. Nobre et al. (2009); Flocard et al. (2016) and Vasileiou et al. (2017), the latter considering a combined offshore wind-wave system. While multi-criteria analyses offer a logical way to categorise sites by location, choosing the different category weightings is a somewhat arbitrary exercise and can significantly influence the final results.

The model that has been developed for this paper uses LCOE to define the most suitable wave energy project locations: by calculating spatial energy and spatial costs. It also has the ability to define exclusion zones for deployment. This approach has the advantage that LCOE is a commonly used metric that is of interest to investors and policy makers as well as developers. This is because it allows for comparison with other energy technologies and the market as a whole.

To date, there has been similar research undertaken in offshore wind (Cavazzi and Dutton, 2016) and tidal stream energy (Vazquez and Iglesias, 2016). For wave energy, there are also examples of work in this area, however there have been limitations adopted that warrant further study. Catro-Santos et al. used a GIS tool to map the LCOE around Portugal, filtering out locations corresponding to restricted areas. The wave resource was considered with spatial dependence, using mean power per metre from a resource atlas. However costs were not given spatial dependence, estimated using a high level, top down approach (considering €/kW of installed capacity), resulting in significant underestimation of LCOE for locations far from shore. An additional example, Behrens at al., focussed on the wave energy potential around Australia (Behrens et al., 2012). This study considered three different device types and determined LCOE around the coast using data from the US National Oceanic and Atmospheric Administration's (NOAA) WaveWatch III. However only sites 5 km from the coast were considered for the LCOE analysis, again with costs considered fixed (for example operations and maintenance (O&M) costs were considered per MWh of produced energy, without adjusting for local sea conditions).

The spatial distribution of costs and LCOE, as well as the methods used to calculate them, represent an area of great interest to developers, investors and policy makers. This study aims to expand on previous knowledge by presenting a model which incorporates spatial cost estimations of the export cable, installation and planned O&M into the analysis. This allows robust estimates of LCOE to be made.

The paper continues with a theory section, describing the LCOE calculation process. Section 3 then introduces the main features of the model and how the parameters are calculated in practice. A case study to demonstrate the model, focussing on the Scottish Western Isles, is described in Section 4, with the results presented and discussed in Section 5.

2. Theory

In order to calculate LCOE for a particular energy system two quantities are required: the total project cost and the total energy produced over its lifetime, both discounted to present values. As the model described by this study is spatial, the calculations are performed over a two dimensional domain, each point defined by a latitude and longitude. The metocean data that are used are hindcast data, obtained from numerical wave simulations, with wave parameter time series defined for every point.

To obtain the total energy, first a two dimensional power matrix is used to obtain a power time series for each location in the domain. Power matrices are the most common way of representing wave device output power as a function of sea state, and are derived by developers by performing numerical simulations of the device at different combinations of significant wave height, H_s and peak period T_p (or energy period, T_e). The power values can be verified experimentally, for example through tank testing or sea trials, and adjusted accordingly. Given time series of H_s and T_p, a time series of power can be obtained by using the power matrix as a lookup table, interpolating the metocean data at each time step. This interpolation is required when the metocean