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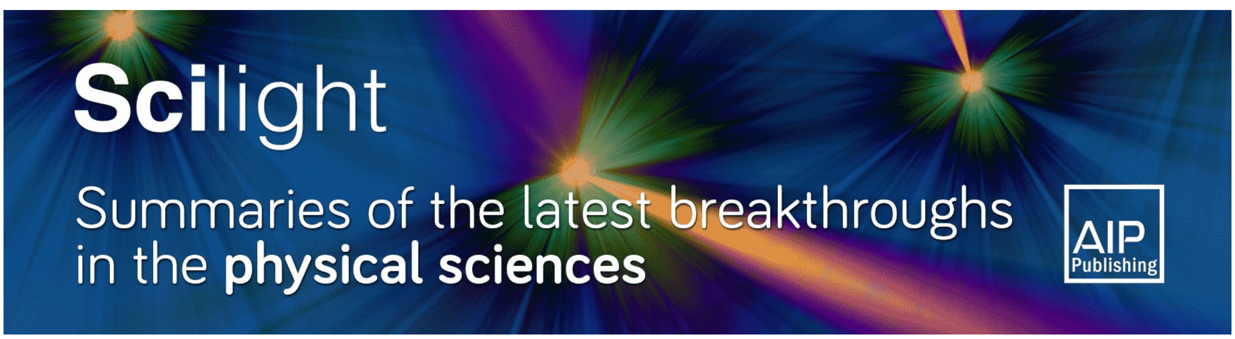

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ABSTRACT

The ocean contains a variety of renewable energy resources, little of which has been exploited. Here, we review both tidal range and tidal stream energy, with a focus on the resource, feedbacks, and environmental interactions. The review covers a wide range of timescales of relevance to tidal energy, from fortnightly (spring-neap) and semi-diurnal variability, down to array, and device-scale turbulence. When simulating the regional tidal energy resource, and to assess environmental impacts, it is necessary to account for feedbacks between the tidal array and the resource itself. We critically review various methods for simulating energy extraction, from insights gained through theoretical studies of "tidal fences" in idealized channels, to realistic three-dimensional model studies with complex geometry and arrays of turbines represented by momentum sinks and additional turbulence due to the presence of rotors and support structures. We discuss how variability can be reduced by developing multiple (aggregated) sites with a consideration of the enhanced phase diversity offered by exploiting less energetic tidal currents. This leads to future research questions that have not yet been explored in depth at first-generation tidal sites in relatively sheltered channels (e.g., the interaction of waves with currents). Such enhanced understanding of real sea conditions, including the effects of wind and waves, leads to our other identified primary future research direction—reduced uncertainties in turbulence predictions, including the development of realistic models that simulate the interaction between ambient turbulence and the turbulence resulting from multiple wakes, and changes to system-wide hydrodynamics, water quality, and sedimentation.

I. INTRODUCTION

Investment in emerging renewable energy technologies is essential if the global energy sector is to transition from fossil-based toward zero-carbon by the second half of this century, limiting the impacts of climate change.[1] Many of these emerging technologies are based on a resource that surrounds us—the ocean. Although there are many forms of ocean energy conversion, including wave energy,[2] Ocean Thermal Energy Conversion (OTEC),[3] and ocean currents,[4] one ocean energy resource has the dual advantage of high predictability and excellent opportunities for grid connectivity—tidal energy—the focus of this review.

Tides are predictable because of their origin in (astronomical) tide generating forces. These manifest as a number of tidal constituents, the dominant of which are the *semi-diurnal* lunar (M2) and solar (S2) constituents, with periods of 12.42 and 12 h, respectively (Table I). The combination of M2 and S2 leads to the fortnightly spring-neap cycle, with enhanced tidal range (spring tide) when the Earth–Moon–Sun system is in-line (either New Moon or Full Moon) and reduced tidal range (neap tide) when the Earth–Moon–Sun system is perpendicular (either First Quarter or Third Quarter Moon). It can therefore be seen that there is variability of the tides (and hence the potential of the tides for electricity generation) at both semi-diurnal and fortnightly time scales (Fig. 1). In addition to M2 and S2, other important tidal constituents that significantly affect the temporal variability of the tides are the lunar (O1) and lunisolar (K1) *diurnal* constituents, and the larger lunar elliptic semi-diurnal constituent (N2) (Table I). At longer timescales, the tidal resource is also influenced by the effect of the 18.6-year lunar cycle, which is mainly driven

TABLE I. The main diurnal and semi-diurnal tidal constituents. The amplitude of each tidal constituent relative to M2 is calculated using mean amplitudes extracted from TPXO9 global tidal atlas[152] for water depths less than 200 m (representative of shelf sea regions), between latitudes 66.5 °S and 66.5 °N.

Symbol	Name	Speed (°/h)	Period (h)	Amplitude relative to M2
O1	Lunar diurnal	13.943	25.819	0.26
K1	Lunisolar diurnal	15.041	23.935	0.37
N2	Larger lunar elliptic semi-diurnal	28.44	12.658	0.21
M2	Principal lunar semi-diurnal	28.984	12.421	1
S2	Principal solar semi-diurnal	30	12	0.35

by the changes of the inclination of the Moon's orbital path relative to the plane of the Earth's equator.[5]

Global tidal dissipation is around 2.4 TW, with the majority of this, 1.7 TW, occurring in shelf sea environments.[6] This represents an upper theoretical bound for tidal power, but due to interaction between tidal energy extraction and the resource (e.g., Ref. 7), in addition to technical and practical constraints, the available resource is likely to be considerably less. To put this in perspective, annual mean global electricity consumption is around 3 TW,[8] and so even if 10% of the shelf sea resource was exploited, that is, 170 GW, tidal energy could have a substantial contribution to the global energy mix. Further, in some regions such as the UK, tidal dissipation is around 200 GW, whereas mean demand for electricity is currently around 40 GW; therefore in some areas, the potential contribution of the tides to the electricity mix significantly outweighs the global mean.

There are two main ways of converting the energy of the tides into electricity—tidal range power plants and tidal stream turbines. Tidal range power plants (Sec. II) rely on the *potential energy* of the tides. Water is impounded behind an artificial embankment and released through turbines when there is sufficient head difference between the artificial water level inside the barrage and the natural tidal level outside of the barrage. In contrast, tidal stream turbines (Sec. III) rely on the *kinetic energy* of the tides. In regions where the tidal streams are of sufficient magnitude, the flow is intercepted by an in-stream tidal turbine, which spins a generator and produces electricity. Although tidal stream turbines can be installed individually, it is only when they are deployed in arrays (i.e., like a wind array) that they can reach their full potential.

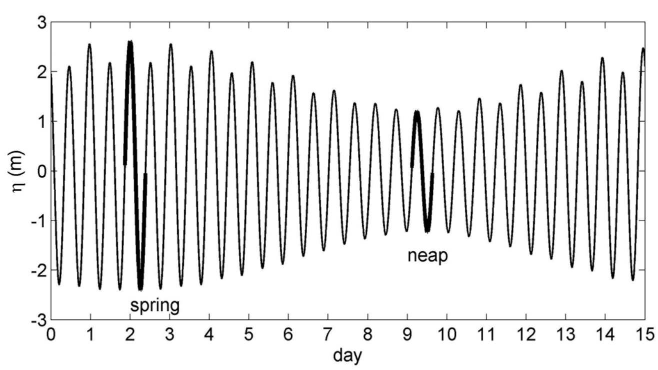


FIG. 1. Elevation time series based on four tidal constituents (M2, S2, K1, and O1) showing a typical spring-neap (fortnightly) cycle, in addition to semi-diurnal and diurnal variability. Reproduced with permission from Neill and Hashemi, *Fundamentals of Ocean Renewable Energy: Generating Electricity from the Sea* (Academic Press, 2018). Copyright 2018 Academic Press.

In this review, we consider these two forms of tidal energy conversion—tidal range energy and tidal stream energy—discussing the resource, projects, and research questions. We also discuss turbulence and wakes, and the environmental consequences of extracting tidal energy, particularly at significant scale, from the oceans. Finally, we identify future research areas that need to be addressed before the tidal energy resource can be exploited to its full potential.

II. TIDAL RANGE

Converting tidal range into other useful forms of energy has a history that extends back to the tide mills of the 6th Century.[9] However, converting the potential energy of the tides into electricity began with the construction of La Rance power station (France) in 1966.[10] La Rance comprises a 720-m-long barrage and impounds an area of approximately 22 km^2 in a region that has a mean tidal range of around 8 m. The barrage houses 24 Kaplan bulb turbines, which provide a combined rated power output of 240 MW. Four other tidal range power plants have been constructed (Table II), but it is notable that no scheme has been constructed in the last 25 years, setting aside the complication that the embankment for the 254 MW Lake Sihwa barrage was constructed in 1994, and the power plant in 2011. Further, all of the existing tidal range power plants are of the *barrage* type; that is, they span the full width of an estuary or channel. It is generally considered that the next generation of tidal range power plants will be *lagoons*, which only partially span an estuary, since these are associated with lower capital cost and reduced environmental impacts.[11]

A tidal range power plant is based on a number of components, the most important of which is the embankment. The embankment, which constitutes the majority of the capital cost of the power plant, is a barrier that is used to impound an area of sea, the filling or release of which is controlled by diverting the flow either through sluice gates (e.g., to transfer water into or out of the enclosed basin) or through turbines (i.e., to generate electricity). There are two main modes of operation of a tidal range power plant, and a third operation mode that is a combination of the other two. For *ebb generation*, the flooding tide enters the enclosed basin through sluice gates and idling turbines. Once the maximum level inside the lagoon is achieved, these gates are closed, until a sufficient head develops on the ebbing tide. Power is subsequently generated by the turbines and generators until a predetermined minimum head difference, when turbines are no longer operating efficiently. For *flood generation*, the process is reversed to produce electricity during the flood phase of the tidal cycle. *Two-way*

TABLE II. Characteristics of existing and proposed tidal range schemes (data from Neill and Robins[156]).

Power plant	Year	Capacity (MW)	Basin area (km^2)	Operation mode
La Rance, France	1966	240	22	Two-way with pumping
Kislaya Guba, Russia	1968	1.7	2	Two-way
Annapolis Royal Generating Station, Canada	1984	20	6	Ebb only
Jiangxia, China	1985	3.9	2	Two-way
Lake Sihwa, Korea	1994[a]	254	30	Flood only
Swansea Bay tidal lagoon, UK[b]	*Proposed*	*320*	*11.5*	*Two-way*

[a]1994 is the date of the construction of the sea wall for flood mitigation, but the actual power station was constructed in 2011.
[b]The Swansea Bay tidal lagoon is in italics as it is a proposed scheme.

generation is a combination of the two and can be used to reduce variability in the resulting power time series. Two-way generation can also be supplemented by pumping to further reduce variability.[12]

Tidal waves propagate at a phase speed $c = \sqrt{gh}$, where g is gravitational acceleration and h is water depth. Therefore, tidal waves travel much slower in shelf sea environments than they would in the deep ocean. For example, the mean depth of the world's oceans is 4000 m, and a tidal wave would travel at 200 m/s. In a shelf sea with water depth of 100 m, the tidal wave would propagate at 31 m/s. When a wave propagates along a channel that is relatively long compared to the tidal wavelength, at a distance of 1/4 of a wavelength from the head of the bay or estuary the crest of the incoming wave passes at the same time as the trough of the reflected wave (and vice versa). The two waves (incident and reflected) cancel at this point, known as a node, and so there is no tide at this location. Since the incoming and reflected waves combine, the tidal amplitude at the head of the bay is doubled in such a *standing wave* system.

Tidal resonance occurs when the length of a channel coincides with the quarter wavelength. In such a case, the tidal range at the entrance to the seaway is amplified at the head of the estuary. The most famous case of tidal resonance is the Bay of Fundy on the east coast of Canada, which has the highest tidal range in the world (16-m spring tidal range). With a mean depth of 66 m, the tidal wave propagates at a mean speed of 25 m/s along the channel. For quarter wavelength resonance with the semi-diurnal tide ($T = 12.42$ h—Table I), this represents a length of 280 km, which is very close to the actual length of the Bay of Fundy (290 km), that is, the channel is in near resonance with the semi-diurnal tide. Since tidal power is related to the basin area and the square of tidal range, these regions of high tidal range are sought for the placement of large tidal power plants; for example, the mean tidal range at La Rance is 8.2 m, and 5.6 m at Lake Sihwa.

Since the tidal range resource is a function of tidal range squared, the resource is discretely distributed across shelf sea regions (Fig. 2), with Australia alone containing 30% of the global resource, and Canada (Fundy) containing 23% due to its near resonance semi-diurnal tides. The UK and France each have an equal share of around 13% of the global tidal range resource,[11] with much of this focused in the Severn Estuary (UK) and the Gulf of St. Malo (France). Since we know the speed of propagation of the tidal wave (a function of water depth), we know the timing of the tides at any single location, but also the relationship between the phase of the tides between multiple locations. It is therefore possible to stagger a series of tidal range power plants along a coastline to reduce variability in the aggregated power output.[13] Tidal range power has more potential for this "tidal phasing" compared to tidal stream power (Sec. III), where the majority of energetic sites are in phase with one another.[14]

As stated earlier, all of the existing tidal range power plants are barrages (Table II), but a newer concept is that of a *tidal lagoon*, where only part of an estuary is blocked off to create an artificial basin. A much studied location for a tidal lagoon is Swansea Bay in the Bristol Channel, UK,[15] where the spring tidal range is 10.5 m. This site has also been the subject of a UK Government commissioned review, known as the Hendry Review, which investigated the role of tidal lagoons in the future UK energy mix.[16] The proposed Swansea Bay tidal lagoon would comprise a 9.5 km embankment,[17] enclosing an area of 11.5 km^2. Using 16×7.2 m-diameter turbines, installed in 60 m draft tubes, the power plant would have a nameplate capacity of 320 MW. Using dual (flood/ebb) mode, the project is estimated to have a capacity factor of 19%. The turbine design is triple regulated,[18] that is, adjustable guide vanes, blade pitch angle, and variable speed—the latter potentially reducing harm to fish. The Hendry Review supported the development of the Swansea Bay tidal lagoon, known as a "pathfinder" project; however, the review further recommended that the pathfinder project should be operational for a reasonable period of time before construction of any further (and potentially larger) tidal lagoon projects. This is to allow the full range of environmental impacts to be monitored over time. One important point about tidal range schemes, in comparison with other energy projects, is the lifetime of the embankment, which is generally estimated to exceed 100 years, and this could be accounted for when estimating the levelized cost of energy (LCoE).

Little research has been conducted into how climate change, particularly changes in mean sea level, will affect the tidal range resource. This is particularly relevant, since the embankment of a tidal range power plant is estimated to have a lifetime that is highly likely to witness significant changes in the climate. For example, an increase in sea level in a tidal basin will lead to an increase in the speed of propagation of the tidal wave, altering the resonance characteristics. A model study of the Bay of Fundy shows that a 1 m rise in mean sea level would lead to an increase in approximately 0.1 m in tidal amplitude due to the basin approaching true resonance.[19] This may seem like a small change, but since the tidal range resource is related to the tidal range squared, it could lead to a significant change in the resource. Global tidal modeling under a more extreme scenario of 2 m sea-level rise leads to a complex picture of regional changes in tidal amplitude, with no consistent pattern emerging of increase or decrease in tidal amplitude over shelf sea regions.[20] Further, such model studies, which

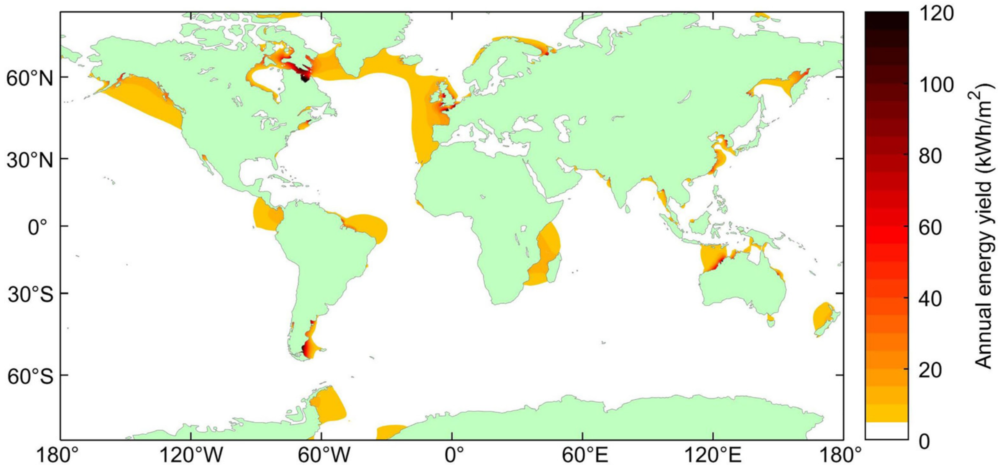


FIG. 2. Global distribution of the tidal range resource, calculated using five tidal constituents (M2, S2, N2, K1, and O1) from the TPXO9-v2 dataset, at a resolution of $1/30^\circ \times 1/30^\circ$. Reproduced with permission from Neill *et al.*, Renewable Energy **170**, 683–692 (2021). Copyright 2021 Author(s), licensed under a Creative Commons Attribution (CC BY) license.

examine future changes in tidal dynamics due to sea-level rise, should do so concurrently with changes in developed energy infrastructure.[21] On non-tidal influences to the tidal range resource, it has been demonstrated that storm surges will not significantly impact the resource compared to that estimated by astronomical constituents alone.[22]

III. TIDAL STREAM

Tidal streams are regions with concentrated tidal flows, posing an energy resource with significant potential. The kinetic energy may be extracted from these tidal streams using hydrokinetic turbines, analogous to wind energy. Similar to offshore wind, turbines are typically deployed in arrays, increasing system redundancy, and resilience. The vast majority of tidal turbines use rotors to convert the kinetic energy of the flow into mechanical energy, either with the horizontal axis parallel to the flow or with the axis perpendicular to the flow. However, there are examples of turbines using other means such as oscillating hydrofoils and underwater kites.[23] Regardless of the specific type of technology being used, all projects require resource assessments to first determine project feasibility, then to design the turbine array layout, and finally to compute the project annual energy production (AEP). The International Electrotechnical Commission (IEC) has published a technical specification for performing tidal stream energy resource assessments for projects at both feasibility and design stages.[24]

Starting with small-scale resource assessments, the theoretical power available for an individual turbine is computed as a cube of the free stream velocity

$$P_t = \frac{1}{2}\rho V^3, \tag{1}$$

where ρ is the density of the fluid and V the flow speed. Accounting for the efficiency of a particular turbine, this equation can be modified by multiplying by the power coefficient C_p,

$$P_d = \frac{1}{2}C_p\rho V^3, \tag{2}$$

where P_d is the electrical power density. Sometimes C_p is referred to as the performance coefficient and represents the shaft power rather than the electrical power. An upper bound (16/27, or 59.3%) for turbines in an unconstrained flow was derived using actuator disk theory and is formally referred to as the Lanchester–Betz–Joukowsky limit, but is most frequently called the Betz limit.[25–27] This analysis was performed for wind turbines; however, it is generally accepted that it also applies to tidal energy, providing the turbine swept area is small relative to the channel depth and width.[28]

The actual power output depends on the properties of the turbine. In particular, the power for the turbine (P) is found by multiplying the power density by the swept area of the turbine, A_s,

$$P = \frac{1}{2}C_p\rho V^3 A_s. \tag{3}$$

The power coefficient can be a function of the velocity with variable efficiencies, including a minimum cut in speed below which the turbine does not operate and a rated speed at which the turbine does not generate more power for higher flow velocities. The IEC has a technical specification outlining the methodology for empirically determining the power coefficient as a function of the incoming current speed.[29] Finally, the total energy converted by the turbine is found by integrating the power over the desired period of time, most commonly a year, to get the AEP. Optimal efficiencies of tidal power converters are generally lower than the Betz limit and are reported to be typically between 16–50%.[30,31] However, for many tidal streams, the Betz limit is irrelevant and may be exceeded under conditions with constrained flow[32] or when using turbines with ducted intakes.[33]

On a much broader scale, high-level reconnaissance studies are implemented at country or regional scales to identify regions with significant tidal energy resources by evaluating existing data or using numerical simulations of large regions. One example of a reconnaissance study is the geodatabase of tidal constituents developed using the Regional Ocean Modeling System (ROMS), which presents the regional assessment of tidal stream power resource and identifies locations with high kinetic power density in the USA.[34]

Feasibility studies are used to compute a preliminary estimate of the upper bound for the potential available power for a project.

These are generally done using simulations with depth-averaged 2D models that reasonably reproduce the general characteristics of the tidal flows. However, estimating the power for larger projects with the current velocities from model simulations without accounting for the effect of energy extraction can be erroneous. Vennell *et al.*[35] suggested that the any project with a total swept area larger than 2–5% of the cross-sectional area may be considered large, requiring consideration of the effect of the turbines on the flow field. As illustrated in Fig. 3, starting with a small array with a few turbines, the inclusion of additional turbines will reduce the residual available kinetic power density, and each individual turbine will produce less overall power. However, the power produced by the array will still be increased. The rate of the increase in total power will be reduced as more turbines are included, reaching a threshold where adding further turbines will actually reduce the total power output from the full array, thereby leading to a maximum possible power that may be extracted for a given channel configuration.

In order to provide an estimate of the maximum power available, Garrett and Cummins,[36] hereafter referred to as G&C, identified that the backflow effect created by the obstructions in the channel would increase the pressure differential driving the flow and enhance the flow velocity. For a constricted channel connecting two large bodies of water in which the tides at both ends are assumed to be unaffected by the currents through the channel with a tidal fence consisting of turbines across the entire channel cross section, a general formula gives the maximum average power between 20–24% of the peak tidal pressure head multiplied by the peak of the undisturbed mass flux through the channel. Maximum average tidal stream power, P_{max}, is given as

$$P_{max} = \gamma \rho g a Q_{max}, \tag{4}$$

where g is a parameter, a is the amplitude of the tidal water level constituent, and Q_{max} is the maximum corresponding tidal flow rate. The maximum average power may be estimated with an accuracy of 10% using $g = 0.22$, without any need to understand the basic dynamical

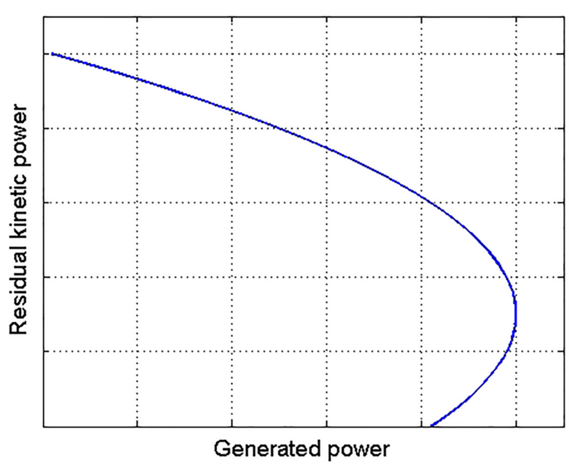


FIG. 3. Illustration of the diminishing return of additional turbines in a channel. Starting from the top left, as more turbines are added the residual kinetic power decreases, and the generated power increases. There is an optimal point where generated power is maximized, beyond which the generated power is decreased as further turbines are added.

balance.[36] A multiplying factor is used to account for additional constituents (–, –) given as

$$1 + (9/16)((r_1)^2 + (r_2)^2 + \cdots), \tag{5}$$

where $r_1 = a_1/a, r_2 = a_2/a, \ldots$. This upper bound on the available power ignores losses associated with turbine operation and assumes that turbines are deployed in uniform fences, with all the water passing through the turbines at each fence.

Using numerical simulations of tidal flows, Haas *et al.*[37] applied Eqs. (4) and (5) to produce the United States national tidal energy reconnaissance resource assessment. Other studies have looked at various applications of G&C. The validity of the value of g in Eq. (4) was demonstrated by Sutherland *et al.*[38] using numerical simulations of channel-wide energy extraction. However, they did find that for more complex channel geometries such as split channels, Eq. (4) overestimated the maximum power by up to 50%, demonstrating one of the limits to the applicability of this method. Recognizing the unlikely scenario of installing tidal fences across an entire channel, Garrett and Cummins[32] analyzed partial fences across a channel. Analytically, it was found that the resultant maximum power was reduced by a factor of 1/3 to 2/3. This work was extended by Whelan *et al.*[39] for the case of high flow blockage where the free surface drops immediately downstream of the turbine, and by Nishino and Willden[40] who considered the case of a tidal fence partially blocking a wide channel.

Vennell[41,42] also looked at the effects of partially blocked channels, finding that by adjusting the flow reduction (ratio of the wake velocity to the incoming velocity), the turbine array could be better optimized. Vennell argues that changes to individual turbines will affect the overall array drag and therefore found that flow reduction ratios could be tuned in the range from 1/3 to 1, in contrast to Garrett and Cummins[32] where the optimal limit was 1/3. Vennell[42] also discusses the need to tune multiple rows of turbines "in-concert" because even if the rows are widely separated such that the wake sufficiently recovers, they will still have interactions due to the full array's effect on the overall array drag coefficient. An excellent discussion comparing the results from Garrett and Cummins with the work by Vennell is found in Vennell.[43]

The previously discussed studies generally focused on relatively simple channel geometry and idealized flow conditions. The comparison of array efficiency estimates obtained from analytical and numerical models suggests that analytical models underestimate the tidal energy yield potential, particularly as they do not realistically reproduce the flow structure in the vicinity of the turbines, especially three-dimensional effects and turbulent mixing.[44] Further, tidal estuaries are frequently much more complex and may contain multiple channel branches and intertidal storage. Under these more complex scenarios, kinetic power density is sometimes still used to estimate the resource.[45–47] However, additional work has been completed to extend the analytical approaches above to more complex geometries. Blanchfield *et al.*[48] modeled a closed bay and open ocean, which was successfully verified by Yang *et al.*[49] numerically. Polagye and Malte[50] treated tidal networks like electrical circuits and found the most power efficient turbine deployment in networks required equally deploying turbines across sub-channels, or deploying prior to the channel bifurcation to a reduce flow diversion.

The project design process and final AEP calculations require much higher levels of resource assessments, using additional levels of complexity. Individual effects from turbines that must be considered can be small scale, where turbines interact directly (i.e., wake effects), or large scale, where the energy extraction from the turbines affects the tidal flow in the entire estuary. While it is not possible to resolve all these scales in a single model, it is necessary to resolve a broad range of scales, which is computationally challenging. Resource assessments utilized for siting considerations require a much higher model resolution than feasibility studies. This may be accomplished using models with unstructured grids, such as the resource assessment for New Jersey by Tang *et al.*[51] or Yang *et al.*[52] for the Western Passage. Another study by Ramos *et al.*[53] coupled several structured grids with varying grid resolutions in a relatively simple estuary. In another example, Bomminayuni *et al.*[54] used a model with an unstructured grid and therefore higher resolution in the region of interest to simulate the flows in tidal channels near Rose Dhu Island, Georgia. Recently, Lewis *et al.*[55] simulated the Irish Sea with a structured grid model and determined that model resolution had a significant effect on the local resource assessment. They demonstrated that higher model resolutions ($<$500 m) are required for siting considerations. Yang and Haas[56] used grid refinement with a structured grid to produce higher resolution within the region of interest for two different case studies.

In order to account for array effects, numerical simulations of the project site must quantify the effects of turbines on the flow field. Due to the necessity of resolving a large domain to capture the far field effects, simplified approaches to resolving the effect of turbines are generally utilized. While there are many options for incorporating the impacts of turbines into models, they generally have comparable approaches.[49,57–61]

One approach for simulating energy extraction incorporates an extra retarding force into the momentum equations. This force may be written as

$$\vec{F} = -\frac{1}{2}\rho C_{ext}|\vec{V}|\vec{V}, \quad (6)$$

where C_{ext} is an extraction coefficient. To evaluate far-field effects, the grid resolution may be relatively coarse where each grid point may represent multiple turbines, leading to larger overall extraction coefficients. At such a coarse resolution, the turbines within each grid cell cannot be individually tuned, and so the optimal grid layout cannot be determined. In order to optimize the turbine layout, individual turbines must be resolved by one or more grid cells. In these cases, three-dimensional (3D) models may also resolve the vertical structure of the flow with multiple layers resolving the swept area.[62,63]

Tidal turbines and their support structures will also have a pronounced effect on the turbulent characteristics of the flow field. Therefore, models must include modifications to the turbulence closure scheme.[64] This includes an additional turbulent kinetic energy (TKE) source term, an additional term accounting for the transfer of large-scale turbulence to small-scale turbulence, and a term to model reduction in the spectrum of the turbulent length scales due to the partial generation of turbulence from fluid–structure interactions.

There have been numerous tidal power assessments performed while accounting for the effects of tidal power extraction for different regions around the world. Tidal stream energy resources in northwest Spain were modeled numerically, and the impacts of tidal stream energy were assessed.[45,53] The maximum tidal power potential of Johnstone Strait, British Columbia, Canada, was studied by Sutherland *et al.*[38] using a 2D finite element model, and the maximum extractable power in northwestern Johnstone Strait was estimated to be about 1.3 GW. The available tidal power from in-stream turbines placed in the Minas Passage of the Bay of Fundy and the Passamaquoddy-Cobscook Bay located near the entrance to the Bay of Fundy has also been examined.[65–67] Polagye *et al.*[68] studied and characterized the in-stream tidal energy potential of Puget Sound, Washington, and quantified the far-field, barotropic effects of energy extraction. The Kennebec River of the central Maine coast was found to contain narrow passages where mean tidal energy capacity is sufficient to meet the consumption needs of about 150 homes.[69] The Tanana River at Nenana, Alaska, was studied for its potential for installing and operating hydrokinetic turbines, and suitable locations were recommended.[70] Coles *et al.*[71] performed 2D model simulations around the Channel Islands and found benefits in developing multiple sites simultaneously. Hakim *et al.*[72] modeled the Muskeget Channel and found modest impacts on the underlying hydrodynamics. Marsh *et al.*[73] modeled the Clarence Strait in Australia both with and without the effects of energy extraction and found that modest sized arrays had a limited impact on the underlying hydrodynamics. In contrast, Coles *et al.*[74] modeled the Alderney Race and documented a reduction in flow due to the impact of the turbines, resulting in a total power estimate 57% lower than the previous assessment without energy extraction.

IV. TURBULENCE AND WAKES

Tidal stream energy sites are characterized by high Reynolds numbers. For instance, the order of magnitude is 2.5×10^7 for the Alderney Race, France.[75] The flows are thus highly turbulent, and this has strong implications on the design of turbines. Whereas the smallest scales of turbulence increase the fatigue of the turbines by inducing vibrations, the larger scales are responsible for fluctuations of power[76,77] and loads.[78] Indeed, instantaneous velocities (and associated loads) result from the superposition of turbulence-induced velocity fluctuations and time-mean velocities. The characterization of turbulence is thus crucial for the design of tidal turbines. Turbulence is also known to have a significant effect on the wakes that form behind the turbines, as demonstrated experimentally[79] and numerically.[80] Basically, the higher the turbulence intensity, the greater the mixing behind the turbines and the faster the flow recovery between two consecutive rows of turbines in an array. This effect should thus be considered when optimally positioning turbines within an array, especially the longitudinal spacing between rows of turbines. Finally, as turbulence acts on the mixing processes and bed shear stress, it influences sediment transport and the transport of solute and suspended substances that pass through the array (e.g., biochemical particles). Wake turbulence should thus be considered when assessing the influence of tidal turbines on the physical conditions.

The turbulence at tidal energy sites results from a combination of processes that interact with each other. In this section, we first review studies dedicated to the characterization of the ambient turbulence (the turbulence that is naturally present in the flow). Then, we review investigations on the turbulence generated by the turbines.

A. Ambient turbulence characterization

Whereas measuring time-mean flows at tidal energy sites is relatively common today, measuring turbulence in fast currents is still technically challenging because of sensor limitations (sampling frequency) and difficulties in deploying and firmly fixing the sensors in harsh environments. Nevertheless, ambient turbulence measurements have been performed in the Fall of Warness, UK;[81,82] Puget Sound, USA;[83] the Sound of Islay, UK;[84] Ramsey Sound, UK;[85] and the Alderney Race, France.[86–88] Such measurements are performed with acoustic Doppler velocimeters (ADV) that provide high-frequency data with low noise at a single location, acoustic Doppler current profilers (ADCP) that provide lower-frequency data along a profile (generally, the sensor is upward looking from a sea bed mooring), or two coupled ADCPs that allow the six components of the Reynolds stress tensor to be evaluated.[86–88] The most popular metrics used to characterize turbulence are turbulence intensity (i.e., the turbulent velocity fluctuations normalized by the tidal currents), turbulent kinetic energy (TKE), the production and dissipation of TKE, and the time and length scales of the turbulence. Turbulence intensity (in percent) is

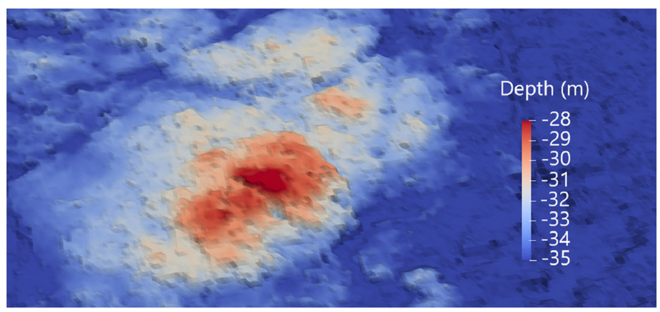
$$I = 100\sqrt{\frac{\frac{1}{3}\left(\overline{u'u'} + \overline{v'v'} + \overline{w'w'}\right)}{\bar{u}^2 + \bar{v}^2 + \bar{w}^2}},$$

and turbulent kinetic energy (TKE) is

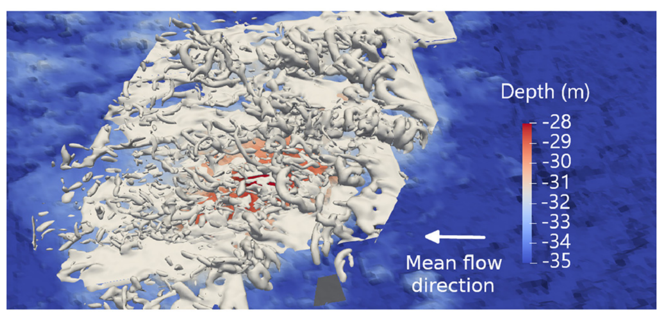
$$TKE = \frac{1}{2}\left(\overline{u'u'} + \overline{v'v'} + \overline{w'w'}\right),$$

where, according to the Reynolds decomposition, the current velocity (u, v, w) is the sum of a time averaged velocity $(\bar{u}, \bar{v}, \bar{w})$ and a fluctuating part (u', v', w').

The investigations mentioned above showed that (1) ambient turbulence intensity is of the order of 10% at hub height,[83,86] and (2) turbulence is highly site-specific and strongly dependent on the (ebbing or flooding) tidal conditions because its characteristics are influenced by the (local and upstream) seabed features.[85,86] They also highlighted that (3) turbulence is anisotropic with greater turbulence intensities and time-length scales in the streamwise direction than in the transverse or vertical directions.[88] *In situ* measurements are essential for understanding the turbulence characteristics at a given tidal energy site. However, the data are generally only available at one particular location (or along a profile if measurements are performed using an ADCP). Hence, numerical models are required to map the turbulence characteristics over the entire tidal stream energy site. There are two main ways of modeling the turbulence in tidal flows. The RANS (Reynolds-averaged Navier–Stokes) approach consists of resolving the time-mean variables and using closure schemes (such as the $k-\varepsilon$ model) to simulate the effect of the turbulence on the flow. This is a temporal filtering of the Navier–Stokes equations. The other way is LES (large eddy simulation) and consists in resolving the greatest scales of the turbulence and in mimicking the effect of the smallest (dissipative) scales with subgrid models (e.g., Smagorinsky[89]). This is a spatial filtering of the Navier–Stokes equations. The RANS approach is generally used in regional models because it is suited to simulating the slowly varying tidal dynamics over large domains. Numerous regional models, such as Telemac, ROMS, or FVCOM (Finite Volume Community Ocean Model), have thus been applied to appraise the time-mean flow hydrodynamic characteristics of tidal energy sites as well as the resource.[90] Several attempts were also undertaken to characterize turbulence from the turbulence closures of RANS models. Togneri *et al.*[91] used the $k-\varepsilon$ closure of the ROMS model to predict the turbulence properties at the West Anglesey Demonstration Zone off the coast of Wales (UK). The comparison with ADCP data showed good agreement in terms of TKE, especially in the lower part of the water column, where the influence of wave action was minimal. Dissipation agreed less well. Applying a comparable methodology to the Chacao Channel (Chile), Guerra *et al.*[92] also showed that the regional model FVCOM can suitably predict the strength of turbulence at tidal energy sites. The comparison of the model predictions to ADV measurements showed good agreement in terms of dissipation rate. Nevertheless, TKE was significantly underestimated because the model was not able to capture the anisotropy of the low-frequency turbulence scales. LES models simulate the transient flow characteristics and thus enable more insights into the processes controlling the turbulence at tidal stream energy sites. LES has been performed in Ramsey Sound[93] and the Alderney Race.[94,95] The simulations of Zangiabadi *et al.*[93] relied on the Fluent model and covered a 800×1800 m^2 domain. This highlighted the capabilities of LES to simulate flow patterns over complex seabed morphology, especially the dynamics of large eddies that form behind a large rock. Focusing on comparable length and time-scales, Mercier *et al.*[95] characterized quantitatively the turbulence in a 240×960 m^2 zone of the Alderney Race with a LES model based on the Lattice Boltzmann method (Fig. 4). The model validation relied on measurements performed by two coupled ADCPs and showed a remarkable agreement for all components of the Reynolds stress tensor. Because of their high computational cost, LES focusses on small domains and is used to investigate only a particular snapshot of the tidal cycle (generally peak ebb or peak flood current).



(a) Without λ_2 visualisation.



(b) With λ_2 visualisation.

FIG. 4. Turbulent structures over a rocky seabed in the Alderney Race, France. (a) Without vortices. (b) with vortices represented with instantaneous iso-contour of the λ_2 criterion.[153] Domain dimensions are 70×150 m^2. Reproduced with permission from Mercier *et al.*, Appl. Ocean Res. **97**, 102082 (2020). Copyright 2020 Elsevier.

To cover larger temporal and spatial scales, Bourgoin *et al.*[94] modified Telemac3D so that it solves both the RANS and the LES equations. In the outer domain, solving the RANS equations resolved the tidal propagation, whereas in the inner domain, application of the LES equations resolved the transient characteristics of the flow and the largest turbulence scales. This model was applied to simulate a tide cycle in the Alderney Race and was used to map the turbulence characteristics, investigating the differences in turbulence properties between the flood and ebb phases of the tidal cycle. Table III synthesizes the main characteristics of the models mentioned above.

B. Wake turbulence

The turbulence induced by tidal stream turbines is the result of different processes. In the near wake (typically within five turbine diameters downstream of the device), the turbulence is mostly governed by the swirl (rotational motion of the flow generated by the blades) and by the vortices shed by the blades and the support structure. In the far wake (typically greater than five turbine diameters), turbulence results mainly from the shear between the accelerated flows that bypass the turbine and the slowly moving flows in the turbine wake. The interaction of these processes with the ambient turbulence determines the wake properties. To predict wake characteristics, different techniques can be applied. Here, we review measurements in real sea conditions, laboratory experiments of scaled studies, and numerical models.

In situ experiments can either be used to assess the influence of turbulence on turbine performance (thrust and power) or to map the wake characteristics (in terms of velocity deficit and turbulence intensity for instance). Whereas several *in situ* experiments highlighted the influence of ambient turbulence on the performance of full-scale tidal turbines,[76,77,96,97] measurements of wake turbulence in real sea conditions are sparse in the scientific literature. The main reason is that acquiring data in the wake of a full-scale tidal turbine (in operating conditions) is highly challenging. Indeed, in addition to the technical limitations of current measuring devices, sensors are difficult to deploy close to the turbine, and multiple sensors are required to capture the shape and properties of the entire wake. In addition, data are generally not publicly available. The only existing studies on wakes found by the authors are those of Schmitt *et al.*[98] and Verbeek *et al.*[99] Schmitt *et al.*[98] investigated the spatial distribution of the velocity deficit in the wake of a 4 m diameter turbine with two ADCPs and an ADV. Verbeek *et al.*[99] measured, using two ADCPs, the velocity deficit, turbulence intensity, and the integral time-length scales behind a row of 5.3 m diameter turbines.

As wake data acquired in real sea conditions are sparse, the knowledge on the wakes of tidal turbines comes mainly from experiments on scaled turbines in laboratory flumes.[100] The first measurements were carried out by Myers and Bahaj[101] who mapped the near wake behind a 0.8 m diameter turbine with laser and acoustic Doppler velocimeters. Measurements in the far wake were also performed using an experiment in which the turbine was represented by a porous disk of diameter 0.1 m. Numerous experimental studies were then performed on the wake of a single turbine and showed, in particular, that the ambient turbulence has a strong influence on the flow recovery behind the turbine.[79,102–105] Investigations were also conducted on the interactions between the wakes of two turbines,[106] three turbines,[107] and up to ten turbines.[108] Finally, large arrays of tidal turbines were investigated by Coles *et al.*[71] with porous fences representing several rows of devices. This experiment enabled an investigation of flow development through up to ten rows of turbines.

Experimental studies are essential for understanding the processes controlling wake characteristics. However, the results are difficult to transpose to full scale, especially because the Reynolds similarity is not achievable experimentally. Numerical investigations are thus widely used to characterize the wakes of tidal stream turbines. Here, we present different types of wake models starting with the most sophisticated. Blade resolved models (e.g., Afgan *et al.*[109]) can be used to simulate the performance of turbines under different flow conditions. In such an approach, the rotating blades, the hub, and the support structure are physically represented in the model. Since they resolve the blade and support structure, they are able to simulate all turbulent processes generating turbulence in the near wake. However, due to their high computational cost, they cannot be applied to simulate an entire wake (or several interacting wakes). Blade element method (BEM) consists of applying on the fluid the forces experienced by different sections (elements) of the rotating blades (lift and drag forces). BEM is particularly suited to investigating turbine and array scales, and numerous investigations have been conducted to simulate isolated or superimposed wakes.[110,111] The vortex method[112] focuses on comparable scales and relies on a velocity–vorticity numerical implementation of the Navier–Stokes equations. In this approach, the vorticity is carried by particles emitted at the trailing edge of the turbine blades and advected in a Lagrangian framework. This method showed good agreement with experiments on a scaled turbine both in terms of performance and wake characteristics. The Actuator Line

TABLE III. Examples of modeling studies dedicated to the characterization of turbulence at tidal energy sites.

Reference	Site	Turbulence model	Model	Domain dimension/ minimal resolution
Togneri *et al.*[91]	Anglesey (UK)	$k-\varepsilon$ (RANS)	ROMS	$600 \times 300\,\text{km}^2/300\,\text{m}$
Guerra *et al.*[92]	Chacao Channel (Chile)	Mellor and Yamada[155] and Smagorinsky[89]	FVCOM	$66\,400\,\text{km}^2/50\,\text{m}$
Zangiabadi *et al.*[93]	Ramsey Sound (UK)	$k-\varepsilon$ (RANS)	Fluent	$1800 \times 800\,\text{m}^2/0.25\,\text{m}$
	Ramsey Sound (UK)	Smagorinsky[89] (LES)	Fluent	$1800 \times 800\,\text{m}^2/0.25\,\text{m}$
Bourgoin *et al.*[94]	Alderney Race (France)	Spalart and Allmaras[154] (RANS) and Anisotropic Minimum Dissipation model (LES)	Telemac3D	$150 \times 120\,\text{km}^2$ (RANS) and $1.8 \times 2.5\,\text{km}^2$ (LES)/3 m
Mercier *et al.*[95]	Alderney Race (France)	Smagorinsky[89] (LES)	Palabos (LBM)	$240 \times 960\,\text{m}^2/0.25\,\text{m}$

(AL),[113] Actuator Disk (AD),[80,114,115] or Actuator cylinder (for vertical-axis turbines) concepts represent turbines by applying on the fluid the force exerted by the turbines (thrust and eventually drag). This modeling approach has a lower level of fidelity then the methods mentioned above (especially because the rotational motion of the blades is neglected), but can successfully simulate far-field wakes (Fig. 5), provided the turbulence models are adequately tuned[116] (and suitably mimic the effects of the unresolved turbulence processes, especially swirl and the shedding of vortices). The main interest of AD methods is that, due to their simplicity, they can be integrated into regional models (e.g., ROMS, Telemac3D). Hence, they enable wake studies to be performed under realistic sea conditions (e.g., Roc *et al.*,[64] Michelet *et al.*,[62] Thiébot *et al.*[63]), which are required to assess the energy conversion potential of tidal arrays.

V. ENVIRONMENTAL IMPACTS

Tidal stream energy projects are generally located in coastal bays, estuaries, and tidal channels that are characterized by strong tidal currents. These coastal waterbodies present not only a great potential for electricity generation but also provide important nearshore habitats for many species of marine wildlife, including seabirds, fish, and marine mammals.[117] The deployment of tidal turbine arrays in the coastal oceans will cause disturbances to the ambient ocean environments. The level of disturbance, or impact, depends not only on the amount of energy extraction and size of the tidal turbine arrays, but also the geometric features and volume of the tidal system where tidal turbine arrays are deployed.[118] Therefore, to accelerate the development of tidal energy, it is important to assess, understand, and minimize the impacts of the deployment of tidal turbine arrays on coastal ecosystems, and to protect the marine wildlife while maximizing its contribution to the renewable energy portfolio. Environmental effects of tidal turbine array installations on tidal systems typically include the following areas:[117,118]

- Physical processes
  - Effects on the far-field flows and water levels
  - Transport timescales such as residence time
- Biogeochemical processes
  - Water quality
  - Sediment erosion and transport near the tidal turbine arrays

Common approaches for assessing the environmental impacts of tidal energy extraction include numerical modeling, laboratory experiments, field monitoring, and measurements. However, field monitoring and measurements are limited because very few tidal turbine arrays have been deployed in the world, and the associated costs are extremely high. Therefore, numerical simulations using advanced state-of-the-art models are often employed to evaluate the level of environmental impacts associated with tidal energy extraction in marine systems.[35,63,119]

The following two subsections (V A and V B) provide an overall review of the current state of research for the environmental impacts in each subject area.

A. Physical processes

Effects of tidal stream energy extraction on physical processes in marine systems, such as ambient flow fields, are the most evident phenomena in tidal energy projects. Assessment of the effects on physical processes generally can be divided into two groups—system-wide far-field effects and localized near-field effects. In a series of pioneering work on understanding and estimating the maximum power potential in tidal channels, Garrett and Cummins[32,36,120] established a theoretical formula that relates the maximum extractable energy vs the

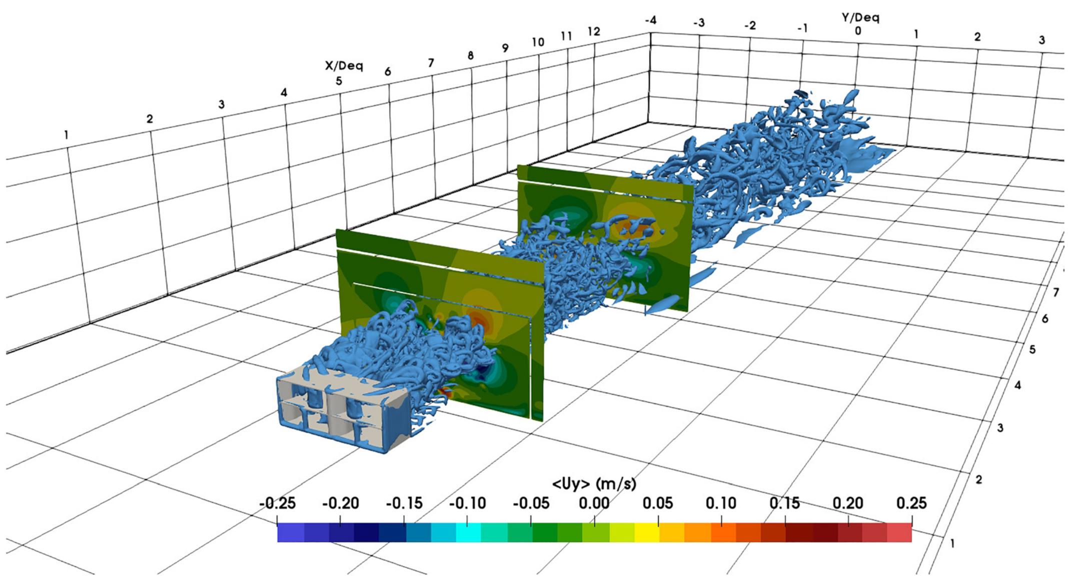


FIG. 5. Wake behind a vertical double-axis turbine. Transverse velocity is displayed along two vertical planes; $\langle Uy \rangle$ is the time-averaged velocity along the *y*-axis. Vortices are represented as instantaneous iso-contours of the λ_2 criterion.[153] *X*/*Deq* and *Y*/*Deq* are *x*- and *y*-directions normalized by the equivalent turbine diameter $Deq = 25$ m. Reproduced with permission from Grondeau *et al.*, Energies **12**, 4273 (2019). Copyright 2019 Author(s), licensed under a Creative Commons Attribution (CC BY) license.

maximum tidal flux across the channel. They discovered that the maximum extractable power is significantly less than the average kinetic energy flux in the undisturbed tidal channel, and the volume flux across the channel will be reduced by 42%. Subsequently, a number of modeling studies confirmed the conclusions by Garrett and Cummins,[36] using numerical simulations in real-world cases and idealized test domains, and further extended the formula to a tidal channel connecting to a coastal bay case.[38,48,49,66,121] It is important to note the previously mentioned studies were based on one-dimensional (1D) or two-dimensional (2D) governing equations. However, in reality, tidal energy extraction is a three-dimensional (3D) process. For example, Yang *et al.*[49] found that the volume flux is reduced by 32.7% when maximum tidal energy is extracted in a 3D case, which is smaller than the 2D case and the results of Garrett and Cummins.[36] Physics-based 2D and 3D models are often used to investigate the far-field effects of tidal energy extraction for real-world study sites.

Most studies showed that the effect of tidal energy extraction on water level was small.[59,122–124] For example, Zhang *et al.*[124] applied a 3D model to assess the impact of proposed tidal array with 115 turbines in the Zhoushan Archipelago of China and they found the impact of the tidal turbine array resulted in a water-level change of less than 3 cm. Similarly, Yang *et al.*[123] also found that a hypothetical tidal array with 100 turbines in Tacoma Narrows, USA, resulted in a change in water level of less than 1 cm. Pacheco and Ferreira[125] investigated the hydrodynamic impacts of a small array of thirty E35 turbines and found the change in a water level due to tidal turbine array operation was less than 2.5 cm. Hakim *et al.*[72] studied the impacts of tidal stream turbines on hydrodynamics and sediment transport in the Muskeget Channel, Massachusetts, using an unstructured-grid model FVCOM. Model results suggested that water level was only affected by 0.8% when 9% of the natural tidal energy in the channel is extracted. However, some studies found that the presence of large arrays of turbines can potentially result in noticeable changes in water level, especially where tidal flats are present in the system or when tidal phase is affected. For example, Karsten *et al.*[66] discovered a maximum of 7 GW of power can be extracted by turbines in the Minas Passage based on numerical simulations. However, such a large level of energy extraction could result in the system moving closer to true tidal resonance, increasing tidal amplitudes throughout the Bay of Fundy and Gulf of Maine. In a modeling study on the effect of tidal turbine arrays on the tidal regime, intertidal zones, and flushing time, Nash *et al.*[126] pointed out the tidal range upstream of the tidal arrays could be affected significantly, varying from approximately 5–42% depending on the size of the tidal array. Similarly, intertidal mudflats could be affected by 14–32% and thus result in loss of nearshore habitat.

In addition to currents and water level, another important parameter used to characterize the far-field, or system-wide effect of tidal stream energy extraction is the transport timescale, such as flushing time, residence time, and age, of a system where the tidal turbine arrays are installed. Information on the effects of tidal energy extraction on residence time and water renewal can be used to guide the optimal siting and layout of tidal turbine arrays during the permitting process. A detailed review on the methodologies of assessing the impact of tidal stream energy extraction on transport timescales was provided by Yang and Wang.[127] For example, based on simulated tracer concentrations with and without tidal turbine arrays (Fig. 6), Yang and Wang[127] showed that if a 10% change in flushing time is the acceptable upper limit for the environmental concern due to tidal energy extraction in Tacoma Narrows, USA, a smaller percentage reduction in volume flux must be considered because the change in flushing time is several times greater than the change in volume flux. Guillou *et al.*[128] used model simulations to evaluate the effects of tidal turbine arrays on water renewal in a tidal stream energy site of the Fromveur Strait in northwestern coastal waters of Brittany, France. Their study demonstrated that the residence time in the tidal stream energy site was modified by less than 5.3% with an array of 207 tidal turbines. Nelson *et al.*[129] developed a modeling framework for optimizing tidal turbine deployment in Cobscook Bay in Maine that maximizes the energy extraction with consideration of environmental constraints, such as criteria for the changes to flow fields and bed shear stress. James *et al.*[130] applied a similar modeling approach to design turbine arrays in the Tanana River, Alaska, and evaluated the effects of different array layouts on power production and environmental impacts.

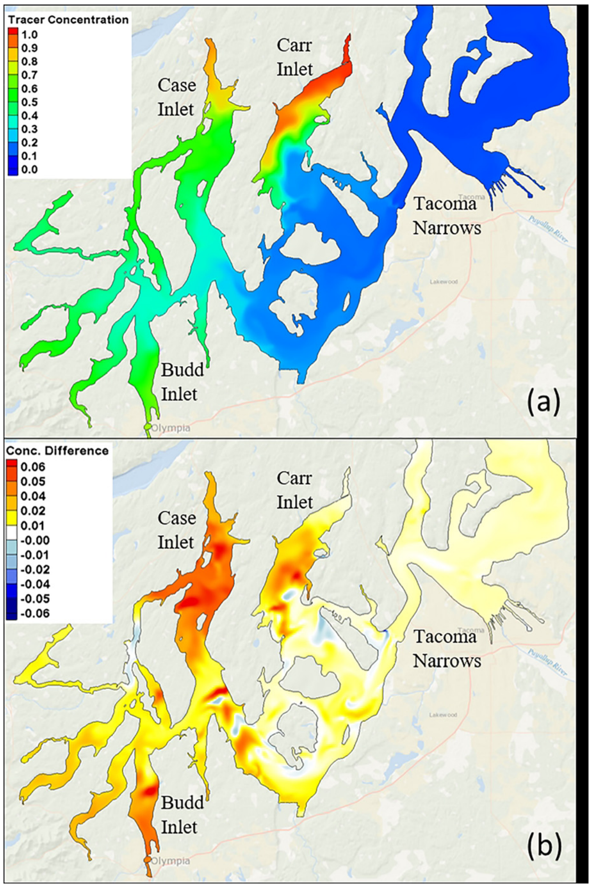


FIG. 6. (a) Simulated instantaneous tracer concentrations without tidal turbines in the South Puget Sound (baseline condition). (b) Difference in tracer concentrations between the tidal turbine array (63 MW extraction) and baseline conditions in the South Sound. Tidal turbines were deployed in the Tacoma Narrows of Puget Sound. Reproduced with permission from Yang and Wang, Effects of tidal stream energy extraction on water exchange and transport timescales, in Marine Renewable Energy, pp. 259–278 (Springer, 2017). Copyright 2017 Springer.

B. Biogeochemical processes

Marine biogeochemical processes, such as water quality, sediment transport, nutrients, and marine habitats, are driven by coastal hydrodynamics. When the physical processes, including flow field, turbulence, vertical mixing, residence time, and bed shear stress, are modified due to the operation of tidal turbine arrays biogeochemical processes will also be affected.[119,123,131,132] Changes to water quality such as dissolved oxygen, nitrogen, turbidity, and primary production in a marine system will ultimately affect the marine ecosystem services. Modification of turbulence characteristics and bottom shear stress within the vicinity of the tidal turbine array will also cause sediment erosion, re-suspension, and deposition. While there have been many studies conducted to investigate the effects of tidal energy extraction on the ambient hydrodynamics, studies on the effect of tidal energy extraction on biogeochemical processes are extremely limited. Therefore, there is a strong urgency to promote the research to assess the effects of tidal energy development on biogeochemical processes and minimize the negative impacts.

Wang *et al.*[132] discovered that tidal stream energy extraction in a tidal channel can result in either positive or negative impacts to the water quality of a system, based on an idealized case of a tidal channel connecting with a coastal bay. Energy extraction by the tidal turbine array decreased flushing rates in the bay, which causes a negative impact on the water quality in the coastal bay. However, tidal energy extraction also enhanced vertical mixing, which could lead to higher bottom dissolved oxygen. Ashall *et al.*[133] simulated tidal energy extraction in the Mina Passage of the Bay of Fundy, Canada, and found that a high power extraction case (5.6 GW) will cause 15% change in tidal amplitude, 10% change in velocity, and 37% change in suspended sediment concentration (Fig. 7). Nash *et al.*[126] showed that the flushing time would be significantly altered if tidal turbine arrays were installed in the Shannon Estuary in the west of Ireland. Ahmadian *et al.*[134] applied a hydro-environmental model to investigate the impacts of tidal energy extraction on water levels, tidal currents, and sediment and fecal bacteria levels in the Severn Estuary and Bristol Channel, UK. Their study found that 200 tidal turbines with 20 m diameter would cause noticeable changes of current speed and suspended sediment concentrations within 15 and 10 km from the turbine array, respectively. Shapiro[135] applied a 3D coastal ocean model to simulate the effect of tidal energy extraction on far-field current distribution and transport process in the neighboring Celtic Sea. By simulating the presence of a hypothetical tidal array, current speeds in the vicinity of the array were significantly reduced due to tidal energy extraction and the backwater effect. In particular, residual tidal currents and pollutant transport were affected as far as a hundred kilometers away from the tidal turbine array.

A detailed review was provided by Neill *et al.*[136] on the impact of tidal (and wave) energy extraction on sediment dynamics. Neill *et al.*[137] first demonstrated that sediment impacts of tidal energy arrays are not confined to the site of energy extraction, but can extend over distances of up to 10 km. Other factors on the siting of tidal arrays are important, such as increased impacts in regions of tidal asymmetry[137,138] and the proximity to headland systems (regions of strong tidal flow) affecting the morphodynamics of associated headland sand banks[139]—large sedimentary features that protect the neighboring coastline from the impact of waves. Goh *et al.*[140] investigated the effect of tidal energy extraction on flow field and sediment erosion adjacent to headlands along Negeri Sembilan (Malaysia) coastlines using

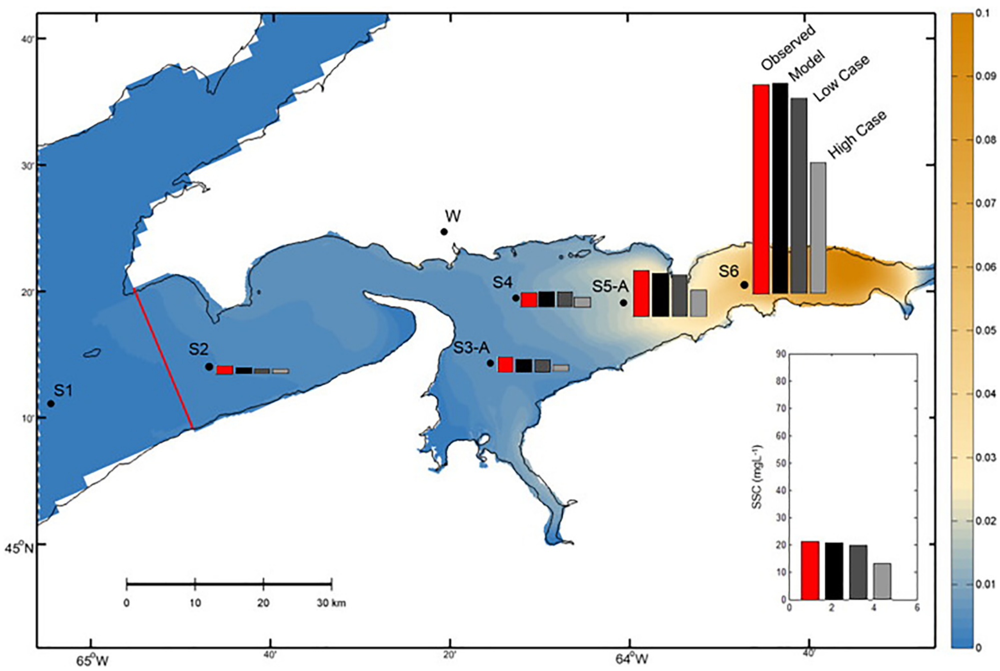


FIG. 7. Predicted time- and depth-averaged fine suspended sediment concentrations (mg L^{-1}) at five sites (S2–S6) in the Minas Passage over the period June 6–13, 2013. Bar plots indicate the observed (red) and predicted (black = no turbines; dark gray = low power extraction case; light gray = high power extraction case) time- and depth-averaged SSC. Reproduced with permission from Ashall *et al.*, Coastal Eng. **107**, 102–115 (2016). Copyright 2016 Elsevier.

numerical modeling. Their study showed that the deployment of a tidal energy array resulted in reduced velocity and increased sediment deposition within the vicinity of the tidal array, and increased velocity accompanied by sediment erosion along either side of the tidal array. It is also important to consider the impacts on sediments in relation to natural variability. For example, during summer months, when natural variability of waves and hence sediments is lower, the impact of tidal energy extraction will be relatively greater than during the energetic winter months.[141] Prior to the construction of large arrays of tidal energy devices, impacts on sediments can only be assessed via numerical models. There are various techniques to incorporate energy extraction into numerical models[139,141,142] and no standardized methodology, and therefore, *in situ* validation of such models and benchmarking against laboratory experiments is an important step. Finally, tidal range schemes (Sec. II) are likely to have significant impacts on the sediment dynamics of a region, due to the presence of the artificial embankment and the operation of the turbines. The region inside the lagoon will be characterized by reduced energy, especially during periods of holding,[136] leading to reduced sediment concentrations in the water column and increased sedimentation.[143] Closely spaced turbines in one section of the lagoon wall will lead to strong wake effects, further disturbing the sediment regime—increasing the spacing of these components of the lagoon along the embankment as much is practically feasible will reduce such impacts.[144]

VI. DISCUSSION—FUTURE RESEARCH DIRECTIONS

A. Semi-diurnal and fortnightly variability

One of the major advantages of tidal energy is predictability. However, this predictability is associated with variability at two main timescales: semi-diurnal and fortnightly (spring/neap cycle).

It could be possible to phase tidal power plants along a coastline to minimize the semi-diurnal variability of the aggregated power signal,[14] but it has been demonstrated that for shelf sea regions, the currents at the most energetic "hot spot" sites are either in phase with one another or 180° out-of-phase,[145] and hence so would be the aggregated power signal. However, by diversifying tidal stream site selection to incorporate less energetic tidal current amplitudes in the energy mix, the resulting increased phase diversity has considerable advantages in minimizing variability at semi-diurnal timescales.[13] At fortnightly timescales, since the tides everywhere on Earth are simultaneously affected, it is not possible to significantly reduce variability. However, by selecting sites that exhibit larger ratios of M2:S2 amplitudes, it is possible to optimize multiple site selection, reducing fortnightly variability.[90] Such a reduction could also be achieved by optimizing the joint development of a range of semi-diurnal, diurnal, and mixed sites, considering the K1 and O1 constituents alongside the principal semi-diurnal constituents M2 and S2.[146] However, to counteract the spring/neap cycle, other forms of low carbon (renewable) energy conversion, or significant grid storage, will likely be required.

The development of less energetic tidal sites (to increase phase diversity) comes with its own set of challenges.[55] Such locations tend to be in deeper water, further from the coast (and hence grid connections), are potentially more exposed to waves, and the currents are less rectilinear. Therefore, the development of such sites requires a new type of device (e.g., a floating technology with yaw capabilities) and a new set of research questions (e.g., the interaction of waves with currents at such sites).[147] However, in addition to the advantage of increased phase diversity, there is also considerably more sea space available at such sites (Fig. 8). Taking an M2 current amplitude of 2.5 m/s as the current technology standard,[55] lowering the M2 current amplitude to 2 m/s approximately doubles the available sea space. Further reduction of the threshold to 1.5 m/s increases sea space by a factor of 8 compared to sites suitable for current technology. Note also that less energetic tidal sites, far offshore and so not suitable for grid connection, could be used to power the "blue economy," meeting the power demands of, for example, weather buoys, tsunami warning devices, communication, defense, and aquaculture applications.[148]

B. Turbulence

As seen in this review, numerous investigations have been performed that rely on numerical models and/or measurements performed in real sea conditions or in the laboratory. Despite these efforts, the understanding of processes controlling turbulence of tidal-stream energy sites is still incomplete for various reasons: (i) the difficulty with transposing experimental results to realistic sea conditions (which is partially due to similitude problem), (ii) the limitations of actual CFD (Computational Fluid Dynamics) models that cannot resolve the entire range of scales, and (iii) the scarcity of measurements in real sea conditions (for both ambient turbulence and wake-added turbulence). Future research is thus necessary to reduce uncertainties in turbulence predictions. The challenge will be to reliably model the interactions between ambient turbulence and the turbulence resulting from multiple (superimposed) wakes, and to predict the characteristics of wakes in real sea conditions, that is, with irregular sea bed, complex flow structure, and under the combined influence of waves and wind. Furthermore, existing studies show that the turbulence at tidal-stream energy sites is highly variable in space. To explain this heterogeneity, it is necessary to investigate the links between the local characteristics of turbulence and the (local and upstream) seabed morphology. In particular, it is not clear yet how different sea bed features (e.g., micro or macro seabed roughness, the presence of large boulders, abrupt changes of bathymetry) influence the turbulence. Finally, turbulence measurements are only available at specific locations, and so spatial coverage is incomplete. Although numerical models allow us to investigate the spatial distribution of turbulence, computational constraints mean that these models only cover short periods of time (ranging

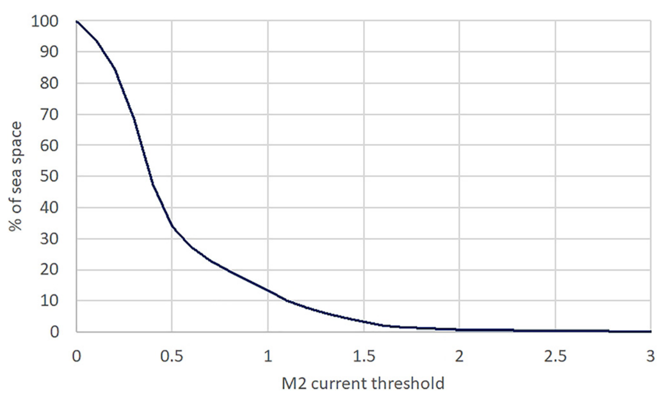


FIG. 8. Availability of UK shelf sea area (for water depths less than 100 m) for a range of M2 current amplitude thresholds.

from minutes to hours), thus preventing investigation of the wide range of realistic tidal flow conditions (e.g., spring/neap tidal cycles). It is thus important to combine different methodologies (numerical, laboratory, and *in situ* measurements) in order to achieve a better understanding of processes controlling the generation and the transport of turbulence.

C. Improved resource assessments

An ongoing challenge for the industry is how to best perform resource assessments and characterizations in a cost-effective manner, particularly for smaller scale projects. One option for addressing this challenge is the application of a measurement-based approach for resource assessments. The IEC technical specification for tidal energy resource assessment[24] specifies a methodology in which a fixed current profiler can be used to collect 90 days of continuous data. However, additional approaches using short-term high-resolution measurements need to be developed to eliminate the requirement for long-term measurements at the location of each turbine. These approaches can adopt recent developments in remote sensing applications for measuring tidal currents. For example, initial analysis of different measurement approaches for reconstructing volumetric currents including vessel mounted profilers, X-band radar, and surface floats has recently been completed.[149] Ongoing work needs to further develop these methodologies, combining short-term and long-term measurements to create the velocity probability distributions necessary for performing accurate AEP calculations.

D. Environmental impacts

Over the last decade, many studies have investigated the potential environmental impacts of tidal energy extraction on physical and biogeochemical processes in coastal bays and estuaries. Most of these studies are based on numerical simulations. However, model validation of the biogeochemical processes was rarely performed because of lack of field measured environmental data, especially pre- and post-tidal array installations. Therefore, conclusions drawn from unvalidated model simulations may be associated with high uncertainties. To increase model confidence in predicting the environmental impacts due to tidal energy extraction, it is important to collect field data relevant to environmental impacts to support model validation. Environmental impact modeling and related field measurements should be considered as an integrated element throughout the course of tidal array development. It is important to understand that tidal energy extraction is a 3D problem since tidal turbines are typically located at certain depths (hub height) in the water column, in the form of either free-floating or bottom-moored systems. Therefore, the environmental impacts associated with tidal energy extraction are also three-dimensional. To simulate the far-field and localized environmental impacts using numerical models, selection of models and specification of model resolutions are important.[150] It is not sufficient to use depth-averaged 2D numerical models in the context of tidal energy extraction, since 2D models are not able to simulate vertical variability in the flow field and the associated water quality and suspended sediment dynamics in the water column. To accurately assess the environmental impacts associated with tidal energy extraction, 3D models should be used. More importantly, water temperature, salinity, vertical mixing, stratification, and estuarine circulation induced by density gradients should be considered.[151] The biogeochemical processes must be dynamically coupled with the coastal circulation models with the capability of simulating tidal energy extraction. It is worth noting that the effects of tidal energy extraction on biogeochemical processes may not always be negative, because of the complex interplay of multiple factors. For example, increased mixing in the water column as a result of tidal energy extraction could potentially reduce the hypoxia problem in an estuary.[132] Furthermore, because estuarine biogeochemistry and sediment transport are long-term processes, model simulation periods should be of sufficient length to cover the seasonal variabilities that are governed by other factors such as river discharge, heat flux, and longer-term sea-level rise.

VII. CONCLUSION

Tidal energy, consisting of tidal range and tidal stream, has huge global potential, but there are several research challenges that must be addressed before realizing even a fraction of this potential. In this article, we have identified several evolving research areas that will help enable this goal. These are:

- Exploitation of the phasing between multiple tidal range or tidal stream locations to minimize variability in the aggregated power output. Since there is more phase diversity offered by less energetic sites, the unique site characteristics of these locations lead to additional related research topics, including the interaction of waves and currents at such exposed sites.
- Improvements in simulating the interactions between the ambient turbulence and the turbulence resulting from multiple (superimposed) wakes, and in predicting the characteristics of wakes in real sea conditions, that is, irregular sea bed, complex flow structure, and under the combined influence of wind and waves.
- Improved resource assessment and characterization through novel approaches using short-term high-resolution measurements (e.g., using X-band radar and vessel mounted profiles) to eliminate the requirement for long-term measurements at the location of every turbine within an array.
- Increased confidence in predicting the environmental impacts of tidal energy extraction, by collecting appropriate field data relevant for validating numerical models that are used to assess impacts to a range of physical and biogeochemical processes. Environmental impact modeling and supporting field measurements should be considered as an integrated element throughout the entire course of tidal power plant development.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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