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Review

2002–2012: 10 Years of Research Progress in Horizontal-Axis Marine Current Turbines

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Abstract: Research in marine current energy, including tidal and ocean currents, has undergone significant growth in the past decade. The horizontal-axis marine current turbine is one of the machines used to harness marine current energy, which appears to be the most technologically and economically viable one at this stage. A number of large-scale marine current turbines rated at more than 1 MW have been deployed around the World. Parallel to the development of industry, academic research on horizontal-axis marine current turbines has also shown positive growth. This paper reviews previous research on horizontal-axis marine current turbines and provides a concise overview for future researchers who might be interested in horizontal-axis marine current turbines. The review covers several main aspects, such as: energy assessment, turbine design, wakes, generators, novel modifications and environmental impact. Future trends for research on horizontal-axis marine current turbines are also discussed.

Keywords: marine renewable energy; horizontal-axis marine current turbine; marine current energy assessment; marine current turbine wake; generator

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1. Introduction

The energy crisis has long been one of the top concerns for mankind because modern lifestyles rely heavily on electricity [1]. Conventional electricity generation using fossil fuels alone is viewed as insufficient and unsustainable to support the needs of a worldwide population of more than seven billion people. In addition, the burning of fossil fuels produces undesired greenhouse gases. Decades ago, in order to create a sustainable environment, researchers and developers started the journey of researching potential renewable energy resources [2–5] and of trying to harness those energy sources for electricity generation through the development of innovative technologies. Currently identified renewable energy sources include solar energy, hydropower, wind energy, geothermal energy, biomass energy and ocean energy.

Ocean energy or marine renewable energy, which to most people is an unfamiliar renewable energy resource, has undergone notable growth in the past decade [6,7]. The oceans store enormous amounts of energy, which could be harnessed in different ways. The forms of ocean energy can be categorised into tidal, wave, current, thermal gradient and salinity gradient [8,9]. Of these five categories, the most significant developments of the past decade have been in both tidal and wave energy, with notable research carried out by various research groups, as well as some technology demonstrations presented by different developers. Tides and waves are said to have great potential for providing predictable and consistent power generation [10–13], in comparison with solar and wind energy, which are subject to weather fluctuations that are much more difficult to predict.

In the field of tidal or ocean current energy, the horizontal-axis marine current turbine (hereinafter known as HAMCT) has undergone intensive research in the past decade. Compared with other devices, currently the HAMCT appears to be the most technologically and economically viable one and a number of large-scale marine current turbines have been deployed [6,7]. As a result, some academic researchers have occasionally reviewed the technology of HAMCTs demonstrated by industrial community [14–17]. Most of these reviews focus on industry developments, but seldom discuss the progress of research in academia, yet parallel to the development in industry, research on HAMCTs in academia has also shown positive growth. Therefore, it is definitely worthwhile to investigate the growth in tidal and ocean current research over the past decade.

It is foreseeable that this particular field will continue to develop at an increasing pace and a growing number of countries will start to look into the feasibility of tapping marine renewable energy. Hence, a review on past developments in academia at this point could provide a concise overview for researchers who might be interested in exploring this field in near future. This paper aims to gather and review briefly the research outcomes published by various researchers worldwide (special focus is given to those research groups that have published many series of works) during the past decade and to provide an overview of research trends in the HAMCT research community. It is also hoped that this paper might help researchers, new to the HAMCT field, identify easily those experienced researchers within the community.

2. Research

2.1. Energy Resource Assessment

Examining the open literature, the majority of the research has started with the ultimate aim of installing a real large-scale marine current (hereinafter used to represent tidal and ocean current unless otherwise specified) energy extraction device. For a successfully developed device to generate the quantity of electricity for which it is designed, it is important to identify the availability of marine current energy resources at potential sites. In a review by Blunden and Bahaj in 2006 [18], the beginning of marine current energy assessment on the northwest European continental shelf can be traced back to the late 1970s, when different researchers applied different approaches for estimating the available marine current energy. Pioneering efforts by European countries and North America in initial energy assessment work was not surprising because marine renewable energy had already gained their attention [8,19]. At that time, the majority of marine current resources were said to be located in these two areas.

In fact, most of the countries that in the past decade have been actively involved in estimating potential marine current energy availability (mostly focused on tidal current energy) are within these two continental regions, which will be discussed in the following sub-sections. The assessment generally started with the measurement and modelling of current velocity and tide height at the identified potential sites, followed by the calculation of the energy density. The estimated energy can be categorised into two types: one is the total available energy, which is the energy possessed by the undisturbed current flow and the other is the energy extractable by the turbine after consideration of hydrodynamic factors, the efficiency of the devices and environmental aspects.

2.1.1. Research on Theoretically Extractable Energy

To the best of authors' knowledge, there are two groups of researchers that throughout the past decade, have attempted to determine the theoretical extractable marine current energy. In the UK, Bryden and Couch along with their co-workers [20–27] have focused on the extractable energy. They developed a simple one-dimensional open channel flow model to investigate the maximum extractable energy from a tidal channel without significantly altering the hydrodynamic nature of the flow. Based on their findings, they proposed that the limit of extractable energy should be 10% of the accessible undisturbed kinetic energy flux of the marine current [20,21]. They also studied the possible changes in current velocity when the marine current turbine is present in the channel by using a Tidal Development Model (TDM), which is a numerical model developed at the University of Strathclyde [22,24,25].

Success in studying the changes of current velocity flow pattern caused by marine current turbines is said to be crucial for understanding the possible changes in the tidal system [26,27]. In addition, the changes in current velocity might not occur just around the extraction plane but could extend to the upper surface flow, the lower near seabed boundary flow and the downstream flow. These changes in current velocity profile could affect the total extractable energy, either positively or negatively, if the marine current turbine were to be deployed in large arrays [23]. The numerical study in [22] also revealed that the changes in current velocity, due to the operation of marine current turbines, would

potentially cause environmental impact, such as seabed scour and disturbance of marine microorganisms at the ocean surface.

Garrett, Cummins and co-workers from Canada [28–34] also studied the maximum extractable energy by using a fence of marine current turbines. Their work was focused on the channel connecting two basins and a channel connecting a bay with the open ocean. They developed an equation to estimate the maximum power for the channel connecting two basins (for details of assumptions and derivations, see reference [29]), as well as the channel connecting a bay with the open ocean (for details of assumptions and derivations, see references [28,32]). In contrast to the simple open channel model proposed by Bryden and Couch (considering the flow to be driven by static head difference), the equation developed by Garrett and Cummins for the channel connecting two basins, considers the flow to be driven by pressure gradient (caused by the surface elevation of the natural sinusoidal tide). In addition, Garrett and Cummins's model includes the fraction of the channel that is occupied by the fence of marine current turbines; whereas Bryden and Couch merely assumed a 10% extraction of energy without considering the blockage effect of the marine current turbine in the channel.

Based on Garrett and Cummins's calculation for the channel connecting two basins, the maximum extractable energy by using a uniform fence is approximately 22% of the peak tidal pressure head across the channel, times the peak volume flux in the undisturbed state [29]. The equation derived in [29] was validated numerically by using a two-dimensional finite element model (TIDE2D), which was used to evaluate the maximum tidal power in the Johnstone Strait, Canada [31]. However, the maximum extractable energy given by the equation will lead to a drop of volume flux by up to 42% of that in the natural regime. For environmental considerations, they decided to allow only a 10% reduction in current. This limit allows only 44% out of the 22% suggested in the equation to be harnessed. Consequently, the suggested limit of extractable energy becomes approximately 10% of the peak tidal pressure head across the channel, times the peak volume flux. This agrees surprisingly well with the limit suggested by Bryden and Couch, although the two models are different.

The model developed by Garrett and Cummins was further extended for the channel connecting a bay with the open ocean, as developed in [28] and [32]. The initial assumption was that the availability of the power could be derived from the potential energy stored inside the bay at high tide. Using their calculations, they showed that the power ratio is sensitive to the ratio between the surface area of the bay to the cross-sectional area of the entrance. Thus, they stated that simple kinetic energy flux is not suitable to be used directly for the channel connecting a bay with the ocean, because it is likely to overestimate the available energy. After taking into consideration the dynamic balance for the model, the maximum extractable power for the channel connecting a bay with the ocean was found to be 22% of the tidal pressure head outside the bay, times the peak volume flux in the undisturbed state for any bay geometry. This allowable percentage is similar to that derived from the model of the channel connecting two basins.

Although the value of maximum power for the two models is the same, the tidal pressure head used for the two models is different. For the channel connecting two basins, the tidal pressure head means that it is the tidal head across the channel that is important. For the channel connecting a bay with the open ocean, the tidal pressure head means the amplitude of the dominant tidal constituent in the open ocean just outside the channel connected to the bay. The amplitude of the dominant tidal constituent is usually much larger than that of the tidal head. In addition, this potential energy is usually larger than

the kinetic energy flux but for the channel connecting the bay to the open ocean, the reduction in flow through the passage might have a bigger impact. Hence, there is a trade-off between the extractable energy and the impact on tides (we acknowledge an anonymous reviewer's comment for this notion).

Another argument from Garrett and Cummins based on their analysis and worth noting is that the classic Lanchester-Betz limit, which is traditionally used as the benchmark of the upper limit for wind turbine energy yield, is not suitable to be transferred directly and used for marine current turbines [30]. The applicability of the Lanchester-Betz limit for marine current turbines was questioned by Gorban and co-workers back in 2001 [35]. The applicability of the Lanchester-Betz limit for marine current energy was discussed in their attempt (utilising uniform fences of marine current turbines that only occupy a fraction of a channel's cross-sectional area) to investigate the maximum extractable energy that can be harnessed. They introduced a factor of blockage ratio (ratio of area of marine current turbine fence, to the channel's cross-sectional area) into the Lanchester-Betz theory.

The first scenario considered by Garrett and Cummins was an isolated ideal turbine in a channel. They developed an equation to calculate the power availability based on the combination of integral forms of the continuity, momentum and energy equations. The velocity terms they defined included: initial upstream velocity, velocity flow through the turbine, velocity of the downstream wake and velocity outside the downstream wake (not equal to far end upstream velocity). The streams bypassing the turbine are allowed to merge at the downstream wake region, which eventually restores the velocity to the same as the initial velocity. When they assumed the channel's cross-sectional area to be so large (infinitely wide compared with the turbine) that the velocity outside the downstream wake becomes equal to the initial velocity, they obtained the same result as the Lanchester-Betz limit. Such a large unconfined channel flow assumption might be true for wind turbines, or a single turbine that occupies only a very small fraction of the channel's cross-sectional area. However, this assumption becomes impractical when the single turbine occupies a large fraction of the channel's cross-sectional area (or marine current turbine fences that occupy large fractions of channel's cross-sectional area).

The efficiency of an ideal turbine, which occupies a small fraction of a channel's cross-sectional area, was proven by them to be in agreement with the Lanchester-Betz limit. In this case, the extractable energy that could be harnessed was about 67% of the available energy that a channel could provide. For an ideal turbine that occupies a large fraction of the channel, the efficiency of the turbine increased beyond the Lanchester-Betz limit. This extra efficiency was claimed to be the result of a higher pressure drop across the channel, due to the confining influence of the channel boundaries. However, under such conditions, the extractable energy that could be harnessed drops to 33% of the available energy that a channel could provide. This is somehow illogical, as one would expect higher extraction when there are more turbines inside the channel. This occurs because their model is not valid when the blockage ratio approaches one. Nevertheless, the range of 33%~67% revealed that there is a limit for extractable energy. Moreover, this range has yet to take into account the possible changes in the hydrodynamic pattern of the channel flow.

In the second scenario, in which Garrett and Cummins considered that those streams that bypass the turbine do not merge with the downstream wake, the efficiency of the turbine differs from first scenario. Their obtained efficiency of the turbine falls into a range of 0.59~0.38, as the fraction occupied by turbines increases from small to large. Findings obtained from two different scenarios in [30] suggested that the Lanchester-Betz limit is not suitable to be used directly to estimate the

efficiency of marine current turbines. Modification of the Lanchester-Betz limit with a blockage factor is also required, based on Garrett and Cummins's work. This finding agrees with the fact that only a fraction of the total available energy from a channel could be harnessed, which suggests that using a simple kinetic energy flux might lead to an over- or underestimation of extractable energy from a channel. Instances where the extractable energy was underestimated by using a simple kinetic energy flux happened in the case of the channel connecting a bay and the ocean.

An apparent real example is the energy assessment conducted by Karsten and co-workers in estimating the extractable energy from the Minas Passage in Canada. Karsten found that the power estimated by Triton Consultants Ltd. using kinetic energy flux gives only 1.9 GW for the Minas Passage. This value is significantly less than the power estimated based on twice the mean potential energy released over half a tidal period, which gives a value of more than 10 GW. However, the maximum extractable power, estimated by Karsten using the equation derived by Garrett and Cummins in [28], gives a value of 7 GW. As discussed by Karsten, extracting energy from a flow will actually increase the tidal head across the channel and drive more flow passing through the channel. Hence, a simple kinetic energy flux that does not take into account the potential energy will eventually underestimate the available energy. This proves that the assumption by Garrett and Cummins in [28], which is the estimation of available energy based on potential energy stored in a bay, is reasonable.

This interesting feature, which gives higher estimated energy than a simple kinetic energy flux, had already been observed by Bryden and Couch [20]. As their model was based on kinetic energy flux, they were surprised by the small reduction in the flow speed when they allowed for 30% energy extraction. They also came to the conclusion that extracting energy would increase the head difference across the channel because of the decrease in the rate of loch filling or emptying. Garrett and Cummins's theory in [34] was checked with a case study to estimate the marine current energy at Masset Sound, Haida Gwaii [33]. This is also a case study of a channel connecting a bay to the ocean. The extractable energy estimated using the theory gives a value of 79 MW. Although not shown by them, this value is two times higher than the extractable energy estimated using kinetic energy flux. All these findings show that in order to carry out a reliable preliminary energy assessment, selecting a suitable method is important.

Research outcomes from these two groups have had effects on the research into energy assessment carried out by other researchers. Vennell from New Zealand brought Garrett and Cummins's models to another level by combining the models proposed in [29] and [31] with a more precise tuning of flow through the turbine [36–39]. The tuning parameters suggested by Vennell include the blockage ratio, the ratio of downstream wake velocity to initial upstream velocity and the density of the turbine (for details of assumptions and derivations, see reference [36]). By using various contour plots relating the three tuning parameters, Vennell demonstrated that it is possible to extract more energy by occupying a larger fraction (higher blockage ratio) of the channel. This contradicts the finding of Garrett and Cummins in [30]. This contradiction, as mentioned by Vennell, is due to the fact that the optimal tuning (ratio of downstream wake velocity to initial upstream velocity) is not constant in a tidal channel that is driven by a head loss.

In the first scenario discussed by Garrett and Cummins in [30], they assumed that the optimal ratio of downstream wake velocity to initial upstream velocity remains constant (a value of 1/3), even when the fraction of turbines inside a channel changes from single ideal turbine to a turbine fence. This

means that the efficiency of each turbine in a turbine fence would need to be limited in order to achieve the 1/3 optimal ratio. However, this is not practical, because when the turbines are tuned to the flow conditions, the efficiency of turbines could actually be increased as the fraction of the turbines inside a channel is increased, which is as reported by Vennell. In addition, the feedback effect of the tidal fence on the tidal head was not included. All these reasons limit the validity of Garrett and Cummins's models when the fraction of turbines in a channel approaches 100%. When the optimal tuning is allowed to vary, the extractable energy could approach almost to 100% as the fraction of turbines in the channel approached 100%. The success of Vennell's effort in combining Garrett and Cummins's models allows the optimal tuning, in order to maximise extractable energy, to vary from 1/3 to 1. The estimated extractable energy changes smoothly from the Lanchaster-Betz theory (using kinetic energy flux) to the head loss across the tidal fence, when the optimal tuning varies from 1/3 to 1 [36]. One more advantage of the combined model is that the number of turbines can be determined for any optimally tuned turbine. The proposed model was tested to estimate marine current energy from the Cook Strait and Kaipara Harbour in New Zealand [38]. The difference between the estimated extractable energy using Vennell's model and Garrett and Cummins's model was also compared. Generally, the values obtained from both models are close to each other. A possible 60% reduction in current velocity was reported for both models and this percentage is also similar to the findings in [31].

In another attempt to understand the effects of the interaction between different marine current turbine rows in a channel and the maximum extractable energy, Vennell showed that the required optimal tuning for all turbine rows occupying a channel is almost the same. This optimal tuning is different from the optimal tuning of a single turbine row, which does not consider the presence of other turbine rows [38]. Such a tuning strategy was shown to give higher efficiency compared with the tuning of a single turbine row and the tuning based on the Lanchester-Betz limit. The interesting thing is that the efficiency of turbine farms based on such optimal tuning actually increases when the number of rows increases. This is very encouraging, because after almost a decade of endeavour, researchers have shown that it is theoretically viable to extract more marine current energy for a given channel by using the appropriate approach. The reader is referred to [39] for a short review of the relation between the models of Garrett and Cummins and Vennell.

Inspired by Garrett and Cummins's work, Atwater and Lawrence from Canada, looked into the maximum extractable energy in a split tidal channel, where only one of the sub-channels would have the marine current turbine [40]. Their model is said to be in agreement with the model of Garrett and Cummins of a channel connecting two basins and a case study was performed to estimate the extractable energy from the Current Passage in the Johnstone Strait. In addition to Garrett and Cummins, there are other researchers who have studied the applicability of the Lanchester-Betz limit. Whelan and co-workers tried to modify the Blade Element Momentum (BEM) theory for marine current energy assessment by incorporating the effects of free-surface proximity and blockage [41]. They also incorporated the Froude number into their analysis. Their free-surface proximity model expresses bypass velocity (similar to velocity outside the downstream wake, as defined by Garrett and Cummins in [30]) in terms of the Froude number, axial induction factor and the blockage ratio.

Based on Whelan's model, allowing the Froude number to approach zero reduces the equation of bypass flow to the same as Garrett and Cummins's equation. Furthermore, allowing the blockage ratio to approach zero means that the equation will produce a coefficient that is the same as the

Lanchester-Betz limit. One interesting feature of the model is that at blockage ratios higher than 0.3, the power efficiency curve discontinues at values of induction factor smaller than 1. This feature was claimed to be a result of the bypass flow wake reaching a supercritical point. Experiments using porous discs were carried out to validate the theory. Whelan showed that the prediction of maximum power is in reasonable agreement with the experimental results under lower tip-speed ratio for highly blocked flows. The predicted efficiency is higher than the Lanchester-Betz limit. In fact, Whelan and co-workers started to look into the effects of free-surface proximity back in 2007 [42]. However, they did not compare their model with Garrett and Cummins's model at that time.

2.1.2. Numerical Assessment

Apart from the aforementioned numerical studies used to check the models proposed by Bryden and Couch's group and Garrett and Cummins's group, other researchers have suggested and used different numerical analyses to estimate the tidal range and extractable marine current energy in their sites of interest. Some of the numerical modelling research done in the past decade is listed in Table 1.

Table 1. Numerical assessment of marine current energy by various researchers.

Year	Place	Model	Developer	Reference
2006	Portland Bill, UK	TÉLÉMAC	Électricité de France	[43]
2007	Raz de Sein, Brittany, France	Matlab-Simulink	MathWorks	[19]
2008	Minas Passage, Bay of Fundy, Canada	2-D finite-volume model (FVCOM)	C. S. Chen, Cowles G & Beardsley	[44]
2009	Ría de Muros, Spain	Delft 3D-FLOW	Delft Hydraulics	[45]
	Various sites in Norway	Bergen Ocean Model & High Resolution Tidal Model	University of Bergen & University of Oslo	[46]
	Puget Sound, Washington, USA	1-D time dependant model	University of Washington	[47]
2010	Various sites in Ireland	2-D depth-integrated numerical model	RPS Kirk McClure Morton	[48]
	South Wales coast, UK	Refined finite volume numerical model	Cardiff University	[49]
	Various sites in Malaysia	Princeton Ocean Model (POM)	Princeton University	[50]
2011	Georgia coast, USA	Regional Ocean Modelling System (ROMS)	Rutgers IMCS Ocean Modelling Group	[51]
	Verde Island Passage, Philippines	Delft 3D	Delft Hydraulics	[52]
2012	Langyatai Strait, China	Delft 3D-FLOW	Delft Hydraulics	[53]
	South Carolina coast, USA	Regional Ocean Modelling System (ROMS)	Rutgers IMCS Ocean Modelling Group	[54]

The table demonstrates the different approaches used in the research and provides an extensive view on which part on the globe is involved in marine current energy research. From Table 1, it is obvious that most of the early assessments were carried out in the two continents mentioned in Section 2.1. Countries outside of those two continents have only started to estimate extractable marine current energy using marine current turbines in recent years. Although the numerical models used differ from researcher to researcher, generally, the purpose of all numerical models is to simulate tidal flow. After obtaining details of the flow, such as current velocity and tidal height, the extractable energy can be estimated. Almost all the researchers listed in Table 1 have validated their simulated results obtained from numerical models. Some of them compared the simulated results with tidal flow data published by authorised government sectors, such as Blunden and Bahaj [43], Ben Elghali *et al.* [19] and Lim *et al.* [50]; whereas some of them, like Carballo *et al.* [45] conducted *in situ* measurement of tidal flow for validation purposes. However, there are some cases in which the simulated results were not properly validated, as in [52].

While simulating tidal flow is the main aim in most studies, there are exceptional cases where researchers used their numerical models for other purposes. For instance, Karsten and co-workers used the FVCOM model to check whether the equations proposed by Garrett and Cummins's group were applicable [44]. On the other hand, Polagye and co-workers used the one-dimensional time dependant model to quantify the effects of marine current energy extraction. The studied effects included changes of the tide, transport, power dissipation and kinetic power density. In addition to the numerical analysis, there have been attempts to estimate marine current energy analytically at Alderney Race in the UK [55], Cook Strait in New Zealand [38], the Agulhas Current along South Africa's East coast [56] and Khowr-e Musa Bay in Iran [57]. All these analytical studies of extractable energy were based on data published by authorised government sectors [55,57] and *in situ* measurements [38,56].

Despite the criticism by Bryden and Couch's group, Garrett and Cummins's group and Vennell on the subject of the applicability of kinetic energy flux, an interesting thing is that most of the studies listed in Table 1 still used kinetic energy flux for extractable energy estimation. However, some of them agreed and adopted the extractable limit, as suggested by Bryden and Couch or Garrett and Cummins, in estimating the extractable energy [46,47,53]; they just roughly estimated an extractable limit value that is lower than the Lanchester-Betz limit. Then, they used the proposed limit along with the kinetic energy flux equation to estimate the extractable energy. The authors' comment towards this situation is that some researchers might find it difficult to apply the equations discussed in Section 2.1.1, or that these researchers might not be aware of the existence of those theoretical works by Bryden and Couch, Garrett and Cummins and Vennell.

As marine renewable energy has been studied intensely throughout the past decade, guidelines for preliminary marine current energy assessment have been published in Europe [58] and the USA [59]. However, as a reminder, most of the mentioned assessments in this section and Section 2.1.1 are preliminary studies, which do not consider the types, actual design and efficiency of HAMCTs. However, it is still essential to understand the availability of extractable marine current energy before moving into other aspects of HAMCTs, such as design considerations for optimum performance, hydrodynamic of marine current flow around HAMCTs and generator issues.

2.2. Performance of Marine Current Turbines

Although there are similarities between the operating mechanisms of wind turbines and HAMCTs, different working fluids and the environment of the ocean makes the design criteria for HAMCTs different from that of wind turbines [60]. As mentioned in a previous section, most of the earlier research started with the aim of the actual deployment of marine current turbines. As a result, particular interest was paid in the initial stages to the potential energy yield at the sites of interest. Nevertheless, it is unlikely that a reliable energy yield would be obtained if the behaviour of the marine current turbine is not clearly known. Moving into the second stage, the actual performance of marine current turbines deployed at the sites, either singly or in arrays, became an important question to be answered.

Throughout the past decade, much research has been carried out through simulations and experiments, in order to understand the hydrodynamic design parameters of HAMCTs. Apart from the basic design parameters, researchers also tried different approaches to establish ways of optimising device performance and these approaches included: finding the optimum depth position for the turbine in the marine current flow, determining the optimum layout for turbine arrays, studying suitable generators for constant output and the modification on design through built-in auxiliary systems, such as ducts. From time to time, novel designs that differ from conventional turbines were also proposed by some researchers.

2.2.1. Design Consideration

Since the early 2000s, a research group led by Bahaj from the UK has been actively involved in the study of HAMCTs. The scope of the research carried out by this team covers energy yield estimation [43,55,61], hydrodynamic design parameters [62,63], turbine performance [64–67] and flow field patterns around turbines [68–77]. A significant number of published works on the study of flow fields should be accredited to Myers. These research works were conducted step-by-step, involving analytical, numerical, simulation and experimental work. Research by the team has also gradually switched from the study of the hydrodynamic characteristics around individual turbines, to that of arrays or multiple-rows of turbines (as discussed in the next section).

Regarding hydrodynamic design parameters, Bahaj and co-workers have studied the characteristics of lift, drag and cavitation of two-dimensional foil sections (derived from the NACA series), both numerically and experimentally. Particular interest was paid to cavitation inception and the results showed that the cavitation-free bucket changes with respect to the section chamber [62]. Based on the findings on blade section studies, another numerical study was performed to investigate the change in stall performance and it was found that cavitation delay results from different blade pitch angle or changes in the chamber [63]. It was shown that for tidal flows greater than 2.5 m/s at 0° pitch, the stall is delayed.

An experiment using an 800-mm-diameter three-bladed horizontal-axis turbine was carried out by Bahaj and co-workers to study the performance of HAMCTs under different flow conditions. It was found that the power decreases when the turbine is in a yawed condition or when the turbine tip immersion is reduced; whereas a study on two turbine rotors working in close proximity showed no

significant loss of performance [64]. Based on the same experimental data, the team tested a numerical model developed by them and applied the model to estimate the performance of an assumed large-scale turbine. They reported that when the design speed increases from 2 to 3 m/s, there is a trend of slowing in the energy increment together with large increases in maximum thrust [65]. This implies that the structure of the HAMCT would need to carry greater loads for a small increment in annual energy output. Other numerical methods were also validated using the data from this experimental work and were used to predict the performance of a large-scale turbine by Bahaj and co-workers [66,67].

The reasons for choosing an 800-mm-diameter three-bladed horizontal-axis turbine for the experiment are due to the consideration of the Reynolds number and the blockage effect. The experiment was tested in a cavitation tunnel with a cross-sectional dimension of 2.4 × 1.2 m and a towing tank with a cross-sectional dimension of 3.7 × 1.8 m [64]. Hence, the portion of the tunnel occupied by the turbine must be limited; otherwise, excessive tunnel blockage correction might be required. In their later work, this diameter was claimed to be a 1/20th scale model of a 16-m-diameter HAMCT. The reason for this was not mentioned in their work but interestingly, this 16 m value coincides with the diameter of a twin-rotor used by Marine Current Turbines Ltd. in their SeaGen project (the first large-scale commercial HAMCT) deployed in 2008. The blades were designed by modifying the profile shape of the NACA 63-8xx series aerofoil.

Bahaj's team compared two simulation tools (a commercial code, GH-Tidal Bladed and an academic in-house code, SERG-Tidal) with the data generated from the aforementioned experiment [66]. Both simulation models are based on BEM theory with modifications necessary for marine current energy applications. It was demonstrated that both models give similar values of the power and thrust coefficient to the experimental value for tip speed ratio, ranging from 4 to 7. However, there is a general trend for both models to overestimate the power and thrust coefficient for tip speed ratios larger than 7. Bahaj's team explained such a phenomenon as the result of errors in the large blockage corrections for the experimental data, or perhaps because the turbulent wake correction for both models was not appropriate. Anyhow, this reveals the limitations of BEM theory for HAMCT design. For any preliminary design of HAMCTs, BEM theory must be extended accordingly to give a more reliable result.

In addition to Bahaj's team, Coiro and co-workers from Italy also conducted experiments to study the hydrodynamic parameters of a small-scale horizontal-axis turbine [78]. The hydrofoil used was a combination between an *ad hoc* designed thick aerofoil and a modified S805 aerofoil. The numerical model used and the scale of the turbines were not described in detail. Hence, it is not suitable to make comparisons between their results and Bahaj's results. However, the use of a different hydrofoil showed that the power coefficient of HAMCTs made of different hydrofoils will vary significantly even under the same operating configuration, such as pitch angle and flow velocity. A recent work reported by Jo and co-workers [79], which utilised an S814 series aerofoil for the turbine blade, created by the National Renewable Energy Laboratory (NREL) in the USA, showed a better power coefficient compared with that reported by Bahaj and Coiro. Experimental results and Computational Fluid Dynamics (hereinafter known as CFD) analysis have shown that the turbine could perform well in a velocity of 1.0 m/s. The maximum power coefficient of the turbine could reach up to 0.51 when the tip speed ratio is at 5.

Although thrust coefficient can provide some information on the load imposed on HAMCTs, Bahaj's team have only recently started to look into the loading on turbine blades [80]. There were cases of blade failure experienced by some HAMCT developers in the early stages of prototype testing [60,81–83]. The actual inflow speed was a few times higher than the designed inflow speed and the blade was under-designed to tackle the load. Hence, understanding the loading acting on the blade is also crucial in the design of HAMCTs. In 2007, Barltrop and co-workers studied the effects of waves towards loading on turbine blades using an extended BEM model. It was found that a shorter wave might lead to the stalling of the blade and consequently, increase the axial loading on it [84] Experiments were conducted to validate the model. Their process of aerofoil selection is different from that of Bahaj's team. The S814 series created by NREL was selected and used to achieve the experiment requirements.

McCann studied fatigue load experienced by three-bladed turbines under different flow environments using the commercial code, GH-Tidal Bladed [85]. McCann concluded that mean flow turbulence affects the variation of fatigue loading on turbines appreciably, which suggested that detailed tidal flow measurement studies are essential when designing HAMCTs for any sites. Nicholls-Lee and co-workers investigated the possibility of utilising adaptive turbine blades to improve performance of HAMCTs through a reduction of the thrust coefficient and thus, suggested that a shape changing blade (tailored with desired characteristics) could enhance the performance of HAMCTs [86,87]. Recently, Faudot and Dahlhaug tried to predict the wave load acting on a turbine blade through validation of two extended BEM algorithms using experimental data [88]. However, the focus was not given to the loading behaviour on blade caused by waves; the effects of the load on the turbine blade were not discussed in detail in their work.

Milne and co-workers studied the blade root out-of-plane bending moment coefficient under different oscillatory motions using a 780-mm-diameter rotor [89]. They showed that the unsteady bending moment is sensitive to the oscillatory frequency and amplitude. The point of flow separation was found to be sensitive to the frequency, as would be induced by surface waves and the depth-wise mean velocity profile. Flow separation occurs earlier at higher frequency and causes stall effects to persist for much of the oscillatory cycle. As a result, the stall will cause greater unsteady loads. Based on their findings, they suggested that those HAMCTs that are stall regulated or that operate in conditions where stall might be experienced would encounter faster fatigue failure.

2.2.2. Wake of Marine Current Turbine

A series of experiments was carried out by Bahaj's team to study the wake behaviour of HAMCTs. Both small-scale three-bladed horizontal turbines and static mesh disc rotors (also known as actuator discs) were used to investigate the wake. Studies were performed in order to understand the parameters affecting wake patterns [68–70], such as the thrust coefficient and the proximity to the free water surface or seabed. Their findings are listed as follows:

- Higher thrust coefficient leads to higher velocity deficit in near wake region [69],
- Wake persists further downstream when the turbine is placed in deeper water, where the distance from the turbine to the seabed is considerably large with respect to the turbine diameter [70],

- Close proximity to the free water surface and seabed causes wake recovery to become slower [71].

An eddy viscosity model was used to replicate the findings in [71] and was said to give a wake recovery trend that is similar to the wake recovery trend obtained from the actuator disc experiment. It should be noted that Bahaj and co-workers recognised the findings by Bryden [68], which led them to start studying the flow field around marine current turbines.

Apart from the far wake region, the flow field at the near wake region was also studied and the team discovered that there is a synergetic effect from the support structure and rotor upon the flow field immediately downstream of the turbine [72]. In another study to investigate wake recovery, the team identified that the surface roughness might reduce wake recovery [74]. If any devices were to be installed at a site with a rocky seabed, it is suggested to avoid locating the device in the lower third of the channel's depth. Following these findings, the team started to study the wake pattern in dual-rotor turbines (in the same row) and dual-row turbines [76,77]. It was shown that an optimum spacing is required to prevent a combined wake from dual-rotor turbines. Another interesting finding is that with proper tuning of lateral spacing between two turbines, the flow passing through the middle of the two rotors can be accelerated and subsequently provide more energy extraction to a third turbine located right behind the middle of the spacing.

A point worth discussing here is that the small-scale turbine used by Bahaj's team to study the wake effect was different from the scale of turbine used previously to study the power coefficient. A 400-mm-diameter three-bladed horizontal-axis turbine was selected based on the expected blockage ratio of a full scale HAMCT, as suggested by the European Committee. The small-scale turbine was tested in a circulating water channel with a cross-sectional area dimension of 1.4 × 0.84 m. As the suggested blockage ratio is approximately 12%, the tested scale model ended up being a 400-mm-diameter turbine. Nevertheless, Bahaj's team claimed that this could be a 1/30th scale model of a 12-m-diameter HAMCT. Again, this reveals some important considerations that are associated with the use of test rigs, as mentioned in Section 2.2.1. The size of the test rig will determine the suitable scale model to be used. This in turn will require the researcher's judgement to identify whether the data produced by the scale model is sufficiently reliable to be transferred to the full-scale HAMCT or not, as the observed operation of the scale model in the test rig might be different from that of a full-scale HAMCT [68].

Similarly, scaling and the use of actuator discs to produce similar wake characteristics of a full-scale HAMCT also possess similar limitations and have been discussed by Bahaj's team [69]. Therefore, simulation plays an important role in supporting the data obtained from scale model experiments. Simulations that are based on proven theory should be able to produce similar characteristic of the flow. Conversely, scale model experiments could provide insights into the suitability of the assumptions made in the theory. The same goes for the experiments using small-scale turbines. For instance, the centreline velocity deficit, which is measured at a distance of 5 turbine diameters (thrust coefficient = 0.77) downstream of an 800-mm small-scale turbine is approximately 0.5 (normalised to the upstream flow) in [72]. However, the centreline velocity deficit measured at a distance of 5 turbine diameters (thrust coefficient = 0.86) downstream of a 100 mm actuator disc is only about 0.35 (normalised to the upstream flow) in [69] and about 0.45 (normalised to the upstream flow) in [74]. As a reminder, the size of the actuator disc and experimental settings for [69] and [74] are the same. Hence, under such circumstances, detailed comparisons between the two values might

not be practical; however, a comparison of the general trend in the recovery of velocity deficit ranging from 1 to 5 turbine diameters is still acceptable.

A similar thing happens between the simulation data and experimental data obtained from the actuator disc. For example, the extended eddy viscosity model used by Bahaj's team in [71] only gives a wake recovery trend that is similar to that from experimental data using an actuator disc. In fact, the model underestimates the wake recovery rate for downstream distances larger than 6 turbine diameters. The study on far wake prediction using CFD and actuator discs in [75] also revealed the same limitation. CFD tends to underestimate the wake recovery rate of an actuator disc. A recent work by McSherry and co-workers, in using CFD to model HAMCT performance, showed that proper mesh selection is crucial for giving good predictions on turbine performance [90]. All these suggest that prior to the application of developed numerical models for full-scale HAMCT design, researchers or engineers should always be aware of the differences between the experimental data from small-scale turbines, the experimental data from actuator discs and the simulation data from numerical models.

Certainly, Bahaj's team is not the first team to study HAMCT wakes. Macleod and co-workers [91] studied the wake effects by using CFD in 2002. Their findings were in agreement with Bahaj's team experimental results obtained a few years later. For instance, the CFD simulation showed that higher thrust coefficients result in slow wake recovery. This shows the feasibility of CFD to be used to simulate the general trend of flow around the turbine. Despite the aforementioned limitations, CFD is still capable of simulating the characteristics of flow up to an acceptable level. This has made CFD a tool, commonly used in recent years, for studying the flow around HAMCTs, as well as for determining the performance of the device. Because Bahaj's team is one of the earliest that conducted experimental work, their published data and results have often been used by other researchers as a comparison for validating their own CFD simulation results.

Maganga and co-workers from France tried to develop three-dimensional software to simulate the wake of HAMCTs. They ran the simulation by defining the shape of the blade to be similar to that of Bahaj's team [92,93] in order to validate the feasibility of their simulation model. An interesting thing is that their model predicted a higher wake recovery rate compared with the wake recovery rate predicted by an actuator disc in [70]. The reason given by Maganga and co-workers for this was because the model does not take into account the possible effects of the free surface and bed on the wake expansion. In 2009, Maganga and co-workers conducted an experiment using a three-bladed horizontal-axis turbine developed by Tidal Generation Limited, in order to test the performance under the effects of different flow characteristics, such as velocity gradient and flow orientation [94]. The study of the wake from the same experimental setup showed that with great ambient turbulence intensity, the recovery of wake is faster [95]. The simulation model developed in [92,93] was also validated by Maganga and co-workers using the data obtained from this experiment [96].

Recently, an experiment has been conducted by Mycek and co-workers (same research team as with Maganga) to study the effects on wake created by an upstream HAMCT towards a downstream HAMCT by using two 1/30th scale horizontal-axis turbines [97]. The experimental results were similar to those obtained by their previous work [93] and those of Bahaj's team. An interesting idea concluded from this work is that there might be a need to compromise between the performance of an individual turbine and the total number of turbines deployed in arrays. In other words, to fully utilise the marine current energy at a site with limited space, the performance of individual turbines should be adjusted to

control the wake generation, which could affect the performance of other turbines. At first glance, this finding might seem to be contradictory to Vennell's work mentioned in Section 2.1.1 but it actually proves that the optimum energy extraction is achievable through optimal tuning of all the turbines in each row.

Jo and co-workers studied the velocity reduction caused by a turbine towards turbines located 1.5 turbine diameters downstream [98,99]. They used three identical 500-mm-diameter three-bladed horizontal turbines to run the experiment. The spacing between each turbine was set to be 1.5 turbine diameters. Two interesting observations were reported. Firstly, when the incoming velocity becomes higher, the rpm reduction rates decrease. Secondly, CFD simulation shows that the decrement of mean flow velocity becomes smaller for turbines located further downstream from the first turbine. As most of the aforementioned experiments in studying wake characteristics were using single small-scale turbines or actuator discs, Jo and co-workers' work could provide more information in validating the findings of these experiments.

If Jo and co-workers' results are correct, they surprisingly show that the velocity deficit after a turbine is not as high as predicted in [72], which used an 800-mm-diameter turbine. Comparison between these two experimental findings might not be practical because the turbine used and experimental set up are different. In addition, the nearest downstream distance measured in [72] started from 3 turbine diameters, whereas the nearest distance in Jo and co-workers' work started from 1.5 turbine diameters. Nevertheless, as mentioned before, comparison of the general trend should be acceptable.

Another comparison between the data obtained from small-scale turbines and actuator discs can be made between Bahaj's team and Stallard and co-workers. Stallard and co-workers studied wake interaction between HAMCTs using three 270-mm-diameter three-bladed horizontal-axis turbines [100,101]. They reported that the wake generated by two turbines with a lateral spacing of 1.5 turbine diameters would interact after a distance of 2 turbine diameters downstream. This is somewhat contradictory to the findings reported by Bahaj's team in [77], where Bahaj's team reported that the wake from two actuator discs with a lateral spacing of 1.5 turbine diameters do not merge, even in the far wake region. Further studies on the interaction between HAMCT wakes will be required in order to investigate the causes of the differences between these two results.

2.2.3. Marine Current Turbine Generator

Regarding the performance of HAMCTs, the ability to produce constant electricity is also one of the concerns. In order to operate and perform well in an environment where inflow velocity can fluctuate continuously, HAMCTs normally possess built-in passive pitch control to maintain the angle of attack of the turbine blade. This helps to maintain the rotation speed of the turbine to stay within the rated power and prevents the device from overloading. Apart from the physical control, identifying the generator that is best able of allowing the device to provide constant electricity output is another interesting field in the research of HAMCTs. A review of the different generators being used in the industry by different developers can be found in [102].

Ben Elghali and co-workers from France have been actively involved in research on HAMCT generator performance since 2007 [19,103–112]. They started by developing a Matlab-Simulink model to model the marine current energy [19] and step-by-step, they validated the developed model for

different generator-based HAMCTs. They have simulated the performance of doubly-fed induction generators (DFIGs) [103,106], permanent magnet synchronous generators (PMSGs) [109,110], modified DFIGs and PMSGs [105,107,108] and comparisons between DFIGs and PMSGs [109,111]. It was not until 2011 that Ben Elghali and co-workers started to conduct experiments and validate the control systems they had proposed. Prior to that, they had validated their simulation results using the experimental results published by Bahaj's team.

Ben Elghali and co-workers suggest that the PMSG is a better power control option for HAMCTs compared to the DFIG. They extended the PMSG by introducing the second-order sliding mode control that takes into consideration the turbulence and swell effects of marine current flow [108]. In addition, it was shown that multiphase PMSGs could help in maintaining the power output of HAMCTs, even when there is an electrical fault in the power converter [109,110]. Recently, they fabricated a rim-driven prototype HAMCT with a radial permanent magnet generator for experimental purposes to test the actual performance of the control system proposed by them. Nevertheless, one finds from [102] that most generators currently applied in large-scale HAMCTs are induction generators.

It is worth noticing that the concept of a radial magnet generator for HAMCTs had already been proposed by Drouen and co-workers in 2007 [112]; this came from the same research institute as Ben Elghali in France. The analytical tools used were different to the later work conducted by Ben Elghali and co-workers and the aim of the design was focused on the minimisation of cost. Additionally, there was research in producing a novel generator to improve the performance of HAMCTs. Keysan and co-workers from the UK studied a direct-driven air-core permanent magnet generator, named by them as C-GEN for the Scotrenewables Tidal Turbine. The C-GEN was claimed to be capable of increasing the efficiency of the turbine [113].

2.2.4. Novel Design

Research interest on improving the performance of HAMCTs has driven researchers to seek a better design that differs from the conventional design. Researchers has been performed on understanding the performance of a type of HAMCT called the diffuser augmented marine current turbine [114–119], in which an additional structure is manufactured to accelerate the marine current inflow velocity. Theoretically, as the energy captured by the turbine is proportional to the inflow velocity, the turbine should be able to harness more energy when the inflow velocity becomes faster. The structure used for diffuse and augmentation purposes is normally a duct with a small diameter inlet facing upstream and large diameter outlet facing downstream.

Lawn studied the performance of a diffuser augmented turbine analytically using one-dimensional theory [114]. Lawn reported that there is an increment in the power coefficient by up to 30% compared with a conventional type turbine. Setoguchi and co-workers tried to develop a two-way diffuser for a tidal current that has the nature of changing direction [115]. They found that the shape of the diffuser is an important factor in determining the efficiency of the diffuser. Münch and co-workers designed and studied the performance of a four-bladed diffuser augmented marine current turbine using an unsteady turbulent flow numerical simulation performed by ANSYS CFX [116]. They claimed that with a tip speed ratio of 7, the power coefficient of the designed turbine could reach up to 55%.

Shives and Crawford applied CFD simulation using ANSYS CFX to analyse the overall efficiency of the diffuser augmented marine current turbine [117]. It was shown that the power coefficient improvement in the diffuser augmented marine current turbine comes at the cost of a reduction in efficiency due to induced drag. In their recent work, they recalculated and validated the model proposed by Lawn [118]. Meanwhile, an empirical model was developed by them to estimate diffuser efficiency and the base pressure that is parameterised by the geometry of the diffuser and thrust coefficient. Although there is a shift in interest towards this type of HAMCT in the industry [119], the open literature available regarding diffuser augmented marine current turbines is still limited. As a reminder, most of the studies mentioned have not included actual experiments to test the performance of a real small-scale diffuser augmented marine current turbine.

There have been other attempts to creating novel designs for the performance improvement in addition to the diffuser augmented type. Clarke and co-workers from the UK have designed and tested a contra-rotating HAMCT, which they named the Contra-Rotating Marine Turbine (CoRMaT) [120–125]. CoRMaT comprises two turbines with a three-bladed turbine at the front and a four-bladed turbine at the back, both rotating in opposite directions to each other; a detailed design can be found in [120]. According to experiments, the contra rotation of the turbines can lead to a near-zero reaction torque on the supporting structure [121]. A simple mooring system was said to be sufficient for supporting CoRMaT when the reactive torque is minimised [122]. This potentially helps in eliminating costly foundation construction and subsequent maintenance work.

A 250 kW rated CoRMaT was tested in the Sound of Islay in Scotland in order to investigate the feasibility of a single-point tethered floating system for CoRMaT and the performance of a direct drive generator [123,124]. It was claimed that electrical power output underwent rapid fluctuation, which could be improved through a better system design. After various trials, they concluded that for power take-off and conversion of CoRMaT, the most reliable, efficient and cost-effective option would be directly-driven contra-rotating permanent magnet generator with controllable tip speed ratio [125]. As a reminder, the aim of CoRMaT is not on performance improvement but more on the designing of a cost-effective and maintenance-friendly HAMCT.

2.3. Environmental Aspects

Environmental considerations are a crucial issue that need to be addressed in all stages (construction, operation and decommissioning) of marine renewable energy devices, including HAMCTs. However, there is limited information from the open literature of the research community that deals with the actual environmental impacts caused by HAMCTs, especially the impacts on marine organisms [126]. Some potential environmental impacts are shared among all types of marine renewable energy devices, such as the noise generated during construction and operation and the electromagnetic field from subsea cables, which could affect migratory fish movement behaviour [127].

The most significant environmental impact from HAMCTs might be the change in the hydrodynamic flow of the marine current, as discussed in Section 2.1.1. The change of hydrodynamic flow could alter the habitat of marine microorganisms that rely on the established tidal flow pattern. Neill and co-workers studied the effects of marine current turbine farms on sediment transport at the seabed [128]. They developed and used a one-dimensional morphological numerical model to study

the sediment dynamics and found that the influence on the morphodynamics could reach a considerable distance beyond the point of energy extraction. In other words, the scour effect caused by the existence of marine current turbines is not limited to local scour but could increase to global-scale scour effects. In another recent study by Neill and co-workers, it is identified that the operation of HAMCT arrays near to headlands could cause changes in the deposition of sand on sand banks (important for coastal protection) by up to 30% [129].

Shields and co-workers discussed the possible ecological implications resulting from the alteration of marine current hydrodynamics [130]. Changes in marine current flows are likely to affect the dispersion of marine microorganisms that rely on marine current for transportation. For example, alteration in dispersion of propagules, which is a key part of the life cycle of marine ecosystems, could affect the distribution of other marine organisms. Changes in marine current conditions might well affect benthic predators that rely on olfaction to locate prey. Hydrodynamic processes are said to play an important role in propagating odour in marine environment. Difficulty for benthic predators in identifying odours might arise due to the alteration of hydrodynamic processes, which could affect their ability to locate prey.

Hydrodynamic changes could also lead to the alteration of ambient marine noise. Recently, Broudic and co-workers reported their findings on the monitoring of underwater noise at Ramsey Sound in Wales, UK [131]. The channel has a tidal current flow of up to 4 m/s. It was found that the noise of the sediment and cobbles' motion has an important impact on the ambient noise. This implies that the ambient noise might increase or decrease when the motion of sediment is altered by changes in marine current hydrodynamics. Further studies are required to investigate whether such alterations in ambient noise would have any impact on marine organisms. Lloyd and co-workers studied underwater noise propagation using the *AcTUP* software suite distributed by Curtin University [132]. Although they claimed that the results are considered conservative, it was found that threshold shift (primary cause of injury and physiological damage to wildlife) is predicted at a range within a distance of a turbine radius, which is a zone where fish will not stay for a long period. This finding suggests that noise generated by HAMCTs might exert lesser impact on marine organisms compared with alterations on the ambient noise.

So far, this section has only discussed background work by various researchers. Nevertheless, there is a published report on an environmental monitoring programme for Marine Current Turbines Ltd.'s SeaGen project [133]; the first commercial-scale HAMCT, which was commissioned in 2008 and produced up to 5 GWh in September 2012 [134]. The report was published in January 2011 and presented findings on three years' post-installation environmental monitoring. Overall, the report showed that SeaGen caused minimal impact on the three identified receptors (marine mammals, benthic ecology and tidal flows and energy) in Strangford Lough, Northern Ireland. There is a degree of local avoidance of the device by seals and harbour porpoises. A new colony was found to form at the foundation of SeaGen, which illustrated the recovery of benthic community that had been lost during construction. Last but not least, no significant changes in ambient current velocity were measured.

Based on the environmental monitoring programme of SeaGen, it seems likely that the operation of single HAMCTs will not exert significant impact on the surrounding marine environment. However, this might not be the case for HAMCTs deployed in farms or arrays, such as those background works discussed previously. If we imagine that marine mammals, such as seals and harbour porpoises tend to

avoid HAMCTs, then what is likely to happen if HAMCTs are deployed on a farm-scale that occupies a large cross-sectional area of the channel? This will surely affect the distribution of these marine mammals around the HAMCT farms.

3. Future Perspectives

The previous brief review on research carried out by various researchers throughout the past decade provides an outline of the trend of research of HAMCTs. Generally, it falls into two categories. The first category is the trend of using suitable numerical models to generate marine current data for potential sites in order to estimate the availability of marine current energy. The second category is the trend of improving the performance of HAMCTs. This category had been explored by researchers through different perspectives, including the fundamental design parameters that govern the performance, the hydrodynamic response of marine currents around the turbine, electrical components and research on novel designs.

Current and future trends in the HAMCT field are on using CFD to simulate HAMCT performance (not discussed in this paper). The reason for using CFD is its ability to simulate the marine current conditions up to an acceptable accuracy and the cost-effectiveness compared with experimental work. Based on the knowledge established from the first stage (energy assessment) and second stage (performance) of research, it is now possible to move onto the third stage, which focuses on the maintenance and survivability of HAMCTs. Routine maintenance is essential to ensure continued performance of HAMCTs. However, maintenance costs could be huge if frequent maintenance or repair works for unforeseen damage are required. Thus, research in prolonging the sustainability of HAMCTs is definitely beneficial in terms of providing reliable and cheaper electricity.

Recently, there have been some works related to maintenance issues on HAMCTs. Prickett and co-workers proposed a methodology of using a microcontroller-based condition monitoring approach to perform early detection of possible failures of HAMCT components [135]. This kind of reactive approach to monitor HAMCT health is essential and important, as the potential causes of HAMCT failures are not yet well understood. However, if the possible causes of HAMCT failures, such as higher loading due to velocity perturbations, as discussed in Section 2.2.1, could be identified, then it would be possible to lower the risk of failure by enhancing the design of HAMCTs at an early stage. Proper prediction of velocity perturbations using reliable methods would definitely benefit the design of HAMCTs for a specific site. Harding and co-workers are working on this issue and have tried to identify suitable methods for predicting velocity perturbations [136]. Obviously, a better design, together with a good monitoring approach, could significantly prolong the lifespan of HAMCTs.

Apart from velocity perturbations, there are other causes that could affect HAMCT performance. A common problem faced by all marine structures is that of the bio-fouling. To the best of authors' knowledge, no research has been done in studying how to effectively remove bio-fouling (excluding fouling release paint) from the turbine blade, although the effects of bio-fouling have been studied [137]. Moreover, for HAMCTs that have foundations, scour around the foundation could cause instability in the structure. Again, to date no research work on HAMCT scour has been published. In fact, the problems associated with bio-fouling and scour on HAMCTs have been recognised and studied in the

industry [138,139]. Hence, both anti-fouling and scour of HAMCTs are potential research areas in the maintenance and survivability category (research interest of authors' research group).

Environmental impact is another issue that requires further study, such as the research carried out by Lloyd and co-workers [132,140], in order to establish some fundamental knowledge towards the stressors created by HAMCTs and to fill the "gaps in understanding", as reported in the "Tidal Energy Environmental Effects Workshop Report" [141]. For example, questions to be addressed are: How is the noise generated during operation and how does it propagate in the ocean environment? And: Are there any possibilities of lubricant leakage and will the wake of the turbine affect the leakage distribution? The impact of these stressors could become greater in the case of large farms or arrays. Hence, these stressors should be quantified in order to show how severe the impact could be upon the receptors such as marine organisms. Bear in mind that marine renewable energy is explored in order to open another possible path for a sustainable future, which places environmental considerations at the forefront. Developing marine renewable energy at the cost of damaging the environment is definitely undesired. These environmental issues might also be related to the environmental problems due to the exploration of offshore gas hydrate [142–144].

4. Conclusions

Research in HAMCTs over the past decade has been reviewed. Although there is some research that has not been covered in this review (such as the research using CFD), the progressive growth of research in HAMCTs during the past decade is apparent. Early research in energy assessment provided fundamental knowledge of extractable marine current energy, which has acted as a reference for later researchers who have studied the power extraction potential of HAMCTs. Early experimental works also provided insights on how to optimise the design of HAMCTs through different approaches. The interrelation between the various research interests has created strong momentum in pushing forward the research in HAMCTs from different perspectives. All the research outcomes will contribute to a useful resource pool for future researchers.

Obviously, the knowledge of design has not yet converged, as witnessed by the many different methods that could be used to estimate energy assessment or to improve the performance of HAMCTs. However, as marine current energy is very site specific, innovative ideas should always be allowed in exploring all the possibilities in harnessing and generating the desired electricity by using HAMCTs, or other marine renewable energy devices. Readers who are new to the HAMCT field are encouraged to pay attention to papers published in European Wave and Tidal Energy Conference (EWTEC) and the International Conference on Ocean Energy (ICOE) for leading research in the HAMCT field.

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