Tidal current turbine power capture and impact in an idealised channel simulation

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Abstract—An idealised tidally-forced flat-bottomed channel with a symmetric headland is modelled in ROMS with and without simulated turbines. The simulation is intended to examine a common geometry to many areas of interest for tidal energy development around the world. The turbine model is implemented in ROMS with terms in the momentum equations as well in the turbulence parameterisation. This model allows for a detailed investigation of turbine impacts due to its parameterisation of several physical effects of turbines on a flow field and, additionally, can be implemented at a specific location in the water column. Several methodologies for accurately calculating the power capture from two turbine array layouts are compared. A methodology which allows for accounting over the whole system leads to a more realistic result. Additionally, the impact of the turbines on the system is assessed hydrographically. Coherent structures found in the speed, vorticity, and turbulent kinetic energy are disrupted near the headland tip due to the presence of turbines, leading to a weakened system downstream. The path of a large lee headland eddy is slightly altered, and all effects have potentially significant impacts for a real system.

Index Terms—tidal energy, turbine model, ROMS, tidal current turbine, headland

I. INTRODUCTION

Tidal current turbines are currently being considered as a potential green, renewable source of energy for several areas world-wide. Many areas of research contribute to the understanding necessary for development of tidal energy. The focus of this work is to connect ocean and turbine modelling in order to better understand the effects of turbines on a realistic, though idealised, flow field.

Several groups are examining the existing flow fields in areas of interest for tidal current turbine (TCT) development using a numerical modeling approach [1]–[3]. This site characterisation typically seeks to assess the potential power available to hydrokinetic turbines and to understand flow features that are pertinent to the extractability of the available power. However, it is also well-known that the presence of turbines alters the flow fields, with implications both for the environment [4]–[7] and for power production. For example, given enough turbines, several studies have found a reduction in tidal range landward of the turbine array and an increase in tidal range seaward [6], [7]. From the power production perspective, adding turbines to a system is coupled with the effects on the system, making a numerical model with a turbine model all but necessary to understand the interplay between the systems. As such, some oceanographic models seek to understand the effects of turbines on the system.

Garrett and Cummins developed a one-dimensional time-averaged model based on flow conservation where the presence of the turbine array is simulated through a power-law term corresponding to the drag force associated with the turbines [8]. This simplistic approach gives a good preliminary assessment of the upper bound on the available power of constricted flows but excludes numerous factors which turn out to be significant for realistic power assessment [8]. A number of studies improved this approach by simulating the hydrodynamic turbine effect on the flow via an increased quadratic bottom shear stress [9]–[12]. In such an approach, instead of searching for the maximum extractable power, the extracted power is assumed equal to 10% of the total available and accordingly dissipated as additional bottom shear stress. It should be highlighted that the previous models have been built on very restrictive assumptions.

The natural progression is to extend the scope of resolution of numerical models to a second dimension. The first intuitive method for assessing tidal resources is to simulate a site and apply a tidal resource assessment on the model output without incorporating any TCT effects into the computation [13]–[15]. Unfortunately, since the volume flux dynamics are essential to properly estimate the potentially extractable energy [16], ignoring the device effects when assessing the tidal resource from the natural flow can lead to significant discrepancies in realistic cases [7]. Accordingly, a quadratic force was injected in the right-hand side of the momentum balance in several studies [17]–[19]. This formulation of the turbine-induced force on the flow is also referred to as the actuator disc theory.

Since 2D models are depth-integrated, this new force is uniform over the water column. Furthermore, its physical meaning can be equally regarded as a drag force [17] or an additional shear stress [18], [19]. As a consequence, although this type of representation allows a better understanding from a horizontal point of view, the vertical flow behaviours such as the relation between water column height and corresponding drag coefficient [16], vertical flow bypassing of the device or distinction between bottom friction and energy extraction [20] are misrepresented and also poorly estimated. Another induced hydrodynamic effect of turbines which cannot be neglected in a large-scale turbine-farm yield-assessment is the induced
wake [7], [13], [21].

Thanks to rapidly increasing computer-power development, accurately understanding wake behaviours at a fine-scale implies a use of numerical models. These models allow for the solving of the complete Navier-Stokes equations at fine enough resolution to accurately simulate the local flow conditions. However, in the scope of large-scale array deployment and regional scale simulations, this approach carries one main issue: the prohibitively high requirements of computational time. As a consequence, a 3D model based on relevant regional-scale hydrodynamic assumptions appears to be the most promising alternative in developing a tool to treat the power and impact assessment of large-scale TCT array deployment in realistic environments. This is the approach followed in this work.

While potential tidal energy sites are varied in geometry, some common features can be found, allowing idealised numerical domains to be relevant for site characterisation in other areas. In one study, Admiralty Inlet in Puget Sound, WA, is modelled for site characterisation, with an emphasis on a headland in the system, Admiralty Head, as a dominant geometric feature on the flow [1]. A study of Admiralty Head, idealised as tidal flow past a prominent headland, was examined previously from the perspective of tidal power and provided energy metrics [3]. Prominent headlands and islands are found to dominate the flow in other areas of interest for tidal energy development as well. The Pentland Firth in Scotland is being investigated for TCT placement, leading to a need for research to understand the flow dynamics in the area [2], in particular, in relation to vortex-generation due to islands in the channel [22]. Recirculation areas due to vorticity detaching from headlands are found in Minas Passage, in the Bay of Fundy [23]. Additionally, an Ocean Renewable Power Company (ORPC) development in Cook Inlet is near a headland [24]. Furthering the understanding of the effect of turbines on flow features and site characterisation near a headland will aid in turbine placement in many regions throughout the world.

The methodology for this study is explained in Section II, with the turbine model introduced in Section II-A and the domain and system setup in Section II-B. The differing effects of two different array layouts are examined in Section III. Several approaches for calculating the power capture by the turbines are examined then applied to the simulation output. The effect of the turbines is examined from the perspective of impact on the flow field in Section IV. Included in the results and analysis is how the character of important flow features change in time due to the presence of the turbines, as well as the overall effects to the system. Conclusions and future work are described in Section V.

II. METHODOLOGY

A. Numerical Model and Turbine Representation

To ensure the sustainability of commercial-scale TCT projects, a balance between power extraction maximisation and impact minimisation must be found so that device layout optimisation can take into account environmental considerations. The difficulty of this problem lies in the fact that the length scales required to fully understand viscous flow dynamics over a rotating turbine are much smaller than the length scales required to fully understand the potential impacts which might be generated by arrays of turbines at realistic tidal sites [25]. Therefore, large-scale ocean circulation models appear to be the best suited for such investigation. Nonetheless, it has been shown that nonlinear sub-grid scale effects linked to turbine-induced turbulence may have non-negligible impacts on a large scale [1], [5], [26]. As TCT layout decision-making requires both accurate impact and resource assessments, it seems clear that the best approach is to inject a three-dimensional TCT representation coupled with a sub-grid scale effect parameterisation into an ocean circulation model in order to address many involved issues.

Such requirements have been met through the adaptation of an existing ocean circulation model framework, Regional Ocean Modelling System (ROMS), by including a TCT representation module [27]. ROMS is a 3D, split-explicit, free-surface, terrain-following, hydrostatic primitive equation oceanic model and has been widely used for a wide range of studies. The TCT representation method used is an innovative method treating each individual device as a 3D object and accounting for the momentum capture as well as the sub-grid scale turbulence balance perturbations caused by discrete TCT devices on flow hydrodynamics [28].

The turbine is modeled in ROMS by adding a force term to the momentum equations, representing the turbine in a grid cell. The form of this term is

$$E = -\frac{1}{2} \rho A_d C U_d^2,$$

where $\rho$ is the fluid density, $A_d$ is the rotor-disc area of the turbine, $U_d$ is the flow velocity passing through the turbine grid cells, and $C$ is a function of the coefficient, $C_t$ [28]:

$$C = \frac{1 - \sqrt{1 - C_t}}{1 + \sqrt{1 - C_t}}.$$

Additionally, a term is added to each of the two $k$, $\omega$ turbulence closure scheme equations to simulate reduced turbulence length scales ($P_k$) and additional production of wake turbulence due to the turbine’s presence ($P_\omega$). The equations are as follows

$$\frac{Dk}{Dt} = \frac{\partial}{\partial z} \left( \frac{K_M}{\sigma_k} \frac{\partial k}{\partial z} \right) + P_s + P_B - \varepsilon + P_k$$

$$\frac{D\omega}{Dt} = \frac{\partial}{\partial z} \left( \frac{K_M}{\sigma_\omega} \frac{\partial \omega}{\partial z} \right) + \frac{\omega}{k} (c_1 P_s + c_2 P_B - c_3 \varepsilon F_{wall} + P_\omega),$$

where $D/Dt$ represents the material derivative, $k$ is the turbulent kinetic energy, $K_M$ is the vertical eddy viscosity, $P_s$ is the shear production, $P_B$ is the buoyancy production, $\varepsilon$ is the turbulent dissipation rate, $\omega$ is the turbulent frequency, and $F_{wall}$ is a wall function. Constants have the following values: $c_1 = 0.555$, $c_2 = 0.833$, $c_3 = -0.6$, $\sigma_k = 2.0$, and
using the Chapman \cite{29} and Flather \cite{30} boundary condition. A semi-diurnal East) and two closed no-slip (north and south) boundaries. with 20 vertical layers. 30 meters in the x-direction and 10 meters in the y-direction requires one grid cell in thickness and three grid cells across over 2 km into the channel (Figure 1). Since the turbine model has been shown to be the most significant hydrodynamic element of the headland to be reached. The vortex propagation has been idealised case permits the effects due to the headland. This simplified headland domain with overlaid magnified views of the regular (left) and staggered (right) array layout. Green dots represent the TCT location. After \cite{3}.

\[ \sigma_\omega = 2.0. \] The added terms to represent the turbine are given by

\[ P_k = C_p \frac{U_d^3}{\Delta x} - C_d \frac{U_d k}{\Delta x} \]

\[ P_\omega = C_\omega \frac{P^2}{\Delta x} \]

where \( \Delta x \) is the grid spacing of the porous disc, and parameters \( C_p, C_d, \) and \( C_\omega \) are functions of the grid spacing and the turbine blade chord length and pitch angle. See \cite{28} for further details.

On the basis of grid and time resolution tests, this power/impact assessment tool has been shown to be convergent and stable. The ability of the method to adequately reproduce features of the turbine wake, wake recovery, and wake interactions for TCTs of various thrust coefficients has been validated against laboratory experiments involving standalone porous disc set-ups. In the absence of in-situ data, the scale applicability of the proposed model has been tested against analytical benchmarks and theoretical predictions. The detailed validation of this model can be found in \cite{28}.

**B. Simulation Features**

In this study, Admiralty Inlet has been represented as a symmetric headland with a flat-bottomed rectangular channel. This idealised case permits the effects due to the headland to be isolated from the effects of complex bathymetry and thus a better understanding of the interaction between the TCT farm and the vortices and other features occurring at the tip of the headland to be reached. The vortex propagation has been shown to be the most significant hydrodynamic element of this tidal flow \cite{1}, \cite{25}. The headland model domain has a length of 40 km, a width of 7 km, and a 100 meter deep flat bathymetry. The headland is symmetric and extends just over 2 km into the channel (Figure 1). Since the turbine model requires one grid cell in thickness and three grid cells across \cite{28} and knowing that each simulated turbine has a diameter of 3 meters, the resolution employed for these simulations is 30 meters in the x-direction and 10 meters in the y-direction with 20 vertical layers.

The numerical channel domain has two open (west and east) and two closed no-slip (north and south) boundaries. A semi-diurnal \( M_2 \) tide is applied on both open boundaries using the Chapman \cite{29} and Flather \cite{30} boundary condition types and outward-moving baroclinic momentum is radiated out of the system. The phase difference between the open boundaries is approximated using the shallow water wave speed \cite{1}. A linear density profile (from 1023 kg.m\(^{-3}\) at the surface to 1025 kg.m\(^{-3}\) at the bottom, giving a buoyancy frequency of \( N=0.01 \text{ s}^{-1} \) is initially in place and is forced at the open boundary. The bottom roughness is parameterised by the ROMS quadratic bottom friction expression, whose dimensionless friction parameter is \( C_D = 3 \times 10^{-3} \). The Coriolis force is included and the \( k-\omega \) turbulence closure scheme is used \cite{31}. The model was run for two tidal cycles for each case. The first tidal cycle is considered ramp-up and the second tidal cycle is considered as suitable for analysis as the ebb and flood flows are almost symmetrical. Simulation outputs were recorded every 15 minutes.

Two turbine array layouts were studied, both composed of 10 turbines (Figure 1). The turbines have a 30 diameter rotor (which is on the large side but leads to a realistic blockage ratio), a thrust coefficient \( C_t = 0.86, \) and run bidirectionally. The turbine model rotor axis is aligned east-west and cannot yaw. The fact that the turbines cannot yaw in a flow region where the bidirectionality can be an important factor means that the power capture will not be optimum. The fixed orientation of the device, however, is inherent at this stage of the numerical platform development and will be improved in the next stage of its development. In most real cases, turbine rotors would be placed outside of the surface and bottom layers in order to avoid as much shear and wave strain as possible, reducing additional loading and fatigue on the turbine structures and blades to increase the device life time \cite{32}. In the present case, due to the high blockage ratio (i.e., Rotor Diameter/Water column height=1/3), the turbine hubs have been situated at mid-depth or 50 meters deep. The first layout is referred to as "regular" and the second layout is referred to as "staggered". Here the array layouts have been chosen a priori and without performing row-by-row simulations and therefore without considering the potential flow accelerations or turbulence intensity increases which could be induced by the wake interactions within the farm. The distances between each device within the farm have been chosen to maintain a minimum spacing of 6 rotor-diameters between them (in both \( x \) and \( y \) so that none of the turbines are placed in the near-wake of an upstream device. The arrays were placed near the headland tip in order to access the most energetic area in the domain. It is worth noting that, although the blockage effect is not negligible, \( C_t \) corresponds to the thrust coefficient in an unconstrained flow. This is due to the fact that, in the present method, the blockage effects are not accounted for through an empirically increased \( C_t \) but through the set of momentum and turbulence source terms.

**III. ARRAY LAYOUT EFFECT ON POWER CAPTURE**

**A. Power Assessment Methodology**

The power of a TCT is calculated as follows:

\[ \text{Power} = \frac{1}{2} \rho C_p A_d U^3 \text{ [Watt]}, \]
where $C_p$ is the power coefficient. However, within an array of devices, $U$ is impacted by the devices deployed upstream, affecting the power calculation. For that purpose, two new approaches are considered to assess the power capture of the different TCT farm layouts in the present document. Firstly, the power captured by a TCT deployed in a flow can be defined as the flow rate through the disc multiplied by the pressure drop across the disc [33]:

$$\text{Power Capture} = A_d U_d (p_d^\infty - p_d) \text{ [Watt].}$$ (1)

Although Equation 1 does not account for any mechanical loss nor device yield, it should theoretically give a direct and accurate estimate of the power extracted by a TCT. According to momentum theory, the expression of thrust force [34] and the definition of the induction factor (i.e., $a = (U_\infty - U_d)/U_\infty$), the pressure drop across the disc can be expressed as follows:

$$(p_d^\infty - p_d) = 2 \rho U_d (U_\infty - U_d).$$

Consequently, the power capture (Equation 1) can be rewritten as follows:

$$\text{Power Capture} = 2 \rho A_d U_d^2 (U_\infty - U_d).$$ (2)

This formulation of the power capture is useful in this work since, contrary to most existing methods for TCT representation, the present method gives a direct estimate of the flow velocity passing through the rotor disc. $U_d, U_\infty$ is often defined as the unperturbed flow velocity and the flow velocity far upstream of a given device which, in the case of a standalone device system, amounts to the same thing. In a multi-device system, defining $U_\infty$ turns out to be more complex. It is worth noting that the turbine $C_t$ and $C_p$ values were kept constant, regardless of the upstream flow velocity. The latter assumption implies some sort of artificial control at the blade level, however, this simplification was necessary in order to isolate the effects of turbine placement.

Yet, the present simulations are subjected to time varying forcing. Therefore, the following adaptation of Equation 2 must be made to obtain the power captured by each turbine within the farm:

$$\text{Mean power} = \frac{1}{T} \sum_{t}^{n} 2 \rho A_d U_d^2 (U_\infty - U_{d_{\text{sim}}}) \times \Delta t,$$

where $T$ is a full tidal cycle (43200 seconds), $\Delta t$ the time step between each output (900 seconds), $n = 50$ and corresponds the time-step index, $U_\infty$ the $u$-velocity component of the unperturbed flow simulations at the appropriate disc location and $U_{d_{\text{sim}}}$ is the $u$-velocity component from the simulations including the turbine at the same disc location for a given time index. By extension, in the case of a 10 device farm, the overall power capture of the farm is determined by the following formula:

$$\text{Power of the farm} = \frac{1}{T} \sum_{N}^{10} \sum_{t}^{n} 2 \rho A_d U_d^2 (U_{\infty_{N,t}} - U_{d_{\text{sim}}}) \times \Delta t.$$ (3)

Here $N$ is the index related to each turbine composing the farm, $U_{\infty,N}$ the $u$-velocity component of the unperturbed flow right at the disc location of the $N$th turbine and $U_{d_{N,t}}$, is the $u$-velocity component right at the disc location of the $N$th turbine for a given time index $t$.

A second approach based on simple energetic considerations is also performed. The base statement is that the power available for the devices equals the amount of kinetic energy present in the flow without devices over a tidal cycle period:

$$\text{Available Power} = \sum_{t}^{n} \frac{1}{2} \rho ||\mathbf{v}_{\infty,i,j,k}||^2 \times \Delta V_{i,j,k} \times \Delta t,$$

where $i, j, k$ correspond respectively to the numerical index along the $x, y, z$ directions, $||\mathbf{v}_{\infty,i,j,k}||$ is the unperturbed flow velocity norm and $\Delta V_{i,j,k}$ represents the control volume of the $(i,j,k)$th cell composing the numerical mesh. In the same manner, by computing the amount of kinetic energy present in the flow with devices over a tidal cycle period, one can estimate the remaining power of the so-exploited tidal flow:

$$\text{Remaining Power} = \sum_{t}^{n} \frac{1}{2} \rho ||\mathbf{v}_{\text{t,i,j,k}}||^2 \times \Delta V_{i,j,k} \times \Delta t,$$

where $||\mathbf{v}_{\text{t,i,j,k}}||$ is the flow velocity norm of the studied case. Therefore the amount of power dissipated by the present of the TCT farm can be assessed through the following expression:

$$\text{Power Capture} = \text{Available Power} \quad \text{— Remaining Power.}(4)$$

These local (Equation 3) and global (Equation 4) approaches permit a complementary investigation of the power extraction induced by the two-considered TCT farm layouts on the tidal system.

$\textbf{B. Results}$

For most of the tidal cycle, except near slack tide, the devices’ wakes are overlapping in the case of the staggered layout. The velocity deficit, $U_{\text{def}} = U_{\infty}(1 - a)$, demonstrates this and is shown in Figure 2. Oppositely, in the case of the regular layout, the device wakes surge into the device inter-space without overlapping over the next row. This counter-intuitive feature is due to the headland geometry, which aligns the staggered array turbines as the flow moves parallel to the headland. In this regard, the regular layout appears regular from an east-west direction consideration but appears as staggered from a wake consideration, and vice versa for the staggered array layout. This observation tends to suggest that the regular layout farm should extract more energy out of the tidal flow than the staggered layout farm. Interestingly, the local approach for power extraction finds that the energy extraction difference between the layouts is negligible, whereas the global approach for power extraction (Equation 4) confirms the hypothesis. Indeed, by applying the local approach for power extraction over a full tidal cycle, the regular layout farm extracts 6.008 MW while the staggered layout farm extracts 6.051 MW. However, considering the energy budget over the entire domain and over a full
tidal cycle by using the global power capture approach, the power extraction assessment for the regular layout farm equals 7.5348 MW and for the staggered layout farm is 6.1845 MW. Consequently, the global approach reveals a 18% difference in terms of power capture between the two farm layouts and thus confirms the hypothesis made on the wake over-lapping observations. The local approach seems to exclude potential flow acceleration within the farm and thus underestimates the real power extraction.

The turbulence intensity, \( I = \sqrt{2/3k/U} \), is shown in Figure 3. The overall farm-induced turbulence does not differ much between the layouts either in magnitude or spatial spreading. In addition, by performing a TKE budget over the entire domain for the two layout cases (Equation 5) and subtracting them, the difference in TKE is a thousand times smaller, and therefore negligible, than the difference in power extraction between the two cases. The TKE budget is

\[
\text{TKE Budget} = \sum_{i,j,k}^{n} \rho \times k_{i,j,k} \times \Delta V_{i,j,k} \times \Delta t, \quad (5)
\]

where \( k \) is the turbulent kinetic energy. Consequently, we can approximate that all of the 18% of power extraction difference between the two farm layouts is due to actual power capture improvement rather than an increase in turbulent dissipation. Additionally, Figure 3 shows that, for the staggered layout, the turbulence intensities are higher in front of the turbines located in the farms wake than they are for the regular layout. Accordingly, one could expect more turbulence-related loading on the turbine blades and structures for the staggered layout than for the regular layout.

To conclude, although a priori staggered layouts tend to be more adequate for tidal flows in straight channels, the previous section showed that the optimum farm layout cannot be found on a-priori considerations but solely by accounting for site-specificities, namely channel geometry and farm-induced turbulence in this case.

C. Analysis

Based on the previous simulation results, a rule of thumb for assessing the power capture might be worked out. Knowing the power capture of the entire farm thanks to the global approach (Equation 4), one could postulate that this quantity can be expressed as a function of the velocities taken at a similar distance upstream of each turbine composing the farm:

\[
\text{Farm power capture} = \frac{1}{T} \sum_{i}^{10} \sum_{t}^{N} \sum_{i,j,k}^{n} \frac{1}{2} \rho A_d U_{ud,i,j,k}^3 \times \Delta t, \quad (6)
\]

where \( U_{ud} \) is the velocity at some particular upstream distance. If such rule of thumb exists and could be applied to any kind of array layout, the power capture assessment would be heavily simplified. In order to find the upstream distance, velocities at different distance upstream of each device constituting the regular layout farm were recorded over a full tidal cycle. These velocities were then used in Equation 6. The power extraction estimations obtained were normalised by the power extraction estimation obtained via the global approach (7.5348 MW), and are shown plotted against the distance upstream of the devices in Figure 4.

In Figure 4, the dashed line, representing proper representation of the normalised power capture, meets the solid line, representing the estimated power capture obtained via Equation 6, at 2 diameters upstream of the device. One could therefore postulate that by applying the velocities at 2 diameters upstream of each device to Equation 6, an accurate estimation of the real power capture could be obtained. To validate this hypothesis, we apply this calculation to the staggered layout case and compare this power capture estimation to the estimation obtained thanks to the global approach (Equation 4) for the same case. Unfortunately, by doing so, the power capture estimation is 26% lower than the estimation obtained via the global approach for the staggered layout case. This observation tends to show that, as the optimum farm layout, precise power capture assessments of TCT arrays cannot be made on a priori considerations but solely by accounting for site flow-specificities.

IV. ARRAY HYDRODYNAMIC IMPACTS

A. Results

This section focuses on the unaltered initial case with no turbines, and the regular array layout. The staggered turbine array layout generally affects the flow field less than the regular turbine array. This is probably due to the fact that with the angle of the flow past the tip of the headland, the staggered array layout causes the turbine wakes to align, having less effect on the flow field, whereas in the regular layout, the wakes are staggered. The staggered array can be assumed to have an effect on the flow field that is less extreme than the regular array.

The results are discussed in terms of changes to significant flow features, both in time and in overall changes to the pertinent fields, and changes to a tidal energy metric. Results are shown at a hub height of 50 meters (mid-water column), but effects from the turbine array are found throughout the water column.
Even this idealised headland channel flow has many complicated flow features that are realistic in their scope. The effects of tidally-generated headland eddies dominate the flow field, directly and indirectly. See the left-hand column of subplots in Figure 5 for snapshots at a single time during ebb tide in the initial case with no turbines. Vorticity is generated along the stoss side of the headland and detaches at the headland tip (Figure 5(c)). The vorticity rolls up and separates into multiple small vortices, lee of the headland tip, which coalesce together into a larger eddy with a much lower vortex strength. This behavior is reflected in the magnitude of the horizontal velocity, or speed, which is largest moving past the headland and around the outside of the large eddy (Figure 5(a)). The turbulent kinetic energy is strong both near the headland tip, as seen in an organised structure streaming from the tip, and around the outside of the large lee eddy (Figure 5(e)).

Plots from the simulation with a regular array layout are shown in the right-hand column in Figure 5. The presence of the turbines is clear in all of the plots. In the top plot, Figure 5(b), the turbines reduce the speed in very localised areas at their location and in their wakes. Additionally, they affect the speeds further downstream: while a thin jet of strong currents extends beyond the headland tip in the initial case, the currents pushing past the headland in the regular array case do not have as large of maximum values and are spread out over a larger area. A coherent structure can be seen in all of the fields in the initial case near the headland tip, but this structure is mostly disrupted by the presence of the turbines in the regular array case. The far-field TKE, as seen in the outside of the large eddy, is weaker and less prominent in the case with turbines.

The behavior in all of the fields in the regular array case follows directly from the turbine model. The turbines locally extract momentum and increase turbulence, which in the near-field decreases the speed and increases the TKE. The increased energy dissipation near the turbines leads to decreased speed and TKE in the far-field. The presence of the turbines right at the headland tip, where vorticity that is being generated along the stoss side of the headland is to detach to form structures downstream, disrupts the processes and leads to a less coherent feature, as seen in the vorticity and TKE.

Several aspects of the bulk flow field effects of the turbines are summarised in Figure 6. Maximum speed is used as a proxy of the location of the large lee eddy and other areas of strong currents. The speed is significant to power production since power is proportional to the speed cubed. The difference in the maximum speed values at each \((x, y)\) location between the initial and turbine array cases are shown in Figure 6(a). Areas where the initial case has larger speeds are positive (red), and areas where the turbine case has larger speeds are negative (grey). The effect of the turbines on the speed field is to shift the main areas of strong currents (mainly in the large eddy field and streaming from the headland tip on both tidal directions) outward, across the channel from the headland, and to weaken it. The line to the outside left of the plot shows the along-channel average of the difference in maximums, indicating a shift of the speed field across-channel from the...
headland in the turbine case, relative to the initial case.

This shift is probably due to the decrease in energy in the system moving past the headland tip. This decrease in energy, combined with the disrupted vorticity past the headland, leads to the strong currents tending slightly more straight beyond the headland with less curvature into the eddy when compared with the initial case. The main positive, red areas indicate where the initial case has stronger currents than the turbine case, due to extraction by the turbines, whereas the southern negative grey areas are where the currents have shifted to in the regular turbine array case.

Figure 6(b) shows the difference in maximum TKE between the initial and regular array simulations. There is a distinction in relative behavior in the cases in the near- and far-field. Very near to the turbines and in their wake, the TKE is stronger in the turbine case, which is expected given that several terms have been added to the turbulence equations in order to model the increased turbulence caused by the turbines. Further downstream, the initial case TKE is larger than the turbine case, probably due to the near-field dissipation due to the turbines in the regular array case which leaves less energy to be dissipated downstream. These trends are reflected in the across-channel average shown below the plot: the initial case tends to be larger except near the turbines themselves.

The mean kinetic power density, shown in Figure 7, gives a measure of the potentially extractable resource present in a system. Like in the plot of the difference of maximum speeds (Figure 6(a)), this plot shows a large-scale shift away from the headland tip of the resource. In the near-field area to the turbines, which is the area of largest resource, the field is completely altered by the turbines. In fact, the area of largest resource has decreased substantially, as seen in the difference between the corresponding filled and black line contours.

B. Discussion

The far-field disruption by the turbines to the structure set up lee of the headland tip (seen in all fields) could have significant impacts in a real-life situation. The path and characteristics of the large lee eddy change slightly in the turbine case. While in reality the eddy pattern would be much more complicated than in this idealised case (due to bathymetry, complicated coastline, and a more complex tidal forcing, among other things), a small shift in the eddy trend could have a bulk effect on the system. In Admiralty Inlet, for example, the lee eddies from Admiralty Head dominate the flow over a large area.

It is clear in Figures 5(e), 5(f), and 6(b) that the far-field TKE is weaker when the turbines are in place. Turbulence alters mixing in a system, and this shift in where the mixing occurs due to the turbines may be significant.

In the near-field, the change in the structure of speed, vorticity, and TKE streaming from the headland tip is limited
in distance from the headland tip, but could have significant impacts in that small area, besides the impacts on the far-field. The change in the eddy locations and rate could affect bottom sediment transport, which could affect the bathymetry in the area [1], [35].

All of these effects are somewhat minor in scope on their own, but could have major implications, especially given that only ten turbines were being modelled in this case. An important follow up to this work is to move the location of the turbine array to an area with a good available resource, but with a less important location hydrographically (that is, not right at the headland tip where vorticity is being shed), in an attempt to limit impact on the system.

V. CONCLUSIONS AND FUTURE WORK

Several power assessment methodologies have been used and compared in order to calculate the power capture of two different layouts of 10 device arrays. The first assessment method is based on the flow velocity passing at the position of each device for each time step (Equation 3, the “local approach”). The second calculation estimates the amount of power dissipated by the turbines over a tidal cycle (Equation 4, the “global approach”). A third assessment method is a function of the velocities taken at a similar distance upstream of each turbine composing the array (Equation 6). Comparison between the results has demonstrated the global approach to be most realistic methodology. Additionally, in Equation 3, $U_{\infty}$ should not represent the unperturbed flow velocity but the flow velocity perturbed by the upstream devices without the presence of the considered device. Written as it is, the local approach (that is, Equation 3) is equivalent to the classic approach (i.e., $P = -\frac{1}{2} \rho A_d C_p U_{\infty}^3$) as it does not account for fluid surging into the row gaps nor the upstream wake velocity yet it does not require any power coefficients. Nonetheless, the global approach can be considered as unbiased only when the open boundaries of the simulation are not directly subject
Fig. 6. Difference in maximum speed and TKE between the initial, no turbine case and the regular turbine array case. Positive (red) values indicate areas in which the initial case has larger maximum values and negative (grey) values indicate areas in which the turbine array case has larger values. Line plots to the left (bottom) of the main plot area show the along- (across-) channel average of the plot values, with coloring indicating position greater than (red) or less than (grey) zero.

Fig. 7. Mean kinetic power density. The values for the initial simulation are shown in colored, filled contours and corresponding values for the regular array simulation are overlaid in black contours and labeled.

Allowing for device yawing and blade design adaptation and control would also improve the turbine model, and will be implemented in future versions of the model. Furthermore, it has previously been suggested that natural flows intrinsically possess both potential and kinetic energy and the energy extraction is partly balanced between these two components [10]. Consequently, integrating the potential energy variations and transfers in the power capture assessment approach might have to be considered and raises the question of the relevance of assessing the potential of a site only on kinetic considerations [36].

The power output assessment could be even more realistic by taking into account cut-in speed and rated power speed. The cut-in speed is the flow velocity below which the turbine does not produce power and turbine rotor stays still. On the other hand, the rated power is the maximum power that a turbine can produce. This maximum of power production coincides with a threshold flow velocity above which pitch-control mechanism reduces angle of attack of the blades and thus maintains a power output close to the rated power [37]. This threshold aids in avoiding failure and dismantling of the turbine structure and blades due to extreme loadings [37]. Along with a more realistic blade control of the device power production, an estimate of electrical and mechanical losses involved in the process would ameliorate the power extraction assessment.

In terms of impact of turbines on the system, it was shown that even a relatively small number of turbines, placed in the area of strongest resource near the headland tip, have a noticeable impact of the system. Near the headland, the coherent structure in the speed, vorticity, and TKE that was seen in the initial simulation with no turbines was disrupted by the presence of the turbines. The local vorticity and TKE were increased and the speed was decreased by the presence of the turbines. The upstream increase in dissipation by the turbines led to less turbulence in the far-field. Additionally, there was a slight shift in the area of strong currents across the channel from the headland, probably due to weakened momentum and vorticity in the system.

The effects of the turbines could be significant for a real system. Each of these changes could affect the location, timing, and rate of mixing and transport. This in turn could affect many processes in the area, including sediment transport. Future work will examine the impacts of turbines at other locations in the system, in an attempt to mitigate the effect of the turbines on the system while maximising the power production.

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