Robustness testing of techno-economic assessment tool for tidal energy converters

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***Abstract*— This paper looks at the development of a Techno-Economic Assessment (TEA) for tidal energy converters. The TEA has been established to help developers by providing a high-level assessment of their tidal energy conversion device which gives an estimate of the affordability offered by the technology for a given resource. The affordability of the device is ultimately what will determine its commercial success and therefore being a decisive metric in supporting the development of a technology. To estimate the affordability of the device the TEA considers the fundamentals that impact on the costs and revenue thus evaluating the core design. Using different inputs to the TEA that represent different design approaches allows the developer to make design choices based on the outputs of the tool. This allows multiple design options to be analysed at an early stage of the design process, to establish the most promising configuration that could result in a commercial solution. The TEA aims to help developers at low TRLs as this is where the largest benefit can be realised. However, the assessment can still be used at higher TRLs to evaluate different approaches and to confirm progress. By carrying out this TEA at early TRLs it supports developers throughout the development of their technology, helping to find the optimal solution at the earliest development stage. This approach identifies areas of high risk early in the development program, a stage where costs and the impacts of change are lower.**

***Keywords*— Techno-economic assessment, tidal energy converter, decision support tool, affordability, design optimisation**

I. Introduction

Many countries have set targets for reducing their reliance on fossil fuels so that they reduce their carbon emissions to combat climate change. For example, the Scottish government set a target to deliver 'the equivalent of at least 100% of gross electricity consumption from renewables by 2020' [1]. To enable countries to reach their targets and to clean up the electricity generation market, the integration of renewable energy sources has become of considerable importance. Whilst renewable energy offers the opportunity to reduce carbon emissions, it often has the problem of being an intermittent source due to the nature of the resource, i.e. solar energy requires the sun, wind energy requires wind, and tidal stream energy requires tidal currents. For this reason, a mix of renewable energy technologies could offer a workable solution by taking advantage of the different resources and their different timings as the combination will contribute to a smoother energy generation profile. To enable this approach there needs to be a range of technologies commercially available, however, at present only conventional hydro, solar and wind energy are well established. Tidal stream energy converters are another technology that offers the potential to contribute to a diverse energy generation mix. Currently the tidal energy conversion devices are not commercial but with further development could deliver significant quantities of predictable energy to the national grid.

The focus of this paper concerns the development of commercial tidal energy converters. The potential for tidal stream devices to deliver large quantities of energy is great, in the UK alone it is estimated that there is a resource of 95 TWh/year [2], equivalent to approximately one quarter of the UKs current electricity consumption. To be able to capitalise on this resource, the technology needs to become commercially competitive so that it can compete in the energy market. Tidal energy converters are nearing commercialisation with the first commercial sites being utilised with the MeyGen project in the North of Scotland, the first large scale tidal energy farm, and in Shetland through the deployment of the Nova Innovation turbines [3] as two examples. These deployments have been installed as phased deployments with the first phases having been completed. The first phase of the MeyGen deployment is being used as a demonstration phase to provide evidence of both its commercial viability, technical feasibility and environmental impacts associated with the technology. This is being achieved by adopting a deploy and monitor strategy to help minimise some of the associated risks [4].

Although the above examples are being deployed on a small array scale, they are still being developed to try and lower the LCoE of the devices [5]. The lessons learnt from the first or early phases of the project will be fed into later device designs and used for the following phases. Both the MeyGen and Nova Innovation deployments use turbines which are 1st generation devices. These are sea bed mounted devices that use gravity anchors for their station keeping method which is simply using large quantities of mass to hold the device on station, 2nd generation devices are still under development and in varying stages of development. The aim is to lower the costs with the new generation of technologies to increase their competitiveness with other energy converters in the generation market. There are currently different methods to try and reduce the costs and improve the competitiveness, some of these include Scotrenewables using floating devices to improve accessibility [6] and Nautricity using a direct drive contra rotating generator to decrease costs [7]. There are also technologies considering different installation methods from Sabella using large construction support vessels to increase their operational window range [8] to Tocardo looking to use lower cost vessels to reduce OpEx costs [9]. Then there are developers considering other options for station keeping such as Sustainable Marine Energy using rock anchors in an effort to reduce costs [10]. These differences all have an impact on device affordability and some more specific to individual technologies and could contribute to commercial success for the industry. By carrying out the technical assessment the scale of the effect that the changes impose on the affordability can be measured, resulting in a cost benefit analysis to judge the value of the changes.

As previously mentioned, the assessment that has been created aims to help technology developers assess the affordability of their device. This will support them through the incremental scaling of their technology from the early stages of development, ensuring that they are developing a technology that is on the correct development trajectory where economic performance is being assessed alongside commercial readiness. Completing this assessment at the early stages of development, where the impacts of change are less and the associated costs lower, offers the best chance of commercial success. The ongoing development in the sector to reduce costs show that technology assessment will be useful in the efficient development of future technologies. This will result in more thoroughly developed designs with the core design satisfying the requirements from an early stage thus leaving only small areas to be refined or optimised as the development continues to reach a level of affordability that can reach commercialisation.

The project to develop the TEA has been undertaken as part of a Knowledge Transfer Partnership (KTP) between EMEC, the European Marine Energy Centre, and the University of Strathclyde's Energy Systems Research Unit. Both partners contribute to the technical skills and commercial information as well as valuable resource and environmental data. The project builds on previous work completed by a partnership between the Offshore Renewable Energy Catapult and EMEC [11]. This project involves developing an assessment tool which estimates the device affordability and acts as a decision support tool for developers.

II. Benefits of the Assessment Process

The assessment would see many potential beneficiaries such as;

- Technology developers will gain an understanding of where the competitiveness of their technology lies and in which areas it is strong or lacking.
- Money will be saved by investors, developers and funding bodies as the core design can be realised during early stages of development where costs are much lower.
- Similarly, to the above reasons, time will be saved by working on finding the best design early in the development life rather than having to go back and repeat stages.
- The assessment report can be used as evidence of a thorough development process which ensures it is working to achieve the most affordable device in the most efficient manner. The value of this report will be high as it will be from a third party therefore having no bias.
- It can be used as a design tool, fulfilling the generator capacity for a particular resource through adjusting the rated/cut in speeds and rotor diameter to suit site conditions. The impact on structural loadings can be observed through the increase of rated speed or the increase of rotor diameter.

III. Approach

The approach taken to help developers find a cheaper, quicker and more successful route to commercialisation is to assess the affordability of a technology. The affordability of a device is determined by the incurred costs and quantity of energy converted. To increase the affordability the associated costs, need to be reduced and/or the energy yield increased. To assess the affordability, the assessment considers the fundamentals affecting the costs and energy yield. If the figures do not add up when considering the fundamentals, then they never will.

The fundamentals are related to the performance, CapEx costs and OpEx costs. The performance is based on Betz law for horizontal axis tidal turbines which enables an energy yield to be estimated when applied to a resource. The CapEx cost estimation is derived from the mass and material breakdown of the device as per the Carbon Trust methodology [12]. An allowance for the OpEx costs is based on a percentage of the CapEx costs due to the current unknowns associated with OpEx costs within the industry at this time which is due to a lack of operational data in the sector. This figure can then be crosschecked with EMEC data containing known costs of the proposed vessels used and number of service intervals claimed by the developer. Finally, the tool considers the environmental costs related to the technology.

The chosen method of measuring affordability is the Levelised Cost of Energy (LCoE). The LCoE is not without its flaws due to their being different LCoE models, each producing different figures making comparisons with different models unrepresentative. The information used in the calculation can make a significant difference, an example of this being the chosen discount rate being used. This can vary as it is related to the associated risk and can also have a significant effect on the outputs. However, when using the same LCoE methodology and inputs then comparisons can be made to show the sensitivity of an input variable.

If the initial assessment shows that the core design does not meet a reasonable level of affordability, then design changes should be made. The tool can then be used to confirm the benefit of the design changes, assessing if they reduce the costs or increase the performance or a mixture of both by considering design options and running them through the tool to find the economic outcome.

IV. Methodology

The process of assessing the affordability of a device considers the performance, CapEx, and OpEx. These are the three main contributors to the LCoE of a device, the metric for measuring affordability. The LCoE is discussed in more detail later in the paper.

To complete an assessment the initial stage will consist of giving the developer a questionnaire, which on completion will provide the inputs to the tool. These inputs will allow the tool to estimate the performance, CapEx and OpEx for the device. Further explanation of these can be found under the headings below.

A. Performance

To estimate the performance of a Horizontal Axis Tidal Turbine (HATT) the power formula shown in Eq. 1 is used. The coefficient of performance (C_p) of the device will be provided by the developer in the questionnaire as well as the rated power of the device and the rotor diameter. The C_p of the rotor can be found from tank testing of the device and/or by using numerical modelling approaches. The rated power of the device will be determined by the size of the electrical generator used. To find the peak power then a peak velocity is used which can be found from the resource data and is restricted either by the maximum flow velocity or the generator size. The tool can accept resource data from different sites that best represent the conditions that the technology has been designed for or to model how the device will perform in different resources.

$$P = \frac{1}{2} \cdot C_p \cdot \rho \cdot A \cdot u^3$$

Eq. 1

Where:
P = Power (W)
C_p = Coefficient of performance
ρ = Density of the working fluid (kg/m^3)
A = Swept area of the rotor (m^2)
u = Velocity (m/s)

The peak power only illustrates part of the performance of the device. To gain an insight into how the performance affects the affordability of the device then the energy yield needs to be considered. The energy yield then directly determines how much revenue can be generated as this is the commodity being sold or consumed when offsetting another fuel source. The device itself and the resource available are what determines the energy yield but when making comparisons the same resource should be used. Device qualities such as peak power, cut in speed, rated speed and availability contribute to the energy yield as they can all have an impact on how much time the device spends in a position where it is able to generate rather than being serviced, waiting on weather windows, the correct operating conditions etc. To allow for this in the calculations, the developer provides an availability factor given as a percentage and multiplied by the energy yield. The other factor that determines the energy yield is the resource itself, this is how much energy is available to capture. The way in which the energy yield is calculated is to multiply the power by time as shown in Eq. 2. This gives the energy at the rotor, to allow for other losses in the system the developer is asked to provide figures for losses in the generator and gearbox for example.

$$E = P \cdot t$$

Eq. 2

Where:
E = Energy (MWh)
P = Power (MW)
t = Time (h)

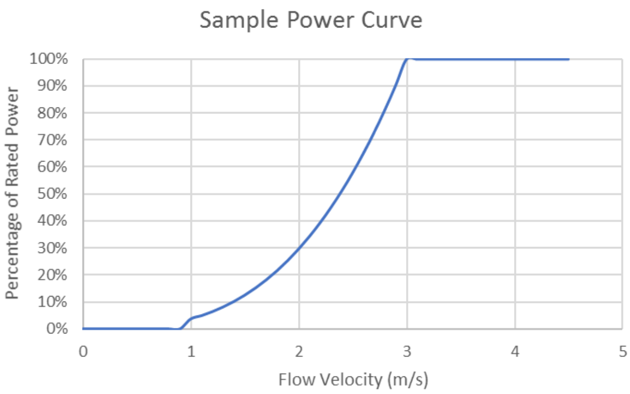

Fig. 1 – Example power curve for a tidal device

To get the power and time elements of Eq. 2, a power curve and velocity exceedance curve are created based on device and site data respectively. An example power curve is shown in Fig. 1 which requires the Cp, cut in speed and rated speed of the device. The peak Cp is used between the cut in speed and the rated speed, then altering the Cp to maintain the rated power once the rated speed has been exceeded. To control the Cp a device could use pitch control blades or passive blades with load control. These mechanisms can alter the Cp by adjusting the rotor speed relative to the flow speed, thus altering the tip speed ratio (λ). The tip speed ratio is the ratio between the tip speed of the blade and the velocity of the fluid upstream of the rotor. The Cp - λ curve, as shown in Fig. 2, illustrates that the Cp varies with respect to λ. Changing the rotor speed for a single flow speed will alter the Cp therefore producing an over speed or under speed of the rotor allows control of the Cp and therefore power output.

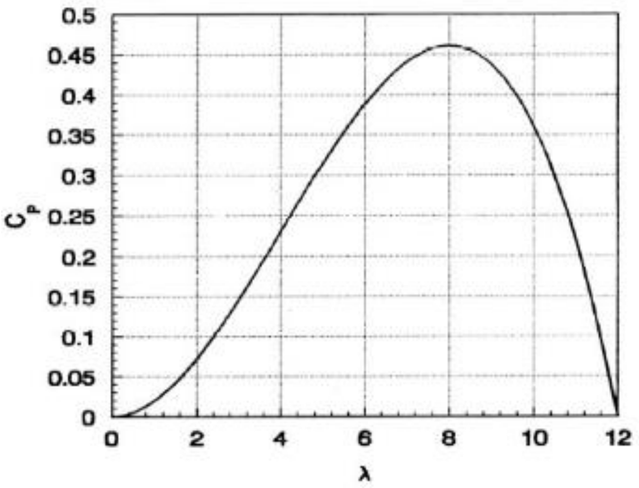

Fig. 2 – Cp - λ curve

From the power curve, the power generated at different flow velocities can be identified, fulfilling the power element of the energy equation. To calculate the time element, a velocity exceedance curve for the site will show how much time the flow velocities occur over a defined period. An example of a velocity exceedance curve for a specific location on one of EMEC's test sites can be seen in Fig. 3. Applying the data from the velocity exceedance curve to the power curve equates to multiplying power by time, which provides the energy yield. The velocity exceedance curve covers a full set of spring and neap cycles which allows realistic energy yield information to be gathered.

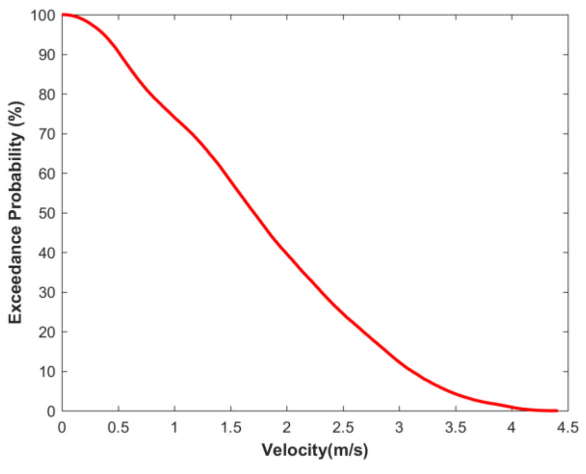

Fig. 3 – Velocity exceedance curve

An estimated energy yield allows for an estimated revenue to be calculated. There are assumptions when estimating the revenue also as there is currently no specific revenue support mechanism within the UK for tidal devices meaning it must compete with offshore wind, already a commercialised industry. This assessment uses a support revenue of £180/MWh. This figure was used as a starting point figure as this was a strike price originally considered by Tidal Lagoon Power [13], a technology that tidal stream devices would have to compete with. However, this figure is not fixed, and the tool can use any figure that is required. Later in the report, the effect that the strike price has on the affordability of the technology is explored further.

B. CapEx

CapEx costs include all the upfront costs faced by a project such as the device, the station keeping, installation costs, and grid connection costs. To estimate the CapEx costs of the device a method based on that used by the Carbon Trust [12] has been used.

The Carbon Trust method involves scaling up the CapEx costs from the cost of the structure where the cost of the structure is a product of the mass of material used and the cost of that material.

For this assessment the developer questionnaire asks for the CapEx breakdown which would include a percentage for moorings, installation costs, device etc. and the material breakdown of the device showing what materials the device consists of and how much there is of each. This then allows for an estimate to be made for the CapEx costs. Within the tool there is a list of worked material costs for materials, which can be used to estimate the cost of the device. Worked material costs represent a material cost where the material is ready to be fabricated. There is also the ability to add in a complexity factor for complex shapes that will make an allowance for higher manufacturing costs. This is not a very accurate measure, but it will allow extra for more complex manufacturing and therefore get the cost estimate closer to the actual cost. This will be sufficient for a cost/performance trade-off analysis to be completed. When considering a refined design, prices would be obtained from the fabrication industry.

C. OpEx

The OpEx costs cover all the running costs such as the planned and unplanned maintenance, insurance, wages, etc. These combined with the CapEx and decommissioning costs cover all the financial costs that are experienced over the life time of the device.

To consider the OpEx costs in the assessment a simple value of a percentage of the CapEx cost is used. Is is not possible to gain a true value of the OpEx cost due to the current stage of development of the industry. A true understanding of the OpEx costs would require long durations of operational data which the industry does not yet have. Longer operational periods would determine fatigue rates to give true values on service intervals both planned and unplanned and would allow opportunistic servicing in the appropriate weather windows rather than having to wait for these windows leading to lost revenue.

In the developer questionnaire, the developer will be asked what the anticipated OpEx costs are in terms of the percentage of the CapEx costs. They will also be asked which type of vessels are to be used for the maintenance activities allowing for the values to be crosschecked for accuracy.

D. Environment

The environmental considerations of the tool are mainly regarding the cost of consenting both with regards to money and time. There is the option to consider a virgin site with no prior consenting or baselining and also the costs associated with a test site, with the EMEC test sites being used initially. The aim of this is to estimate the costs faced by a developer to aid with the affordability calculations but also to ensure the developer is aware of the scale of costs that will be faced. This will help the developer to prepare financially for what is coming up. It will also help them to see the length of time it takes to have all the licenses and consents in place.

The environmental tool highlights the main impacts that should be considered. These impacts are taken from a tool developed by Aquatera on behalf of the Scottish Government [14] as one of the outputs from the commissioned study. The tool provides a set of recommendations that can help developers monitor and manage key issues. The tool only considers the ecological environment and not the physical or human environment.

E. Affordability

As previously stated, to measure affordability this assessment uses the LCoE. The LCoE measures lifetime costs divided by energy production, thus providing the cost to produce a unit of electricity [15]. LCoE models are used at national and regional levels to help design energy systems, energy generation projections, and technology assessment [16]. The LCoE approach is well developed and is a standard technique to measure the economics within the energy sector. However, there are different models available which have been developed depending on the information required or the data available.

The LCoE adopted by this assessment is similar to the UK Governments electricity costs model. This method consists of few steps with less specifics as in the Bureau of Resources and Energy Economics (BREE) Australia Energy Technology Assessment (AETA) model which was developed for specific devices within the Australian energy market mix [16]. The more general approach of the UK model makes it more versatile for different generating methods as it is less prescriptive. However, it doesn’t consider items such as capacity degradation, device availability, and losses. The adopted model for this assessment uses an estimated energy yield from the performance tool which has rotor efficiency, electrical losses and availability allowed for within it. There is no allowance for device degradation yet as it is unclear what the level of degradation over time will be at this stage in the sector.

V. Robustness Testing

On completion of the assessment tool it is necessary to complete robustness testing of the tool to ensure that it works as intended by providing correct outputs and responding correctly to the different input variations. This aims to show that the tool is free from errors and the methodologies give representative estimates.

The robustness testing has been completed in two forms, initially by checking the outputs against known values and then by carrying out a run-through with developers that are further down the route of development. The developer run-throughs will not only help to verify the tool outputs by comparing them with the developers answers but will also help to determine the strong points of the tool and identify areas of weakness that can be improved upon to further develop the tool/assessment process, potentially adding further functionality and benefit to the end users.

A. Initial Robustness Testing Using Sandia Reference Model

The first stage of the robustness checking was to ensure that the methodology used within the tool worked and provided accurate estimates. To do this required a reliable source of data, which is not an easy thing to find in a developing and infant industry. The data needed to include performance information, CapEx and OpEx cost breakdowns. The required data is not publically available from a developer as it would contain commercially sensitive material, however, the U.S. Department of Energy sponsored the Reference Model Project (RMP) [17]. This project developed open source point designs for the ocean energy sector, to be used as reference models complete with a full range of costs including CapEx, OpEx and a set of data to determine the device performance. Along with the data there are also illustrations to show what the device looks like, how the device is kept on station and the typical resource required. The project came up with a range of designs for different resources, one of which was for tidal stream energy, referred to as Reference Model 1 (RM1), ideal for using to verify the tool created in this project.

The available data provides enough information to perform an assessment on the device. The first problem encountered was that the resource data used within the tool was ADCP data from EMEC’s test site and the resource data used for the reference model was different, a generalised version of Tacoma Narrows. The peak power outputs were the same for both resources, but this is due to the device being rated at flow speeds below the maximum flow speeds for both sites. Where the errors become apparent were in the energy yield outputs which is due to the EMEC resource being much greater. The EMEC data was also entered into the tool in a higher resolution, with a velocity for every 30 seconds over a 30 day period. The resource data used in the RMP was summarised in a frequency table with the velocities divided up into intervals of 0.2 m/s between 0.1 m/s and the maximum flow speed. To check the outputs of the tool, the RMP resource data had to be entered in to the tool. This proved to be successful with identical peak performance and energy yields, confirming the performance assessment methodology adopted. Due to the different methods in which the resource data had been presented, the EMEC data needed to be summarised into a frequency table as the RMP used to ensure that both methods worked the same in the tool. Once this had been completed and compared, the two methods of using the resource data produced identical methods, thus again confirming the performance segment of the tool.

The RMP gives estimations for the energy yield of a single device or for devices installed in arrays of different sizes. However, it does not consider array efficiency losses to account for the effect of the energy available to a turbine that is downstream of another turbine nor does it consider that each spot on a site is likely to give different energy yields due to different specific conditions influencing the velocity exceedance curves. This means that the effect of multiple devices being installed is that the energy yield is the same for each device so for ten units then the energy yield is ten times that of one device. To keep consistency, this process follows the same principle, as the array efficiency will be site specific, depending on how the turbines are installed and the variations within the site itself. This does however provide an estimation of the performance of multiple devices being installed in an array, which will lead to an LCoE estimate for an array.

To test the CapEx estimation element of the tool the RMP can be used again. Along with a set of performance figures for the RM1, there is also a cost breakdown structure (CBS). Within the CBS is a list of the components that make up the device including connection costs, the station keeping system, the device, the power take off components, and installation costs. Where appropriate, there is also a list of masses for components and individual costs.

The inclusion of the component mass column in the CBS is very useful for the robustness testing as it provides the necessary input into the tool to allow the tool estimation methodology to be used. One thing missing from the CBS is the material breakdown of the device to allow the full functionality of the tool to be evaluated. However, reference model one was inspired by the SeaGen turbine [17] and SeaGen released a life cycle assessment of their device, which included a material breakdown of their device [18]. Due to the closeness of the two designs, it was suitable to use SeaGen's material breakdown to estimate the costs of the RM1 and compare these to the CBS costs for accuracy.

To find the costs for each material, research into the cost of the worked material was completed and entered into the tool. Complexity factors have been applied to allow for extra manufacturing costs, tidal blades being an example of where this is applicable.

To scale up the other costs to get the complete CapEx costs, the CBS is used to show how the costs are split up into different sections such as installation, station keeping, sub sea cables etc. This is required to gain an LCoE figure. The CBS in the RMP considers some aspects that are outside the scope of the assessment process. For example, for a single device the RMP includes a dedicated O&M vessel. These costs are not included in the tool and therefore have been removed from the list of costs in the CBS for the RMP. This is to make sure that the two methods are being compared fairly. The list of costs were analysed and adapted as required.

The cost breakdown structure gives an estimate of how the device will vary in cost through mass production, showing costs for a single unit, ten units, fifty units, and one hundred units. This allows the option to estimate the LCoE for arrays by being able to work out the scaling factor. This has been used in the tool to indicate the likely LCoE at array scale.

In the CBS, there is a value for the OpEx costs of the RM1. By using this figure and checking what it contains, it allows a % of CapEx to be calculated, based on the amended CapEx (for comparability issues). The developer provides the OpEx values, so a robustness test of the estimation method is not required at this stage.

When comparing the LCoE figures, there was a discrepancy between the RMP values and the tool values. This was due to multiple reasons. The large factors were down to the RMP not considering a single device in its LCoE calculations, the smallest deployment it considered was for an array of 10 units. For the robustness testing of the tool, it had to be altered slightly by applying the scaling factors to represent an array of 10 units so that the LCoE figures could be compared to see how close these were. Another factor that played a role in the discrepancy of the results was that the LCoE methods for the tool and the RMP are different. The tool uses different assumptions to the RMP. For example, the RMP requires more inputs such as more detailed tax inputs, specific to the US, that are not necessarily technology specific when comparing design changes as the tool is designed to do.

Table 1 shows the results of the robustness testing using the RMP data. The biggest discrepancy being in the LCoE figures which have been discussed as being the difference in LCoE models being used between the tool and the RMP. The second biggest being from the CapEx costs which can be explained by the different approaches to reach the estimate. The RMP went out to manufacturers and fabricators to get their costs whereas the tool used an estimation method that scaled up the mass of materials used. A difference of 6% is not considered to be too large considering that the estimation method takes considerably less time, important when carrying out a low cost, high level assessment.

TABLE I

TOOL ACCURACY

	Assessment outputs	***RMP outputs***	***Difference***
LCoE ($/MWh)	379	407	7%
CapEx ($)	13,534,000	14,336,878	6%
OpEx ($)	3,312,888	3,333,230	1%
Peak power (MW)	1.115	1.115	0%
Energy yield (MWh/yr)	2727	2727	0%

B. - Developer Run-through

The developer run-through is the next stage of robustness testing of the tool and a test for the assessment process to see how effective it has been.

The process included approaching a tidal developer to see if they were willing to work with EMEC to test the process. The aim was to find a willing developer that also had some figures of their own, so they could at least provide some feedback on the values from the tool. After finding a suitable developer, they filled out a questionnaire, which once run through the tool, gave the outputs with an LCoE figure and a series of graphs. The results were written up in report form and discussed with the developer.

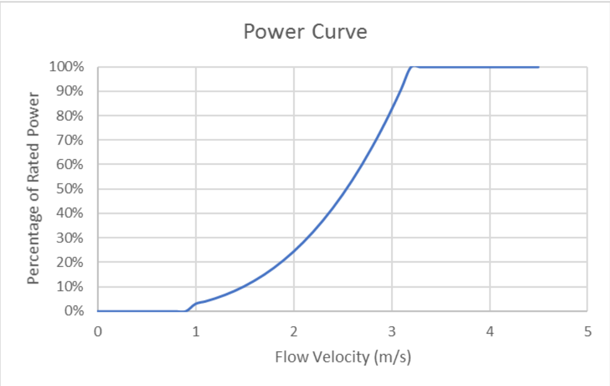

Fig. 4 Normalised power curve

Fig. 4 shows the normalised power curve for the device. This shows maximum power being reached at a tidal velocity of 3.2 m/s with electricity being generated from 1 m/s. In between the cut in speed of 1 m/s and the rated speed of 3.2 m/s, the rotor is maintained at peak Cp by maintaining the optimal tip speed ratio for the rotor. This graph can show whether the device is operating at rated power or not within the resource.

Fig. 3 shows the velocity exceedance curve created from EMEC ADCP data. This provides the time element to the calculation that then allows the energy yield to be calculated as shown in Fig 6 when plotted against the power curve.

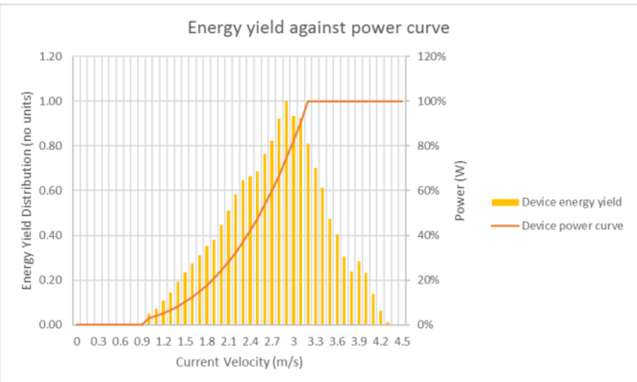

Fig. 6 Energy yield with the device power curve

Within the report would be a set of graphs showing the impact of change to; the OpEx figures, borrowing rates, and the effect of a revenue support scheme.

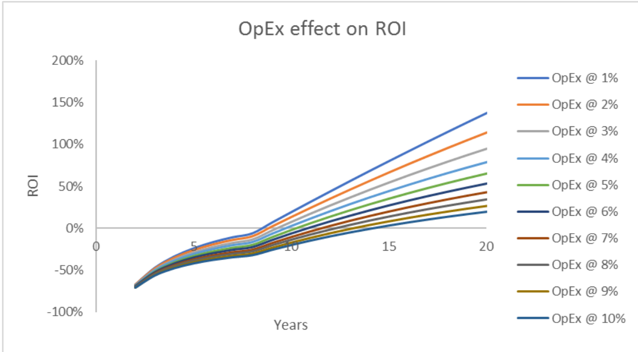

Fig. 7 Effect of OpEx

Fig 7 shows the effect that the OpEx costs have on the affordability. It shows that the OpEx costs have a significant impact on the affordability of the device and that consideration of the reliability, accessibility, and maintainability are important as these all influence the OpEx costs.

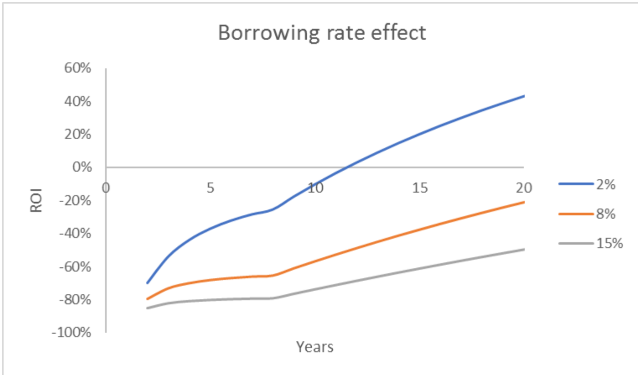

Fig. 8 Impact of borrowing rate change

Fig 8 shows the influence that the cost of capital can have on the affordability. Although this is not a technical parameter of the device, it is an important consideration for funding. The three rates shown are to represent three types of capital borrowing. The 15% represents an SME finding its own funding through loans and is high due to the uncertainty involved and the risk being taken by the lender. The 8% rate represents a middle ground which could be energy bonds for example. Finally, the 2% represents the low cost of borrowing which may be possible if there was a utility company involved thus reducing the risk of lending the capital.

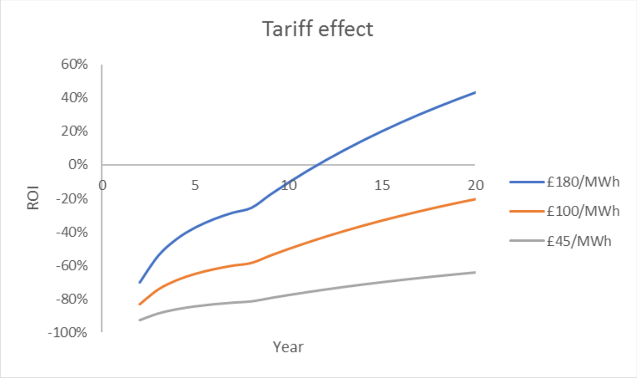

Fig. 9 Impact of a revenue support scheme on the Return On Investment (ROI)

Fig 9 shows the effect that a revenue support scheme can have on affordability. The three figures shown represent three different rates with the lowest being a typical market rate for electricity.

Fig. 7 – 10 show the output graphs for a revised design deployed in an array of 50 devices. This represents a commercial scale deployment based on the RMP scaling for 1 device deployments and 50 device deployments.

These will be done before and after any changes having been made with the developer to show the scale of the impact that has been made.

Further to this, the tool can be used with a set of benchmark data. For this report the data for the RM1 was used which isn't entirely fair as the RMP was never intended to show fully optimised designs, however it is intended as a starting point from which to measure against. The comparable ROI can be seen in fig. 10.

Fig. 10 Energy yield with the device power curve

Whilst this doesn't compare the device to an optimised design it does show that it is much more affordable than the reference model which has been designed as a starting point [17].

The results from developer run-throughs have shown strong results with close correlation of CapEx costs where most of costs in the tool stem from outside of the performance estimations. When reviewing the next generation of designs with the developer the tool performed as expected which shows that the tool can work as a decision support tool, showing the benefit of different design configurations with regards to loadings and costs.

TABLE II –

SENSITIVITY STUDY RESULTS

	CapEx	*LCoE*	*LCoE difference*	*OpEx*	*LCoE*	*LCoE difference*
60%	£1,786,667	£135	*-27%*	£877.088	£117	*-18%*
70%	£2,084,444	£147	*-21%*	£1,023,269	£123	*-13%*
80%	£2,382,222	£160	*-14%*	£1,169,450	£129	*-9%*
90%	£2,680,000	£173	*-7%*	£1,315,632	£135	*-4%*
100%	£2,377,778	£185	*0%*	£1,461,813	£141	*0%*
110%	£3,275,556	£198	*7%*	£1,607,994	£148	*4%*
120%	£3,573,333	£211	*14%*	£1,754,176	£154	*9%*
130%	£3,871,111	£223	*21%*	£1,900,357	£160	*13%*
140%	£4,168,889	£236	*27%*	£2,046,538	£166	*18%*
Input variation	**Energy yield (MWh)**	**LCoE**	**LCoE difference**	**Discount rate**	**LCoE**	**LCoE difference**
60%	11,695	£276	*67%*	4.8%	£161	*-16%*
70%	13,643	£237	*43%*	5.6%	£168	*-12%*
80%	15,592	£207	*25%*	6.4%	£175	*-8%*
90%	17,542	£184	*11%*	7.2%	£183	*-4%*
100%	19,491	£166	*0%*	8.0%	£190	*0%*
110%	21,439	£151	*-9%*	8.8%	£198	*4%*
120%	23,389	£138	*-17%*	9.6%	£206	*8%*
130%	25,338	£127	*-23%*	10.4%	£215	*13%*
140%	27,287	£118	*-29%*	11.2%	£223	*17%*

VI. Decision Support Tool

To illustrate the decision support tool element of the assessment process, part of the developer run-through included assessing a revised design to show the effect that the changes made on the outputs. The current configuration of the device is run through the tool with assumptions of a revenue support scheme being in place and the cost of capital being low. The ROI for this configuration can be seen in Fig. 11.

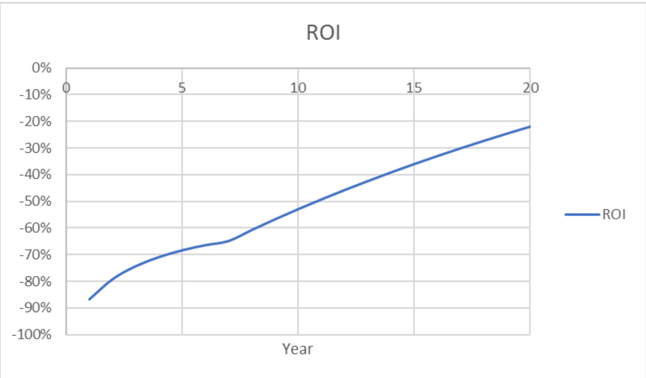

Fig. 11 ROI for original device

For the revised device, the mass of the device was reduced by 30% to allow for an optimised design rather than a device over engineered with a high safety factor as is often used in a testing scenario. Further reductions were in the power converter system. These costs were reduced by 45% which represent the anticipated costs for off-the-shelf products in a mature sector instead of having bespoke components due to the current development stage of the industry. The final reductions have been to the installation costs; these were reduced by 50%, which was deemed a conservative reduction for changing the vessel use from a large construction support vessel to a small multicat type vessel.

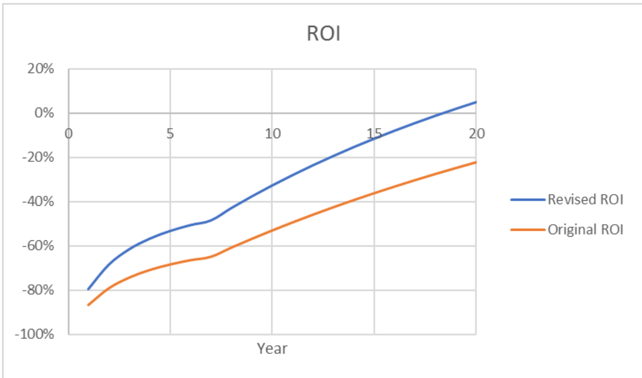

Fig. 12 ROI before and after revisions

The ROI for the revised device with the cost reduction is shown plotted next to the original ROI in Fig 12. The only differences made are the reductions stated, so the support revenue scheme, cost of capital, and remaining device parameters is kept equal. The results are that the device now shows a positive ROI of 5%, an increase of 27% over the proposed 20-year lifespan.

To assist with the decision making, a sensitivity study of the inputs was carried out to see which had the greatest impact. The results of the sensitivity study can be seen in Table II. To perform the study, the CapEx, OpEx, Energy yield, and discount rate were changed by 10% each. From this study the energy yield can have the biggest effect on the LCoE. This could be altered by (a non-exhaustive list) optimising the maintainability, survivability, installabillity, the Cp of the rotor, electrical efficiencies, and resource selection.

Following the energy yield would be the CapEx costs, these can be reduced through (a non-exhaustive list) a reduction of materials, lowering the coefficient of thrust (Ct), mooring costs, and power conversion costs.

The OpEx costs and discount rate effect have a similar effect on the LCoE. The discount rate cannot be influenced by the technology other than providing a risk-free investment. It does show that this is worth investigating though as it can have a significant influence on the affordability. The OpEx costs have a significant effect on the affordability also and can be influenced by the reliability, accessibility, maintainability, many of which also affect the energy yield showing that a positive effect on one area also has a positive effect on another, thus multiplying the positive effect.

VII. Future Work

Future work for the tool will see it cover wave devices also. For wave devices it will follow a similar approach, by considering the performance, CapEx and OpEx and result in an affordability figure. Robustness testing will follow the same route, firstly by comparing it against known data, using the RMP again as within it there are several wave devices of different architectures, all with performance data and a set of costs like that of the RMP tidal device.

Following this project there would be scope for the tool to be further developed into an optimisation tool for early stage developers. Using the same fundamentals mentioned earlier in the paper, it could find the best solution for a certain resource, considering the power output, cut in speed, rated speed, rotor diameter, station keeping method, etc. for example.

VIII. Conclusions

In conclusion, the assessment achieves what it sets out to do by providing a high-level assessment of a tidal energy converter resulting in an estimation of the device affordability. The tool outputs have been validated through comparing results with Sandia data and showing that the values are close, proving the assessment methodology works. The tool is flexible enough to show the effect that design alterations can have on the affordability which demonstrates that it can be used as a decision support tool to move a device towards commercialisation in an efficient manner.

With the use of a technology assessment, assessing the affordability of devices at an early stage offers the opportunity to refine the core design of a technology at an early stage of development. This could occur right at the concept appraisal stage and where information is unknown, estimates could be put in which could then act as targets which need to be achieved.

This feature is useful in showing the scale of improvement that is likely through carrying out a series of updates and can help to inform future decisions and whether it is worthwhile pursuing with the current configuration of the device or if further design revisions are required.

The tool outputs could also spark research and innovation ideas, identifying areas of research depending on what the performance or cost targets are for an affordable device. This could provoke further ideas which could help the wider industry, for example if it was noted that O&M costs had to come down significantly then further research could take place to address the issue.

Acknowledgment

I'd like to thank my supervisors Cameron Johnstone and Elaine Buck for their help in preparing this paper and in general with the project to date. I would also like to thank Dr Stephanie Ordonez and Dr Kate Johannesen for their input and support throughout the project.

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