First Steps toward a Multi-Parameter Optimisation Tool for Floating Tidal Platforms – Assessment of an LCoE-Based Site Selection Methodology

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Abstract — **The aim of this paper is assess and alter the method of tidal stream site selection, so as to ensure deployments are commercially viable. This paper has demonstrated the inter-site variability of LCoE, and that deploying in higher flow speed locations is not necessarily favourable if the site is exposed to harsh environmental conditions, despite potentially having higher yield. Neglecting to investigate the impact of MET-Ocean characteristics can lead to underestimation of the associated costs of an exposed site by up to 48%. For a sheltered site, however, current methods of site assessment generally used by the tidal stream industry are acceptable. When comparing the two types of site, taking into account the effects of MET-Ocean conditions indicates that the LCoE of a sheltered low flow site can be 75% lower than an exposed higher flow site over a 20yr PLAT-I deployment**

Keywords— **Tidal Stream, Site Selection, LCoE, Optimisation**

I. INTRODUCTION

Tidal stream deployments are limited to locations with appropriate bathymetry and sufficient resource for power extraction. To capitalise on a limited number of locations and offset the costs of being an emerging technology, the tidal stream industry has opted towards a site selection methodology that seeks primarily to maximise power output (1,2). This means that sites are chosen to maximise resource, and to minimise the losses associated with potential wake interactions and electrical transmission (3).

While these parameters are undoubtedly of high importance, they are but a few of many that should be factored into the choice of a deployment site. For tidal energy to become commercially viable, the site selection process should seek to minimise the project's Levelised Cost of Energy (LCoE) through means other than solely maximising output. The aim of this paper is to facilitate the transition towards commercial tidal energy deployments through the assessment and alteration of the site selection procedure.

The LCoE of a project is highly sensitive to choice of site and the utilised tidal energy device. The Sustainable Marine Energy Ltd. (SME) PLAT-I (PLATform-Inshore) device will be utilised as a case study (Figure 1). PLAT-I is a floating 30x26m trimaran platform that houses four SCHOTTEL In-stream Turbines (SITs) which generate electricity from the energy of the tidal flow. The platform is moored to the seabed by a spread of four caternary moorings emerging from the bearing turret on the bow. The mooring lines are anchored to the seabed via rock anchors at four points. The mooring spread and turret allows the platform to passively align with the flow, such that the SITs are always capturing the maximum amount of energy.

This paper will first examine the binary constraint parameters that must be satisfied to deploy a single SME PLAT-I at an arbitrary location. These parameters designate the characteristics that a site must have for potential deployment.

With the binary constraints identified, this paper will then investigate how accounting for and varying multiple site-specific parameters has a potentially positive or negative impact upon the annual revenue and LCoE of a 20yr PLAT-I deployment.

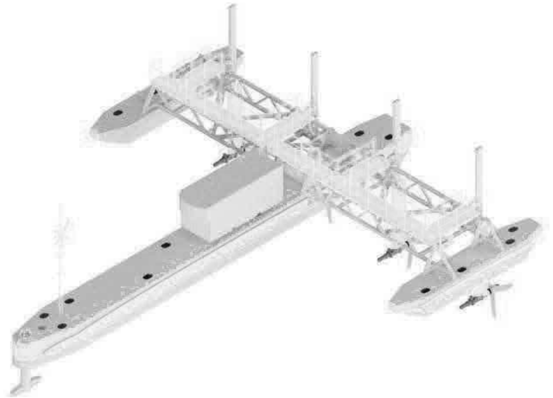


Figure 1. PLAT-I tidal energy platform with bow mooring turret and four suspended rotors.

II. PARAMETER METHODOLOGY

A. Binary Parameters

The following constraints are traditionally considered in tidal site assessments, and will be referred to here as 'Binary Parameters'. They demonstrate the viability of a site in a binary format; does the site have at least one deployment area where all of these conditions are satisfied? The overarching characteristics explored in this paper through binary parameters are as follows: Resource, Bathymetry, and Spatial Allowance.

1). Resource: The minimum value for flow speed is denoted by the cut-in speed of the SITs, and the maximum value by the braking speed. Standard tidal resource assessments often examine several locations and select the site with the highest flow speeds, while ensuring that the braking limit is not exceeded. For the PLAT-I device, which is capable of housing 6.3m or 4m rotors, this would mean flow speed bounds of 1.6-4.4m/s (4), but with a preference towards higher flow sites so as to maximise output. However, this binary selection process does not account for variation in yield with rotor rating characteristics. It also leads to the disregard of lower flow sites that have potentially far more favourable overall operational costs. Therefore, a separate parameter called Yield has been designated, and is explored in greater detail in Section B.

Vertical flow profile should also be taken into account because resource and therefore output will vary throughout the water column. In this study depth-averaged values are used due to data availability. The values used are an approximation, but an appropriate one, as rotor performance is not the primary focus of this research. Future work will seek to estimate output variations over the appropriate rotor depths using site specific velocity profiles.

Increased turbulence also has the potential to cause operationally inhibiting, and even damaging, cyclic loading on the SITs. However, the likely maximum turbulence intensity is already accounted for within the SIT rotor design (5), and as such turbulence is not considered as a constraining parameter within this first-pass investigation. Future work will look at incorporating turbulence intensity as a potentially constraining parameter, but also as an impacting factor upon component fatigue and therefore maintenance operation scheduling.

2) Bathymetry: The minimum depth constraint relates to the safe operation of the PLAT-I device, namely the amount of clearance that the rotors require from the bed. The designed hub depth is 6m, with the addition of the SIT rotor blades meaning a vertical excursion of up to 9.15m. A 10% safety factor on top of the total vertical excursion gives a minimum depth requirement of 10m.

The maximum depth constraint is a function of the mooring spread size and cost. Assuming that the required mooring profile can still be maintained with increasing depth, every additional meter of mooring line adds exponential cost to the project as well as increasing the device footprint. For these reasons, it was determined during the design stages of PLAT-I that the maximum deployment depth would be 50m.

The PLAT-I anchors are deployed by the A-ROV drilling rig (6), which provides a limitation on the steepness of the seabed. It is preferred that PLAT-I be installed in an area where the furthest reaches of its mooring spread are at more than ±5° incline.

3) Spatial Allowance: As stated previously, the extent of the mooring spread will change with the depth of the deployment location. As a baseline for design, SME determined that a uniform (flat) site of depth 21.5m at Highest Astronomical Tide (HAT) would require an approximate mooring spread area of 26.3x72.6m (7).

However, superseding the mooring spread allowance is the flow alignment parameter. Sufficient space must be allowed for the PLAT-I device to align with changing flow direction. Detailed tank testing of the mooring spread and model device at FloWave (8) revealed that a swing radius of 40m is required for the device to turn through 180°. Since this report is not investigating the optimisation of intra-site array layouts, a uniform scope of 80x80m has been designated as the minimum spatial requirement for a PLAT-I deployment.

Finally, this paper details the process of inter-site selection for an individual PLAT-I device, and therefore does not explore the potentially constraining effects of device/wake interaction that are traditionally investigated. It is worth noting however, that the mooring spread footprint will ensure a minimum separation of 80m between adjacent device rotors. Existing literature on wake analysis states that 10 rotor diameters distance is sufficient for wake recovery (5,9). For PLAT-I this would be a maximum of ~63m, and as such wake interactions are not expected to be a constraining factor in future work.

4) Summary: The binary parameters listed in Table 1 are used to identify suitable sites for deployment. If their upper/lower bounds are satisfied then the site is deemed acceptable for deployment. However, these are not the only parameters that should be investigated, and within these bounds is the potential for further optimisation.

TABLE 1

BINARY PARAMETERS

Site Characteristic	**Resource**	**Bathymetry**		**Spatial Allowance**
Binary Parameter	**Flow Speed**	**Depth**	**Bed Angle**	**Flow Alignment**
Lower Bound	1.6 m/s	10 m	-5°	80x80 m
Upper Bound	4.4 m/s	50 m	5°	

B. *LCoE Parameters*

The LCoE varying parameters explored below are the focus of this paper. Assuming that a site meets the binary constraints detailed in the previous section, it is these parameters that can now be varied to positively or negatively impact upon the LCoE of a PLAT-I deployment.

Some designated parameters such as Yield and Electrical Losses have been investigated previously in the existing literature (10,11) due to being obvious drivers of project cost/revenue However, there are many parameters which have not yet been investigated rigorously with respect to tidal site selection. Callout Costs, MET-Ocean Characteristics and the compound effect of Weather Windows all have the potential to significantly impact upon LCoE. To highlight the value of incorporating these parameters into a site selection process, real-world data from potential deployment sites has been utilised to produce characteristic exposed and sheltered sites. The annual costs and revenue of deploying at these two hypothetical sites are then explored, again utilising real-world data from previous SME marine operations, the specifications of the SIT rotors, and design constraints of the PLAT-I device.

1) Yield: The power output of PLAT-I is dependent upon the flow speed at its proposed deployment site, and the energy extraction characteristics of its SIT rotors. Figure 2 describes how the power output will vary as flow speed increases within the designated bounds of 1.6-4.4m/s. Although the power output for the 6.3m rotor is higher than that of the 4m, at flows above 2.7m/s the thrust on the larger rotors becomes potentially damaging. Therefore, if flow speeds are expected to be higher than 2.7m/s, the rotor size for PLAT-I will be decreased to 4m. These rotors are capable of producing power up to a braking speed of 4.4m/s, but have a reduced electrical power output when compared to the 6.3m rotors.

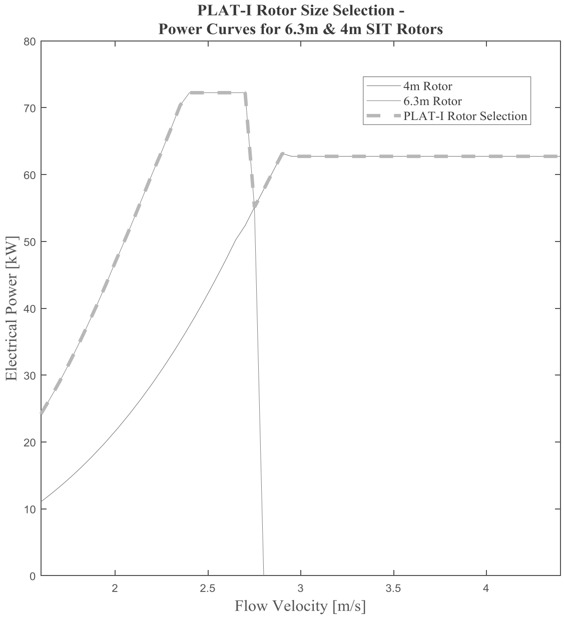


Figure 2. Variations in rotor size and electrical power with respect to flow velocity for a PLAT-I device.

It is assumed that a Contract for Difference (CfD) of £300/MWh (12) is constant over the 20yr project lifespan, and that long-term variation in tidal strength is negligible. To avoid potential inaccuracies associated with site-specific flow characteristics, this paper bases its power extraction and revenue calculations on a simple sinusoidal flow, where a designated power extraction flow speed is reached for an average of 8 hours per day, 365 days a year.

While in this analysis flow speed is not calculated to vary with distance from shore, the annual revenue data is represented as a surface plot (Figure 3) to allow for an overlay of other LCoE parameters, many of which vary with distance. Note the expected similarity between the power curve and the shape of the annual revenue plot. The highest output and revenue is observed at 2.4-2.7m/s, where the 6.3m rotors are operating at maximum power.

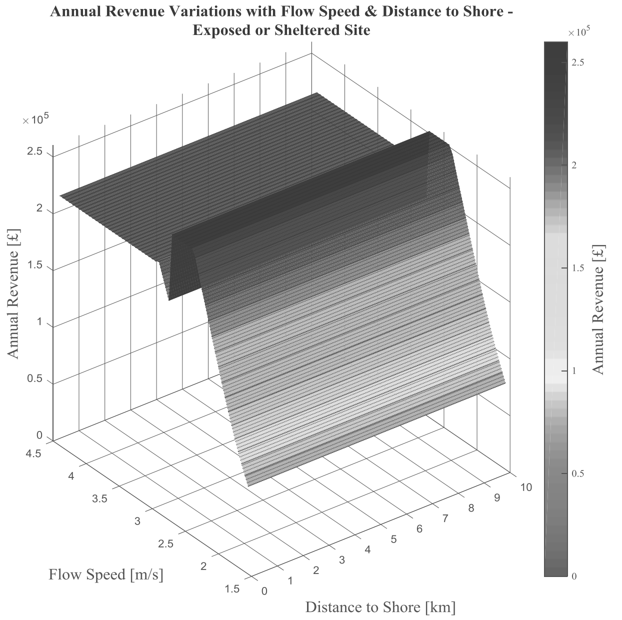


Figure 3. Variation in Annual Revenue with flow speed and distance, accounting for rotor induced variations in electrical power output.

2) Electrical Losses: Losses associated with power transmission have has been thoroughly investigated in existing literature (11,13) and therefore the theory will be mentioned here only briefly. An Electrical Losses parameter is included in this paper not only to ensure the accuracy of LCoE calculations, but also to demonstrate its contribution to project LCoE when compared to other distance-varying parameters such as Callout Costs & Weather Windows.

For a grid connected PLAT-I device, a 250kVA on-board transformer (with assumed >98% efficiency) and up to 3km of cable with cross sectional area 10mm^2 will be used as an export system. These characteristics will be used to calculate the active power losses in a three-phase export system as per Equation.1 (14).

$$\text{Eqn.1} \qquad P_{LineLoss} = 3\sqrt{3}\left(\frac{P_{Line}}{V_{Line}}\right)^2 . R_{Line} = I^2 . R$$

Reactive losses are expected to be minimal over this distance and configuration of components, they have therefore not been included in this investigation (15). For future work concerning PLAT-I array configurations and more complex transmission solutions, it will be necessary to investigate reactive losses.

The annual loss of revenue relating to electrical losses is presented in Figure 4 (left). These losses respond to two contributing factors, shown in the simplified right expression of Equation.1. The first is the current (I) flowing through the cable increases with the power output from the rotors, and as such Figure 4 (left) is reminiscent of the power output graph, Figure 3. The second is the losses associated with cable length. The longer the export cable, the higher the resistance (R), and therefore greater electrical and revenue losses. Reducing power output is not advisable due to the much greater revenue gain from higher yield. If one only seeks to minimise electrical

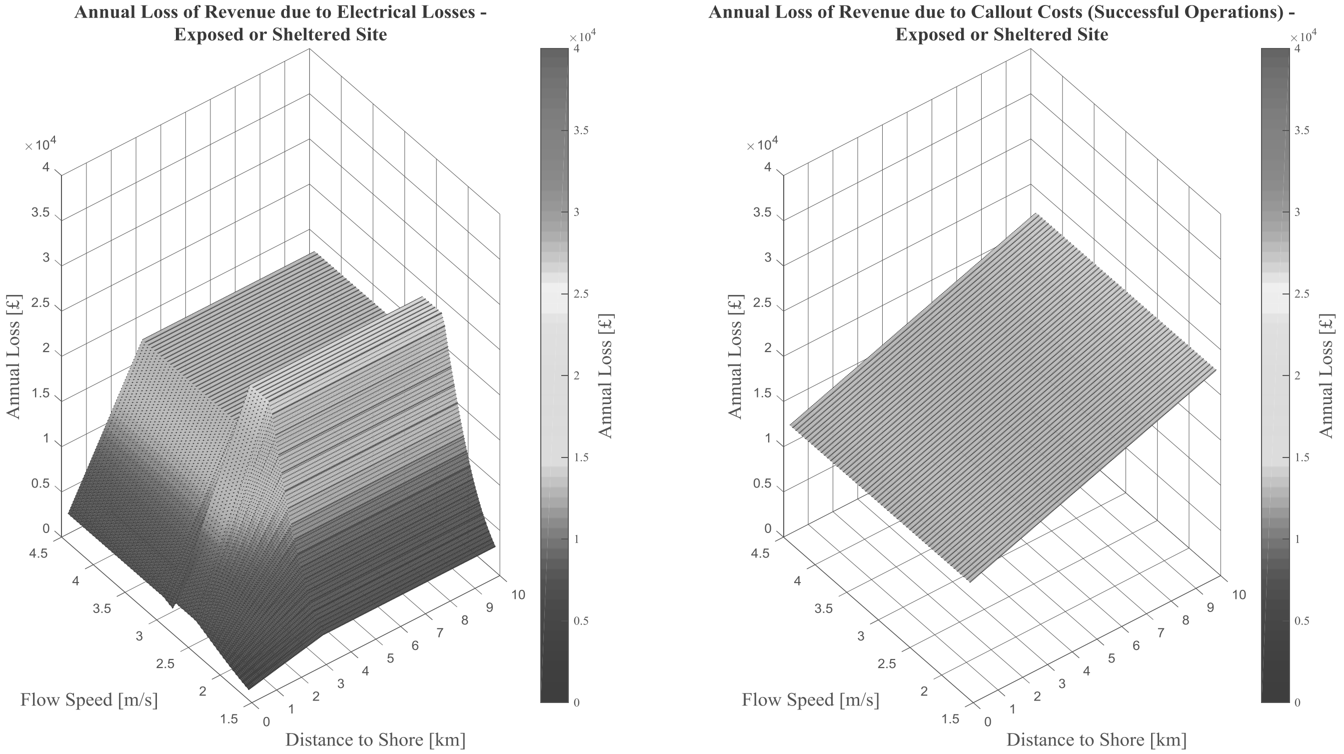


Figure 4.Annual Loss of Revenue due to electrical losses (left) and successful callout operations (right). Additional site characteristics are not yet considered.

losses, it is therefore preferable to choose a deployment location that minimises the distance to the onshore connection point. Future work will incorporate multi-parameter optimisation techniques to prioritise for LCoE as a whole, rather than through optimising individual parameters. This is explained further in Section IV, but for now note that in terms of overall project LCoE, a short, low voltage cable with high losses, may be preferable to including a transformer and a long, high voltage cable, as it allows for considerably smaller callout distances and their associated costs.

3) Callout Costs: Two maintenance callouts are accounted for per year to ensure the continuing operation of a PLAT-I device. One of these operations will be scheduled, while the other is to account for the possibility of component failure. In both cases, a fully equipped maintenance vessel is required, with an expected maximum response speed of 3m/s. Said vessel must be housed in an adjacent and appropriately sized port/dock when on standby. The approximate costs of a single SME callout maintenance operation in Northern Scotland are given in Table 2.

While a large portion of the callout operation is a flat cost, many parameters such as vessel running costs and staff time are dependent upon the distance between the maintenance port and the PLAT-I deployment location. Figure 4 (right) shows the annual loss of revenue when considering the callout costs presented in Table 2, and how these costs increase with distance to shore (port). Maintenance operations would appear to have a similar revenue cost to that of electrical loss; relatively low compared to the overall annual revenue (Figure 3). However, Figure 4 (right) only represents the cost of successful operations.

TABLE 2

CALLOUT OPERATION COSTS

Marine Operation (x 1)	Vessel Running Costs (£/km)	3 x Staff Costs (£/h)	1 x Daily Vessel Hire (£)
Cost	100	1500	5000

4) MET-Ocean Conditions: The meteorological and ocean characteristics of a site have the potential to create periods where conditions are too extreme for power generation or for the completion of marine operations such as installation, maintenance and decommission. Both such occurrences have an associated cost, but the financial consequences of these site characteristics are not yet included in tidal energy site assessments to the knowledge of the authors.

The PLAT-I platform and SITs are designed to generate when significant wave heights (H_s) are less than 2m. If this significant wave height is exceeded, brakes will be applied to the turbines, and power generation will cease. H_s exceedance at a characteristic exposed site was estimated through use of Acoustic Doppler Current Profiler (ADCP) data collected from a real world site in a highly exposed area of Northern Scotland. This data was discretised into bins and the probability of exceedance calculated.

The full exceedance curve cannot be presented here due to data confidentiality. However, the probability of H_s>2m occurring was calculated to be 8%. This means that a PLAT-I device would be unable to produce electricity 8% of the time at a similar characteristically exposed site. The annual loss of revenue due to wave induced operational downtime at an exposed site such as this is presented in Figure 5 (left). The trend of the graph is inherently linked to the power curve, and does not vary with distance from shore in this analysis.

The probability of downtime occurring due to H_s exceeding 2m at a characteristic sheltered site, was calculated to be 1.4% by using Hoy Sound in Northern Scotland as a case study. Due to the protected nature of the site, navigational charts state that significant wave heights are 50% smaller than those observed at the aforementioned exposed site. This analysis assumes a similar overall sea state due to site proximity; lower waves but with the same distribution. This assumption is a potential source of error, but is unavoidable due to data unavailability.

The annual loss of revenue due to environmentally induced downtime at a characteristic sheltered site is shown in Figure 5 (right). The influence of the power output curve can still be seen within the graph, but the loss of revenue is markedly lower than that observed at the exposed site shown in Figure 5 (left).

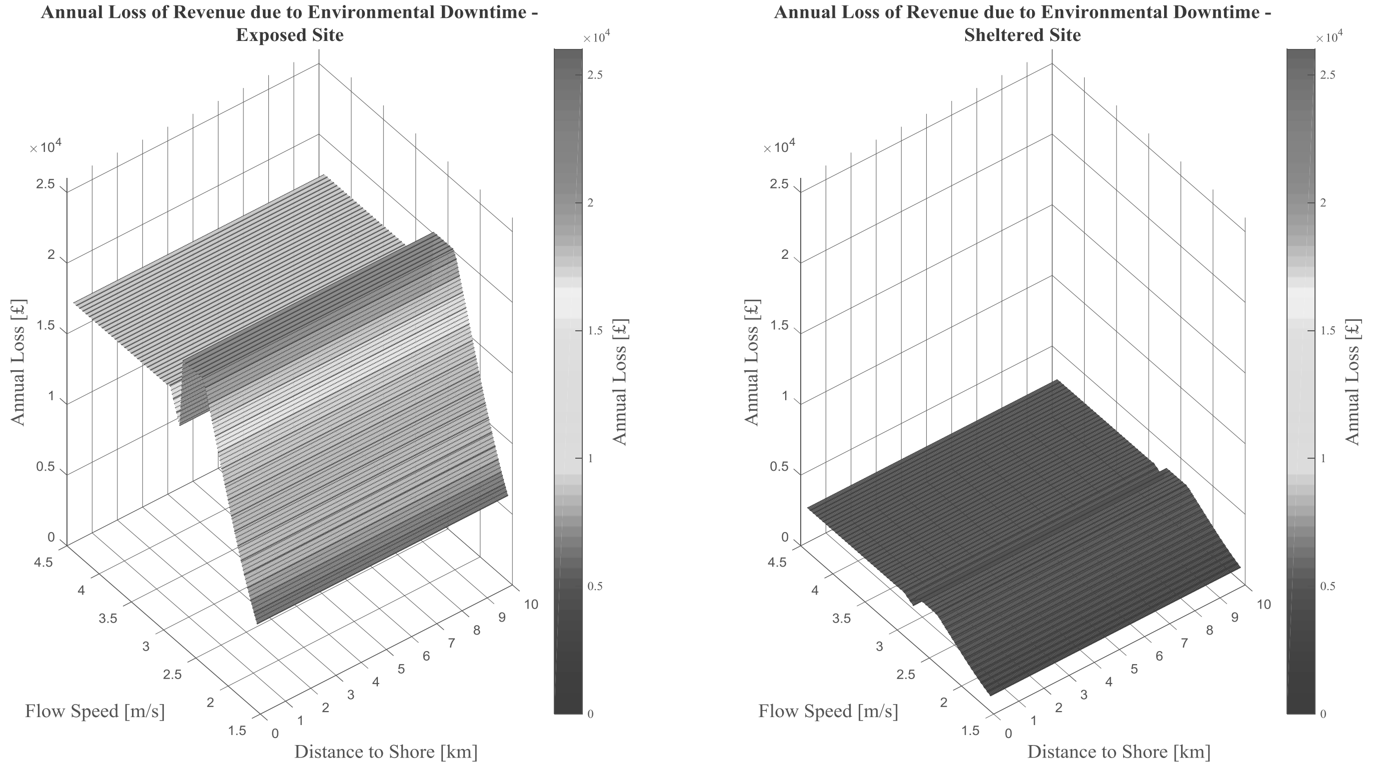
Wind is not a limiting factor in terms of PLAT-I operation, as it does not impact upon the rotors or structure. However, if wind speeds exceed 20m/s, marine operations will be cancelled to ensure the safety of vessels and staff. In the following section, this probability is utilised alongside flow speed and wave exceedance, and estimated Operation & Maintenance (O&M) costs to calculate the impact of weather windowing effects on the cost of a project.

5) Weather Windows: In a harsh and changeable environment, it is rare that marine operations will always be able to go ahead as planned, and operational failure is a real possibility. The following section investigates the compounding effect of many of the LCoE Parameters investigated so far, and how this impacts on the costs of marine operations, and the project as a whole.

The flow speed, wind speed and wave height exceedances have been calculated for exposed and sheltered characteristic case sites for a PLAT-I deployment. Equation. 2 gives the probability of at least one of the restrictions being exceeded on a given day of the year, leading to the cancellation of a marine operation. The probabilities of exceedance for flow (P_{FlowEx}) wind (P_{WindEx}) and wave (P_{WaveEx}) are considered to be independent.

Eqn.2 $$P_{OpCancel} = P_{FlowEx} + P_{WindEx} + P_{WaveEx}$$

Flow speed exceedance is an important restraint for marine operations, as it provides a limiting factor for operation length and frequency. For the safety of vessels and staff, marine operations will not be possible in flow speeds above a threshold of 2.4m/s. Bottom-mounted ADCP flow speed data for the Rapness area over 1 year (16) reveals that marine operations for PLAT-I would be limited to the neap periods at such a site (179 available days out of 365). The probability of the flow



Annual Loss of Revenue due to Environmental Downtime - Exposed Site

Annual Loss of Revenue due to Environmental Downtime - Sheltered Site

Figure 5. Annual loss of revenue due to environment induced downtime at an exposed site (left) and sheltered site (right).

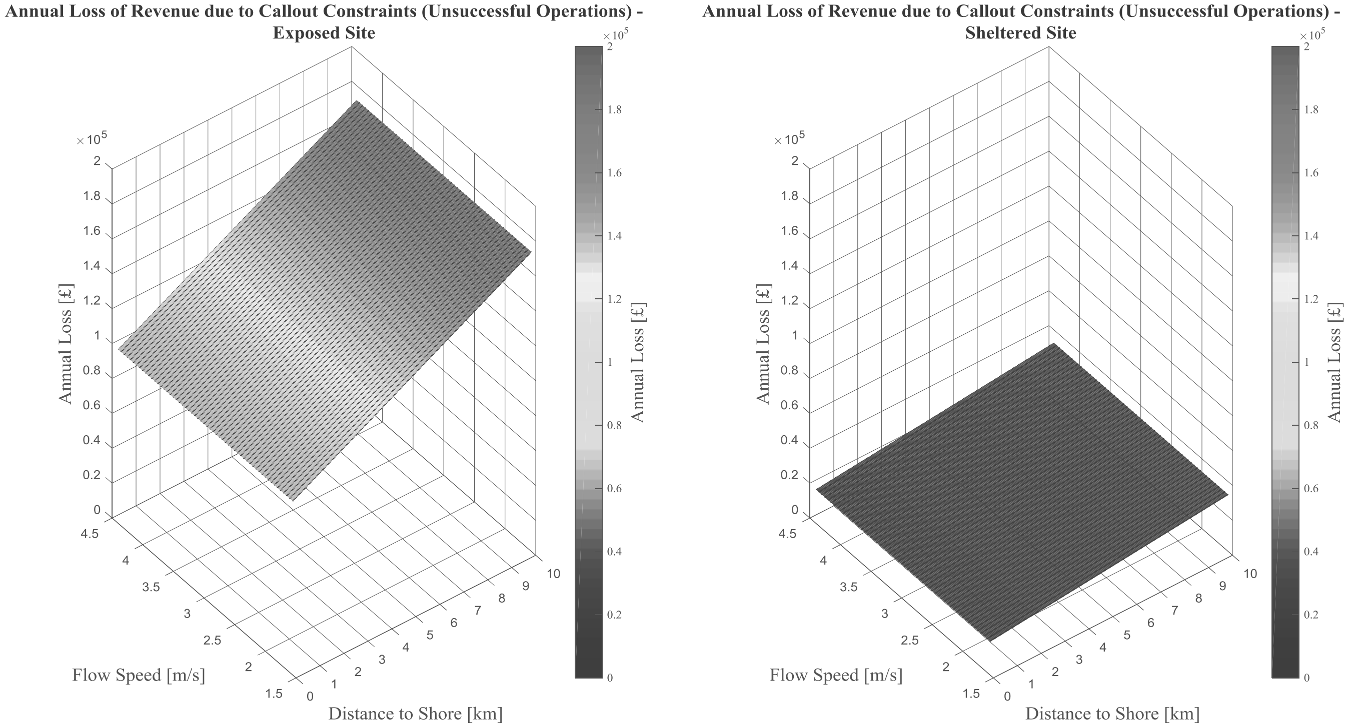


Figure 6. Annual loss of revenue due to unsuccessful marine operations at an exposed site (left) and a sheltered site (right).

exceeding 2.4m/s on a given day is therefore 50.96%. However, for adjacent sheltered lower flow sites such as Hoy Sound, hull mounted ADCP data (17) exhibits average flow speeds of approximately 40% slower than at Rapness. Marine operations would be far less limited (317 days out of 365). Here the flow exceedance probability is just 13.15%, making callout operations far more likely to proceed and be successful.

Wind data was collected from the Supervisory Control and Data Acquisition (SCADA) weather measurements at the Barrel of Butter Station (of the Orkney Islands). This data was then discretised into bins and the probability of exceedance calculated. Wind is inherently highly site dependant, and classifying a characteristic exposed and sheltered site based on specific site data would be erroneous; this investigation does not directly compare two real-world sites. Therefore, the same exceedance curve and probability is utilised for the exposed and sheltered case sites. The full curve cannot be presented here due to data confidentiality, but it was calculated that wind speeds have a 1% probability of exceeding 20m/s.

For the wave exceedance probability, if significant wave heights at either the exposed or sheltered site exceed 1m then marine operations are deemed to be too dangerous, and will therefore be cancelled. Utilising the same wave exceedance curve and relationships as described in the previous section, the probabilities of H_S exceeding 1m at an exposed and sheltered site were calculated to be 35% and 18.7% respectively.

The compounding problem of weather windows decreases the size and occurrence of viable time periods for operations, meaning successful operations occur less frequently. These cancellations and repeat operations mean that project costs increase.

Table 3 summarises the probabilities and number of potential operations required to ensure a successful operation. These probabilities are utilised alongside the estimated callout costs presented in Table 2 to calculate the impact of weather windowing effects on the cost of a project. The annual losses of revenue associated with a PLAT-I deployment at an exposed and sheltered site are presented in Figure 6 (left and right respectively).

TABLE 3

PROBABILITY OF EXCEEDANCE FOR ENVIRONMENTAL CHARACTERISTICS AT AN EXPOSED AND SHELTERED SITE

Site Characteristics		**Exposed**	**Sheltered**
Probability of Occurrence	**Flow Exceeding 2 m/s**	0.51	0.13
	Wind Exceeding 20 m/s	0.01	0.01
	Wave Exceeding 1m	0.35	0.19
	Unsuccessful Operation	0.87	0.33
	Successful Operation	0.13	0.67
Number of Operations Required for Probable Success		8	2

III. DISCUSSION OF RESULTS

A. *Influence on Annual Revenue*

Comparing the left and right plots of Figure 6 highlights the importance of accounting for the compounding problem of weather windowing in a tidal energy site assessment. Selecting a sheltered site keeps operational costs relatively low and constant with distance, while choosing an exposed site means that sixteen rather than original two marine operations must be accounted for financially per year (Table 3). This not only pushes up the baseline callout costs, but leads to distance becoming a more dominant parameter. At large distances from the maintenance port, the annual expense of running a specialised manned vessel for long periods of time present costs that are of the same order of magnitude as the generation revenue. This demonstrates a large flaw in site selection procedures, which only account for flow speed as the significant site-dependent driver of profitability.

Figure 7 takes the analysis a step further, showing an estimate for annual revenue and highlighting the importance of comprehensive LCoE Parameter incorporation into site selection methods.

The translucent surfaces show the annual revenue for a PLAT-I device at varying flow speeds and distance to shore, while accounting only for Yield, Electrical Losses and assuming that both callout operations are successful; these are seen to be identical on both plots . The translucent surface would be the output of a regular site assessment, and produces what the authors consider to be an immense overestimation of profitability.

Compare this to the solid layers of Figure 7, which account for all of the above parameters, as well as environmentally induced device downtime and the cost of failed operations due to weather windows. The solid surface for a sheltered site (right plot) reveals a much higher annual revenue relative to the exposed site. It would appear that using just the flow speed, electrical loss and successful operation parameters gives a close representation of the annual revenue of a project, but only if the PLAT-I deployment is located at a sheltered site.

Both graphs clearly follow the shape of the power output plot, with the other main similarity between the graphs being the steep decrease in annual revenue with distance for the first 3km. This steep gradient relates to the electrical losses. The accuracy of the export solution is limited to 3km, so the electrical losses are purposefully kept constant above this distance, and only the callout distance defines the revenue gradient. Aside from these resemblances, the similarities in the graphs are few.

For the exposed site (left plot), increasing the distance from shore has a large negative impact on the annual revenue, while the sheltered site remains relatively constant. At an exposed site, a significant factor is the distance from shore impacting upon the probability and therefore cost of ensuring successful marine operations. For an idealised 2.7m/s flow, 1km from shore scenario, the annual revenue is ~48% lower than current site assessments would predict at an exposed site. Indeed, the vast majority of exposed site scenarios examined produce a negative annual revenue.

For the sheltered site, distance from shore makes very little difference to the annual revenue. The cost of a few successful marine operations is small compared to the positive influence

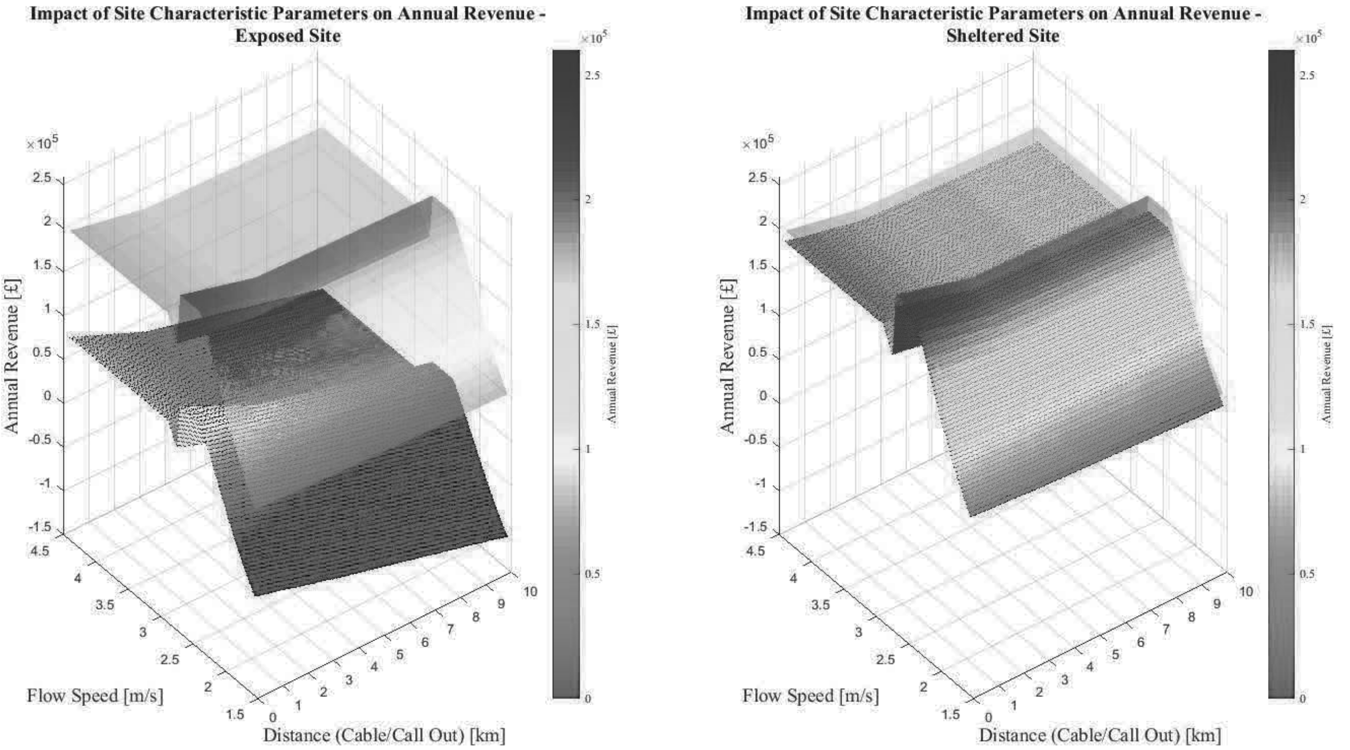


Figure 7. Impact of site characteristics on annual revenue at an exposed site (left) and sheltered site (right).

of power output. Also for a sheltered site, the relatively minor losses associated with electrical export are a far stronger influence upon annual revenue than the callout costs. For annual revenue, it appears important to incorporate a comprehensive parameter methodology into the site selection procedure. But exactly how much can the choice of an exposed or sheltered site impact upon the LCoE of a project over its lifetime?

B. Site Characteristic Influences on Levelised Cost of Energy

The Levelised Cost of Energy in £/MWh can be calculated through use of Equation. 3 (18). C_i are the initial costs incurred (development, manufacture, installation), C_t are the costs incurred throughout the project lifetime (marine operations, maintenance) and C_d are the costs incurred at the end of the project (decommission). AEP_t is the Annual Energy Production (with downtime subtracted). The project lifetime, n, is 20 years and the time interval, t, is 1 year (annually calculated costs and revenues). The discount rate, r, in this investigation has been set at 5% (19).

By inserting all of the costs and revenues of a project into this equation, it is possible to measure the cost effectiveness of a proposed location. Therefore, LCoE can be used not only as a way of comparing the profitability of different types of energy production, but also as a normalised basis from which to compare different tidal energy deployment sites.

$$\text{Eqn. 3} \quad LCoE_{20} = \frac{\frac{C_i}{(1+r)^0} + \frac{C_d}{(1+r)^{20}} + \sum_{t=1}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r)^t}}$$

The left plot of Figure 8 shows the variation in LCoE with flow speed and cable/callout distance at an exposed site, with all LCoE Parameters investigated in this report accounted for (Yield, Electrical Loss, Downtime, and Weather Windows). In order to compete with other renewable sources of generation such as offshore wind, it is necessary for tidal stream projects to achieve LCoE of below £300/MWh. For an exposed site, this can only be achieved in two circumstances; at maximum flow (4.4m/s) with 4m rotors within 500m of the shore, or at moderate flows (~2.5m/s) at the top of the 6.3m rotor power curve, within 2km of shore.

It is clear that deploying in an exposed site drives up the LCoE of the project, and designates very stringent limits for commercial viability. A site must be very close to shore/maintenance port, and have relatively high flow characteristics. Below 2.5m/s flow and above 2km from shore/port an exposed site is simply not commercially viable. Additionally, not accurately accounting for the exposed characteristics during the site selection phase would generate a false positive; where a high yield but exposed site would appear to have a desirable relatively low LCoE, when in fact the site would barely be profitable.

The right plot of Figure 8 shows the LCoE distribution for a characteristic sheltered site (while still accounting for Yield,

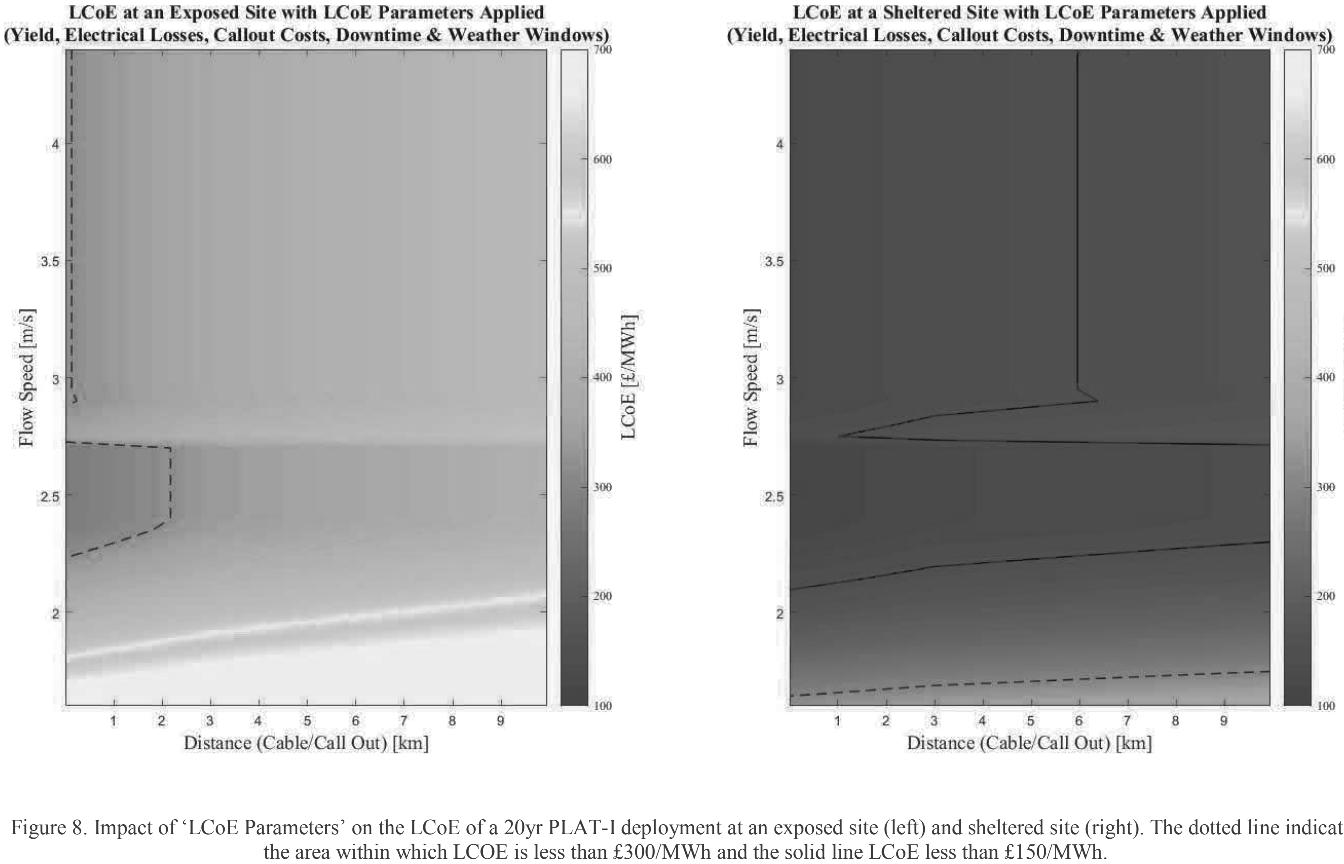


Figure 8. Impact of 'LCoE Parameters' on the LCoE of a 20yr PLAT-I deployment at an exposed site (left) and sheltered site (right). The dotted line indicates the area within which LCOE is less than £300/MWh and the solid line LCoE less than £150/MWh.

Electrical Loss, Downtime and Weather Windows). Here the vast majority of the plot can be shown to be commercially viable, with under £300/MWh LCoE. The distance to shore does not impact hugely on the LCoE due to the higher likelihood of successful marine operations. Indeed, only very low flow speeds (<1.8m/s) and therefore low revenues are commercially unviable if the site characteristics have appropriately been accounted for.

One of the premises of a more sheltered site is the limitation of flow speeds increasing the duration of weather windows. This does provide a limitation on the LCoE plot, in that higher flow speed sites will have already been disregarded. However, this is in fact one of the main ethos of this paper; to not prioritise high flow sites with potentially exposed conditions. As the LCoE plots show, by appropriately accounting for the sheltered nature of a site at the selection phase, a 2m/s flow speed can be seen to be far more lucrative than 4.4m/s flow at an exposed site.

As a final comparison and summary, Table 4 gives the parameters of two sites where the energy generated is equal at ~£700MWh. Both sites are designated to have satisfied the binary parameters discussed in Section A (previously summarised in Table 1). Table 4 demonstrates how a low flow, close to shore, sheltered site has ~75% lower LCoE than a very high flow, far from shore, exposed site.

TABLE 4

LCOE EXPOSED/SHELTERED SITE COMPARISON

LCoE Parameter		**Exposed**	**Sheltered**
Yield	**Depth-Averaged Flow**	4.4 m/s	2.6 m/s
Distance	**Export Cable**	3km	2km
	Callout Port	10km	2km
MET-Ocean Downtime	**Wave Exceedance (Hs>2m)**	8%	1%
Weather Window Probabilities	**Flow Exceedance (>2.4m/s)**	51%	13%
	Wave Exceedance (Hs>1m)	35%	19%
	Wind Exceedance (>20m/s)	1%	1%
	Successful Marine Ops.	13%	67%
Project LCoE (£/MWh)		***465***	***121***

IV. FURTHER WORK

Future iterations of this work will to look at the existing parameters in more detail, and investigate additional parameters that may impact upon the selection of a site, and therefore the LCoE of a project.

Some improvements are apparent, such as the inclusion of downtime not only due to the direct impacts of the MET-Ocean conditions, but also the potential downtime associated with not being able to perform successful repair operations for a number of days. Additionally, faults are more likely to occur in adverse weather, resulting in more frequent downtime and need for callout operations.

Others are less straightforward, such as the incorporation of a relationship between distance to shore and exposure. If a deployment site is further from shore, there is a greater potential for a longer fetch, which increases the probability of waves exceeding the threshold values for operational downtime and marine operation cancellation. This may not be possible in terms of a hypothetical site comparison, as the probability of the wind aligning with the fetch, and indeed the threshold fetch distance is highly site specific. If wind and waves can no longer be treated as independent variables, then the complexity of the investigations increases; it may be necessary to invest a considerable amount of time in data acquisition or collection, so as to perform a direct comparison of multiple real-world sites.

However, this would also assist in the development of other parameters, such as investigating how to incorporate a sheltered site with an exposed callout route (or vice versa). It would also allow for the development of the yield assessment to account for site turbulence and variations in velocity profile. Another parameter to include is wireless Communications & Control, and how this has the potential to financially limit the distance to shore more than the electrical losses.

This paper has only investigated the deployment of a single PLAT-I device. In order to increase revenue and offset costs the tidal stream industry will need to move towards array deployments. This means that factors such as spatial layout, transmission configuration, mooring sensitivity and varying device capacity/characteristics will need to be incorporated into future investigations.

Finally, the increase in complexity and number of parameters also highlights the need for an optimisation procedure that can adequately account for such a multitude of inputs. This is where the investigation must delve into the world of heuristics, in order to provide an optimisation procedure that prioritises user-specified outputs. In this case, the desired output is a minimised LCoE. With sufficient site data, techniques such as Genetic Algorithms (GAs) can be used to efficiently hone in on an LCoE optimum inter- and intra-site geographical location (20).

V. CONCLUSIONS

This paper has demonstrated the inter-site variability of LCoE over a 20yr PLAT-I deployment, and that deploying in the highest resource location is not necessarily the most favourable option in terms of overall project LCoE, despite potentially having a higher yield.

Neglecting to investigate LCoE Parameters such as the MET-Ocean characteristics of a site, leads to underestimations of the associated site costs. This produces a misleadingly low LCoE for an exposed location, when in fact the site characteristics may render the project unprofitable. Indeed, this paper has shown that a characteristic low flow, nearshore, sheltered site has ~75% lower LCoE than a high flow, far from shore, exposed site. The hypothetical energy generated was equal at ~£700MWh for both the exposed and sheltered site.

At a sheltered site, accounting for LCoE Parameters appears to not significantly impact upon the annual revenue of a PLAT-I deployment. However, this only highlights the need for further investigation into the LCoE parameters. Annual revenue is ~48% lower than would be expected at an exposed site in an optimistic nearshore scenario, and potentially negative in the majority of far from shore scenarios.

It is clear that LCoE Parameters should be investigated thoroughly as part of the tidal energy site selection procedure, with as much importance being assigned to them as the typically prioritised resource-related parameters.

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REFERENCES

1. Vennell R. Estimating the power potential of tidal currents and the impact of power extraction on flow speeds. Renew Energy [Internet]. Elsevier Ltd; 2011;36(12):3558–65. Available from: http://dx.doi.org/10.1016/j.renene.2011.05.011
2. Ahmadian R, Falconer RA. Assessment of array shape of tidal stream turbines on hydro-environmental impacts and power output. Renew Energy [Internet]. Elsevier Ltd; 2012;44:318–27. Available from: http://dx.doi.org/10.1016/j.renene.2012.01.106
3. Funke SW, Farrell PE, Piggott MD. Tidal turbine array optimisation using the adjoint approach. Renew Energy [Internet]. Elsevier Ltd; 2014;63:658–73. Available from: http://dx.doi.org/10.1016/j.renene.2013.09.031
4. Jeffcoate P, Starzmann R, Elsaesser B, Scholl S, Bischoff S. Field measurements of a full scale tidal turbine. Int J Mar Energy [Internet]. Elsevier Ltd; 2015;12:3–20. Available from: http://dx.doi.org/10.1016/j.ijome.2015.04.002
5. Jeffcoate P, Whittaker T, Boake C, Elsaesser B. Field tests of multiple 1/10 scale tidal turbines in steady flows. Renew Energy [Internet]. Elsevier Ltd; 2016 Mar 1;87:240–52. Available from: https://www.engineeringvillage.com/share/document.url?mid=cpx_M42d74753150f88af84dM567b10178163171&database=cpx
6. Jeffcoate P, Cresswell N. Anchor Installation for the Taut Moored Tidal Platform PLAT-O - Anchor Installation with the aROV. AWTEC 2016;
7. Webb DDJ. Tides, Surges and mean sea-level. Mar Pet Geol [Internet]. 1988;5(3):301. Available from: http://linkinghub.elsevier.com/retrieve/pii/026481728890013X
8. Jeffcoate P, McDowell J. Performance of PLAT-I, a Floating Tidal Energy Platform for Inshore Applications. EWTEC 2017.
9. Afgan I, McNaughton J, Rolfo S, Apsley DD, Stallard T, Stansby P. Turbulent flow and loading on a tidal stream turbine by LES and RANS. Int J Heat Fluid Flow. 2013;43(October):96–108.
10. Driver R. Marine Energy Electrical Architecture. 2015;(September).
11. Pillai AC, Chick J, Johanning L, Khorasanchi M, de Laleu V. Offshore wind farm electrical cable layout optimization. Eng Optim [Internet]. 2015;273(December):1–20. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-84922374336&partnerID=tZOtx3y1
12. Department of Energy & Climate Change. Electricity Market Reform – Contract for Difference : Contract and Allocation Overview. 2013;(August):32. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/233004/EMR__Contract_for_Difference__Contract_and_Allocation_Overview_Final_28_August.pdf
13. Green J, Bowen A, Fingersh LJJ, Wan Y. Electrical collection and transmission systems for offshore wind power. 2007 Offshore Technol Conf [Internet]. 2007;(March):10. Available from: http://www.onepetro.org/mslib/servlet/onepetropreview?id=OTC-19090-MS
14. Anders GJ, Vainberg M, Horrocks DJ, Foty SM, Motlis J, Jarnicki J. Parameters Affecting Economic Selection Of Cable Sizes. IEEE Trans Power Deliv. 1993;8(4):1661–7.
15. Cespedes R. New method for the analysis of distribution networks. IEEE Trans Power Deliv. 1990;5(1):391–6.
16. Thompson J. Fall of Warness Berth 7 MetOcean & Physical Description Physical Description.
17. Aquatera. AquaTera ADCP Survey Hoy Sound June 2016. 2016;1:3–6.
18. Jenne DS, Yu Y, Neary V. Levelized Cost of Energy Analysis of Marine and Hydrokinetic Reference Models Preprint. 2015;(April).
19. Hannesson R. The Effect of the discount Rate on the Optimal Exploitation of Tenewable Resources. Mar Resour Econ. 1987;3(4):319–29.
20. McCombie P, Sullivan P. Optimisation of tidal power arrays using a genetic algorithm. Proc ICE - Energy [Internet]. 2013;166(1):19–28. Available from: http://www.icevirtuallibrary.com/content/article/10.1680/ener.12.00011