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Techno-economical tools for WEC scale optimisation

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***Abstract*—The scale (or size) of Wave Energy Convertors (WEC) deployed are often constrained by site specific aspects such as the proximity and availability of port infrastructures to assemble and maintain the system but also funding constraints, larger units being more capital intensive to deploy. To date, studies have been performed for various WEC technology types and have largely focussed on optimising WECs scale to deliver the highest power output. Less often the optimum WEC scale delivering the lowest Levelised Cost of Energy (LCOE) has been studied. This is understandable since this requires a deep understanding of both the technical and financial aspects of the technology studied. This paper presents the tools developed by Carnegie Clean Energy (CCE) to optimise the scale of its CETO technology in order to deliver the best LCOE for a 20 MW project in Albany along the south coast of Western Australia. The model takes into account the cost sensitivity of all major components of the technology with the main design parameters of these components. These tools also provide crucial value during the design process of a technology. Design decisions are quite often related to a trade-off between cost and performance. The tools developed also facilitates those decisions by informing on the design parameter leading to the optimum LCOE. Although developed specifically for the CETO technology at the Albany and Wave Hub site the methodology used to develop these tools can be replicated for all WECs and at any development site. The novelty in the tools developed consists in the fact that the LCOE optimisation conducted for different scales is based on manufacturer estimates rather than using scaling assumptions.**

***Keywords*—CETO, LCOE, Techno-Economical, WEC scale.**

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I. INTRODUCTION

INTENSIVE research on the extraction of ocean wave energy started about 50 years ago [1], yet the wave energy technology industry has not reached the level of commercial maturity hoped for. It is still an emerging industry and all the large projects deployed globally have been demonstration projects at this stage. The wave energy industry is competing with other developing marine renewable energy technologies such as tidal energy or offshore wind energy and needs to demonstrate competitive cost of energy to unlock the investment opportunities required to build large scale commercial project. Weber [2] suggests that wave energy developers have mostly concentrated their effort into improving the readiness of their technology while dedicating too little attention in its the performance level or cost of energy. To reach the level of performance required to become commercially viable within a reasonable timeframe, the wave energy industry needs to

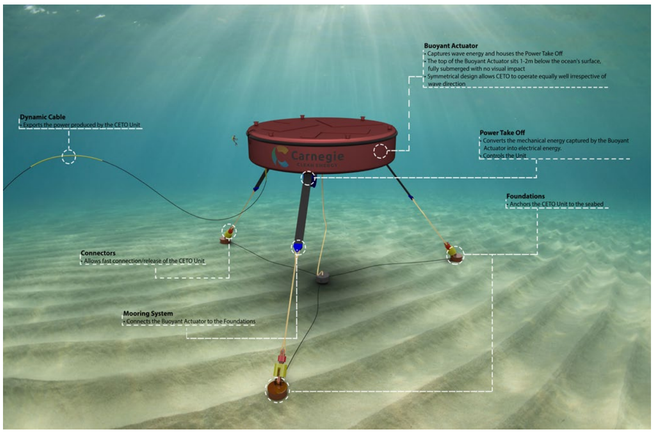

Fig. 1. CETO 6 General Arrangement.

focus on the Levelised Cost of Energy (LCOE) metric and develop the necessary tools to guide the development of Wave Energy Converters (WEC) accordingly. Pushing in this direction, a few techno-economical assessments of WECs have emerged recently with notable contributions from Teillant [3] and Roberts [4].

Carnegie Clean Energy (CCE) has been developing its proprietary WEC technology named CETO for more than 10 years. CETO is a submerged point absorber type WEC. CCE recently developed a series of tools coined LCOE parametric models to support the development of the

CETO technology. Design decisions almost always involve a trade off between cost and performance, so it is important to make those decisions based on the best outcome for the LCOE. Let us illustrate this point further by giving an example. A storm relief system is a common feature in many WECs. Its implementation induces extra cost associated with its design, manufacture and integration. Its integration can also potentially introduce additional power losses and slightly reduce the efficiency of the device during normal operating conditions. The main objective of this feature is to reduce loads and motions experienced by the WEC during extreme conditions which in turn will make the design requirements less onerous and reduce the cost of the structural components. Measuring accurately the relative importance of each of these conflicting parameters can be challenging and time consuming. Having a tool allowing a design team to make informed decisions based on accurate LCOE estimates is crucial to fast track the development of a technology.

This paper presents in details the methodology used to develop an LCOE parametric model and gives an example of its application to determine the optimum scale (or size) of the CETO technology. Convergence toward an optimal unit scale has not occurred yet for the Wave Energy industry. This is mainly because the optimum scale of a commercial WEC is largely dependent of the type of technology deployed and thus industry scale convergence cannot occur with the many different types of technology existing today. Even within a particular type of WEC views diverge on the optimal scale. Companies like CorPower advocate for smaller units with ratings around 250 kW [5]. This concept would allow for early mass production and a maintenance scheme based on replacement of entire units at sea. This could potentially reduce both capital and operational expenditures (CapEx and OpEx). Other developers like former Wavebob are developing much larger devices (about 20 m diameter and 50 m draft [6]). These developers are following the trend observed recently for offshore wind turbines with cost reducing as size and rated capacity of turbines are increasing. During the course of its development, the CETO technology has seen its size increase by an order of magnitude starting from CETO 2 with a 2 m diameter deployed in 2008 to the latest version currently in development, CETO 6, which will exceed 20 m in diameter. For a submerged point absorber, the optimum size of the unit for the power production depends mainly on the wave periods experienced at the deployment site. Finding this optimum is feasible through numerical modelling. Finding the optimum size of the unit for the LCOE is less trivial. This involves a detailed understanding of the costing of the system and its dependency on scale. Several WECs scale optimisation based on a parametrisation of the LCOE have been published but come with limitations. In [7], Costello studies the optimum number of segments for a generic hinged barge device but the main objective of this work is to demonstrate that an optimisation based on power production and LCOE can lead to significantly different sizes of devices. In [8], De Andres conducts a thorough techno-economical optimisation of the rated power of Corpower WEC at different sites, but the results present a strong dependency on initial assumptions around CapEx and power output, both of which are calculated using scaling factors. The models and associated methodology presented in this paper attempt to address some of these limitations. It uses detailed CapEx estimates based on costing estimates established in collaboration with the manufacturers of each components of the unit. Moreover, extensive numerical modelling has been conducted to estimate accurately the power load and motions of the devices at different scale. The models have been developed for the 6th version of the CETO technology and for a 20 MW project in Wave Hub (UK) or in Albany along the south coast of Western Australia. Although developed specifically for this technology and these sites the method used can be applied to other types of WEC and other sites as long as enough information is available.

The following section of this paper details the methodology and the structure of the LCOE parametric models. This is followed by a section that presents the results of the LCOE parametric model applied to a 20 MW project in Albany.

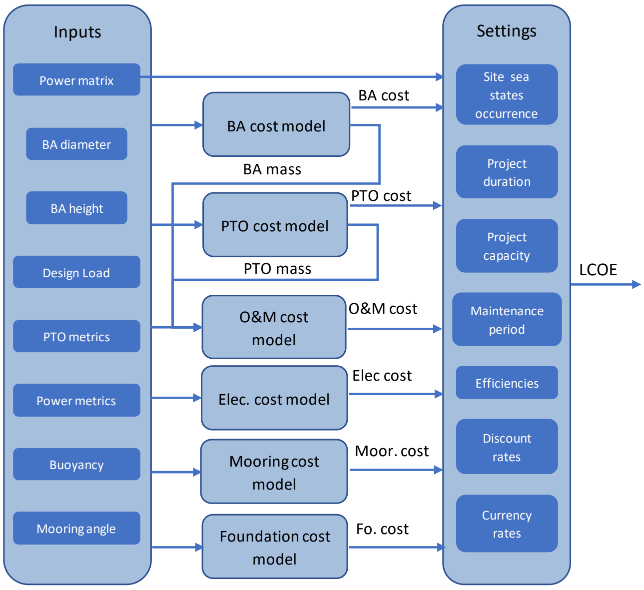

Fig. 2. Structure of the LCOE parametric model.

II. METHODOLOGY

The overall structure of the LCOE parametric model is presented in figure 2. It is composed of cost models for each of the components of CapEx and OpEx and a main block that uses these costs as well as project assumptions to compute LCOE values.

A. *Settings*

The parametric model includes several settings that can be modified by the user. These are separated from the inputs presented in section *B* because they are not expected to be modified regularly and will be kept constant for the unit size optimisation presented in this paper. These settings are presented in Fig. 2 and also listed below:

- The sea state occurrence matrices for each sites considered have been entered in the model but can be updated by the user in case more accurate data become available for a site. The site selected for the example given in this paper is Albany.
- A typical project duration of 25 years has been used in this study.
- A project rated capacity of 20 MW is used in the current model. The total number of units deployed for the project is scaled to maintain this capacity constant for different unit sizes. Alternatively, the model can be set to keep the number of units constant and have a varying project capacity.
- Regular maintenance is planned for each unit every three years.
- Constant mechanical to electrical efficiency and project availability have been assumed. Note that this is a limitation of this model since the project availability is likely to vary with the number of units deployed. This will be addressed in future updates of the model.
- A discount rate of 10 % has been assumed for the LCOE calculation.
- Given some of the costing is based on quotes obtained from overseas suppliers a set of currency exchange rates is used in the model.

B. *Inputs*

The key inputs required by the cost models can be set by the model user but in the case of the example given in this paper they are extracted from a hydrodynamic database. A different hydrodynamic database has been generated for each unit size and for each deployment site considered in the study. The size of the CETO unit was varied by changing the diameter and aspect ratio of its prime mover also named Buoyant Actuator (BA). The aspect ratio is defined as the BA height divided by its diameter. A similar hydrodynamic database can be used at different sites if those have a similar water depth and similar wave spectra characteristics. These characteristics are significantly different for the two sites considered in this study, Albany and Wave Hub, so different databases were generated for each of these sites.

Each database is composed of a set of time series corresponding to different sea states. These can be generated using numerical modelling or physical modelling. In the example presented in this paper the databases were generated using a custom linear potential flow model but also using a Reynolds Average Navier-Stokes (RANS) solver.

The linear potential flow model provides less accurate results than the RANS solver but is computationally faster. The linear potential flow model databases were initially used to cover a large problem space. The BA diameters considered range from 10 to 40 m with a 5 m increment and the aspect ratio varied from 0.2 to 1 with a 0.2 increment. This means a total of 70 databases were generated with the linear potential flow model for all sizes and sites considered. For each of these databases, runs were conducted for a significant wave height (Hs) ranging from 0.5 to 5 m with a 0.5 m increment and peak period (Tp) ranging from 8 to 18 s with a 2 s increment. Each database generated from the linear potential flow model then consisted of 60 time series covering a large majority of the sea state occurrences at both sites. It must be noted that for each sea state the power take-off (PTO) settings were optimised and only the optimum time series was retained which means that a large number of numerical runs were required to obtain those time series.

The RANS solver was used to obtain similar databases, but the number of numerical runs performed to obtain each databased was rationalised due to their high computational cost. Only three BA sizes were considered, 20 by 4 m, 25 by 5 m and 25 by 10 m (diameter by height). These were the sizes that were identified as potential optimums using the linear potential flow model databases.

When comparing the databases obtained with the linear potential flow model and the RANS solver, it can be observed that although absolute values are different between models, trends tend to be similar for both models, as illustrated in Fig. 3. This observation is comforting for the approach chosen and suggests that the linear potential flow model is probably a suitable tool to initiate the study and reduce the unit size searching space.

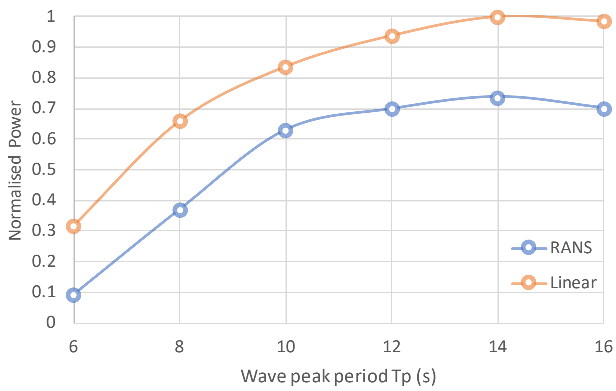

Fig. 3. Comparison of the computed CETO power output for a 25 by 10 m BA, for Hs = 2 m and for different wave periods. Red dots correspond to the results obtained with the linear potential flow model and blue dots with the RANS solver.

The parametric LCOE model loads these databases and for each of them extracts the inputs needed by the model.

A list of these parameters (also shown in Fig. 2) is given below:

- Annual average power. A mechanical power matrix is extracted from the time series of each hydrodynamic database. This is used with the site sea states occurrence matrix to compute the annual average power output used in the LCOE calculation presented in section *I*.
- BA dimensions. Height and diameter are used to compute the BA and Operation and Maintenance (O&M) costs.
- Design load. Sea states are divided into 'production sea states' for which the unit is tuned to maximise the power production, and a set of larger sea states coined 'survival sea states' for which the unit is tuned to minimise loads and motions. Due to the control philosophy adopted for the CETO technology the design load in the system is related to the maximum load in the production sea state and is calculated from the databases. This parameter is used to calculate PTO, mooring and foundation costs.
- Various PTO metrics are used to calculate the PTO cost:
  - Maximum PTO stroke. This is the maximum distance travelled by the PTO during production sea states.
  - Lowest optimal stiffness (K) for production sea states. The force function used for the PTO system is a modified spring damper function. The size of the hydraulic accumulators in the PTO system is directly related to the lowest stiffness required.
  - The maximum PTO force for the spring and damping component.
  - The radial load for the maximum PTO extension, this is relevant for the design of linear PTOs.
- Various power metrics are required to size the PTO and electrical systems:
  - The maximum instantaneous mechanical power during production sea state for a single PTO.
  - The average mechanical power during a large production sea state for a single PTO.
  - The maximum electrical power exported from the unit during a large production sea state.
- BA net buoyancy. This parameter has been optimised for each BA size and is thus different for each database. To maintain equilibrium, the PTO needs to produce a mean constant force that offsets the unit buoyancy. This parameter is thus important for the sizing of the PTO.
- Equilibrium mooring line angle with respect to the vertical. This parameter has been optimised for each BA size and is thus different for each databases. This is used for the sizing of the foundation and mooring system.

C. *BA cost model*

The BA is a standard steel construction similar to classic ship structure. It is composed of an external shell and an internal structure. The external shell volume is calculated from the height and diameter of the BA. The internal structure volume is scaled linearly with the height and diameter from an existing BA design. The total dry mass of the BA can thus be calculated. It is used to calculate the BA cost but also the O&M activities cost. The cost of the BA is composed of:

- a fixed cost for its shipping,
- a fixed cost for the piping system required to ballast the BA
- a cost variable with the BA size based on the total mass calculated and an assumed steel construction cost.

Values for fixed cost and steel construction cost have been obtained from several suppliers. The model calculates the total cost of the BAs for each set of manufacturer cost and takes the average.

D. *PTO cost model*

The PTO cost model is the most complex and the most influential of the LCOE parametric model. It has been developed for four PTO types that are relevant to the CETO technology. For each PTO types, the total PTO cost is computed as well as its efficiency and mass. The efficiency is used in the main LCOE calculation presented in section *I* while the mass is used in the O&M cost model presented in section *H*.

1) *Linear hydraulic PTO*

The linear hydraulic PTO includes a hydraulic cylinder (called a 'Pump' in the rest of the paper) connected between the mooring line and on the underside of the BA. The pressurised fluid generated in the Pump is transferred into a process module housed inside the BA. The process module converts the hydraulic energy into electrical energy using hydraulic motors and electrical generators. The process module also controls the force applied in the mooring line which is crucial to be able to optimally extract wave energy. The PTO cost and mass are composed of a fixed component that is assumed not to vary with the unit size. This includes items such as development, control hardware and cabling costs. The remaining costs and their variations are a function of the input parameters detailed below.

The Pump mass was estimated using a simplified analytical stress model of the Pump rod and by changing Pump dimensions, such that the stress in the main rod remained acceptable when the radial load was applied. The specific cost, or cost per mass, was estimated using historical data from previous CETO projects which used linear hydraulic PTOs.

The spring component of the optimum force function is created using a set of gas bottles and hydraulic accumulators with varying pre-charges. Their total volume was calculated using (1). A cost per volume for the accumulators and the gas bottles was estimated using quotes from several suppliers.

$$V = {}^{\alpha \cdot P_{high} \cdot A^2}/_{K} \tag{1}$$

Where:

V is the total volume of the hydraulic accumulators and gas bottles. 65% of the total volume was attributed to the accumulator and the rest to the gas bottles.

α is a normalising factor between the linear spring volume and the actual volume required and is derived from previous CETO designs.

P_{high} is the maximum circuit pressure.

A is the active area of the Pump piston pushing fluid into the accumulators circuit. This is derived from the Pump sizing presented in the previous paragraph.

K is the lowest optimal stiffness, input parameter presented in section *B*.

The process module cost and mass were divided into a component varying with the maximum instantaneous mechanical power and the average mechanical power during a large production sea state for a single PTO. Each of these components was scaled linearly using the input values.

2) Rotary hydraulic PTO

Design of a rotary hydraulic PTO was developed in collaboration with a third-party. The design comprises a flexible element, such a rope/belt, which coils around and actuates a spool. The spool is connected via a gearbox to a hydrostatic transmission with numerous input hydraulic motors, and fewer output drives connected to electrical generators. PTO force control is achieved via independent control of the hydraulic ports on each input hydraulic motors.

The third-party, based on previous project experience, provided a linear parametric PTO cost equation which is a function of the total system rated output power as defined in (2).

$$Cost = P \cdot x \tag{2}$$

Where:

P is the rated output power.

x is the cost per unit of power.

3) Rotary direct drive PTO

A rotary direct drive PTO design was also developed in collaboration with a second third-party. The design obtained comprises a flexible element which coils around and actuates a spool. The spool is connected directly to an electrical generator which is controlled to provide the torque for the PTO damping force component. CCE provided the buoyancy offset and spring force system, and its costs are considered separately.

The third-party provided a linear cost function with a constant offset, which is function of the system's buoyancy offset force, because this was deemed an appropriate proxy for system size, as defined in (3).

$$Cost = F \cdot c + L \tag{3}$$

Where:

F is the buoyancy offset force.

c is the cost per unit of buoyancy offset force.

L is the fixed cost of the system.

For the spring and buoyancy offset system, CCE used various supplier quotes to create a linear cost function which is a function of the maximum potential energy stored within the hydraulic spring.

4) Rotary geared electrical PTO

CCE developed a fourth concept which comprises a flexible element which is coiled around and actuates a spool. The spool is connected to a gearbox, and multiple hydraulic motors are connected at one stage of this gearbox, with a single generator connected at a subsequent stage.

The flexible element is sensitive to fatigue damage, which is highly dependent on its axial loading and on the diameter it bends around, i.e. the diameter of the spool. The maximum axial loading can be derived from the time series and determines the cross-section of the flexible element, and the size of the cross-section determines the size of the spool. Both components are costed on a per unit mass basis.

Bearing costs were established with quotes from various suppliers and fitted to a quadratic function of radial load, which became the bearing cost function.

The spring and buoyancy system is hydraulic and therefore the cost function is the same as described in section 3).

The gearbox, damping system (inc. generator) and power systems cost functions were linearised as function of the respective mechanical/electrical power they experienced, and based on costs and feedback received from various suppliers.

E. Electrical system cost model

The Electrical system total cost is composed of fixed costs, costs that only depend on the number of units deployed and costs that depend on the maximum electrical power exported. The total cost can be broken down into the component costs listed below.

The power export cable assembly is composed of fixed development cost, electrical connectors and power cable costs that are scaled with the unit maximum electrical power exported and the number of units.

The control system and instrumentation costs include fixed development costs and a component that varies with the number of units.

The costing information used was obtained from specific quotes and from previous projects developed by Carnegie.

Note that the electrical subsea hub (where all units connect), the power cable running from this subsea hub to the grid connection and the onshore infrastructure are not included in the costing. This allows better comparison between site since this infrastructure is often readily available in testing sites such as Wave Hub or EMEC.

F. Mooring system cost model

The Mooring System cost is divided between fixed costs and costs varying with the design load. This was derived from pricing provided by manufacturers.

G. Foundation cost model

The foundation design is assumed to be a drilled and grouted pile. The fixed costs are related to the pile design, the operational planning, transportation costs, as well as the mobilisation and demobilisation costs of the drilling vessel.

The pile diameter and length are scaled on the design load and mooring line angle using the foundation design developed for CETO 5 and CETO 6 projects at Garden Island. From the pile dimensions, cost for pile manufacture, grout and offshore drilling are estimated based on detailed costing provided by an offshore construction consultancy.

Foundation design can vary significantly with geological conditions encountered at different sites. However, since the objective of the model is to provide the LCOE sensitivity to size or other parameters, as opposed to provide an absolute LCOE value, the method proposed for the foundation costing is deemed suitable.

H. O&M cost model

The O&M cost model estimates the expenditures associated with Construction, Installation and Maintenance activities. It is based on costing information received from ship yards in UK and in Australia. Assembly and maintenance activities take place in a staging area. Components then gets transported to the wharf and lifted into their berth. An O&M budget has been established for a 15 units project of a particular size of CETO unit. In this budget, costs that are fixed with the unit size have been identified. Variable costs with the unit size are listed below.

Typical durations of use of berthing and staging area during installation and maintenance activities have been assumed. The length of berth and the area of the staging area required are scaled with the diameter and number of BAs. Using the cost per metre (or square metre) per day provided by the shipyard, the total cost for berthing and staging area estimated.

The cost of lifting and transporting components from the staging area to the wharf have been provided by ship yards for different weight ranges. Using the mass of the BA and PTO calculated in their respective cost models, the total cost of all lifting and transport activities have been estimated.

I. LCOE calculation

The levelised cost of energy (LCOE) is a widely used concept to quantify the economic performance of energy generation systems. It is defined as the revenue required to earn a rate of return on investment equal to the discount rate over the life of the project. The technical definition is given in (4).

$$LCOE = \frac{\sum_{t=1}^{n} {I_t + M_t}/{(1+r)^t}}{\sum_{t=1}^{n} {E_t}/{(1+r)^t}} \quad (4)$$

Where:

I_t is the investment expenditure in year t. This is calculated using the output of the component cost models presented in section *C* to *G*. The majority of these expenditures are assumed to occur during the year preceding the project commissioning, but a small portion is spread up to 3 years preceding commissioning to take into account development cost and long duration manufacturing processes.

M_t is the sum of operation, maintenance and service expenditure in year t. This is calculated from the cost model presented in section *H*. The expenditure is constant during the operational period of the project with a higher expenditure the year preceding commissioning to account for unit assembly and installation activities.

E_t is the energy generation in year t. The energy produced by the project is assumed constant during the operational phase and is calculated from the annual average mechanical power output of each CETO unit, assumed efficiencies and availability.

r is the discount rate. Discount rates of 10% to 14% are typical for new technologies. This range includes the perceived risk of any technology, the risk appetite of different institutional investors and the variation in returns expected in different jurisdictions. 10% is often used as a comparison discount rate between technologies.

n is the lifetime of the project in years, and a 25 year duration was selected in this example.

The main LCOE parametric model loops across a range of CETO sizes defined by the user. For each size the model loads the corresponding hydrodynamic database, calculates the cost, and the subsequent LCOE.

III. RESULTS

Using the methodology presented above Carnegie conducted various LCOE CETO size optimisations for projects located at different sites and using different PTO types. The optimum unit size obtained does not appear to vary significantly with the PTO types and deployment sites considered. For conciseness, only the results related to a rotary direct drive PTO at the Albany site are presented in this paper. The rotary direct drive PTO leads to the lowest LCOE value compared to other PTO types and is another reason to focus on these results. Other less favourable type of PTO such as the linear hydraulic PTO tends to favour slightly larger scale of device. Due to the commercial sensitivity of the costing data, the results presented have been normalised, but the trends and optimum size can still be observed.

Fig. 4 shows a surface plot of the normalised LCOE as a function of the BA diameter and aspect ratio. The plot suggests a stronger dependency of the LCOE with the BA diameter than with the aspect ratio. At higher diameters the power of the CETO unit starts reaching a plateau while the cost is still increasing rapidly which explains the rise of LCOE. For smaller BA diameters, the power output decreases rapidly, requiring a large number of units to deliver the required project power capacity. For those smaller diameters the cost per CETO unit also starts levelling off which explains the higher LCOE observed in this region. The optimum BA diameter lies between 15 and 30 m. Within this range the LCOE tends to decrease slightly when the aspect ratio reduces. The BA size of 25 m diameter by 5 m height was selected as the optimum for this project scenario.

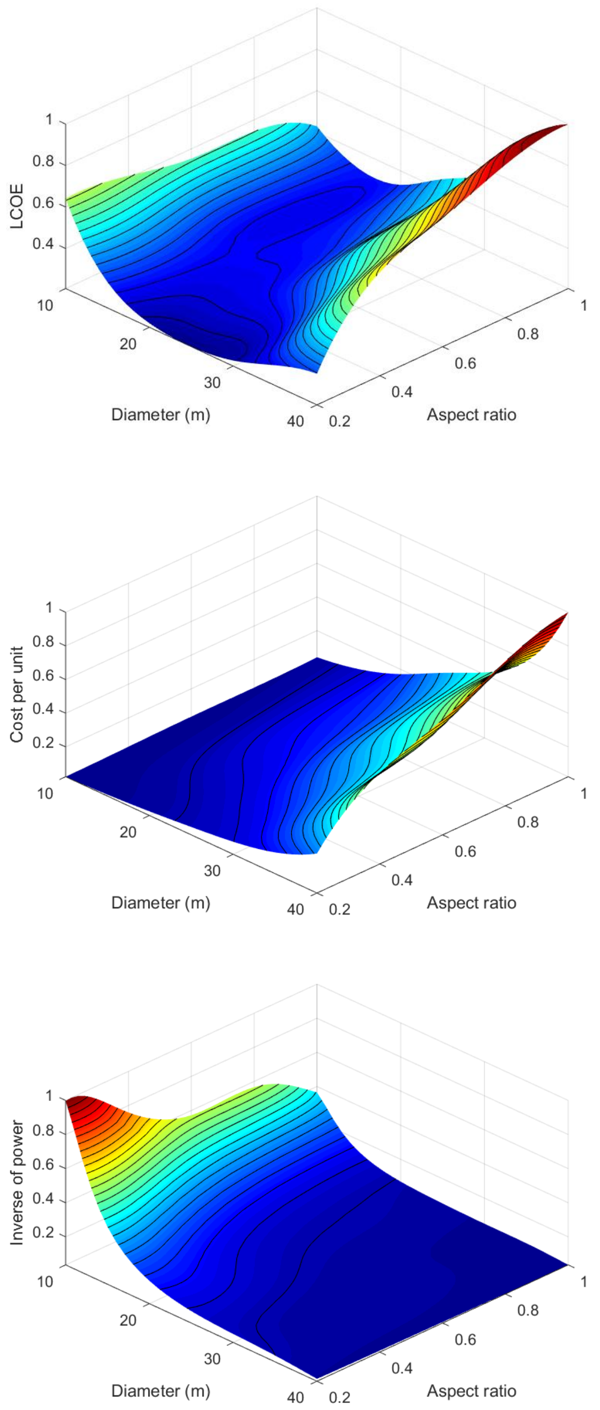

Fig. 4. Relative LCOE (top), total cost per unit (middle) and inverse of annual average power (bottom) computed with the parametric model for a range of unit sizes, a rotary direct drive PTO for the Albany site.

IV. Conclusions

This paper presents in detail the LCOE parametric model developed by Carnegie Clean Energy to optimise the size of its WEC technology. This model is particularly novel since it is based on costing information developed in collaboration with manufacturer as opposed to more commonly used scaling assumptions. The results of the model suggest that a 25 m diameter and 5 m height BA would be optimal for a 20 MW project deployed in Albany. Although the model has been developed specifically for the CETO technology, the methodology presented can be applied to any other type of WEC. Developing such a model requires a vast amount of detailed costing and design data which is typically commercially sensitive and thus not available in the public domain. This could partly explain the somewhat limited development and uptake of these types of tools. Most technology developers have accumulated enough data to develop similar tools for their own technology. This paper advocates for a larger use of these tools and attempts to demonstrate, by following a specific example, how beneficial and powerful LCOE parametric tools can be, especially when used during the early development phase of WECs.

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