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Levelised Cost of Energy for High Tip-Speed Ratio Tidal Turbines Operating in Less Energetic Flows

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The development of the tidal stream industry has been steady over the years. However, this growth is concentrated in areas of the world where the current magnitudes are high, mostly in the northern parts of the UK. Other sites characterized as less energetic sites remain to be untapped due to the high cost of energy of the technology compounded by the low energy yield in these sites. However, there is a benefit to be gained if the technology is developed to accommodate less energetic sites with flow velocities of less than 2 m/s, such as the waters of Southeast Asia, Southern UK, as well as Mexico's continuous Yucatan current, and Taiwan's Kuroshio. Research and development of tidal stream technologies that may be able to harness the energy in these currents have been continuous, but development is yet to start due to technology mismatch. Designing to increase the rated tip-speed ratio of the turbine blades with the notion that faster-rotating blades reduce the overall cost of the generator and its subsequent components, leading to greater savings compared to the usual downsizing, is an option to further the development in these regions. This design approach has been shown to be technically feasible, but the economic feasibility of such a design remains to be seen. The economic benefit is then evaluated using a cost model starting from generator cost modeling and then computing the cost of other components, including auxiliaries, cables, foundations, as well as commissioning and financing. A one-at-a-time sensitivity analysis is then used to evaluate the resulting LCOE when considering array size, turbine diameter, and rated speed. It has been found that there is a region of substantial cost reduction at about 50 RPM regardless of the tip-speed ratio, where the LCOE of turbine operating in less energetic sites at this range are better compared to the LCOE of conventional turbines designed for operating at the same less energetic site. It was also found that 5 m diameter turbines operate at a reasonable LCOE at array sizes of greater than 5 turbines, although 10 m diameter turbines have the most attractive LCOE. Nonetheless, both configurations lead to a better LCOE compared to diesel and the conventional tidal turbine counterparts, which could help in the transition to greener energy technologies, as well as green rural electrification, where diesel remains to be the main source of electricity.

1. Introduction

The development of tidal stream technology has progressed rapidly in recent years, with advancements in the industry resulting in later Technology Readiness Levels (TRLs) and the ability to provide an appreciable supply of energy to the market. Recent developments in the tidal stream technology include the 2 MW Orbital O2 of Orbital Marine Power (Orbital Marine Power, 2022) and the 2 MW AR2000 of SAE Renewables (SAE, 2022) both rated at $U_\infty = 3$ m/s. However, much of the focus has still been on energetic flows with velocities of $U_\infty >$ 2 m/s, including the Nova M100-D 100 kW (Nova Innovation, 2022) turbine, one of the smallest commercial turbines available in the market.

Nonetheless, interest in the technology has grown, albeit the apparent mismatch in flow conditions i.e., current velocities with $U_\infty < 2$ m/s, and design of conventional turbines operating in energetic sites. These include the south, west, and east coasts of the UK (Haverson et al., 2017), most of Southeast Asia (Bausas et al., 2016), as well as other tropical countries such as Brazil (González-Gorbeña et al., 2015) and Mexico (Chávez et al., 2003). However, the use of existing designs of tidal turbines may lead to inefficient power capture and an

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increase in the Levelised Cost of Energy (LCOE) (Quirapas et al., 2015). Additionally, the deployment of turbines designed for energetic sites leads to a loss in power and an increase in LCOE, as observed in Portugal (Pacheco et al., 2018).

Lower velocity magnitudes in less energetic currents allow for lower loads which can help in the reduction of cost. Such a design allows for additional cost reduction since it allows for direct-drive drive trains, as well as smaller and faster-rotating generators, which are generally cheaper and lighter. Designs of tidal stream turbines that operate optimally at less energetic flows of $U_\infty < 2$ m/s using the concept of high-TSR operation have been shown to be technically viable (Encarnacion and Johnstone, 2019). However, economic viability is yet to be established.

This paper evaluates the economic viability of high-TSR rotors via LCOE calculation and comparison to diesel LCOE. This allows for the determination of alternatives to high-carbon power sources that are used in off-grid areas that have low demand, which is deemed to be an appropriate application of the technology due to the relatively low power production of tidal stream technology in less energetic sites compared to conventional turbines in energetic sites (Palconit et al., 2021).

2. Methodology

2.1 Rotor setup

The performance of each rotor is evaluated using Blade Element Momentum (BEM) Theory. The resulting non-dimensionalized hydrodynamic performance of the rotors is tabulated in Table 1. These blades allow for the comparison of low TSR rotors and high TSR rotors. The higher TSR NACA and Wortmann were all optimized (Encarnacion et al., 2019) versions of the base NACA and Wortmann blades.

Table 1: Blade Configurations used in this study.

Blade Configuration	$C_{P_{\max}}$	TSR of $C_{P_{\max}}$
NACA, Bahaj (2007) – 3bladed	0.428	5.75
NACA, TSR7.75 – 3bladed	0.449	7.75
NACA, TSR9.75 – 2bladed	0.419	9.75
NACA, TSR12 – 2bladed	0.346	12.00
Wortmann, Ellis (Ellis et al, 2018) – 3bladed	0.409	3.75
Wortmann, TSR5.75 – 3bladed	0.398	5.75

Hydrodynamic performance is evaluated at U_∞ set to 1, 1.5, and 2 m/s and rotor diameters of 2, 5, and 10 m.

2.2 Generator cost modelling

The cost of each rotor is then calculated using the generator cost model adapted from Hart et al. (2014) using a 6 MW wind turbine as a reference. This model separates the cost of the gearbox and the generator. This allows for the isolation of the cost of the generator, emulating a direct-drive drive train for all cases in Hart et al. (2014), which can then be fitted using an exponential equation (Figure 1a) with RPM as an independent variable. The direct drive configuration uses the most material as it rotates the slowest and requires the highest torque.

Table 2: Material weight for each drive train configuration

Theoretical Drive Train	Supposed Gear Reduction	Theoretical Blade RPM	Material Weight (tons) without gearbox		
			Iron	Copper	Magnet
Direct Drive	1:1	12	30.6	6.6	2.9
1-Stage Gearbox	1:8	96	6.4	2	0.6
2-Stage Gearbox	1:40	480	3.3	1	0.3
3-Stage Gearbox	1:100	1,200	2.8	1.1	0.3

The resulting RPM for each rotor configuration (blade, , and diameter) are plotted, and the weights of iron, copper, and magnets are obtained. A scaling model shown in Figure 1b (Shrestha et al., 2009) is then used to adjust from the 6 MW reference turbine down to the applicable power of each rotor configuration, already accounting for friction and armature losses. The final cost is then obtained using the cost/kg for each material according to Guan et al. (2017) and Hart et al. (2014). Availability is already incorporated in the final power output with a value of 92.7 % with a capacity factor of 35 % (Carroll et al., 2017).

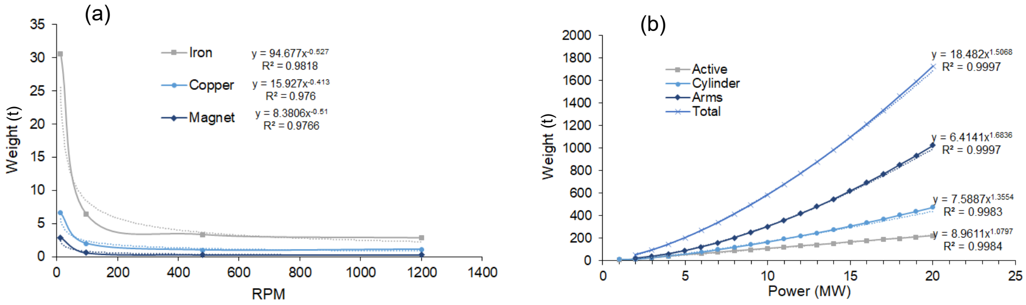


Figure 1: Ax^n regression fits for Weight vs RPM for a 6 MW generator (a) and vs rated power for scaling (b)

2.3 CAPEX, OPEX, and LCOE

Capital Expenditure (CAPEX) is then calculated using the associated generator cost as a reference. Segura et al. (2017) showed that the power take-off account for 13.5 % of the total CAPEX. The percentages for the PTO frame, rotor, nacelle structure, auxiliary systems, and fairing are all adopted as is.

Changes in CAPEX are then incorporated by changing the share of the export power system using Bertheau and Cader (2019) for adjusted values of submarine and ground exportation cables. This change is mainly due to the lower power output of the turbines from 1.2 MW for Segura et al. (2017) and 160 kW for this study. Cost reduction is also envisioned in the use of vessels and labor since the smaller turbines require less specialized vessels that are about 65 % cheaper (Wind Power Monthly, 2013). Foundations are also adjusted by setting the turbine with the largest loading to have a share of 15.75 % share, and all succeeding turbines have reduced cost proportional to the reduction in load.

Operational Expenditure is then taken as a percentage of CAPEX with additional adjustments. The general percentage for OPEX is 4 % (Pennock et al., 2022). This already includes maintenance losses during maintenance since the turbine needs to be lifted. An additional OPEX cost is added to account for changing blades due to the increased risk of cavitation when operating at higher TSRs. The new OPEX is now set at 6.25 % of the total cost, which accounts for a change in the rotor and additional expenses associated with changing rotors.

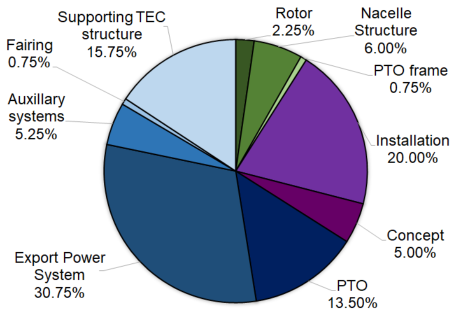


Figure 2: Cost share for each component of tidal stream turbine installation (Segura et al., 2017)

The levelised cost of energy (LCOE) is then given by (Johnstone et al., 2013):

$$LCOE = \frac{ICC+COM}{AEP\times n} + OM_{\text{fixed,annual}} + OM_{\text{variable}} \tag{1}$$

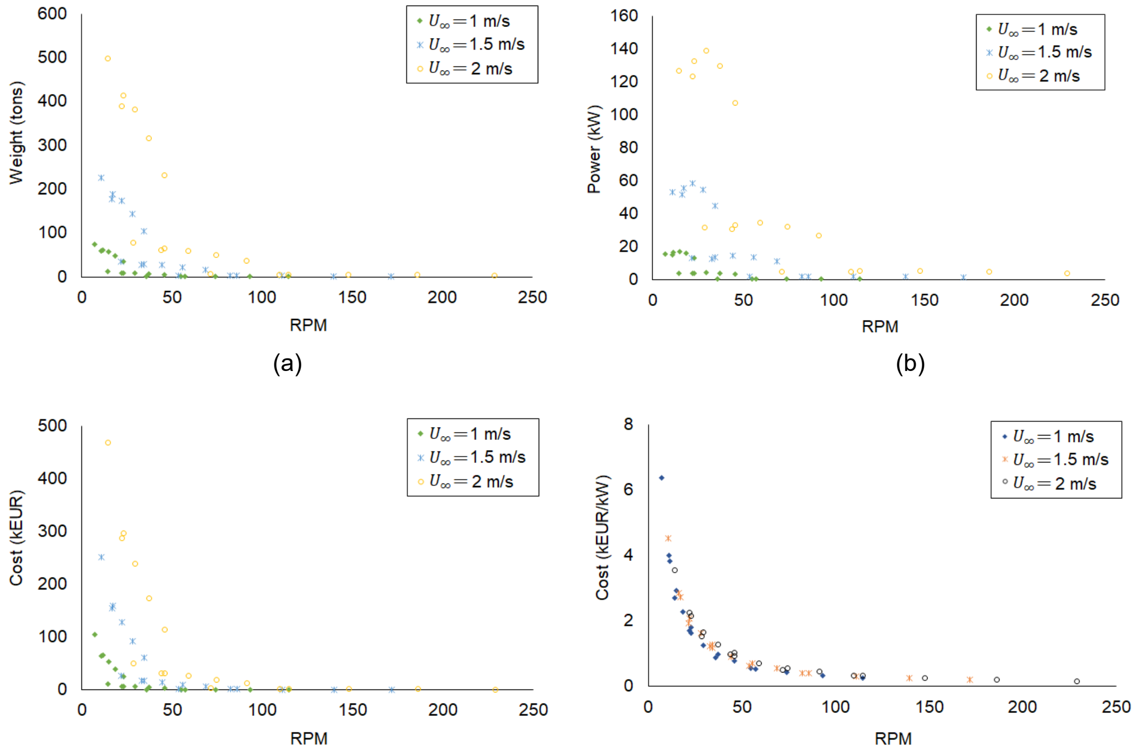
where ICC is the initial capital cost calculated as the CAPEX, $OM_{\text{fixed,annual}}$ is the OPEX calculated as 6.25 % of the CAPEX, OM_{variable} is the cost of fuel set to 0 since the technology is renewable, COM is the cost of money which is the additional cost to amortise the CAPEX over the lifetime n of the turbine with a certain an Annual Energy Production AEP.

3. Results and discussion

3.1 Generator costs

Figures 3a and 3b show that there is a drop in power output (disadvantage) and weight (advantage) as RPM is increased for a certain inflow condition. In Figures 3a, 3b, and 3c, there are three distinct groups that within each inflow velocity setting, which correspond to the turbine diameters of 10 m (highest), 5 m, and 2 m (lowest). Combining the cost and power output graph, a clear trend between the cost of energy (COE) associated to the generator and RPM is observed.

In Figure 3d, the initial drop in COE is significant and then tapers with small reductions after reaching 50 RPM. This supports the hypothesis that operating at higher TSRs are beneficial but there exists a threshold before reductions become marginal.

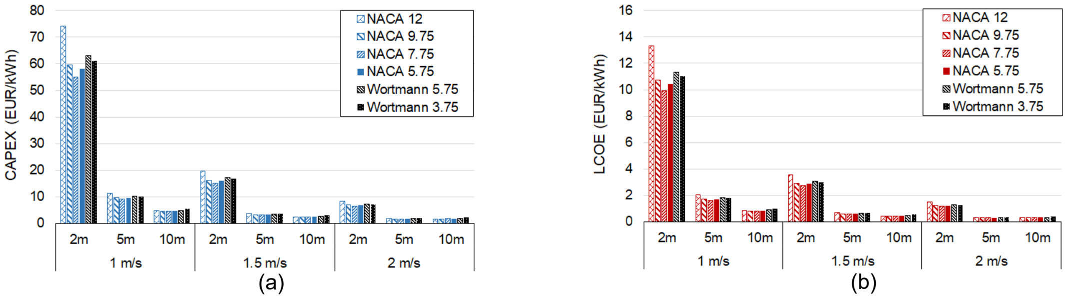


(a) (b)

(c) (d)

Figure 3: Weight (a), Power (b), Cost (c) and Cost per kW (d) for all blades at 2, 5, and 10 m operating at 1, 1.5, and 2 m/s current magnitude

The CAPEX trends observed in this study is the same the ones observed in industry – going for larger turbines generally improve the CAPEX per kWh. This is due to the high cost of the export power system, which can only be offset by going for larger scale turbines.



(a) (b)

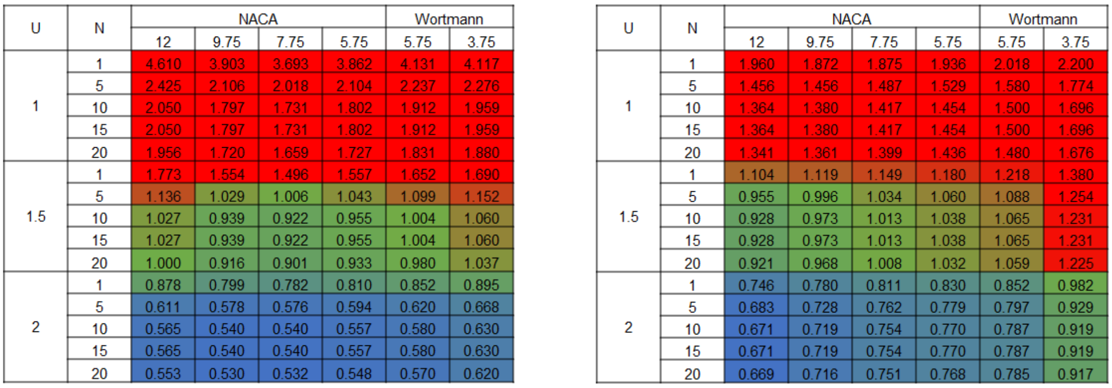
Figure 4: CAPEX (a) and LCOE (b) values for all blades at 2, 5, and 10 m operating at 1, 1.5, and 2 m/s current magnitude

Here, the CAPEX for the NACA TSR12 rotor is the highest, which seems to be against going for higher TSRs. However, this agrees with the previously discussed threshold of 50 RPM since the 2 m diameter TSR12 rotors rotate at the fastest speed, which only sees marginal reductions in cost coupled with a large reduction in power output. This effect is then reduced at larger scales, with NACA TSR9.75 performing similarly to the base NACA

TSR5.75 at a diameter of 5 m and better at a diameter of 10 m. Notably, the NACA TSR7.75 always performs better than the base NACA TSR5.75, which may be attributed more to the optimization of the blade. Expectedly, OPEX trends are similar to CAPEX trends since the former is calculated as a percentage of the latter. Thus, LCOE trends in Figure 4b are also similar to the CAPEX trends in Figure 4a since it is already given in EUR/kWh. The 5 m and 10 m diameter turbines perform similarly for current velocities of greater than 1.5 m/s. Thus, both are considered as viable diameters for less energetic currents and can be considered according to flow conditions and deployment limitations such as depth coupled with distance to shore.

3.2 Sensitivity to array size of LCOE normalized against diesel LCOE

The aforementioned results only consider one turbine. Increasing array size is one way to increase the scale of the technology, and it is generally observed to have better LCOE when array size is larger. Figure 6 shows a one-at-a-time sensitivity analysis for 5 m and 10 m diameter turbines with varying number (N) of turbines. Each LCOE value is normalised against a diesel LCOE of 0.36 EUR/kWh (Bertheau and Cader, 2019).



U	N	NACA				Wortmann	
		12	9.75	7.75	5.75	5.75	3.75
1	1	4.610	3.903	3.693	3.862	4.131	4.117
	5	2.425	2.106	2.018	2.104	2.237	2.276
	10	2.050	1.797	1.731	1.802	1.912	1.959
	15	2.050	1.797	1.731	1.802	1.912	1.959
	20	1.956	1.720	1.659	1.727	1.831	1.880
1.5	1	1.773	1.554	1.496	1.557	1.652	1.690
	5	1.136	1.029	1.006	1.043	1.099	1.152
	10	1.027	0.939	0.922	0.955	1.004	1.060
	15	1.027	0.939	0.922	0.955	1.004	1.060
	20	1.000	0.916	0.901	0.933	0.980	1.037
2	1	0.878	0.799	0.782	0.810	0.852	0.895
	5	0.611	0.578	0.576	0.594	0.620	0.668
	10	0.565	0.540	0.540	0.557	0.580	0.630
	15	0.565	0.540	0.540	0.557	0.580	0.630
	20	0.553	0.530	0.532	0.548	0.570	0.620

(a)

U	N	NACA				Wortmann	
		12	9.75	7.75	5.75	5.75	3.75
1	1	1.960	1.872	1.875	1.936	2.018	2.200
	5	1.456	1.456	1.487	1.529	1.580	1.774
	10	1.364	1.380	1.417	1.454	1.500	1.696
	15	1.364	1.380	1.417	1.454	1.500	1.696
	20	1.341	1.361	1.399	1.436	1.480	1.676
1.5	1	1.104	1.119	1.149	1.180	1.218	1.380
	5	0.955	0.996	1.034	1.060	1.088	1.254
	10	0.928	0.973	1.013	1.038	1.065	1.231
	15	0.928	0.973	1.013	1.038	1.065	1.231
	20	0.921	0.968	1.008	1.032	1.059	1.225
2	1	0.746	0.780	0.811	0.830	0.852	0.982
	5	0.683	0.728	0.762	0.779	0.797	0.929
	10	0.671	0.719	0.754	0.770	0.787	0.919
	15	0.671	0.719	0.754	0.770	0.787	0.919
	20	0.669	0.716	0.751	0.768	0.785	0.917

(b)

Figure 6: LCOE of 5 m (a) and 10 m (b) diameter turbines normalized against diesel LCOE of 0.36 EUR/kWh

Turbines operating at 1.5 m/s and higher, regardless of diameter (at least 5 m), perform similarly or even better than diesel. This shows that the designed turbines are a viable alternative to diesel-fired generators that are generally used in off-grid areas, which are appropriate sites for the technology considering the power output of the technology and the demand of these off-grid areas (Department of Energy, 2021). The optimal array size is 5 turbines, wherein additional turbines result in marginal benefits from an LCOE perspective regardless of RPM and current magnitude.

The viability of the designed turbines is apparent even just considering 2019 values for diesel LCOE. Recent trends in diesel prices boost this viability not only for the current year but can also be considered as more stable as the world moves towards more sustainable sources of power coupled with the increased importance of energy independence.

Turbines operating at 1 m/s are worse compared to diesel in an LCOE perspective. Additionally, individual turbines at this flow velocity generate less than 20 kW of power, which may not be enough for an appreciable supply even in isolated island regions. Thus, this remains a limitation of tidal stream technology in general.

4. Conclusions

Multiple blade configurations with maximum C_p values occurring at different tip-speed ratios (TSR) were evaluated using a levelised cost of energy (LCOE) approach to determine the viability of operating high TSR blades in less energetic currents. The cost of a direct-drive generator coupled with each blade was computed using an adopted cost model. The cost is then used as a base to calculate the cost of the remaining capital expenditure (CAPEX) components are then computed with respect to the generator cost and the base cost share. The LCOE is then computed as a function of CAPEX and operational expenditure (OPEX) taken as a percentage of the CAPEX. It was found that high TSR blades lead to a cost reduction but only when the resulting RPM is less than 50 RPM; cost reduction is marginal after this set threshold. The power outputs of the turbines are low compared to conventional turbines operating in energetic currents. However, the LCOE of the turbines can rival the LCOE of diesel, which remains to be the main energy source in off-grid areas, provided that the diameter of the turbines is at least 5 m. A one-at-a-time sensitivity analysis with respect to array size showed that an array size of 5 turbines is enough to have a good LCOE, whereas additional turbines do not result in significantly better LCOE.

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