Investigation of low order parameters affecting tidal stream energy resource assessments

M. D. Patel, A. S. Smyth, A. Angeloudis, and T. A. A. Adcock

Abstract—**Tidal stream energy may have the potential to contribute to the baseline energy demands of the UK. There is a significant difference between the existing assessments of the UK's resource, highlighting the need for a standardised model. The paper investigates some challenges of quantifying tidal stream energy resource and examines low order parameters affecting the resource, to inform higher order modelling. A 0D channel model was implemented and blockage-corrected blade element momentum theory was used to represent turbines. Results indicate the maximum deviation from the average annual energy production over the 18.6-year nodal cycle is ±8.8%. At a low form factor site, the difference between using 2 or 4 constituents was insignificant. However, for a higher form factor site, that is still semi-diurnal, the peak velocity increases by 0.32 m/s with 8 constituents compared to 2. Random Forest modelling indicates the most important characteristic point on a variable-speed, variable-pitch turbine performance curve is the rated speed. Comparison of capping strategies highlights combined power and thrust capping leads to an increase in energy per swept area.**

Index Terms—**tidal stream energy, resource assessment**

I. Introduction

TIDAL stream energy may have the potential to meet a significant amount of the baseline energy demanded in the UK, if the economic, environmental and technical challenges and risks can be overcome. Tides are predictable and reliable, and multiple sites suitable for tidal stream energy extraction have been identified in the UK [1]. The Crown Estate has identified lease sites with the potential to be commercially sustainable for tidal stream energy development [2]. UK government funding and leasing of sites for tidal stream energy has driven the development and testing of turbine designs. The European Marine Energy Centre identifies 97 companies developing tidal devices of varying configurations across 16 countries [3].

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The extraction of tidal stream energy is limited by technical, practical, accessible and viable constraints. Whilst a number of UK resource assessments have been undertaken, assessments of the practical and technical resource range between 1.5-22.5 GW [1], [4]–[6].

Site-based resource assessments have been carried out across the UK using 2D and 3D models. The UK's most notable site for tidal stream energy is the Pentland Firth and assessments of the resource range between 1-17.7 GW [4], [7]–[12]. Other site-based resource assessments have been undertaken at Anglesey Skerries [13], Ramsey Sound [14], Orkney [15], Portland Bill [16], [17] and Strangford Lough [18], [19].

The variation in resource assessments is due to inconsistent methods, assumptions and consideration of constraints limiting the resource. This makes direct comparison between assessments and potential combination of site-based studies to assess the UK's overall resource untenable [1]. O'Rourke et al. [18] highlighted the need for revising resource assessments based on advances in the field, especially regarding technical and practical limitations on the resource.

The need for a verified, high order standardised model to assess the resource is clear. A number of models have been used but to ensure a robust and validated model, which is applicable to a wide range of sites, a thorough analysis of key parameters affecting the resource must be undertaken. Low order modelling can inform the development of a high order standardised model by identifying key parameters affecting a resource assessment and it is an ideal approach for building the foundations of analysis techniques.

Table I summarises studies that have adopted a low order channel model and the adaptations implemented in each. Actuator disc theory (ADT) and blockage-corrected blade element theory (BC-BEMT) have been used to model turbines. The number of constituents, consideration of support structures, capping strategies, wake deficits and velocity reduction as an environmental consideration in each study are presented. This study is the first to encompass all modelling parameters, as illustrated in Table I.

II. Model

A. Low order parameters

Low order parameters affecting resource assessments were identified from the literature. Parameters are categorised into site-based channel characteristics, array and turbine design, and simulation settings (Fig. 1).

TABLE I
CHANNEL MODEL ADAPTATIONS

Study	Turbine model	Constituents	Support structure	Power capping	Combined capping	Wakes	Velocity reduction
This study	BC-BEMT	8	✓	✓	✓	✓	✓
[20]	ADT	2	✓	✓	✓	✗	✗
[21]	BC-BEMT, ADT	2	✗	✗	✗	✗	✗
[22]	ADT	2+	✗	✗	✗	✗	✗
[23]	ADT	-	✓	✓	✗	✗	✓
[24]	ADT	-	✗	✗	✗	✗	✗

The parameters form the case scenarios modelled for assessing the importance of key parameters affecting the resource. Fig. 1 presents economic and power analysis metrics and links between parameters. Economic metrics are not considered in this study.

The geometry and dynamical balance of two channels, a shallow channel and a deep tidal strait, characterised by Vennell [24], were used as generic idealised channels for this study. The shallow channel is drag dominated and the tidal strait is inertia dominated [25]. The depth of the shallow channel was doubled (to 40 m) for this study to ensure the placement of turbine rotors and support structures complied with minimum blade tip to seabed and blade tip to sea surface clearances outlined in [26].

Form factor (FF) classifies tides based on the ratio of the diurnal (O_1 and K_1) and semi-diurnal (M_2 and S_2) constituents [27]. Sites across the UK are predominantly classified as semi-diurnal (0¡FF¡0.25), which means they are dominated by the M_2 and S_2 constituents and there are two high and low tides a day. Two locations spanning this range were chosen to investigate the effect of FF amongst semi-diurnal sites. The effect of the number of constituents included in the model was considered. Availability of amplitude and phase constituent data highly influenced the choice of sites. The variation of the resource, influenced by the 18.6-year nodal cycle, was studied.

Four blade geometry designs were considered; three designs optimised for a given blockage ratio, and one generic design (Fig. 1). Other design choices relating to turbines were cut-in, cut-out and rated speeds. These characterise the performance curve of a variable-speed variable-pitch (VSVP) operated turbine, which were defined following a standardised approach proposed by Lewis et al. [28]. Power capping and combined power and thrust capping strategies were adopted.

B. Channel model

The tidal dynamics of the channels used in this study were represented with a simple channel model proposed by Vennell [24], which is an extension of the model proposed by Garrett and Cummins [25]. The constricted tidal channel modelled joins two large bodies of water. The head difference between either end of the channel drives the current through it. It is assumed that the velocity does not vary along the length of the channel [24] and the tides either end of the channel are to be unaffected by the currents [25]. Additional simplifying assumptions of the model are that the channel has a rectangular cross-sectional area, A, which is uniform along the channel length, L, and turbines are arranged in a grid. It is assumed that downstream spacing between rows is sufficient for the flow in the near wake of the turbine, u_3, and the bypass flow, u_4, to fully mix and recover to the free stream velocity, u, before the next downstream row of turbines because $u_4 \geq u > u_3$.

The channel flow rate, Q, is found by solving (1),

$$\frac{1}{c}\frac{dQ}{dt} = g\eta - (\delta_0 + \delta_1 + \delta_2)Q|Q| \tag{1}$$

where $c = \frac{L}{A}$, g is acceleration due to gravity, t is time, η is head difference, and δ_0, δ_1 and δ_2 are drag parameters representing channel bed friction, turbine thrust and support structure thrust. The non-dimensional form of (1) is solved using the Runge Kutta 4$^{\text{th}}$ order method and initial conditions are calculated from the approximate analytic solution for velocity given in Appendix A3 in [24].

Vennell [24] uses the model to investigate optimal 'tuning', whereby the turbine through-flow is tuned due to the internal configuration of the array to maximise the farm's power output. In practice, tuning is done by pitching turbine blades or changing the tip speed ratio (TSR). Vennell [24] uses ADT to represent turbines, therefore assumptions about the design, specification or operation of the turbine are not considered. Results in Table 1 of [24] were reproduced to ensure the model had been implemented correctly in MATLAB.

C. Nodal cycle and constituents

Tidal power will vary across multiple different time-scales from seconds to decades. Many studies focus on the effect of the spring-neap cycle, however, a larger time-scale that needs to be considered is the nodal cycle. Due to the orbital path of the moon, the amplitudes and phases of harmonic tidal constituents vary over 18.6-years resulting in a small modulation in tides. Therefore, the 18.6-year nodal cycle contributes to a variation in the resource annually.

A study of the Alderney Race indicated the nodal cycle affected predictions of annual power density up to an order of ±10% [29]. This indicates it is critical to analyse and quantify the effect of the nodal cycle in a low order model to inform the potential annual variation in results in higher order models where it will be computationally exhaustive to investigate.

Nodal adjustments can be accounted for as a sum of harmonics. An example of the harmonic expansion for the S_2 constituent is given in (2),

$$a_{S_2} f_{S_2} \cos(\sigma_{S_2} t - g_{S_2} + (V_{S_2} + u_{S_2})) \tag{2}$$

where a_{S_2} is amplitude, f_{S_2} is nodal factor, σ_{S_2} is angular speed, g_{S_2} is phase lag at the time zone, u_{S_2} is nodal angle and V_{S_2} is equilibrium phase [27].

To calculate the head difference in (1), the difference between harmonic expansions for each constituent be-

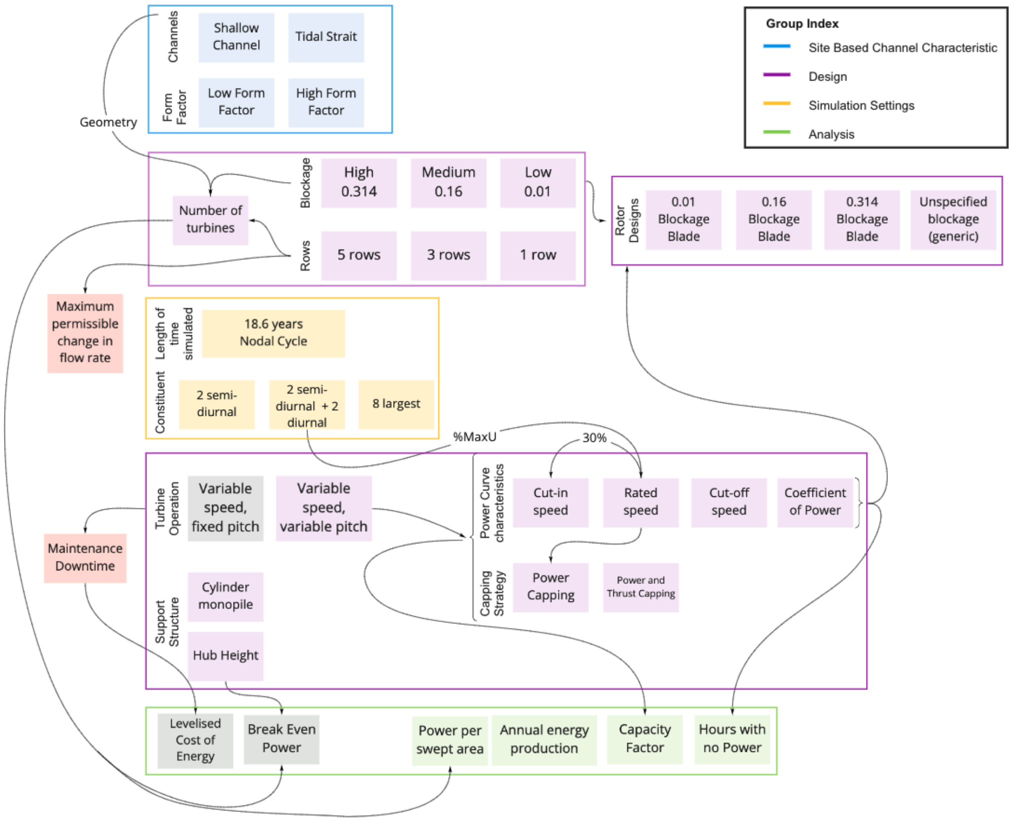

Fig. 1. Organogram of low order parameters and analysis metrics

tween two geographical points were taken at each location studied. Three constituent scenarios were modelled: 2 semi-diurnal constituents (M_2 and S_2), 2 semi-diurnal and 2 diurnal constituents (additional O_1 and K_1) and the 8 largest constituents (additional K_2, M_4, MU_2 and N_2). Admiralty Tide Tables [30] provide phase and amplitude data for M_2, S_2, O_1 and K_1 constituents at sites across the UK. However, published data for other constituents is more limited. The data for sites with higher FFs were from tidal gauges at Weymouth (FF=0.15) and Bournemouth (FF=0.22), presented in Table II [16]. The data for low FF sites were from tidal gauges in Coverack (FF=0.05) and Lizard Point (FF=0.06) and modelled with up to 4 constituents only, due to availability of data (Table III) [30]. Note that all sites are semi-diurnal, however, constituent data from Weymouth and Bournemouth are at the higher end of the semi-diurnal FF range, and Lizard Point and Coverack are at the lower end.

D. *Blockage-corrected blade element momentum theory*

ADT can be used to represent turbines as uniform discs, however, it is an oversimplification of real turbine behaviour and does not consider the design of blades. ADT overestimates the performance of a turbine. Therefore, it can only provide an upper bound value if used in a resource assessment [21]. To account for the design of blades and introduce a more realistic model of a turbine, BC-BEMT was implemented in this study. The traditional blade element momentum theory (BEMT) is an established method in the wind industry. It combines the linear momentum and blade element theories by equating axial thrust forces calculated in each theory. BEMT is underpinned by the assumptions that there is no radial interaction between each blade element and the change of momentum of the fluid passing through the swept annulus, created by the

TABLE II
AMPLITUDE AND PHASE CONSTITUENT DATA FOR WEYMOUTH AND BOURNEMOUTH [16]

Constituent	Weymouth Amplitude [m]	Weymouth Phase [°]	Bournemouth Amplitude [m]	Bournemouth Phase [°]
M2	0.591	190	0.408	373
S2	0.309	242	0.183	292
O1	0.048	350	0.041	348
K1	0.090	111	0.091	112
K2	0.086	238	0.05	291
M4	0.149	24	0.194	75
MU2	0.110	194	0.071	193
N2	0.133	183	0.105	247

TABLE III
AMPLITUDE AND PHASE CONSTITUENT DATA FOR LIZARD POINT AND COVERACK [30]

Constituent	Lizard Point Amplitude [m]	Lizard Point Phase [°]	Coverack Amplitude [m]	Coverack Phase [°]
M2	1.69	138	1.72	144
S2	0.55	186	0.57	192
O1	0.07	97	0.07	99
K1	0.06	328	0.05	336

element, is due to each element independently [21].

Vogel et al [31] extended BEMT to account for volume-flux constraints on the flow field in tidal scenarios, thus proposing BC-BEMT. In wind energy, it is assumed that static pressure fully recovers far downstream to upstream levels. However, the volume-flux constraints in tidal streams cause a streamwise static pressure difference due to the accelerated bypass flow. BC-BEMT equates the axial thrust calculated by the blade element and volume-flux constrained linear momentum theories to account for the pressure difference.

Fig. 2, adapted from [32], presents the calculation sequence for BC-BEMT to obtain the coefficients of power and thrust, C_P and C_T, used to characterise the performance of a turbine. Initial estimates for axial and tangential induction factors are set to $a_{2i} = 0.3$ and $a'_{2i} = 0.01$ to calculate the inflow angle. The relative twist angle and chord length are interpolated and the angle of attack is calculated to interpolate the coefficients of lift and drag. A tip loss correction is applied to account for the gaps between the finite number of blades, given by Glauert [33]. The sectional axial thrust for each element is calculated and the total axial thrust on the blade is obtained through integration. This gives an initial estimate for C_T which can be used to solve the quartic function for bypass wake induction factor, β_4, and the cubic function for wake induction factor, α_4. The axial and tangential induction factors are calculated and updated. Steps 1-4 of the flow chart, shown in Fig. 2, are repeated. The blade element forces and axial thrust and tangential torque equations are balanced and the axial and tangential induction factors are solved before recalculating the thrust coefficient and induction factors. The axial and tangential induction factors are recalculated and checked for convergence within a relative error of 10^{-6}. A relaxation parameter of 20% old value and 80% new value is implemented when updating the solution.

Once the solutions have fully converged, the total axial thrust and tangential torque on the blade can be used to calculate C_P and C_T. The model was verified by reproducing results in the Wind Energy Handbook [34] using the BEM code and comparing results when using BEM and BC-BEMT for a low blockage scenario, which showed good agreement.

Three rotors designed for blockages of 0.01, 0.16 and 0.314 by Cao et al. (low and medium) [35] and Schluntz and Willden (high) [36] were used and one designed for variable-speed operation and unspecified blockage, using the method outlined in Section 3.7 of the Wind Energy Handbook [34]. The hydrofoil used for all blades was the Risø-A1-24 [37], adapted lift/drag coefficient and angle of attack data in [21]. A 20 m diameter rotor was used for all designs.

E. Capping strategy

VSVP turbines cap power between the rated and cut-out speeds. Power capping can improve the capacity factor of a turbine despite the reduction in power overall [38]. Wang and Adcock [20] proposed a combined capping strategy to limit peak thrust and peak power,

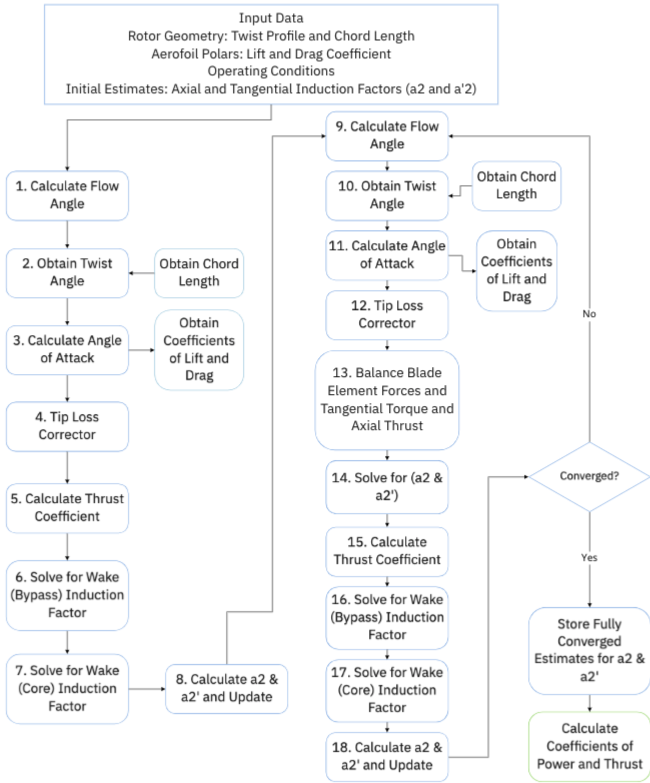

Fig. 2. Blockage-corrected blade element momentum theory calculation sequence, adapted from [32]

which can lead to a reduction in support structure diameter and lower thrust on the flow. They outline a method for converging the required support structure diameter based on a combined capping strategy.

The support structure thrust, F_S, is calculated by

$$F_S = \frac{1}{2}\rho C_{d,S} L_S D_S u^2, \tag{3}$$

where the drag coefficient of the support structure is $C_{d,S} = 1.2$, length of the support structure is $L_S = 15$ m and the initial estimate for diameter is $D_S = 3$ m [23].

Thrust was capped at 80% of uncapped peak thrust and power was capped at the rated power, determined by rated speed. Both capping strategies are investigated in the study but presence of the support structure is only considered in the combined capping cases.

F. Turbine performance curve

Due to the implementation of BC-BEMT, a performance curve is required to calculate the power output of turbines at different flow velocities. Only VSVP operated turbines were considered for simplicity because they are commonly used in practice. Fig. 3 presents performance curves of a VSVP turbine under the two capping strategies. The power capped performance curve (black, solid) is characterised by the cut-in speed, cut-out speed and rated speed. For the power and thrust capping performance curve (red, dashed), there is a region within which thrust is capped by pitching the turbine blades, generating less power at each velocity with respect to power capping. Once rated power is reached, the performance curve behaves in the same

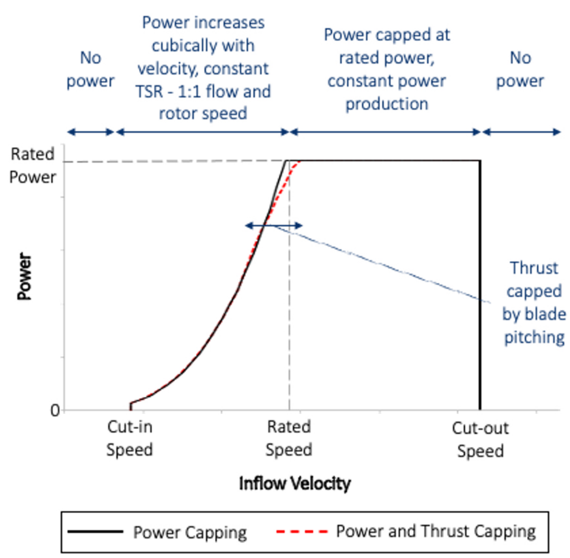

Fig. 3. Performance curve of a variable-speed, variable-pitch operated turbine with power capping (black, solid) and combined power and thrust capping (red, dashed)

way as the power capping strategy curve because the blades pitch to cap power rather than thrust [39].

The cut-in speed is chosen on the basis that the turbine should not operate at very low flow velocities because the turbine will turn slowly for long periods of time without producing much power whilst contributing to the wearing of turbine mechanisms, which is not economically beneficial. The cut-out speed is usually a protective strategy for the turbine. The rated speed is chosen to ensure an oversized generator is not required to accommodate peak velocities in the flow that will lead to spikes in power for a short period of time.

The cut-in, cut-out and rated speeds are usually defined by manufacturers. However, a study of 14 horizontal-axis tidal turbines provides a range of values to define a standardised performance curve proposing the cut-in and rated speeds as a percentage of the maximum flow velocity (% of MaxU) [28]. The study proposes the cut-in speed should be 30% of rated speed. The rated speed is defined as 46% of MaxU at the site-based on 4 constituents (M_2, S_2, O_1 and K_1). Rated speed is defined for a low intermittency scenario based on studies of European sites to enable more consistent power with fewer hours of no power.

G. Wakes

Turbulence and tip vortices create a wake region downstream of a turbine, which can be divided into near-wake and far-wake regions. If turbines are placed sufficiently downstream of upstream turbines, mixing of the flow in the wake of the upstream turbine and by-passing flow will occur and velocity will return to the uniform value upstream of the turbine. However, the space required for this assumption is not realistic for an actual array because tidal stream developments are constrained to areas defined and leased by The Crown Estate and areas of strong current. Myers et al. [40] highlight merging of wakes and increased velocity deficits of closely packed turbines pose a significant issue to developers who want to place turbines close together to maximise lease site areas. Consequently, if the velocity deficit in the wake of a turbine, which has not fully recovered before the next downstream row, is not considered when assessing the power produced by an array then the resource will be overestimated.

Stallard et al. [41] conducted an experimental study of wakes from a tidal rotor in shallow turbulent flow demonstrating the velocity deficit in the wake of an individual turbine becomes self-similar and 2D at 8 diameters or greater downstream. The study only considers a few rows of turbines and might not be accurate for large arrays. Stansby and Stallard [42] give (4)

$$\frac{\Delta U_{max}}{U_0} = -0.216 + 0.8639/\sqrt{x/D}, \tag{4}$$

to calculate centre-line velocity deficit, ΔU_{max}, from the upstream uniform velocity, U_0, for a turbine with diameter, D, at a specified downstream distance, x. The equation shows good agreement with results in [41] within 4 to 8 diameters downstream. Stansby and Stallard [42] proposed blockage correction factors to correct the velocity at each row of turbines and velocity deficits are superimposed to account for wake superposition.

Understanding the structure, expansion and recovery of wakes is important to ensure an accurate resource assessment. Wakes are dependent on turbulence intensity, alignment, blockage, row spacing and array layouts and their complexity is difficult to capture with the method presented by Stansby and Stallard [42]. They state studies of single turbines, in wind and tidal streams, indicate velocity deficit in the wake of a turbine is highly dependent on turbine thrust. Despite the drawbacks of the method it is necessary to consider wake effects on the flow velocity, and subsequently on power, in some way because they will have a significant impact on a resource assessment and it is a simple and effective method to implement at this stage.

III. Results and Discussion

In this study, two idealised channels, a shallow channel and tidal strait were modelled. For each channel geometry, the head difference was calculated with constituent data from four UK sites with FF=0.06 and 0.05 (low) and FF=0.22 and 0.15 (high) to span the semi-diurnal classification range. For the high FF cases, 2, 4 and 8 constituents were modelled and for the low FF cases, 2 and 4 constituents were modelled. Four rotor designs were simulated for each case: three designed for 0.01, 0.16 and 0.314 blockages and one designed for an unspecified blockage. Turbines were operated at the TSR corresponding to optimum C_P from BC-BEMT C_P vs TSR derived curves. Three blockage cases were defined based on the rotors designed for specific blockages. For each blockage, 1, 3 and 5 row arrays were simulated. The channel geometry, blockage and number of rows defined the number of turbines in each case. Power capping and combined power and thrust capping were implemented. The initial simulations were run without wake effects. Wake effects were accounted for by applying a factor and deficit to the

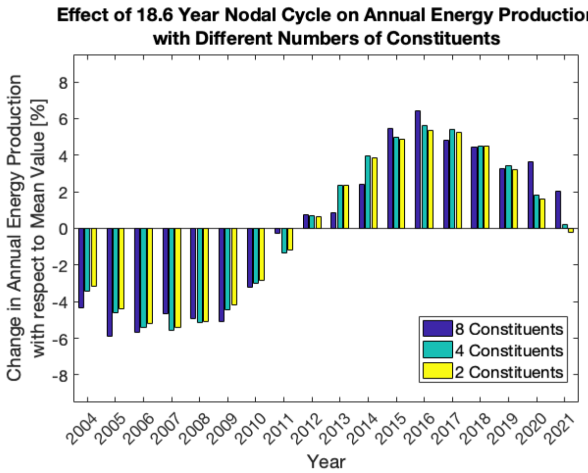

Fig. 4. Annual energy production over the nodal cycle with 2, 4 or 8 high form factor constituents for an array with 5 rows and 0.314 blockage in a shallow channel

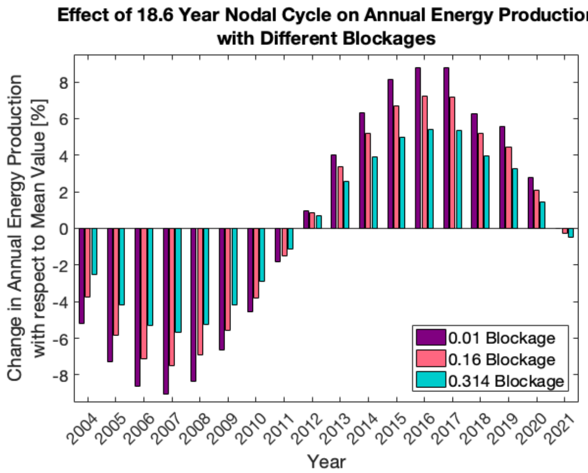

Fig. 5. Annual energy production over the nodal cycle for an array with 5 rows, 4 low form factor constituents with 0.01, 0.16 or 0.314 blockage and in a tidal strait

velocity onset to each row of turbines spaced 8 rows downstream for comparison. The objective is to study idealised channels, to determine which characteristics and operational parameters most impact the resource.

A. Nodal cycle, form factor and constituents

To investigate long-term variability of tidal stream energy due to the nodal cycle, the annual energy production (AEP) was calculated over 18.6 years. Fig. 4 presents the percentage change in AEP with respect to the mean over 18.6 years of a 5 row array, with 0.314 blockage in a shallow channel, modelled with 2, 4 and 8 high FF constituents. The maximum variation is up to 6.42% with 8 constituents and in 2005 the array produced 88% of the energy produced in 2016 (1.36 GWh/year difference). For the same case, but with 4 low FF constituents, the maximum variation from the mean is up to 6.26% in 2016. The maximum variation decreases with decreasing numbers of constituents because when multiple constituents are in phase there is a peak in velocity, and the maximum velocity is greater with 8 constituents than 2 constituents for high FF. Maximum variation decreases with decreasing numbers of turbines for high and low FF constituent data in the shallow channel, which is drag dominated so a smaller number of turbines relative to the friction in the channel is less significant to the flow and therefore power.

For a 5 row array, 0.314 blockage and 8 high FF constituents in a tidal strait, the change in AEP from the mean value over 18.6 years is less significant than the shallow channel case, with AEP 1.97% greater than the mean in 2016 and 2.39% less than the mean in 2005. However, for a blockage of 0.01 the maximum variation from the mean increases to 3.83%.

Fig. 5 presents the percentage change in AEP with respect to the mean for a 5 row array in a tidal strait, modelled with 4 low FF constituents. The figure highlights the decrease in variation with increasing blockage, as indicated by the high FF tidal strait results. AEP varies by up to 8.77% from the mean for 0.01 blockage but decreases to 5.41% for 0.314 blockage in the same year, 2016. For each blockage case in the tidal strait, the maximum percentage change from the mean AEP increases with fewer rows and therefore, fewer turbines. The dynamical balance of the tidal strait is inertia dominated, therefore it is likely adding more turbines (higher blockage and greater number of rows) will have a significant impact on the flow because there is less background friction in the channel compared to a drag dominated channel. The resistance from the turbines has a greater relative impact reducing the variation compared to a very low blockage case.

The results indicate assessing the resource in one particular year could lead to a significant overestimation or underestimation if the whole nodal cycle is not considered. The dynamical balance is shown to be an important parameter for indicating how the maximum variation from the mean increases or decreases with additional turbines. Understanding the trend over the 18.6-year cycle and recognising the years in which the resource deviates greatest from the mean (2005-2007 below, 2016-17 above) in a low order model can inform findings from higher order models to ensure they do not have to be run for the full nodal cycle.

The UK has predominantly semi-diurnal sites. Studying sites at each end of the semi-diurnal FF range indicates the importance of the number of constituents to model based on the effect on the resource. For high FF data, the number of constituents modelled has a more significant impact on the velocity than the low FF site. Peak velocity is up to 0.32 m/s and 0.19 m/s greater with 8 high FF constituents than with 2 constituents for the tidal strait and shallow channel across all arrays. However, the difference between 4 and 2 constituents is only up to 0.01 m/s. The high FF constituent data (Table II) indicates that whilst M_2 and S_2 constituents dominate, K_2, M_4, MU_2 and N_2 tides are also significant and there is a larger difference in amplitude and phase for constituents between the two high FF sites. The K_1 and O_1 constituents are smaller and there is very little amplitude or phase difference between the two sites, therefore the difference

TABLE IV
10% MAXIMUM PERMISSIBLE REDUCTION IN PEAK FLOW RATE FOR HIGH FORM FACTOR CONSTITUENTS (RED=EXCEEDED, GREEN=PERMISSIBLE)

10 % Permissible Change		Maximum Velocity [m/s]					
		Tidal Strait			Shallow Channel		
Blockage	Rows	2 constituents	2 constituents	2 constituents	2 constituents	2 constituents	2 constituents
0.01	1 Row	2.41	2.43	2.73	1.41	1.41	1.60
	3 Rows	2.40	2.42	2.72	1.39	1.39	1.58
	5 Rows	2.40	2.41	2.72	1.37	1.38	1.56
0.16	1 Row	2.33	2.35	2.65	1.26	1.26	1.43
	3 Rows	2.19	2.20	2.48	1.05	1.05	1.29
	5 Rows	2.07	2.08	2.35	0.92	0.93	1.05
0.314	1 Row	2.18	2.19	2.47	1.04	1.04	1.18
	3 Rows	1.87	1.88	2.13	1.04	1.04	1.18
	5 Rows	1.67	1.67	1.91	0.62	0.62	0.70

TABLE V
20% MAXIMUM PERMISSIBLE REDUCTION IN PEAK FLOW RATE FOR HIGH FORM FACTOR CONSTITUENTS (RED=EXCEEDED, GREEN=PERMISSIBLE)

20 % Permissible Change		Maximum Velocity [m/s]					
		Tidal Strait			Shallow Channel		
Blockage	Rows	2 constituents	2 constituents	2 constituents	2 constituents	2 constituents	2 constituents
0.01	1 Row	2.41	2.43	2.73	1.41	1.41	1.60
	3 Rows	2.40	2.42	2.72	1.39	1.39	1.58
	5 Rows	2.40	2.41	2.72	1.37	1.38	1.56
0.16	1 Row	2.33	2.35	2.65	1.26	1.26	1.43
	3 Rows	2.19	2.20	2.48	1.05	1.05	1.29
	5 Rows	2.07	2.08	2.35	0.92	0.93	1.05
0.314	1 Row	2.18	2.19	2.47	1.04	1.04	1.18
	3 Rows	1.87	1.88	2.13	1.04	1.04	1.18
	5 Rows	1.67	1.67	1.91	0.62	0.62	0.70

between the 2 and 4 constituent results do not vary as significantly for the high FF data. The peak velocity occurs when constituents are in phase and adding more constituents, with greater phase difference, leads to a greater difference in velocity.

The low FF sites (Table III) are dominated by M_2 and S_2 constituents. Therefore, the difference between peak velocity for 2 or 4 constituents is only 0.01 m/s because the K_1 and O_1 constituents are much smaller.

Modelling sites on the lower end of the semi-diurnal FF range with 2 additional diurnal constituents does not have a great impact on the resource assessment because they have a relatively small effect on velocity and subsequent power output. However, when modelling with higher FF data, additional constituents impact velocity, power output and variability over the nodal cycle. Constituents with greater amplitude and phase differences for calculating the head difference are critical for accurately representing the channel and should be included for an accurate resource assessment.

B. Maximum permissible change in velocity

Reduction of flow velocity from the peak velocity in the absence of an array can be constrained to reduce the environmental impact of tidal arrays. A study of the hydrodynamic impact on the morphology at Ramsey Sound indicated the reduction in velocity and subsequent reduction of bed shear stress, which is proportional to the square of velocity, leads to sediment accumulation and deposition up to 16 km away from the array [43]. Significant changes in sediment transport can make benthic habitats unfavourable for native species, leading to their burial or displacement.

The restriction of maximum permissible change in velocity will be a limiting factor on the accessible resource. Tables IV and V present the maximum velocities in cases with different blockages, rows, constituents (high FF) and channel geometries. Permissible reductions of 10% and 20% from the peak were considered and red cells indicate exceeded conditions.

For the tidal strait, the maximum permissible change is much less restrictive with 67% of proposed layouts not reducing the maximum velocity in the channel by more than 10% and 85% for 20% permissible change. Note the number of turbines in the 0.16 blockage, 5 row array is greater than 1 row at 0.314 blockage. Therefore, the former exceeds the 10% limit whereas the latter does not. For the shallow channel, more than 50% of the proposed arrays are not within the permissible change in flow rate restrictions. The tidal strait is inertia dominated, therefore the flow can withstand more turbines without affecting the peak velocity substantially, compared to the shallow channel which already has significant friction because it is drag dominated. Vennell [24] confirms the effect of 1 row in the shallow channel reduces flow velocity by 26% compared to a 5% reduction in the tidal strait with 0.25 blockage.

The feasibility of sites for both channels are similar with high or low FF data. For the shallow channel with low FF data, 78% and 67% of arrays are unfeasible for 10% and 20% permissible change, which is one case scenario extra for each. The feasibility of sites remains the same for the tidal strait.

Results show a maximum permissible change in velocity could significantly restrict array developments due to environmental impact, particularly for high blockage arrays. The lease site area will be a limiting factor in the number of rows in an array as well as restrictions on reduction of peak flow rate.

Development of low turbulence sites is more desirable for tidal energy because it reduces unsteady loads. Turbulence intensity is defined as the ratio between the root-mean-square of turbulent velocity fluctuations and the mean flow velocity, indicating how rapidly the flow velocity fluctuates. Typically, turbulence intensity in the boundary layer of a tidal stream (5 m from the seabed) is 12-13% streamwise and 7-8% transverse/vertically [44]. An increase in turbulence intensity can reduce the velocity deficit in the near wake region of a turbine and reduce the evolution of vortices in high turbulent intensity environments but can have a significant effect on the loading and performance of turbines [45]. Therefore, the impact of array deployments on turbulence intensity could be considered as a limiting factor on the size of arrays for environmental reasons and should be investigated in further work.

C. Rotor design

A generic rotor design was compared to the performance of blockage designed blades. For the highest blockage (0.314) the capacity factor increased by up to 44% in the tidal strait and 34% in the shallow channel, when using a blockage designed blade. At a low blockage (0.01) the percentage increase in capacity factor is much less significant with up to 3% increase in the tidal strait and up to 4% for the shallow channel.

Blockage designed rotors enable arrays to produce more power and have higher capacity factors under the same conditions. The increase in performance is significant in higher blockage scenarios because the percentage difference in the coefficient of power between the 0.314 blockage designed blade compared to the generic blade is 35%. For 0.01 blockage the coefficients of power have a percentage difference of 3%. Blockage is significant in tidal streams compared to wind, where flow is unconstrained. Therefore, designing blades for specific blockages in tidal stream energy is an advantage for harnessing the resource.

BC-BEMT allows the performance of rotor designs to be studied but it has limitations. The incorporation of Glauert's [33] tip correction does not account for all losses near the blade tip due to spanwise flows, and empirical corrections to the flow are dependent on blockage and rotor design. BC-BEMT cannot predict the performance of turbines in extreme operating conditions, high TSR and high and low pitch angles, because it does not consider stall delay, and propeller and turbulent wake states of turbines. However, BC-BEMT is a more realistic alternative to ADT, allowing turbine specifications and operation to be studied [21].

D. Performance curve characteristics

The use of BC-BEMT to model turbine performance introduced the need to define cut-in, cut-out and rated speeds. Investigating the effect of defining these points based on a standardised method [28] on the resource is important to justify use of the method going forward.

A Random Forest (RF) model was used to assess the importance of cut-in, cut-out and rated speeds, and the number of turbines on the AEP of an array. A RF model predicts outcomes based on a set of inputs and determines the importance of each input by measuring the error between the prediction and the true outcome once the inputs have been shuffled [46]. If the error increases after permutation this indicates the model relied on that input for its predictions, therefore it is important to the outcome and will have a higher importance estimate. The importance estimates have been normalised to range between 0 and 1, where 0 is the least important and 1 is the most.

To work well, the method requires continuous input data and a realistic range. The input range of performance curve characteristics were defined as percentages of the maximum velocity at the modelled sites, based on 4 constituents, following the standardised power curve method [28]. For Fig. 6, the range of each speed was kept the same size, 20%. The number of turbines as a predictor is not strictly a continuous dataset. However, the number of turbines is defined by the number of rows and blockage, giving a non-uniform and wide enough range to be compatible.

In Fig. 6, the number of turbines has the highest importance estimate, because the model heavily relies on this predictor to predict the AEP of the array. The indication that the number of turbines is an important parameter affecting the output of an array is realistic and provides confidence in the model.

Rated speed has the second highest importance estimate. It dictates the rated power of a turbine and changing it would have a large impact on the AEP of an array because it affects a wide range of velocities onset to the turbine and the subsequent power produced. The cut-in and cut-out speeds have relatively low importance estimates suggesting they are not important when predicting the AEP of an array.

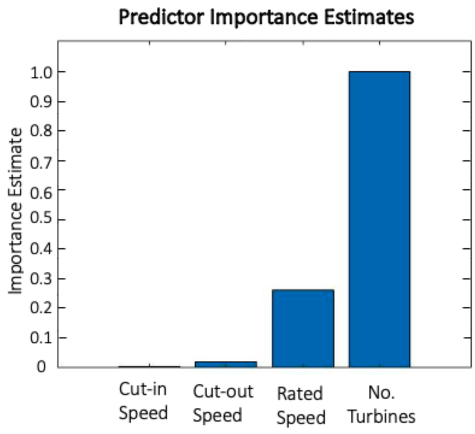

Fig. 6. Random Forest model importance estimates for cut-in speed (10-30% of MaxU), cut-out speed (65-85% of MaxU), rated speed (35-60% of MaxU) and number of turbines (1-50)

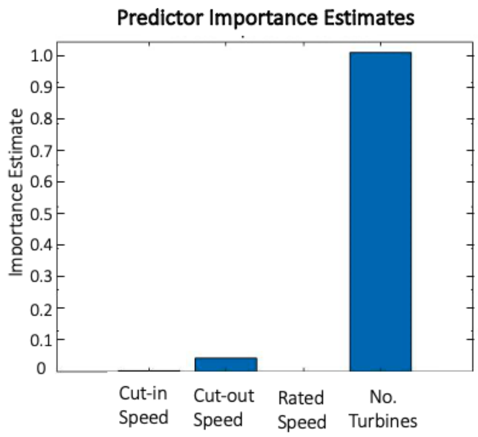

Fig. 7. Random Forest model importance estimates for cut-in speed (10-30% of MaxU), cut-out speed (65-85% of MaxU), rated speed (45-50% of MaxU) and number of turbines (1-50)

The same inputs were used to test the effect of range size on the results (Fig. 7). The ranges were maintained except for the rated speed, which was reduced to a 5% range. The reduced range for rated speed resulted in a significant reduction in the importance estimate, to almost zero. This is realistic because it is unlikely any choice of rated speed within a small range will change the overall array output at this scale. The range provided for rated speed for the case presented in Fig. 6 is a more reasonable choice for turbine specifications. Hence the indication that rated speed is the most important performance curve characteristic is valid.

To ensure observations predicted by the RF model were accurate, the correlation coefficient between the models predicted and actual outcomes was calculated, giving a 90% correlation. A regression method was used to determine the importance of the same inputs to compare with RF modelling. The order of importance estimates were in agreement for both methods.

The choice of cut-in and cut-out speeds do not significantly affect the resource. However, careful consideration of an appropriate rated speed should be taken. Lewis et al. provide multiple definitions of rated speed based on energy yield scenarios and sites [28].

E. Power capping and combined power and thrust capping

The average annual energy density per swept area for 1 row arrays, at all blockages, were within 0.01 MWh/m^2 for power capping and, power and thrust capping scenarios. With the exception of the tidal strait at 0.16 and 0.314 blockages, where the average annual energy density was 0.09 and 0.06 MWh/m^2 greater with the combined capping strategy. However, power capping cases do not include support structure drag. Therefore, with support structure drag, it is likely the average annual energy density of power capped cases will be lower than a combined capping strategy.

The peak thrust from turbines only occurs over small time periods. It is beneficial to cap thrust because the support structure must withstand the maximum thrust the turbine will endure. Thrust capping only has a detrimental effect on power output over a small range of velocities, where the combined capping curve deviates from the power capping curve (Fig. 3). Thrust capping enables optimisation of support structure diameter, which allows savings in material costs [20]. However, the capping strategy does not consider the effect of yawing to align the turbine with the flow and fluctuations in turbulent velocity. The effects of turbulence intensity could increase the peak thrust, which requires blade pitching to cap, therefore, the performance of the turbine whilst thrust capping will be affected. The model does not consider a sheared velocity profile and the effect of loading on the support structure. This needs to be investigated in a higher order model because a uniform velocity profile is inaccurate.

Results in Fig. 4 and 5 include power capping. Capping reduces variability across the nodal cycle because power is capped over short time periods when velocity peaks due to constituents being in phase. Without power capping the variation across the nodal cycle would be greater. Therefore, power capping is an effective strategy for ensuring the size of an energy storage system is appropriate for Spring-Neap variability and longer term variability due to the nodal cycle. In cases with high variability across the nodal cycle, combined capping reduced the maximum variation from the mean. Converging the support structure diameter by capping thrust limits the reduction of flow velocity, therefore the deviation from the mean is smaller.

F. Wake effects and velocity deficits

The inclusion of wake effects as a velocity deficit to downstream rows decreases capacity factor and energy per swept area of multi-row arrays. The change in average annual energy per swept area for 1 and 5 row arrays decreases by 5% without wakes and 28% with wakes, for a high FF tidal strait scenario at 0.314 blockage. In the shallow channel, the change in energy per swept area for 1 and 5 row arrays is 52% (without wakes) and 64% (with wakes). The change in annual energy per swept area for 1 to 5 rows decreases as blockage decreases. This highlights that additional rows in the drag dominated shallow channel has a significant impact on the resource and the inclusion of wake effects enhances this.

Stansby and Stallard [42] compared the blockage correction and velocity deficit superposition method with experimental results from [41] and found root mean square errors in the velocity deficit up to 0.0682. Turbulent length scales and wake interactions are complex, and whilst the method proposed gives an initial insight into the effect of wakes in a low order model, further investigation will be necessary to more accurately capture the effects in higher order modelling.

IV. Conclusion

The study indicates dynamical balance is a key parameter affecting tidal dynamics when turbines are present in a channel and therefore key to resource assessments. The influence of the nodal cycle on the variability of AEP was found to be most significant in a drag dominated channel with increasing blockage, but in an inertia dominated channel the variation from the mean decreased with increasing blockage. Accurately characterising the dynamical balance of a site will be key when transitioning from idealised channels to real sites. Constraints on the maximum permissible reduction in peak flow velocity are more limiting for a drag dominated channel and indicate high blockage arrays are likely to be unfeasible under such restrictions, which should be carefully considered in array designs. Using turbines optimised for a given blockage results in substantial increase in energy yield, compared to using generic turbines, especially at high blockages. Despite UK sites being characterised as semi-diurnal, the FF within the semi-diurnal range has an effect on the number of constituents that should be modelled. For the calculation of head difference, it is important to consider the amplitude and phase difference of each constituent at the two locations chosen to characterise the site. When constituents have large amplitude or phase differences they have a impact on the variability of the resource across the nodal cycle. Modelling with limited constituents, particularly for high FF sites, leads to an inaccurate model of tidal dynamics as constituents move in and out of phase. This highlights the need to distinguish between semi-diurnal sites and the number of constituents required for modelling.

The specification of turbines is vital to harness the optimum resource, and rated speed is the most important performance curve characteristic. The use of an RF model provided confidence in the standardised performance curve method because it gives sufficient consideration for rated speed [28]. Combined power and thrust capping is a beneficial strategy, not only for savings in support structure and foundation material costs, but it also increases energy per swept area compared to power capping alone. Combined capping decreases the variability across the nodal cycle, which is helpful to maintain a steady supply to the grid and for sizing an energy storage system. An initial investigation of velocity deficit on multiple row arrays indicated that change in energy per swept area from 1 to 5 rows is significantly increased when accounting for wakes. However, a more detailed study on turbulence and wake effects will need to be undertaken in a higher order model, to ensure a more accurate evaluation of wake effect on the resource.

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