Tidal Stream and Ocean Current Energy - the benefits of harvesting lesser energetic flows

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Abstract—**An optimum utilisation of the energy available in the ocean could meet our global energy demands. The implementation of tidal stream technologies is striving faster compared to other offshore technologies, aside from the offshore wind sector. Highly energetic tidal energy streams with peak flow velocities in the order of 2.5 – 5.0 m/s are limited around the globe and therefore, the sector may be constrained to a few worldwide locations. To overcome this limitation, attention has been drawn to the exploration of complementary flow streams with lesser energetic flows. This work thus intends to compare the feasibility of harvesting hydrokinetic energy using horizontal axis turbines from two different sites: a typical tidal stream site in the North of Scotland and an ocean current site in the Mexican Caribbean, characterised by developing slower but more stable flows. The viability of using ocean currents against tidal stream sites is analysed in terms of annual energy output, capacity factors and an initial estimation of the levelized cost of energy which considers the size of the turbine and rotor characteristics. As expected the annual energy produced by tidal devices is overall greater than that provided by marine currents but the capacity factor achieved with a typical tidal turbine can be in the order of 44% whereas the capacity factor calculated for a turbine operating in the Yucatan current can achieve factors in the order of 77%, giving confidence that the development of marine projects in lesser energetic flows may be the next step forward to advance this sector. This research also proposes the optimal turbine diameter to reduce the levelised cost of energy for a marine converter installed in a tidal or an ocean current site.**

Index Terms—**Desalination, Tidal stream energy, Clean Water, Modelling**

I. INTRODUCTION

Tidal range and tidal stream energy technologies are possibly the two marine energy sectors that have had the most successful stories to date. Up to now, the installed capacity of tidal stream technology in the UK is nearly 9 MW [1]–[3] and it is expected that in the coming years a substantial increase in worldwide capacity will be achieved due to developments such as the Meygen Project 1B (3 MW) [1], the Pempa'q Tidal Energy Project (9 MW) [4] and the The Nova Tidal Array (1.5 MW) [2].

The Levelised Cost of Energy (LCOE) targets indicate that the tidal energy industry must achieve and LCOE of 15 and 10 cEUR/kWh by 2025 and 2030, respectively [5]. Efforts to predict these values have been proposed by several authors and these indicate that in order for those set targets to be met, an installed capacity of 100MW – 1GW must be achieved [6]. Even though, it has been suggested that a tidal stream installed capacity solely in the UK could be in the order of nearly 4 GW [7], little research has been produced where the environmental effects of large arrays are considered. In some cases, the available literature suggests that in order to avoid alterations to the ecosystems a maximum installed capacity in a specific region should be lower than 5% of the available resource [8]. Therefore, if this information holds true, the limitations to the amount of energy that can be extracted from a tidal stream site will decrease significantly.

In addition to tidal stream sites, the ocean currents have also been studied due to their advantages related to unidirectional and continuous flow patterns. One of the main disadvantages with this type of resource is the drop of energy that could be achieved given the flow characteristics of the ocean currents and the distance to shore where the devices may need to be installed along with the water depths, the study undertaken by [9], suggests that the mean flow velocities of the current passing next to Florida can only achieve peak currents in the order of 1.2 – 1.4 m/s with a distance to shore of about 30-100 km and in water depths between 200 – 1000 m. However, a recent study developed by [10] proposes harvesting the energy from a site nearby the coastline of the Cozumel Island (200 – 400 m) and water depths between of 20 m which may indicate a serious decrease on the LCOE predicted for tidal stream technology. This work thus intends to compare the feasibility of harvesting hydrokinetic energy using horizontal axis turbines for two different sites: a typical tidal stream site in the North of Scotland and an ocean current site in the Mexican Caribbean. The sites will be compared in terms of annual energy output, capacity factor and a non-dimensional levelised cost of energy (LCOE). Note that the intention of this work is not

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to developed a new methodology to quantify LCOE but to draw information about the implications of developing marine renewables in lesser energetic sites, and in this case, ocean currents. We also aim to provide insight on how to adopt existing practices to evaluate the feasibility of extracting energy from lower energetic sites compared to the current practice.

II. METHODOLOGY

The following section will describe the methodology used to quantify the annual energy production based on two turbine designs and Acoustic Doppler Current Profiler (ADCP) information from two particular sites, a typical; tidal stream site and an ocean current site near shore. This information will then serve to calculate the capacity factor of each device and the levelised cost of energy.

A. *Site location*

1) Tidal Stream Site: Acoustic Doppler Current Profiler (ADCP) data was retrieved from seven locations near the European Marine Energy Centre (EMEC). This information was used to approximate the annual output generated by a typical 20 m diameter tidal stream turbine.

The location between ADCP drops to the closest shoreline point to EMEC was estimated at approximately 2.6 km in average, according to great-circle distance estimations. The number of days of data recordings varied from 14 to 41 days, completing at least a full tidal cycle in each location. Figure 1 shows the approximate location of the ADCP drops.

The data bins were processed in order to describe the shape of a turbulent velocity profile. As for many sites, this was described as a 1/8th power law and therefore the approximated velocity at mid-water column was used to infer the power captured by the device. According to the ADCP surveys, the water depths between surveys varied from 26-55 m.

Fig. 1. Location of ADCP drops in the tidal sites.

2) Ocean Current site: The Yucatan Current belongs to the North Atlantic Subtropical Gyre and connects the Caribbean Sea and the Gulf of Mexico. The Yucatan Current bifurcates from the south passing through both east and west of the Cozumel Island, forming on the west, the Cozumel Channel.

The description of the currents carried out by [10] mapped the spatial variability of the flows along the west coast of the continental shelf of Cozumel Island from Punta Sur in the southern region to Punta Molas in the north of the island. The number of observations in a particular site is rather limited and can result in large uncertainty when estimating annual power production.

In addition to the work carried out by [10], the Canek project dedicated efforts to study and characterise the Yucatan Current and the Cozumel Channel. From this oceanographic project, 2-year ADCP data was retrieved and utilised in this study. The data was gathered from an ADCP whihc was installed in the closest shoreline in the Island of Cozumel as it is shown in Figure 2. This region is however outside the site identified by [10] and has challenging characteristics with 400 water depth. Therefore, this site is not currently considered for any marine turbine development. Nonetheless this data can give an insight of the temporal variations of the current in close proximity to the Island of Cozumel.

B. *Device characteristics*

A typical three bladed horizontal axis turbine was considered for this study. The performance curves utilised to quantify the power production of a 20 m diameter turbine operating in a tidal stream were derived from experimental and numerical evaluations reported. These curves are presented in Figure 2 as non-dimensional values of power and thrust coefficients, CP and CT, respectively. These values are then compared to the relationship between angular velocity, turbine radius and flow velocity is represented by the Tip Speed Ratio (TSR) values. These relationships can be inferred from extensive literature including related research; e.g. [11]–[14].

Similarly, Figure 3 depicts the power and thrust curves for a three bladed horizontal axis turbine specifically tailored to operate in low energetic sites. [15] based its design on the bases of increasing angular velocity to maximise power output. As it can be observed in Figure 3, the power coefficient obtained here is in a TSR region between 6 and 8, compared to the rotor design utilised previously which operates more effectively at TSRs between 3.5-4. The design proposed by [15] has been initially analysed using analytical simulations and further rotor design verification are required but these are outside the scope of this investigation.

Other considerations such as the electrical power losses have been set for all case scenarios to 80% to account for friction or electrical losses, as it has been considered in other studies; e.g. [16]–[18].

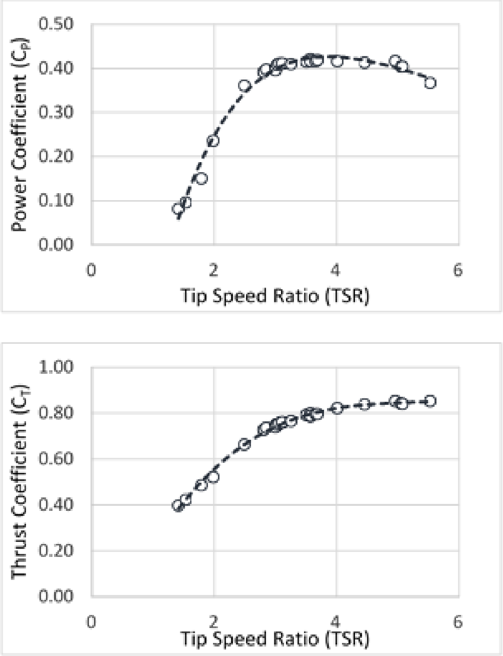

Fig. 2. Performance curves obtained from a 1/20th scaled turbine tested in a tow tank, taken from [11].

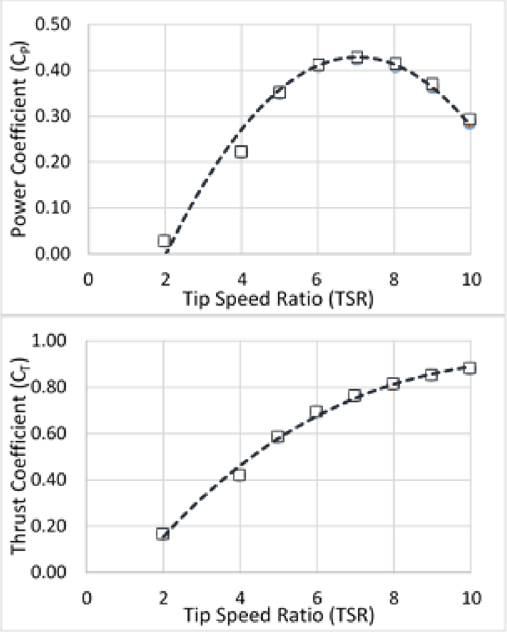

Fig. 3. Performance curves of a marine turbine operating in lesser energetic sites.

C. *Levelised Cost of Energy*

Levelized cost of energy (LCOE) studies for marine energy conversion have been reported in various sources; e.g [refs]. At the time of writing, the LCOE was estimated to be in the order of 100-300 £/MWh [Refs], however, few studies report the actual methods to calculate important parameters such as the capital (CAPEX) and operational (OPEX) costs, which are two of the three main factors impacting this figure, as it can be seen in Equation 1. Moreover, both CAPEX and OPEX, not LCOE, are required parameters for many bottom-up energy system models, such as TIMES, which are widely used to inform energy and climate policy.

Equation 1 is used in this study which simplifies the calculation of LCOE into three main variables: CAPEX, OPEX and Annual Energy Production. In order to understand the effects of each component separately, the present values (PV) is calculated here with typical values of the device lifetime of 20 years and a discount rate of 15%.

$$LCOE = \frac{CAPEX + PV(Opex)}{PV(EnergyProduction)} \tag{1}$$

1) Capital and Operational Costs: Although still limited in the literature, there are few studies that estimate the LCOE for tidal stream turbines and which detail the assessment for CAPEX and OPEX costs, when possible. [19] proposes an approach using some derivations from a series of research items. For example, a formulation to derive rotor costs is based on the rotor diameter and number of units, as shown in Equation 2. There are two other functions used in the CAPEX calculations used in [19] which are related to cable and foundation costs.

Cable costs are approximated by a linear function where the distance to shoreline is the parameter used to assess the function; therefore, excluding factors such as the cost of cable installation which will be heavily affected by weather/site conditions. The implementation of this method is thus irrelevant to this investigation since it is envisaged that device installation and operations will be cheaper when dealing with low energetic sites as it has been shown in [16]–[18].

The foundation costs evaluated in [19] are based on the site water depth, as per analyses undertaken by the wind industry. Although, the latter may be relevant to that sector, these formulations are broad and may not apply to this research, especially if a wide variety of rotor sizes, and hence, weight, are considered. Hence not only the foundation design will change significantly but also the installations. The approach undertaken by [19] to assess the foundations costs (structure and installations) is thus not considered here.

There are other studies that have quantified the CAPEX more comprehensibly. [20] determined the LCOE by assessing numerous parameters including: concept, design and development, manufacturing, installation, operation, maintenance and decommissioning costs with various subdivision such as market research costs, corrective maintenance, insurance costs, to name a few. Although, the proposed methodology is detailed, this has been done specifically for a typical tidal stream turbine (1.2 MW turbine) operating in a highly energetic site in Europe (Alderney Race, UK).

Similarly, [16]–[18] reported a complete analysis of three types of hydrokinetic conversion including a typical 20 m horizontal axis tidal stream turbine, a 33 m diameter HA ocean turbine and a 5 m height (vertical axis) river turbine. The data sets reported by [16]–[18] are exhaustive and are separated in eight main sub-categories: development, infrastructure, mooring/foundation, device structural components, power take-off, subsystem integration and profit margin, installation and contingency.

One simplified approach to calculate the CAPEX of a tidal turbine is by utilising the cost distribution breakdowns reported from various sources; e.g. [21], [22], which is summarised in Figure 4. As it can be observed in both the table and the pie chart, a fairly equal distribution for three main categories was obtained (device (power take-off, including blade manufacture), installation and foundations and cable and grid connection). However, the dispersion of the data is significant especially for the electrical connection (24.4%). These results were expected since the data used to approximate this chart is also influenced by a wide number of parameters; e.g. distance to shore, dimensions of the converter, type of foundation, etc.

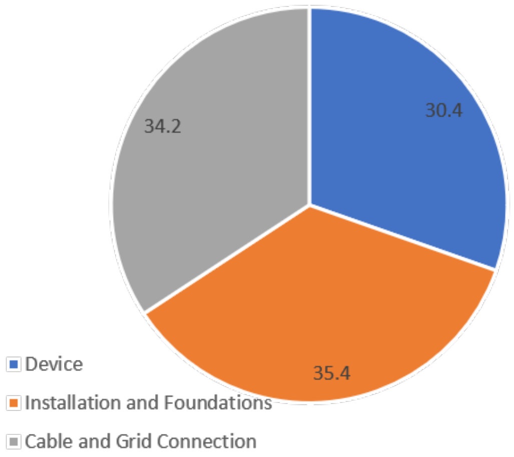

Fig. 4. Performance curves of a marine turbine operating in lesser energetic sites.

In this study, a combination of approaches will be used to approximate the LCOE of two horizontal axis turbines of five different sizes to capture the energy from a tidal and an ocean current site. Therefore, three considerations are essential in this analysis: i) the effect of the rotor size; i.e. power capture and costs associated with distinct geometries, ii) the installation costs of a device in high and low flow speeds and iii) the effect related to the number of units required to capture equivalent energy output.

2) Rotor size: A cost estimation for the rotor size and number of units has been proposed in [19] and presented in Equation 2.

$$C_r = 80.4nD^{2.7} \tag{2}$$

where Cr is the cost of the rotor based on the number of devices (n) and their diameter (D).

In order to partially verify the use of this equation, the results were compared to existing material and based on a single unit (rotor). It can be observed in Figure 5 that this formulation gives an approximate value for small or rather large rotor diameters in the order of 5 m and 33 m, respectively. The deviation between the formulation suggested by [19] is however significant for rotors in the order of 20 m in diameter which at the moment are the most popular choice amongst some tidal turbine developers [1], [3].

In order to account for these discrepancies, a new formulation to approximate rotor costs has been drawn up for this analysis and simplified as follows:

$$C_r = 27.4nD \tag{3}$$

Comparatively with the formulation proposed by [19], Equation 3 thus provides a closer approximation and thus it was deemed appropriate for this study. This can be denoted in Figure 5 where the linear approximation (yellow line) has a closer approximation for each of the points or at least to the average values obtained from literature. Note that at this stage, the number of units/ rotors is not considered for these calculations and when more than 1 unit is considered for the initial analysis, it is accounted linearly; i.e. mass production is not incorporated yet.

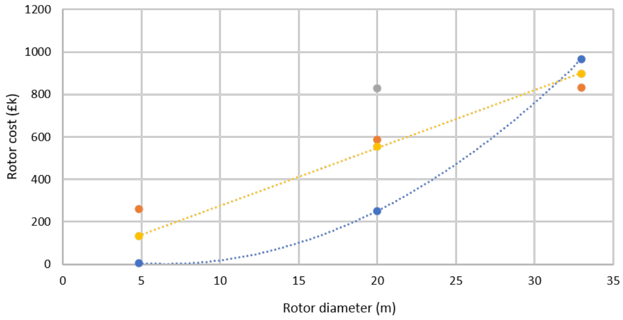

Fig. 5. Turbine rotor costs based on diameter.

3) Breakdown of capital costs: The rest of the capital costs are approximated by using existing information from capital cost breakdowns. Figure 4 was, however, not deemed suitable for this formulation due to the number of assumptions used to derive them. More appropriately in this case was to use the breakdown specifically developed for a tidal stream turbine and an ocean current device, similarly as proposed in this study [16], [18]. Thus, the device costs associated with a tidal stream device are in the order of 5% compared to a figure of nearly 27% for an ocean current device. This, although far from Figure 4, does contemplate the challenges of operating and installing robust devices to withstand maximum flow speeds in the order of 3 m/s whereas the calculations performed for the ocean current device only expect a maximum current of 2.5 m/s.

In this study, five cases are also considered to infer the most viable option for device development in terms of the rotor size. The largest rotor size considered here was of 20 m in diameter and followed up by smaller rotor sizes in the order of 15 m, 10 m, 7.5 m and 5 m. To account for the number of units or mass production cost reduction, an approximation was used based on the rate reported by [16], [18].

D. Operational costs

Perhaps even more elusive than the estimation of CAPEX, is the evaluation of OPEX. The reason is that, at the time of writing, pre-commercial technology has

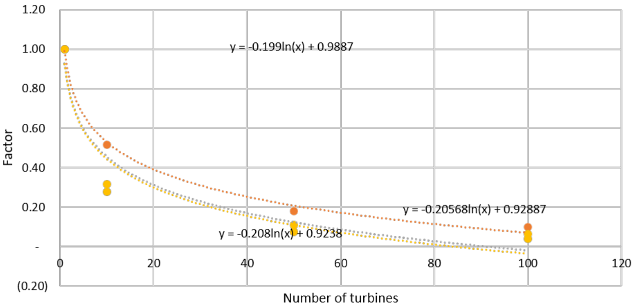

Fig. 6. Turbine rotor costs based on diameter.

not been operating for long periods of time; hence, it could be argued that this data is non-existent. Some studies have based the OPEX costs from the offshore wind sector given the partial similarities between these and the tidal stream technology [23]. However, it is clear from [22] that depending on OPEX and CAPEX figures, the economics of tidal stream renewable projects are highly affected, hence using offshore wind energy figures will not be representative in many cases.

As pointed out in the previous sections, the benefit of extracting energy from lesser energetic flows may also be reflected in the operational costs since it is assumed that the costs of installation will substantially reduce in environments where the flow speeds are not as strong as in a typical tidal stream site. Again, the only two studies that consider these conditions are reported in [16], [18] and adopted here. Figure 7 includes those predictions and how these are affected depending on the number of units (or installed capacity). Therefore, both predictions are utilised in this study depending on the technology of interest.

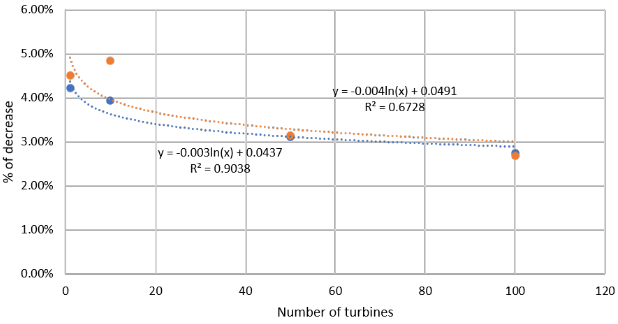

Fig. 7. Opex decrease by type of device and number of units.

1) Annual Energy Production and Capacity factor: The final element to calculate the LCOE according to Equation 1 corresponds to the annual energy production. In order to calculate this component, the power curves of both devices and the temporal variations of flow from both sites were analysed and added up. Transmission and turbine availability losses were incorporated in the calculations and accounted as 98% and 95%, respectively. Before those, a power converter efficiency of 80% was also considered for the energy estimations. Five turbine diameter sizes were also analysed: 20 m, 15 m, 10 m, 7.5 m and 5 m in diameter. The motivation to include a wide range of turbine geometries was to examine the benefits of increasing the angular velocity of the rotor to compensate the low flow speeds in the ocean current site and ultimately in the cost of energy. An additional parameter to compare both technologies is related to the capacity factor of the device. This has been quantified based on a rated speed of 2.5 m/s and 1.0 m/s for the tidal stream turbine and the ocean current converter, respectively.

III. RESULTS AND DISCUSSION

A. Flow variations of site assessment

Figures 6 and 7 display the observations of the flow velocities for both tidal stream and ocean current sites. Both graphs include the average percentage of occurrences obtained from the sites. The error bars indicate the variation between sites for the EMEC data and for four points along the water column for the Cozumel site. For example, for the data retrieved from the North of Scotland, Figure 6 contains the information of seven sites and how much this variation changes from the ADCP drop locations. It can be clearly observed that the spread of the flow velocity on a tidal site is broader than that of the ocean current studied here. This is expected due to the flow directionality changes during both ebb and flood tides. And even though the fastest flow speeds can reach almost 5.0 m/s, the most occurrent flow speeds only belong to a range within 0.45 to 2.55 m/s which account to about 77% of the flow speed occurrences. Hence, the rated speeds utilised to described a tidal device are in the order of 2.0 – 3.0 m/s.

Conversely, in Figure 9 the flow speed rates accounting for 87% of the resource are in a range of 0.4 m/s (0.8 – 1.2 m/s) compared to a range of 2.1 m/s as seen in the tidal site (0.45 – 2.55 m/s). In both instances only occurrences higher than 8% were considered.

In these calculations a rated speed of 2.5 m/s has been used as rated speed for the tidal stream device and 1.0 m/s for the ocean current turbine.

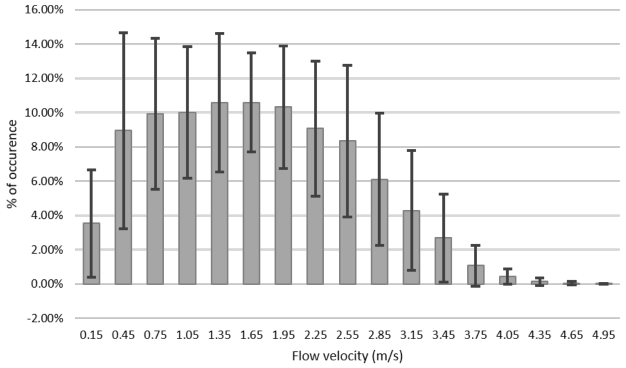

Fig. 8. Flow velocity distribution of a typical tidal stream site in the north of Scotland.

B. Annual Energy Extraction and Capacity factor

Five devices have been explored for the feasibility of harvesting energy from tidal streams and ocean

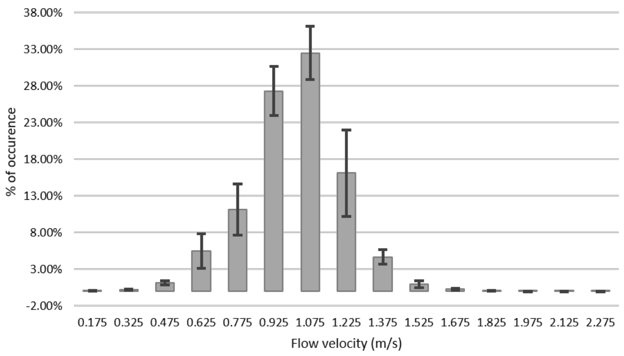

Fig. 9. Flow velocity distribution from an ADCP location in the Cozumel site.

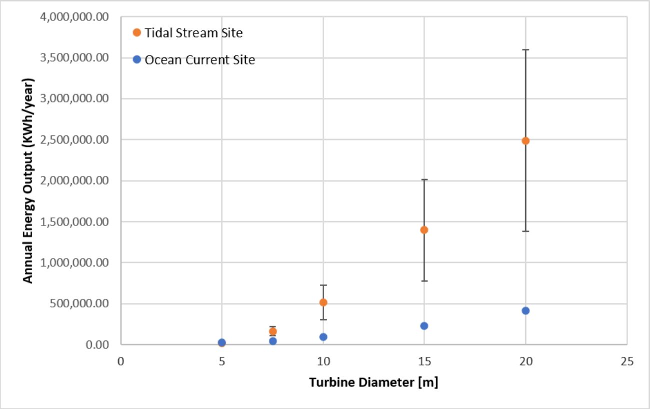

Fig. 10. Annual energy output from a single device according to turbine diameter.

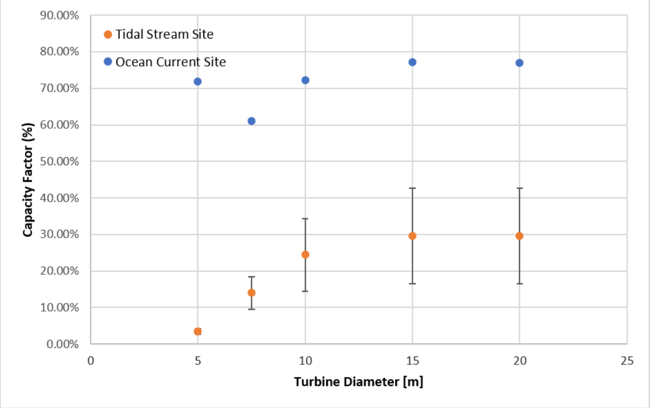

Fig. 11. Capacity factor calculated for a single device based on turbine diameter.

currents. The devices contemplated here range from 5 m to 20 m rotor diameters and according to the rated speeds mentioned in Section 3.1, these have been calculated so as to provide a rated power between 65 kW to 1 MW for the tidal stream turbine and 66 kW to 4 kW for the ocean current turbine.

The results from the annual energy calculations for a single device using the power curves shown in Section 2.2 are summarised in Figure 10. According to the calculations undertaken for both sites, and as expected, the power output generated by a turbine decreases with its rotor diameter. However, the flow speeds distributions and the turbine design effects are evident, where a drop or increase of the annual power harvested by a tidal stream device is more obvious than that for an ocean current converter.

The capacity factor achieved by both designs is summarised in Figure 11. A capacity factor of about 30% can be achieved from this representative tidal site with a device size of 15 – 20 m which compares to similar devices installed in typical tidal stream sites. This capacity factor drops rapidly just as smaller geometries are considered in the calculations. The main reason for such a sharp decrease is down to the limitations of the turbine to capture energy at high hydrodynamic efficiency in faster flows. The design of the turbine thus might need to be reconsidered to slightly increase the capture of the device with such dimension but this is out of the scope from this investigation.

It is clearly evident that due to the resource characteristics of the Cozumel site, the capacity factors can be within 60 - 80% and this factor is not affected substantially independently of the turbine geometry, compared to the tidal stream case. These values agree with the calculations performed by [24] which showed that for a river turbine a capacity factor of 70% can be achieved compared to a tidal site.

C. *Levelised cost of energy*

The levelized cost of energy was evaluated for both technologies using technical information related to the resource data, the technical information from the turbine prototype and the methodology shown in section 2.4. To approximate capital and operational costs the number of devices and their geometrical dimensions were considered in the analysis.

It was found that for a horizontal axis device operating in tidal stream flows, the methodology employed gave a slightly optimistic value of 132 to 237 £/MWh for a 20 m diameter turbine rated at 1 MW, using all the ADCP data from the tidal stream sites. The upper limit is however within the values predicted by [23] who predicted values in the order of 177 to 244 £/MWh for an array of 0.3-0.5 MW of capacity.

The calculations also showed that once a large number of devices is considered, the LCOE costs decay rapidly and the results indicate over-optimistic values in the order of 60 – 100 £/kWh. These estimations affect mostly devices between 10 and 15 m rotor diameters. To put this numbers in perspective, a study showed that these values could be attained but only at an installed capacity of 2GW [6].

Whilst, the capital cost can be approximated by the turbine size and number of components required within the power capture and power take-off, as well, as the structural components to install the devices, the operational and maintenance costs are harder to approximate without the intel from commercial developers. And therefore, these values may have affected the calculations considerably and should be reconsidered for future studies.

Note that in order to investigate the effects of numbers of devices against cost of energy, the number of devices accounted for in the LCOE analysis are calculated in terms of the largest device; i.e. the same number of “smaller” devices should provide a similar annual output as with a single and large device of 20 m of diameter. And therefore, a “mass production” factor is contemplated for some calculations which is another factor that can produce large uncertainties in these results. However, it should be noted that this work does not contemplate to provide LCOE information for a specific tidal or ocean current device but more to investigate the effects of rotor sizes and geometries when an hydrokinetic turbine is proposed for a tidal or ocean current site.

To denote the latter, a normalisation of the LCOE values has been utilised which contemplates the maximum LCOE values from 0-1. It can be seen in Figure 12, that turbine development in tidal sites seems to be more convenient when using turbine diameters from 10-20m in diameter, and in fact, the numbers suggest that a turbine diameter of 15m in rotor diameters would be the optimal turbine geometry to achieve the lowest LCOEs in a site similar to the one studied here.

For an ocean current site with the characteristics of the Cozumel Channel, a maximum turbine diameter of 10 m provides the best LCOE values. Followed up by smaller turbines in the region of 7.5 m and 5 m in rotor diameter, but once the turbines become smaller the trend seems to LCOE values seem to increase gradually.

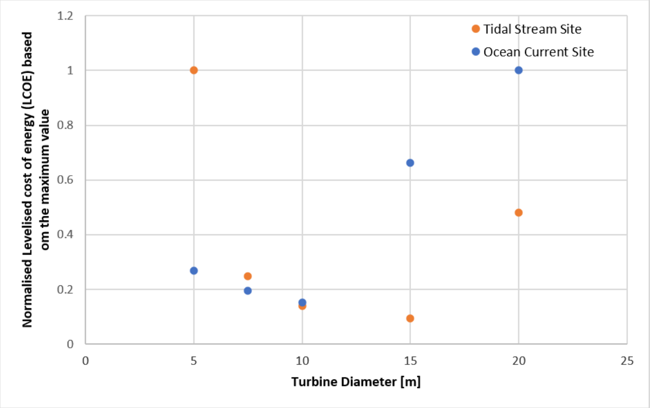

Fig. 12. Normalised Levelised cost of energy (LCOE) based on the maximum value against the rotor diameter.

IV. CONCLUSION AND FUTURE WORK

A study to assess the opportunities to develop marine energy projects in low energetic flows such as those existing in Cozumel, Mexico have been explored in this paper. It has been found that large capacity factors of up to 70% can be achieved when harvesting energy from the ocean currents compared to a maximum value of 44% from a tidal site; and which could be much lower depending on the tidal site.

It was also found that the dimensions of the device may have a large implication on the levelized cost of energy from a marine energy development. This study has shown that potentially the most optimal turbine size for a tidal stream development should be in the order of 10-15m of rotor diameters (perhaps up to 17.5 m, but this calculation was included in the paper). For an ocean current site, the ideal rotor diameter should be of 10 m but the trends obtained here have showed that smaller rotor diameters and in the order of 5 and 7.5 m could be a potential solution.

This study has been based in many assumptions to calculate the cost effects derived form the number of turbines installed on the site, the operations and maintenance costs with most of the figures being taken from existing literature. Therefore, future work must contemplate a better estimation of all these parameters as well as other locations to give a better perspective of the potential arising with the development of marine turbines in low energetic sites.

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