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Attraction, Challenge and Current Status of Marine Current Energy

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ABSTRACT Reducing greenhouse gas emissions becomes a top priority in the world with the emergence of global warming and environmental problems. Various renewable energies appear during the last decades. Ocean captures and stores huge amounts of energy, which could satisfy five times of world energy demand. Due to technology limitations and economic considerations, marine current energy appears the most attractive choice compared with the other ocean energy form. Although the existing expertise and technology in offshore wind energy conversion system can be partially transferred to marine current energy conversion system due to the similar structure, there are still many technological challenges to overcome. Meanwhile, the system operates under the water will inevitably have some negative or positive impacts on the surrounding environment. In this paper, it shows the interest and the principle of the marine current energy, and also discusses the advantages and disadvantages. The environmental impacts around the devices, the technological challenges, and the essential support structures are presented as well. The state-of-the-art horizontal axis turbines and their relative technologies and the latest projects are described finally. This review paper gives the useful information about the attraction and challenge of the marine current energy, and the newest development of the technologies and projects.

INDEX TERMS Marine technology, oceanic engineering and marine technology, turbines, reviews, marine current energy, characteristic, technical challenges, support structure, projects.

I. INTRODUCTION

Due to the serious environmental problems, one worldwide agreement-Kyoto Protocol, which aims at reducing greenhouse gas, emerges at the times required in 1997. All the countries around the world must respect the agreement and simultaneously, vigorously seek to develop a variety of renewable energy to reduce greenhouse gas emissions. In recent years, more and more researchers put more and more attention on this part. As a result, the efficiency and reliability of renewable technologies have been constantly improved, and an important technological advance has been noted [1]–[4]. According to [5], in 2015, renewable energy is estimated 19.3% of global final energy consumption, while accounting for 24.5% of universal electricity production by the end of 2016 (see FIGURE 1 and FIGURE 2).

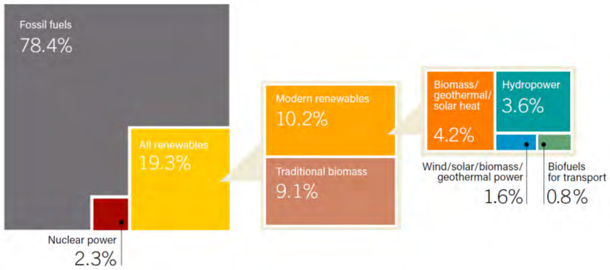


FIGURE 1. **Estimated renewable energy share of global final energy consumption, 2015 [5].**

This paper is structured as follows: firstly, the physics of tidal current is explained and the characteristics of the marine current energy are discussed: the advantages and disadvantages are introduced, and the environmental impact and technology challenges are analyzed. Secondly, the support structures are presented. In general, the seabed-mounted

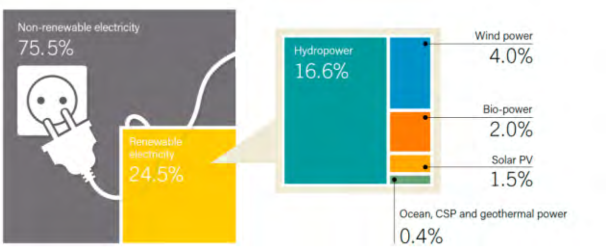


FIGURE 2. **Estimated renewable energy share of global electricity production, End-2016 [5].**

structure is preferred for shallow water as it is relatively simple and cheap to install. Thirdly, comparison of different turbine concepts is studied. Currently, the horizontal axis turbine MCECS appears more technologically and economically than the other forms. Finally, the current status of the state-of-the-art horizontal axis MCECS projects and latest news are presented.

II. OCEAN ENERGY RESOURCE

The ocean represents a vast natural energy resource which is theoretically far larger than the entire human race could possibly use. According to the estimation by the Marine Foresight Panel, less than 0.1% of the ocean power could satisfy nearly five times of world energy demand [6], [7]! Generally speaking, ocean renewable energy resources are more costly and difficult to exploit reliably than the land-based options. Consequently, it's not easy to use much of the ocean energy right now. From the estimated energy share of global electricity production at the end of 2016, the ocean energy takes less than 0.4% of the total energy (see FIGURE 2) [3], [8]. Until now, numerous techniques of exploiting and extracting ocean energy have been proposed. The most prominent options can be classified as follows: wave energy, tidal energy, osmotic energy, ocean thermal energy, and cultivation of the marine biomass [9].

According to the research by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1981, the total theoretical ocean energy capacity is estimated about 76.6 TW [10]. Table 1 just presents the potential of the different ocean energy forms.

TABLE 1. **Ocean energy capacity [8].**

	Ocean Energy Capacity
Ocean Thermal Energy	40 TW
Osmosis Energy	30 TW
Wave Energy	3 TW
Tidal Energy+Ocean Current Energy	3 TW+0.6 TW
Total	76.6 TW

Actually, ocean energy resources could meet the world's energy requirements over. It is considered to be more than 2 million TWh per year and has a technical potential around 2 000 to 92 000 TWh annual [11]–[14]. Ocean thermal energy is estimated about 44 000 TWh every year for theoretical potential [15]. In [16], osmosis energy is evaluated to have a technical potential of nearly 1 650 TWh yearly. The technical potential of wave energy is around 5 600 TWh per annum and with a theoretical potential of 32 000 TWh [11], [17]. The tidal energy (including both tidal current energy and tide energy) is analyzed by Charlier and Justus in [18], the theoretical potential is 26 000 TWh every year and much of them is located in the shallow coastal basins [11], [13], [14].

However, harnessing the kinetic energy in waves still presents different technical challenges and is in its early development stage [19], [20]. Tide energy always needs the construction of tidal barrages near the seacoast; moreover, navigation, shipping water-level requirements and environmental issues must be considered [21]. Ocean thermal energy conversion is possible achieved in some special locations with large temperature differences via a heat engine. Because of technological limitations and economic considerations, these developments are quite restricted in these years. Nowadays, the attraction of marine current (including tidal current, ocean current, etc.) is increasingly evident.

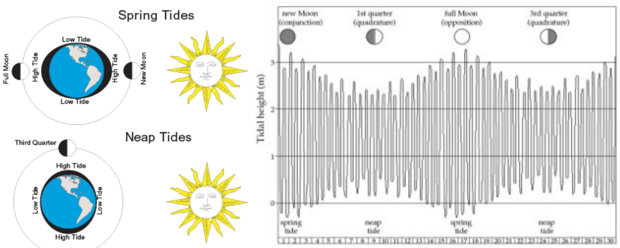
Tidal current, a major part of the marine current, is a typical horizontal movement based on the rising and falling of the tide. Normally, it doesn't have much impact on the open ocean. However, the tide can still create a rapid current up to 7 m/s when the current flows in and out of narrower areas [22]. Moreover, the tides with a great difference between high tide and low tide always bring big current speed and huge energy. It has a regular period, which depends on the relative positions of the earth, moon and sun. The minor part of the marine current is called ocean current. It is a long-time period stable flow between the sea bottom and the channels which is mainly caused by prevailing winds, earth's rotation and the difference in temperature and salinity density. All the marine current can be magnified by underwater topography, especially close to the land or in the straits between the islands and the mainland [9], [23]. FIGURE 3 presents the world first commercial-scale MCECS - Seaflow (300 kW), which is installed on the north coast of Devon on 30 May, 2003. It has a horizontal axis turbine with 11 m rotor diameter and 2.1 m pile diameter.

FIGURE 3. **Seaflow [24].**

III. MARINE CURRENT ENERGY

A. THE PHYSICS OF TIDE AND TIDAL CURRENT

As presented in Section II, marine current energy is a horizontal movement based on the tide rising and falling.



(a) (b)

FIGURE 4. **Spring and neap tides; a) Relative positions; (b) Relative height [27].**

The tide is essentially a long, slow wave which is generated by the interaction of the gravitational fields caused by the moon, the sun and the earth's ocean (see FIGURE 4). The universal gravitation is given by:

$$f = K\frac{mM}{d^2}, \tag{1}$$

Where: m is the mass of the water (kg); M is the mass of the sun or the moon (kg); d is the distance between the ocean and the sun or the moon (m); K is the universal constant of gravitation (6.67×10^{-11} $\mathrm{m^3kg^{-1}s^{-2}}$).

From formula (1), we can deduce that the attractive force depends on the masses and distance. Although the sun has a large mass, as the moon is much closer to the earth, the force produced by the moon is 2.17 times larger than that of the sun (68 % from the moon, 32 % from the sun) [25].

Since the earth rotates, the distances between the earth, the moon and the sun vary. When the ocean is in the aligned position relative to the sun or the moon, the distance between the ocean and the attracting body is less than when the ocean is in the opposite position. At this time, the ocean will have a tendency to escape from the earth. This separating force appears two maxima every day due to the comparative position of each attracting body.

It is also necessary to take into account the beating effect (caused by different relative positions of the earth, the moon and the sun) and the different types of oscillatory effects. If there is no such effect on the ocean, the moon force (the stronger part) will just produce approximately only 5.34 cm high tidal range [25].

Generally, every full moon and new moon, tidal amplitudes pass through a maximum. This tide is called **spring tide**. Each first and third quarter, the amplitudes pass through a minimum. This tide is called **neap tide** (see FIGURE 4). The rise and fall of tide in the water level are always accompanied by a horizontal movement of water. This motion is known as **tidal current**. The strongest current occurs at or around the peak of high and low tides. When the tide is in, the current is towards the shore. This current is called **flood current.** When the tide is out, the current is directed back out to sea. It is called **ebb current** [26]. This means that both tide and tidal current nearly have the exact same period.

B. MARINE CURRENT ENERGY ASSESSMENT

The global ocean resource market potential is evaluated between 2,000 and 4,000 TWh per annum. While for the marine current energy, the potential power is valued at 800 TWh annually, which is equivalent to 3-4% of the whole power consumption. However, there is just an estimated 50 GW or approximately 180 TWh yearly of the economically exploitable resource available worldwide, with an energy density up to 15 kW/m^2 (see Table 2) [24], [25], [28]. Coastal regions with strong currents in the UK, Canada, France and East Asia offer major potential for the utilization of this technology [29]. Principal sites for tidal power development in the world are illustrated in FIGURE 5.

TABLE 2. **Marine current energy potential [28].**

	Estimated Resource
Global Ocean Resources	2,000-4,000TWh /year
Tidal Energy	500-1000 TWh/year
Marine Current Energy	50 GW or ~180 TWh/year (Economically Exploitable)

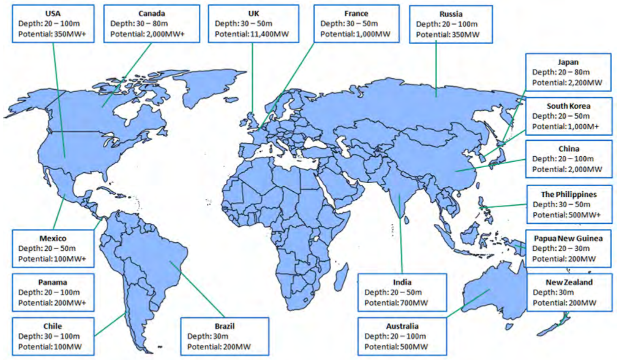


FIGURE 5. **High potential areas for tidal resources worldwide [28].**

IV. CHARACTERISTIC OF MARINE CURRENT ENERGY

A. ADVANTAGES OF MARINE CURRENT ENERGY

Marine current energy is an inexhaustible green energy resource. It is a non-harmful and low visual exposure, which is not like an offshore wind farm. Moreover, compared to the classical tide energy, it does not require barrages across the waterways.

Besides, another important characteristic of the marine current energy is the high power density caused by seawater density (800 times larger than air density). For the same speed, one generator can generate significantly larger power with the higher density. Given that the kinetic power varies with the density and the cube of fluid velocity, it is easy to conclude that, for the comparative size of the turbine, water speed is nearly one-tenth of wind speed providing the equivalent power (see Table 3). At the sites where the marine current moves at a higher speed, between 2 and 3 m/s, the turbine can produce three times energy per rotor swept area, compared to

TABLE 3. **Power density [30].**

	Energy resource						
	Marine Current					Wind	Solar
Velocity (m/s)	1	1.5	2	2.5	3	13	Peak at noon
Velocity (knots)	1.9	2.9	3.9	4.9	5.8	25.9	
Power density (kW/m^2)	0.52	1.74	4.12	8.05	13.91	1.37	~1.0

a similar power level wind turbine. In other words, for the same rated power system, marine current turbine can provide significant power at relatively low velocities; the size and the weight can be much smaller than that of the wind turbine (one-tenth and one twentieth respectively) [28].

Compared with the other forms of renewable energy, marine current energy also has one distinct advantage of predictability. The marine current charts are available up to 98% accuracy. The Service Hydrographique et Océanographique de la Marine (SHOM) and the National Oceanic and Atmospheric Administration (NOAA) can predict the current two days, one week or even years ahead, which are all on the respective website [31]. These make the marine current energy development an attractive resource option compared to the other renewable energy forms. Briefly, it is mainly independent of weather conditions, which can highly impact on the other renewable generation forecasts.

The MCECS technology is very close to Wind Energy Conversion System (WECS) technology, especially offshore WECS. The configurations of a turbine rotating by the moving fluid, which is linked to a drive train, a gearbox and a generator associated with its converter are all common characteristics of these two systems. However, the operating conditions of MCECS present significant specificities. As a result, the existing expertise and methods in offshore WECS can be only considered partially transferable to MCECS [20], [32], [33].

Compared with offshore WECS, they have almost the same system structure such as: offshore transformer platform, submarine cables, directional drilling and cable vault. The only two differences are the turbines and foundations [20]. Some pilot projects and the first commercial project have successfully harnessed the power from marine current using the offshore WECS technologies [28].

Finally, another notable characteristic must be mentioned is the relatively high capacity factor. This factor is described as the actual annual energy output divided by the theoretical maximum power of the installed device. Marine current is likely to get a factor up to 40-50%; while the factor of wind is usually between 25-30%. A high capacity factor is important to achieve an economically viable power production [34].

B. DRAWBACKS OF MARINE CURRENT ENERGY

The marine current always has a very low velocity and is usually less than 5 m/s. Normally, the limitation for the interesting sites is that the current moves at least 1 m/s, which is close to neap tides. The target marine current has an average velocity of 2.5 m/s and with a maximum of 4 m/s. The good tidal sites should have capacity factors bigger than 35% [28]. This means that there are just a few locations around the world which are exploited economically.

Once the power is extracted from marine currents by MCECS, the transmission of the energy to the customer must be a very costly and complex process due to the long distances and subsea cabling issues. This will be an economic problem.

The other drawback is the technology. Although some expertise and energy conversion technique achieved in WECS can be considered partially transferable to MCECS. However, the innovative technology, especially for the marine current energy, is still in its infancy, and has a high capital cost compared with classic fuel resource (some more details are provided in Table 4).

C. ENVIRONMENTAL IMPACTS

It is well known that any system which produces electricity must be assessed as a whole to pinpoint any energy, ecological, environmental, social or economic implications. Until now, due to the limited observation, there are not so many details on the exact environmental impacts of MCECS. As a result, it is impossible to quantify the precise impact of an array of turbines may have on the ecology, environment and existing users [31], [36]–[38]. However, it must be admitted that an MCECS with 18 m in diameter and operating in the sea up to 50 m deep, must inevitably have some negative or positive impacts on the surrounding environment. The level of impact would be dependent upon the quantity of units installed and the marine current farm density [35], [39].

As MCECS has a very similar system with offshore WECS, they own many analogous environmental impacts. Some studies have listed the possible and likely impacts of these systems, and they were classified into two main categories: one is common to offshore WECS, and the other is unique for MCECS [40], [41].

1) COMMON ENVIRONMENTAL IMPACTS

a: VISUAL IMPACT

The principal visual impact would be the electrical substations (offshore transformer platform & cable vault) and overhead lines near the cable vault.

b: CONSTRUCTION, INSTALLATION, OPERATION, MAINTENANCE & DECOMMISSIONING

These activities will have various effects on the environment. They will disturb the seabed and cause sediment displacement, which lead to destruction of habitat and marine benthos, and even contaminate the local environment [31]. It's remarkable that according to the experiences of the offshore WECS, the construction will bring serious noise impacts on the marine mammals, particularly for the pile-driving into the seabed [41], [42].

TABLE 4. Energy comparison [28], [35].

		Renewable Resource	Low Capital Cost	Minimal Environmental Impact	Predictable	Modular	Scalable	Load Factor (%)	Capital Cost per MW (£MM)	Influenced by
fossil		NO	YES	NO	YES	NO	YES	80~90	0.9	Fossil Oil
Nuclear		NO	YES	NO	YES	NO	YES	90	1.2	Nuclear Fuel
Wind	Onshore	YES	NO	YES	NO	YES	YES	20~30	1.1	Climate, Wind, Pressure
	Offshore						YES	35	2.5	
Solar	PV	YES	NO	YES	NO	YES	NO	16	4.5	Solar Intensity/Exposure
	Thermal						YES	-	3.6	
Hydro		YES	YES	NO	YES	NO	NO	30	1.0	Dam, River
Wave		YES	NO	YES	NO	YES	YES	35	4.0~5.9	Wind Seafloor Topography
Marine current		YES	NO	YES	YES	YES	YES	30~50	2.1	Moon, Gravity, Seafloor Topography

c: ECOLOGICAL IMPACTS

The power cables are needed to deliver the electricity from the offshore location to the land. However, the electromagnetic fields emitted by the cables will interfere with the electro-sensitive and magneto-sensitive animals [38], [43]. The significant negative impacts are still uncertain, but should not be ignored. In some places, maybe it's necessary to bury the cables deep into the sediment [44], [45]. Furthermore, the energy converters may also produce low frequency underwater noise which may have effects on marine organisms [45]–[48].

2) UNIQUE TO MCECS

a: PHYSICAL IMPACTS

The influence of the marine current energy extraction on coastal evolution processes, tidal flows, wave structure, seabed scouring (seabed morphology) and sediment transport. In some cases, it was significantly impacted up to 50 km from the point of the energy extraction.

b: ECOLOGICAL IMPACTS

Generally, this may have an effect on the benthic ecosys (floral and faunal species). MCECS and the tidal arrays will affect the benthic habitats due to the physical impacts of the water flows, composition of substrate and sediment dynamics. Moreover, possible interaction between the rotating blades of the subaqueous turbine and sea life which means these moving blades can kill the swimming marine organism (marine mammals, turtles and larger fish) occasionally, and some fish may no longer live in these areas [38].

c: POLLUTION

The mechanical fluids, such as lubricants or the anti-fouling paint, can leak out, which will contaminate the marine environment and be harmful to the sea creatures nearby.

D. TECHNOLOGICAL CHALLENGES

Based on the experience of tested prototypes and commercial projects, some common technological challenges become more and more thorny. This section will focus on the most pressing problems on which all researchers must confront at present [24], [40], [41], [49]–[52].

1) GRID INTEGRATION

The grid integration of MCECS or tidal arrays faces various challenges. Firstly, as all the devices have to connect to the grid, the submarine cables which connect to the shore are needed. Therefore, the distribution and transmission of electricity are very important. Secondly, since the marine current speed varies periodically, the variability will certainly affect the grid integration. Thirdly, power quality and control must be an important issue when arrays are installed. Many technological problems such as fault ride-through capabilities, voltage control, frequency regulation and active power control have to be solved. Fortunately, the FP7 (7th Framework Projects) MARINET project (Marine Renewables Infrastructure Network), which was funded by the European Union, highlighted in the report that the state-of-the-art technology from wind energy can allow for grid-compliant installations of tidal farms [53]–[56].

2) ARRAY CONFIGURATION

Many problems such as turbines interaction and the flow changes are still not clear as they depend on a couple of factors, including gabs for axial, transverse and diagonal arrangement and configuration of devices, but they may have large influences on the environmental impacts. Therefore, the effect of the array configuration (turbine spacing, capacity, etc.) cannot be ignored. However, the knowledge of deploying a turbine array is still very limited. Only a few research papers discuss this problem [57]. In [58], it concludes that water flows and water levels will be affected by the configuration, such as a reduction in tidal range and a delay in high and low tides. This effect will be significant only if large capacity array configurations using a high turbine density are deployed. Consequently, turbine density and array capacity are the most critical factors in the design of array configurations. Meanwhile, this paper also proposes the suggestions for the optimization of the configuration. Generally speaking, it is better to arrange the devices in long rows rather than as a number of rows in series, and that arrays with higher local blockage outperform arrays with lower blockage. What should be mentioned is that according to the FP7 project DTOcean (Optimal Design Tools for Ocean Energy Arrays), the array configuration highly depends on the device or technology chosen, and the chosen specific location has a great effect on the flexibility [31], [59].

3) TURBINE DESIGN

As the basic physical principles for marine current energy extraction are actually very similar to the wind energy, many researchers propose using the similar techniques which have been successfully used in WECS. However, the ocean environment is quite harsh and variable; there are still a lot of differences and difficulties in the design of marine current turbine, including stall characteristics, the effect of high thrust loading on the tips, the synergy between sea water conditions and such tribological phenomena, the possible occurrence of cavitation in the blades. A special attention should be pointed is that the marine current turbine has much shorter and thicker blades than the wind turbine to withstand the greater hydraulic pressure which is caused by the higher density [20], [60].

Recently, certain technology called SmartBlades embodies sensors and micro-processors into the blades to monitor the damage and the strain. According to this information, it will greatly help the designers develop some more efficient blades in the very near future [61].

4) INSTALLATION

Until now, only a few full-scale devices have been installed, as a result, the existing practical experience is very limited. Fortunately, most MCECS devices will have the similar installation, foundation and mooring processes like the offshore WECS. However, construction of the foundations and the device installation in the deeper sea with the strong water movement continues to be a particularly challenging problem right now. Moreover, all the installation must be easy and fast in order to reduce the cost in the remote areas [53], [61].

5) MAINTENANCE

According to [31], annual operation and maintenance costs of ocean energy devices is estimated to be at around 3.4-5.8% of capital expenditure compared to 2.3-3.7% for offshore wind. Therefore, it's necessary and important to find some solutions to reduce this cost.

TABLE 5. Maximum tip ratio for avoiding cavitation [23].

Marine Current velocity (m/s)	Max. tip ratio to avoid cavitation
2.0	3.5
2.5	2.8
3.0	2.3

Normally, for the maintenance of MCECS, an offshore platform or ocean-going vessel is always essential to achieve the devices in the open sea in the favorable weather condition. It would be quite difficult and hazardous. For the economic reasons, the designers have taken some methods at the design stage of the system (such as reduce the moving parts and design robust devices). Moreover, lubricants with strong adhesive force, good quality seals and bearings, and as well as sturdy blades are used in MCECS, to reduce the frequency and difficulty of maintenance procedures. The system only requires the minimum level maintenance [20].

6) CAVITATION

As the size of MCECS devices increasing recently, the speeds at the tips of the turbine blades are comparatively high. The system may encounter certain operational difficulties. One of the important issues is known as cavitation, which may be difficult to avoid at all the points of the blades. It always occurs when the partial pressure locally falls below the vapor pressure of water and its potential damage effect usually appears at low velocity in pumps and propellers. The research in this part needs to propose the choices of blade profiles and materials to resist or reduce the cavitation effects which can bring about the efficiency loss, functional constraints and damage problem.

In order to avoid cavitation, the rotor tip ratio need to be limited. It follows that the turbine speed has to decrease to maintain the same maximum tip ratio when the turbine radius is increasing. For the purpose of keeping the blade tip velocity below the cavitation velocity of around 7 m/s, low tip ratios are needed badly [23] (see Table 5).

7) PACKING DENSITY

It needs to respond that how many and what size MCECS devices will lead to a significant effect on the marine environment and the flow pattern. Numerous factors are taken into account, including the structure and depth of the seabed, flow regime and available area. All the research in this domain will help the companies find the most suitable sites worldwide, and understand the implications of MCECS farms. Based on [32], some results of the packing density of the farms are as shown:

For seabed depth 20-25 m, 5 m in diameter turbine, 1800 units/km^2;

For seabed depth 25-40 m, 10 m in diameter turbine, 82 units/km^2;

For seabed depth > 40 m, 20 m in diameter turbine, 38 units/km^2.

It should be mentioned that the marine current velocity will vary as a function of the depth. For the lower half part of the flow, the velocity at a height Z above the seabed approximately follows a seventh power law [30].

$$V = \left(\frac{Z}{0.32h}\right)^{\frac{1}{7}} V_{\text{mean}}, \quad \text{for depth } Z: 0 < Z < 0.5h \tag{2}$$

And for the upper half part, where the energy mainly stored in this part.

$$V = 1.07V_{\text{mean}}, \quad \text{for depth } Z: 0.5h < Z < h. \tag{3}$$

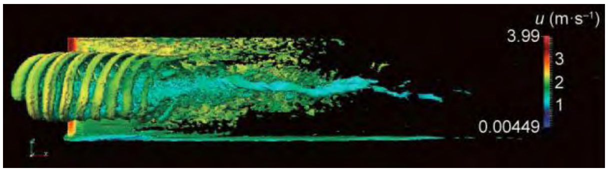


FIGURE 6. Simulation result of the swirling turbulence after the rotor blades [14].

8) TURBULENCE

The turbulent structure of the flow field is another critical design factor, which affects the fatigue resistance of the component. It is quite important to understand the turbulence levels. This not only helps the deployment of individual units, but also has vital significance for the practical limitations of the design. Furthermore, the noise disruption caused by the turbulent waters may affect in particular marine mammals [49]. FIGURE 6 just gives the simulation result of the swirling turbulence after the rotor blades. This turbulence will form a wake which interacts with the turbine downstream and the nearby environment.

9) FOULING

Fouling by unwanted marine growth and biofouling, will extremely increase the drag force and lower the efficiency of the turbine. There are four main physical characteristics (salinity, temperature, sediment transport and turbidity) in the sea, which are very important to the underwater equipments. Various devices deployed in the ocean become artificial reefs, which are very easy to attract a variety of marine life, particularly filter feeding invertebrates, followed by mobile fauna such as crustaceans, fish and eventually apex predators [45], [62]; meanwhile, the metal parts are much easier corroded (see FIGURE 7). All these problems can affect the system performance and cause significant fouling that leads to a necessity of regular maintenance. Regretfully, due to the MCECS size and depth in the water, it is difficult to meet this requirement. As a result, several methods (e.g. antifouling paints and ultra-sonic systems) have been proposed. Unfortunately, each method has its own challenges and drawbacks. For the corrosion, the corrosion-resistant materials such as titanium, stainless steels, nickel-copper alloys and high-nickel alloys are heavily used, which can highly reduce, or even eliminate corrosion damage [51]. Meanwhile, some advanced composite materials with improved fatigue, strength, and anti-corrosion properties, such as carbon-, glass-, and basalt-fiber-reinforced polymers are also proposed as the ideal candidates for cost reduction and increased durability [14], [61], [63]. FIGURE 8 just shows the example of the advanced material. It is made of glass/carbon fiber and powdered epoxy resins using electrically heated ceramic composite tooling [14]. This technology has many significant advantages, including higher fibre volume fractions and straighter fibres, suitable for high-volume, high-quality production, blade can be produced as one piece without adhesives, lower price than the conventional blade. Therefore, this epoxy powder technology is quite suitable for tidal turbine blades [61].

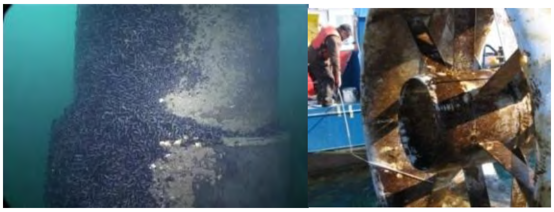


FIGURE 7. Biofouling & Erosion for MCECS [39].

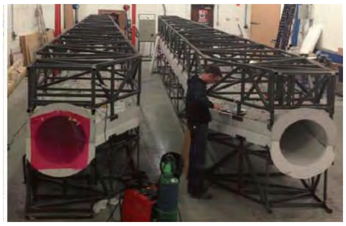


FIGURE 8. Advanced materials for turbine blades [14].

10) STRESS

There are also some challenges due to the higher density (1,025 kg/m^3) which brings a high stress on the turbine. Theoretically speaking, the turbine can extract the energy which is considered as the velocity reduction on both sides of the turbine blades. Essentially, it is the change in momentum when the marine current passes through the blades. A turbine and its anchoring structure must resist this force to ensure safe and stable operation of the device under the water.

V. SUPPORT STRUCTURE

The support structure of MCECS is regarded as a very essential part when designing the entire system. It must bear its own weight and also withstand the harsh operating conditions. All the systems presented to date can be either seabed-mounted (fixed to the seabed) or mooring (suspended from floating platform or seabed) structures (see FIGURE 9).

The choice of suitable support structure highly depends on depth, unit size, the seabed material and the economic considerations. The principle variations are shown in FIGURE 10 [23], [35], [40], [64], [65].

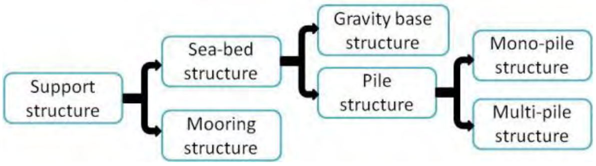


FIGURE 9. **Classification of support structure.**

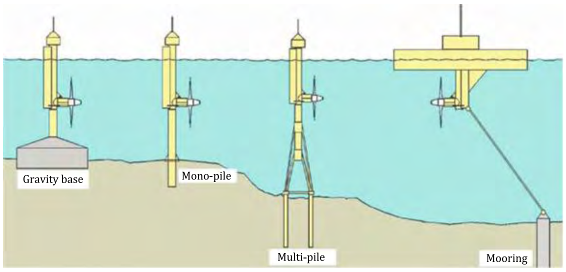


FIGURE 10. **Structure concepts for marine current turbine [66].**

A. GRAVITY STRUCTURE

Primarily, the gravity structure contains a large concrete or steel base and column attached to the seabed. The seabed must be prepared prior to installation. The steel based gravity structure has many advantages, such as ease of production, transportation and installation; however, it is unexpectedly easy to scouring. As this kind of structure may be composed of either steel or concrete and achieve stability by its own weight, it must be more massive than the other options. Atlantis Resources Corporation has just used this structure for their systems [28].

B. PILE STRUCTURE

The principle of this structure is very similar to that used in main large WECS, whereas the device will be attached to at least steel or concrete piles penetrating the seabed. If the seabed condition is soft adequately, the piles can be fixed to the ground by hammering, if the rock is harder, pre-drilling, positioning and grouting can be operated directly over it. The simplest mode of this structure is to fix the turbine to a single pile at the desired depth which has penetrated into the seabed. The pile may stretch out on or below the water surface. Many horizontal axis turbines will usually be suitable to use this structure.

Essentially, there are two variations of the pile structure: mono- and multi- pile structure.

Mono-pile structure (20-30 m depth) is the most interesting choice in recent years. It contains a large-diameter hollow-steel beam which drives 20-30 m into the seabed for the water depth less than approximately 30 m if the surface piercing structure is considered. No preparation of the seabed for the installation is the most considerable advantage of such structure. The first pilot project, SeaFlow, has just used this structure.

In deeper waters, MCECS has been more interesting in a **multi-pile structure** rather than a mono-pile, which increases the costs, but allows the use of a larger and more powerful turbine giving a greater energy capture capability. Multi-pile structure (30-60 m depth) is anchored to the seabed using steel piles, drilled around 10-20 m into the seabed according to the seabed condition at each corner. This structure would be applied to surface piercing designs in greater water depths (perhaps 50 m), but it will be considerably much more expensive. Compared with the other structures, the mainly advantages of such structure are the reduction in structural loadings and the possible corrosion reduction due to a reduction in leg diameter. SeaGen S, the first commercial project, has adopted this scheme.

C. MOORING STRUCTURE

This structure provides a more reliable solution for the deep-water condition. It is clearly much more easily towed to site or removed for maintenance or repair; what's more, it is also not so sensitive to variations in the depth of water at different locations, which is an excessively big problem for the construction and installation of the seabed mounted structure in deeper water, such as SR2000 and BlueTEC [67], [68].

Usually, there are three options for this structure. Firstly, conventional chains, wires or synthetic ropes system fixes at the seabed by drag, pile or gravity anchors. The second option is a taut line mooring using lightweight fiber ropes attaching to the barge hull. In each of the first two cases, 4 to 6 lines should be considered. The last option is that one or more turbines mounted to one single suspended platform, which can move together according to changes in sea level.

D. SUMMARY

Normally, the seabed-mounted structure is preferred for shallow water as it will be relatively simple and cheap to install, and this structure is generally more solid than mooring structure due to the dynamic wave problem. Since piercing structure can solve a number of problems, in particular enabling deployment and maintenance of the turbine from the surface, the system located in shallow water is also considered to adopt this structure. The expected depth limitation of this system will be between 30 m and 50 m, depending on many factors such as seabed material and surface, marine current speed, wave climate, etc. However, if all the systems in the marine current farm are using this structure; this area will be designated as an exclusion zone for all shipping.

For the water deeper than 50 m, either totally submerged seabed mounted, or mooring structure, are the interesting selections. Generally, a turbine even in deep water still needs its relative high rotor as 75% of the marine current energy is typically to be found in the top 50% of the flow according to equations (2) and (3). Some researchers have proposed some special designs for some specific site with deep water: there is the first MCECS for the depth of 20-40 m, and between 40 m and 80 m for the second device (see FIGURE 11).

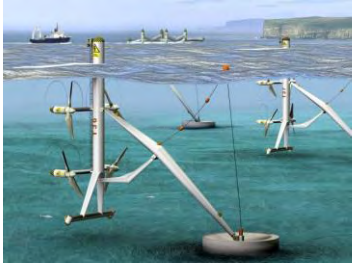


FIGURE 11. 4 MW MCECS with a 20 m rotor at the depth of 60 m [69].

However, increased depth does not only mean higher installation costs, but also leads to significantly higher static pressure on the structure. Experience has shown the difficulties of deploying an MCECS in intense currents and great depths. The desired depth of water is probably more than 15 m at low tide and approximately less than 40 or 50 m at high tide. The minimum condition must accommodate a turbine with 5 m blades. The seabed mounted structure technology using mono or multi-piles is more mature, and carries fewer uncertainties than using floating moored devices [30], [50], [70].

VI. TURBINE CONCEPTS

Marine current turbines can be classified in different ways with overlap between categories. In this paper, these devices will be classified depending on the way they interact with the water in terms of motion. So, the whole of the different models available could be mainly classified as follows:

- Horizontal Axis Turbines
- Vertical Axis Turbines
- Oscillating Hydrofoil

For the sake of increasing the marine current velocity passing through the turbine and the capture of effective power, ducted structure (Venturi Effect) can surround the blades to concentrate the flow towards the rotors for both horizontal and vertical turbines. This design can increase the marine current speed in front of the rotor, and raise power output by up to 40% compared to unducted turbines. Moreover, it will reduce the turbulence and harmful effects on the rotor [8], [64].

A. HORIZONTAL AXIS TURBINE

Horizontal axis turbine (axial flow turbine), the most common turbine concept, is very similar to the wind turbines which are usually seen in wind farms. It extracts energy from the moving seawater, just as the wind energy extraction from the air (see FIGURE 12). The marine current makes the rotors rotate around the horizontal axis to generate power which is parallel to the water flow. The amount of power that can be harvested from the water current also depends on the rotor diameter.

Nowadays, most of the marine current devices are the horizontal axis turbines. This type of turbine can also be classified according to the number of blades. Right now, multi-bladed devices are more favorable compared to single-blade devices as they can produce larger starting torque and decrease equilibrium problems. However, it will bring much more hydrodynamic losses [64]–[70].

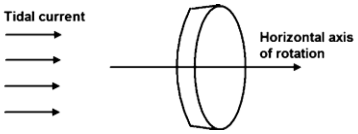


FIGURE 12. Horizontal axis turbine [66].

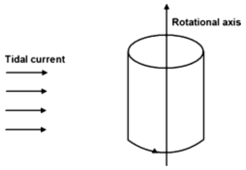


FIGURE 13. Vertical axis turbine [66].

B. VERTICAL AXIS TURBINE

For vertical axis turbines (cross flow turbine), water stream flow is perpendicular to the rotational axis of the turbine as shown in FIGURE 13. One of the most interesting characteristics is the independence of the direction of the flow. It can extract marine current energy from any direction which is an advantage compared to the horizontal axis turbine.

Moreover, the design of vertical axis turbine also varies more than the horizontal axis turbine: Savonius Type (Drag Type) and Darrieus Type (Lift type). Darrieus type can also be divided into Egg Beater Type and H-Type (see FIGURE 14). Most of these designs have been already used in the wind power industry successfully. They can directly transfer the mechanical torque without the complicated transmission systems or an underwater nacelle.

Furthermore, it can be much more easily applied at any specific site than the horizontal axis turbine, since vertical axis turbine has more freedom to change its height and the radius.

However, this turbine still has some drawbacks. The mainly one is that it needs a larger area for installation, and if cavitation occurs, the whole blade will be affected instead of just the tip of the horizontal axis turbine. The primary problems of the vertical axis turbine are high torque fluctuations with every rotation and no self-starting capabilities [34], [64]–[70].

C. OSCILLATING HYDROFOIL

Due to the differential pressure on the both sides of the hydrofoil, the oscillating hydrofoil generates hydrodynamic lift and drag force. These two forces induce tangential force of the fixing arm to make a large wing hydroplane move up and down or a whale's tail hydroplane moves left and right.

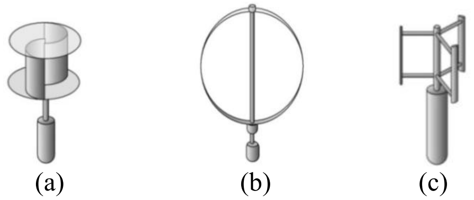


FIGURE 14. **Three different vertical axis turbines: (a) Savonius type; (b) Egg beater type; (c) H-type [71].**

These motions can drive reciprocating hydraulic ram pump, high-pressure hydraulic fluid to run a hydraulic motor and generator. Until now, there are only a few systems using this technology in MCECS. Normally, it is used for wave energy extraction [26], [34], [64]–[70], [72].

D. COMPARISON

The comparisons between horizontal and vertical axis types are given in Table 6.

TABLE 6. **Comparison between vertical and horizontal types [73].**

	Horizontal	Vertical
Design simplicity	Complex	Simple
Cost	High	Less
Generator coupling	Using right angles gear coupling	Placed at one end of the shaft and may be above the water surface
Noise emission	High	Less
Floating and augmentation	Not Easy	Easy
Skew flow	Faces problems	Skew flow
Starting torque	High (self starting)	Poor
Output torque	Ripple-free	Contains ripples
Efficiency	High	Low
Control	Easy	Not easy
Installation	Hard	Less hard
Known technology	Well known based on experience with wind	Not well-known

Although there is no uniform agreement in the optimum shape design of the marine current turbine, however, many developers prefer the horizontal axis turbine for marine current energy extraction [70]. According to [74], right now, for large-scale MCECS with a power capacity over 500 kW, they mainly use the horizontal axis MCECS. Actually, several horizontal axis MCECS technologies are developed more than one or two generations. Some of them have been already selected by the industrial communities to achieve the pilot demonstrative MCECS farms before the final commercial stage [74].

In accordance with the turbine design, the turbine blades can be designed as either fixed-pitch or variable-pitch to operate during flow in both directions. But, due to the uncertain mechanical maintenance requirement caused by the moving parts in the seawater, it's better to design the horizontal turbine with fixed-pitch blades and it's true that nearly half of the large projects use such kind of design.

In the following section, some tidal energy companies, their horizontal axis turbine technologies, projects and the latest news are presented.

FIGURE 15. **SeaGen S [24].**

VII. CASE STUDY PROJECTS

A. MARINE CURRENT TURBINE LTD (UK)

SeaGen S (1.2 MW at 2.4 m/s), the world's first grid connected commercial marine current energy turbine with a mono-pile structure, was installed in Strangford, Northern Ireland in May 2008 by Marine Current Turbine Ltd (belonged to Siemens since 2012, and then be acquired by Atlantis Resources Ltd in 2015) (see FIGURE 15). This device comprises two axial flow rotors of 16 m diameter with 100 tons weight, each driving an Induction Generator (IG) through a gearbox. It has already generated electricity more than eight GWh since its installation [74]. During the strong spring tide of the month, this system could generate more than 20 MWh daily. The rotors have a patented full span pitch control which allows them to operate on both flood and ebb tides. These two rotors can be raised above the water surface to ensure the convenient and safe maintenance.

A 2 MW floating turbine, which is noted as SeaGen F, is agreed to jointly developed by both Marine Current Turbine Ltd and Bluewater Energy Services B.V. (Bluewater) in 2014. This turbine will be deployed in the Bay of Fundy, Canada. The system can generate enough clean and reliable energy which supplies up to 1,800 households in Nova Scotia. The project for a commercial multi-megawatt marine current turbine array at the Fundy Ocean Research Centre for Energy (FORCE) is being developed. The selected site of this project, which is located in the Minas Passage, Bay of Fundy, is leased from FORCE by Minas Energy. This position has up to 15 m tidal range and 5.5 m/s current speeds; moreover, the Feed-in Tariff in Nova Scotia is also very attractive. All of these make this position one of the most remarkable and economic sites worldwide. Scientific researches show that in the Minas Passage, it can harvest clean and predictable tidal power as much as 2.5 GWM [24].

SeaGen U is a new horizontal axis turbine with 1.5 MW capacity designed by Marine Current Turbine Ltd. This system takes many developments from SeaGen S and AR1500, such as the active pitch system and yaw capability. The system has a 20 m diameter rotor and weighs approximately 150 tons, which means it's a little bigger than SeaGen F.

Because of the redundancy design, the turbine can operate up to 25 years and overhaul every six years [28].

Marine Current Turbine Ltd (now Atlantis Resources Ltd) is currently developing a 5 MW array in Kyle Rhea, Skye with 20 m in diameter and a 2 MW system. The other 10 MW array project with the same turbine near Skerries, Anglesey was suspended in September 2014 by Siemens and this project will be resumed by Atlantis Resources Ltd in the coming years. They have a 100 MW project approved at Brough Ness in the Pentland Firth [65] (see FIGURE 16).

FIGURE 16. SeaGen farm [75].

B. SABELLA (FRANCE)

The first France submarine turbine "Sabella D03", 3 m in diameter and 10 kW of power, was successfully installed in April 2008 next to Bénodet, in Odet's estuary in South Brittany for a full year. This is a pioneering achievement in France. Extensive experiments and measures have demonstrated its innocuousness to the wildlife and low acoustic impact in the sea. This turbine is now exhibited for educational purposes at the Ocean Discovery Park Océanopolis in Brest [76].

Following the previous prototype "Sabella D03", SABELLA continues to strengthen its industrial credibility by producing a full-scale demonstrator: "Sabella D10" (see FIGURE 17).

Through the "Sabella D10" project, selected by Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME) for public funding under the "INVESTISSEMENTS D'AVENIR" initiative (€ 3.6M), the full-scale turbine, 10 m diameter rotor, 17 m height and 450 tons weight, was firstly installed in Fromveur Passage at a depth of 55 m off Ushant Island at the end of June 2015 and connected to the Ushant Island's power grid in November the same year. According to the farm project, the Sabella turbine farm contains 4 turbines; and the other 3 ones are scheduled to be installed until 2019.

Unfortunately, there are some cable failures for the first D10 turbine in July 2016. Since then, the turbine has been undergoing maintenance works at the ports of Brest. The redeployment in May 2017 was postponed to conduct some tests for 3-year continuous operation, and the turbine was still up for reinstall later in 2017 [77]. Larger turbines D12 and D15 with 1-2 MW rated power capacity, which will be applied to the turbine farms in the near future are still under design [74], [76], [78].

FIGURE 17. Sabella D10 [76].

All the types of Sabella have more blades, but fixed pitch angle; the Direct Drive Permanent Magnet Synchronous Generator (DDPMSG) is used to eliminate the complex mechanical elements and minimum maintenance; the system does not disturb the ships due to its invisibility from the seawater surface; the turbine can be separated from the foundation support which means the turbine can be easily replaced for maintenance.

C. CLEAN CURRENT TIDAL TURBINE (CANADA) & TIDAL GENERATION LTD (UK)

In September 2006, Clean Current Turbine with 6 m in diameter, 65 kW rated power was constructed by Clean Current Power Systems (CCPS) and was installed on the Race Rocks Ecological Reserve, Canada (see FIGURE 18).

FIGURE 18. Clean current turbine [26].

This system mainly consists of a bidirectional ducted horizontal axis turbine and a variable speed DDPMSG. The only moving part-turbine blades would enhance the stability. Moreover, the generator and rotor disk are designed as a modular unit for easy maintenance and replacement. As a result, every five years, the bearing seals need to be replaced; while for the machine, the designed service life is about 25-30 years and it must be overhauled during every ten years.

In 2009, CCPS and Alstom signed a licensing agreement to bring their first commercial MCECS to market by 2012. Unfortunately, the two companies decided to terminate this agreement on 15th November, 2012. The main reason is that CCPS preferred to focus on river turbines with 200 kW to 250 kW power for the depth less than 20 m; while for Alstom, it intended the larger utility scale opportunities. In September 2012 Alstom announced its acquisition of TGL (Tidal Generation Ltd) from Rolls-Royce PLC and completed in January 2013. On 2nd November 2015, General Electric Co. (GE) acquired Alstom's power and grid business [78].

In September 2010, TGL (now GE) developed its first 500 kW tidal turbine: Deepgen. It was successfully installed and connected to the grid at EMEC's (European Marine Energy Centre) Fall of Warness tidal energy test site off the island of Eday in 2011/2012. Until March 2012, the device had supplied more than 250 MWh of electricity to the

UK national grid from the reliable and predictable marine current [64].

FIGURE 19. GE turbine [64], [80].

On 24 January 2013, just after the acquisition, Alstom successfully deployed the first 1 MW turbine at EMEC. It employed the same tripod support structure which was used for the previously tested 500 kW device of TGL (see FIGURE 19). This system weighs 150 tons, consists of three pitchable blades, 18 m in rotor diameter and 22 m long nacelle, and can be installed in a water depth of 35 to 80 m. This system is designed for the marine current between 1 and 3.4 m/s, and rated at 2.7 m/s. In order to improve tidal power technology, a lot of testing and analysis in different working conditions off Orkney Islands were carried out throughout 2013 over an 18 month period [79]. During this test, it has produced over 750 kWh electric power to the grid. Expanding upon this system and the 10-year combined knowledge and experience, the Oceade 1.4-18 (1.4 MW, 18 m in rotor diameter and can be scalable up to 23 m), the first variant of Oceade platform, has been designed and realized. In December 2014, Oceade 1.4-18 were chosen to equip ENGIE's tidal pilot farm (4*1.4 MW in total capacity) which can supply power to 5000 people at Raz Blanchard by GDF Suez (now ENGIE) (see FIGURE 20) [74], [80]. This project was announced to begin 2017 and operated for 20 years expectantly. However, GE has decided to suspend the development of the Oceade tidal turbine, as a result, ENGIE gas shelved this project, citing ''lack of supplier'' as a result [81].

D. OPENHYDRO GROUP LTD (FRANCE)

OpenHydro Group Ltd, a subsidiary of DCNS since 2013, is an energy technology company which designs and manufactures turbines to generate renewable energy from tidal streams.

All the OpenHydro turbines have a variable speed DDPMSG and a high solidity horizontal axis rotor with symmetric, fixed pitch, rim structure blades. It has only one slow-moving rotor and lubricant-free construction which permits the minimization of maintenance requirements. The OpenHydro turbines are always secured to the seabed by a tripod gravity base [26].

In 2007, the original agreements for tidal farm deployments were announced which aims to deploy four turbines in Paimpol-Bréhat, north coast of Brittany-the first marine current park in France (Cooperation with Électricité De France, EDF) and operate in 2014. However, some delays in the final farm operation could still be envisaged. The first turbine of this project, assembled at DCNS' shipyard in Brest, was firstly installed at a depth of 35 m and has been tested in the Bay of Douarnenez on August 31, 2011 and tested for two months (see FIGURE 21) [74]. Finally, this turbine was deployed after many delays in the Paimpol-Bréhat Tidal Farm for 1,700 hours of tests from December 2013 to April 2014.

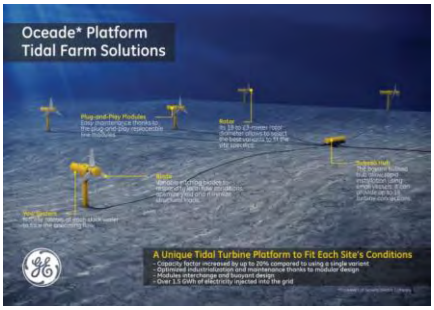


FIGURE 20. GE Oceade platform [80].

FIGURE 21. Tested OpenHydro turbine [82].

According to the latest news from the official website, two OpenHydro commercial-scale tidal turbines (16 m diameter and 1000 tons) have been successfully deployed by the OpenHydro barge on EDF's Paimpol-Bréhat site: the first one was installed on 20 January 2016, with the second one following on 29 May, 2016 (see FIGURE 22). Each of the turbines having 500 kW capacity was connected to a common 1 MW subsea converter developed by GE, which would transform the current to high-voltage direct current. Then the electricity can be transmitted to the French electrical grid via a 16 km single subsea cable which would make the project be the first grid-connected tidal array in the world [77], [83]–[85]. In April and July 2017, these two turbines were successfully retrieved by OpenHydro's partner company Navel Energies for the repairment of the minor fault as it could lead to corrosion. The operation would begin in the port of Cherbourg over the next few months and after the overhaul, they are planned for redeployment next fall [86].

In May 2016, OpenHydro has announced the development of a purpose-built tidal turbine assembly facility at Cherbourg Port. This facility will be an industrial hub for the delivery of the Normandie Hydro project for EDF Energies Nouvelles. This project will deploy an array of seven OpenHydro commercial-scale 2 MW turbines in the Raz Blanchard in 2018, supplying electricity to 13,000 local residents until 2038 [82]. Finally, this project was agreed by the French government in 4 April, 2017 [88]. Later in July 2016,

FIGURE 22. 2 MW OpenHydro turbine [82], [87].

OpenHydro has been selected by the Japanese Ministry of the Environment to supply a MECES. The turbine is scheduled for installation and connection to the grid in 2018 off Goto City, Nagasaki Prefecture. Moreover, OpenHydro also worked with PT AIR for the first 10 MW pilot array in Indonesian in 2019. After that, this project is expected to up to a capacity of 300 MW by 2030.

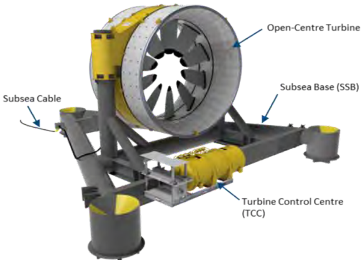


FIGURE 23. Cape Sharp Tidal turbine [89].

In 2014, Cape Sharp Tidal, a new joint venture enterprise, was established officially by OpenHydro Company and its Canadian partner Emera Inc.. Right now, the company is carrying out a plan for a grid-connected 4 MW (two 2 MW turbines) tidal array FORCE. In November 2016, it deployed its first 2 MW turbines, and was producing Canada's first in-stream tidal energy to the Canadian grid since then (see FIGURE 23). On 16 June 2017, this turbine was retrieved for a turbine control center upgrade which will transform the energy to the AC power and send the operational and environmental sensor data. The second turbine, also the last one, will be installed in 2017. The company plans to use this initial 4MW farm as the first phase of a potential commercial-scale project. It aims at establishing a farm with total output up to 16 MW in the next phase, 50 MW in the following step and finally as much as 300 MW. This project can completely supply for nearly 75,000 customers [82], [89].

E. ANDRITZ HYDRO HAMMERFEST (UK)

The HS300 (300 kW), the proof of the concept turbine between 2003 and 2009, was finally deployed in Norway and connected to the grid in 2004. During the test, the prototype operated for more than 17,000 hours, delivered over 1.5 GWh per year to the grid and showed 98% availability.

In December 2011, the 1MW pre-commercial marine current tidal turbine of ANDRITZ HYDRO Hammerfest HS1000, which is based on the technology of the previous one, was tested at EMEC's tidal test site (see FIGURE 24).

FIGURE 24. HS1000 turbine [90].

The device started to deliver its energy to the grid successfully in February 2012 and generated more 3.5 GWh annually. After the redeployment and reconnection to the grid on 28 August, 2013, finally, its nacelle was retrieved in April 2014. This company is planning to develop a 10 MW commercial array in the Sound of Islay and a 95 MW one in Pentland Firth, Scotland based on this technology [64], [74], [78], [90].

The MK1 turbine (1200 kW-1500 kW) is designed to be capable of working at a depth of 35-100 m with a nominal speed of 5-15 RPM, using an IG (see FIGURE 25). The turbine is 35 m height with an 18-26 m diameter rotor, consisting of 3 open blades. The lifetime of the turbine is 25 years with service maintain every 5 years. This turbine was chosen for MeyGen project.

FIGURE 25. MK1 turbine [28], [90].

MeyGen project is a tidal farm project with a power capacity up to 398MW containing 269 submerged turbines, which will provide enough electricity to 175,000 Scottish households. This project will be located between the northernmost coast of Scotland and the island of Stroma. It is the largest planned tidal farm project worldwide right now, and is also the unique commercial, multi-turbine array to have commenced construction. This project is divided into several parts as follows: MeyGen Phase 1A (6 MW), MeyGen Phase 1B (6 MW), MeyGen Phase 1C (74 MW), Phase 2 (166 MW) and 3 (146 MW) [28].

Phase 1A consists of four 1.5 MW turbines (incorporated by two different kinds of turbine technologies: 1 AR1500 turbine and 3 MK1 turbines) installed on gravity support structures. The three MK1 turbines were deployed between November 2016 and January 2017. On 15 November 2016, the first power had been delivered to the 33 kV-grid onshore from the first MK1 turbine. On 6th December 2016, the turbines operated at full power when the water speed reached

FIGURE 26. **AK1000 turbine [28].**

over 3.0 m/s. Operation at full power is a significant milestone for this project and the industry. AR1500, the fourth turbine, has been successfully deployed on 20 February 2017, exported power to the same grid and operated at full power on 24 February 2017. For this phase, it will generate enough electricity to supply 2,600 households [28]. Late in March, MeyGen Phase 1A project generated near 400 MWh power.

However, according to the announcement of the program for system enhancement earlier in 2017, two MK1 turbines were successfully reinstalled and reconnected in July 2017. The other MK1 and AR1500 turbines are due to be redeployed in August 2017. It is expected that MeyGen Phase 1A will be operating at full 6 MW capacity by the end of 2017.

This project will verify that the development of the tidal array project is commercially and technically feasible; moreover, the construction, installation, operation and maintenance of this phase can adequately offer the vital experience and lessons for the following phases.

Construction for the next 6 MW (6 turbines) MeyGen Phase 1B, also known as Project Stroma, is due to commence later in 2017.

F. ATLANTIS RESOURCES CORPORATION (UK)

Atlantis Resources Corporation is a tidal power generation enterprise who focuses on the development of global tidal power projects and the provision of tidal power generation, installation, fixation and subsea equipment evacuation. The first 1 MW fixed horizontal axis turbine AK1000, which is rated at 2.65 m/s and has 22.5 m tall, two 18 m diameter rotors and 130 tons weight, was installed on its subsea berth, at the depth of 35 m at EMEC in August 2010 (see FIGURE 26). The test lasted up to three years.

AR1000 is another 1 MW turbine, but with a single - rotor which drew heavily the experiences and lessons from testing and development of AK1000 turbine (see FIGURE 27). It has almost the same dimension as the previous one, was deployed in 2011 with its own 1,300 tons gravity base structure on Berth 6 at EMEC's Fall of Warness tidal test site. Then, it was connected to the grid for a two years test which made AR1000 the first grid-connected, commercial-scale tidal turbine in Scotland.

FIGURE 27. **AR1000 turbine [28].**

FIGURE 28. **AR1500 turbine [28].**

In January 2013, Atlantis Resources Corporation transported 2 million dollars worth of onshore equipment to China, Energy Conservation and Environmental Protection Group (CECEP). At that time, CECEP leaded a project which was planned to install an AR1000 turbine on its grid connected test site near Daishan in the Zhejiang province in the People's Republic of China (PRC) in 2014. This turbine would be the first commercial scale tidal turbine mounted in PRC and also be a very important milestone for the PRC's tidal power sector. Meanwhile, it would supply sufficient data on the turbine efficiency and reliability, and the environmental performance for the China's State Oceanic Administration (SOA).

In September 2013, Atlantis Resources Corporation and Lockheed Martin Corporation signed a contract consisting of the design details and systems integration for the larger turbine AR1500, and the program commenced in March 2014 (see FIGURE 28). Then, AR1500 (1.5 MW at 3.0 m/s) was designed which contained 18 m diameter rotor, radial flux permanent magnet generator, active pitch and yaw capability, and approximately 150 tons weight. All the key operating systems of AR1500 have triple redundancy built in to maximize reliability offshore to withstand the extreme environmental conditions.

The first unit was assembled by Lockheed Martin Corporation at the Offshore Renewable Energy (ORE) Catapult facility in Blyth, Northumberland in 2016, and then was tested on the Nautilus tidal turbine rig there. Finally, it was installed on 20 February 2017 as one part of MeyGen Phase 1A [28], [74].

In December 2014, one project (Atlantis Resources Corporation and DP Energy group each owns 50 % of the project) was awarded a Developmental Feed-in Tariff by the Nova Scotia government for as much as 4.5 MW tidal generation of the 17.5 MW total capacity. Atlantis can operate up to three AR1500 turbines deployed at FORCE. The turbine installation is planned in 2017.

The other agreement also should be put forward is the Strategic Partnership Agreement between Atlantis Resources Corporation and Hyundai Engineering and Construction regarding the collaboration of development of ocean power globally. Firstly, they will design and develop a 100 MW tidal stream project in the south of Korea [28].

FIGURE 29. CoRMaT [91].

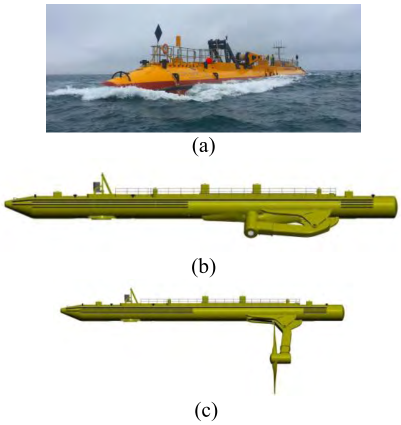
G. NAUTRICITY (UK)

Scottish tidal turbine developer Nautricity has produced the second generation tidal energy converter CoRMaT (see FIGURE 29). It employs two closely spaced contra rotating rotors. The first rotor rotates clockwise with three blades, while the second one rotates another direction with four blades. This opposite movement directly drives a DDPMSG. This device is suitable for water depth from 8 m to 500 m and fixed via a tensioned mooring system which is provided by Mooring Systems Ltd. The full-scale system with 10 m diameter rotor, was installed at EMEC's Shapinsay Sound test site in May 2014. This device survived 2 months at sea without major issues and recovered in July 2014. After this successful sea trail, in 2015, Nautricity signed an agreement with EMEC to use a grid-connected tidal test berth at Fall of Warness tidal test site for the grid-connected test [64], [91].

Finally, in April 2017, Nautricity installed its 500kW CoRMaT tidal turbine at test site using Norwegian vessel Olympic Challenger by Glasgow developer. The seabed-mounted device, featuring a rotating turbine with two rotors, stands on gravity-based foundations. This turbine is due to be tested at EMEC for up to 18 months [64].

H. SCOTRENEWABLES TIDAL POWER LTD (UK)

Scotrenewables Tidal Power Ltd is a renewable energy research and development business in the Orkney Islands. This company focuses on the cost reduction of the marine current energy generation. It proposes to use the low cost, small boat for the simplified and safe manufacture, installation, maintenance and decommissioning of MCECS. The company has already designed an innovative floating turbine. It employs two horizontal axis turbines associated with integrated generator fixed on the floating platform just under the water surface which means it can capture the strongest power in the current flow. The technology has been under continuous engineering development, including rigorous testing of scale systems in both tank conditions and open ocean environments.



(a)

(b)

(c)

FIGURE 30. SR2000: (a) Test in the sea (b) Survivability mode (c) Operation mode [67].

In 2010, after the success of the previous 1/5th scale testing turbine, this company completed the world first large scale floating tidal turbine SR250 (250 kW). The 33 m long and 100 tons weight device was fabricated at Harland & Wolff in Belfast in 2010 and launched at EMEC's grid-connected tidal test site at Fall of Warness, off Eday, Orkney in April 2011. Then, SR250 was lifted from the water for annual maintenance, which focused on grid connection testing and longer deployment on 24 February 2012, and was set back to the water on 29 March 2012. On 18 April 2012, SR250 successfully transmitted the power to the grid, which is the first power to the UK grid by a large floating MCECS. In August 2013, it was lifted out for maintenance purposes and redeployed to a site with stronger tidal current where the device exported electricity to the national grid at its rated capacity in September. During the two and half years test (over 4000 hours) of SR250, there were no major failures of the system in the harsh operating conditions of the North Sea. The test also demonstrated the possibility and ability of the turbine maintenance via the low cost vessels with success. At the end of 2013, after this test, the focus of the company shifted to the global most powerful tidal turbine, SR2000 (see FIGURE 30).

SR2000, the culmination of more than 12 years of research, design and testing by Scotrenewables, is a larger 2*1 MW commercial scale turbine. SR2000 is powerful enough to supply for approximately 1,000 homes over the year and considered to be suitable for the tidal array. The first SR2000 was launched at Harland & Wolff shipyard in Belfast on 12 May 2016 and underwent preliminary trials in Belfast Lough. On June 2016, the 64 m, 500 ton turbine arrived in Kirkwall, Orkney Islands and took a series of test. On 12 October 2016, SR2000 was towed to its position from Kirkwall by Green Marine's vessel the Green Isle and then connected to its moorings at EMEC's Fall of Warness tidal test site. After the grid connected commissioning works at the end of 2016, SR2000 commenced generation and power export to the local Orkney grid. Since then the turbine has undergone a phased testing program leading to the full power. On 12 April, 2017, 2MW rated export capacity was achieved [64], [67]. Later, during 24 hours continuous test, it can generate more than 18 MWh electricity. In May 2017, this turbine was removed and towed to Hatston Pier for the maintenance. In August, just after its redeployment, SR2000 produced over 116 mew power in one week continuous generation which could sufficiently satisfy about 7 % of the electricity demand in Orkeny.

In 2012, Scotrenewables leased from the Crown Estate for the tidal array development at Lashy Sound, Orkney. This project has an installed capacity up to 10 MW and is currently progressing environmental data gathering. Recently, the European Commission (EC) selected Scotrenewables to lead on the enhanced SR2000. Owing to the flagship Horizon 2020 funding, Scotrenewables will optimize the turbine under the Floating Tidal Energy Commercialization (FloTEC) project which is planned to operate by 2019. This project is currently in the design and engineering phase, with the SR2000 Mark 2 due for installation at the EMEC, Orkney in 2018 [67].

I. BLUEWATER ENERGY SERVICES (NETHERLANDS)

Bluewater Energy Services is founded in the Netherlands in 1978. The company focuses on the tanker-based production and storage systems. It has developed one floating MCECS support platform called Bluewater's Tidal Energy Conversion (BlueTEC) platform, according to the expertise and lessons from the floating systems design, marine operations and offshore maintenance. It is a breakthrough solution as it is suitable for any type of turbine (both horizontal and vertical axis turbines). Moreover, it has less cost of installation and maintenance, and as well as more energy production.

Bluewater has partnered with a group of leading offshore companies, Italian company Ponte DI Archimede (PDA) and Scottish-based Environmental Research Institute (ERI), to realize a unique floating tidal energy platform. The first BlueTEC Modular, which was named "BlueTEC Texel" on 9 April, 2015, has been installed with Tocardo T1 (around 100 kW) turbine in June 2015, connected to the Netherlands electricity grid and began to produce electricity in the Wadden Sea of Netherlands in the summer of 2015 (see FIGURE 31). This platform has about 24 m length, 25 tons weight and can work for the place with depth between 20-1000 m. It will work initially with a single 100 kW tidal turbine, soon be upgraded with a 200 kW turbine, and subsequently will be upgraded further to 500 kW carrying two tidal turbines. Finally, two larger turbines will be installed for 2.5 MW. From this platform, it can test multiple turbine types and configurations. In November 2015, the turbine under the platform was changed from a T1 turbine to a larger T2 (250 kW) turbine.

This first system was just a demonstration platform for the distant places around the world. It was the first step for the further higher power capacity platform which aims the larger tidal array [68]. Based on the technology of this device, the other platform, Temporary Foundation Structure (TFS) platform with a T2 turbine (280 kW), was deployed at a temporary location in the Fall of Warness by 4-point mooring system and intended to operate from 24th March 2017 for a maximum 18 months. However, this unit will be removed in October 2017 (see FIGURE 32).

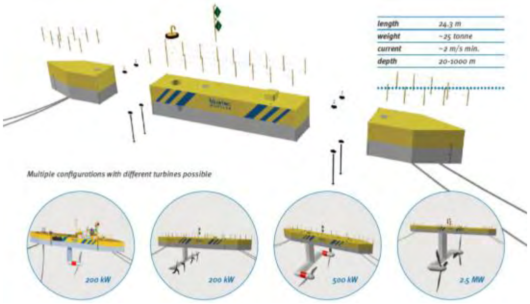


FIGURE 31. BlueTEC [68].

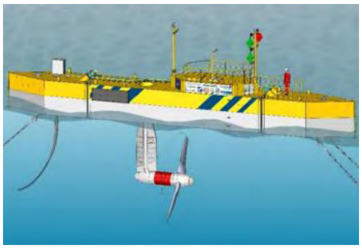


FIGURE 32. TFS platform with T2 turbine [92].

J. SCHOTTEL HYDRO (GERMANY)

TidalStream Ltd is a privately owned renewable energy business focusing entirely on Tidal Energy, who's a subsidiary of SCHOTTEL HYDRO. It has developed a tidal platform called Triton platform system which can accommodate an array of turbines and support a range of different turbine types. Based on this system, it will highly decrease the installation and maintenance cost. Right now, the Triton platform system can be divided into three kinds: Triton S (Power 1-3 WM, Depth: 25-40 m, adaptable to either a few large turbines or multiple smaller turbines), Triton 3 (Power 3-5 WM, Depth: 35-60 m, adaptable to a single row of larger turbines) and Triton 6 (Power 5-10 WM, Depth: 60-90 m, adaptable to several rows of larger turbines) (see FIGURE 33, FIGURE 34 and FIGURE 35).

Until now, Triton concept underwent several stages of development and test, including: a two rotor 1/20th scale model in a UK tow test facility; a six rotor 1/23rd scale model of the Triton T6 stability and fault condition test at institut français de recherche pour l'exploitation de la mer (IFREMER) deep water basin in Brest in 2009; a 1/10th scale Triton T3 (three rotor version) in a tidal stretch of the Thames and in the Haslar marine test facility of Gosport in 2010 and 2011 respectively; scale testing of the seabed

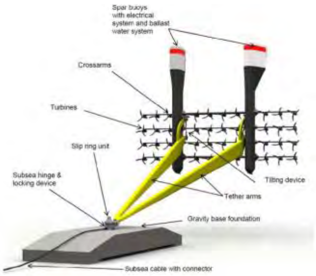


FIGURE 33. Triton S [93].

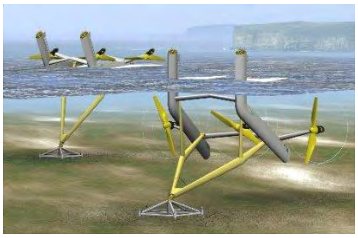


FIGURE 34. Triton 3 [93].

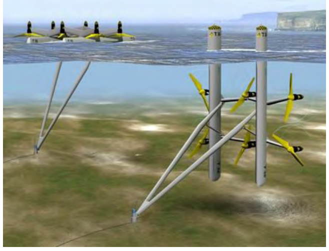


FIGURE 35. Triton 6 [93].

location and deployment system at Plymouth Ocean Energy basin and in the Fall Estuary [93].

Right now, the first full-scale semi-submersible turbine system based on Triton technology is being undertaken by another SCHOTTEL HYDRO subsidiary: Black Rock Tidal Power. This full-scale system uses forty SIT 250 (SCHOTTEL Instream Turbines) turbines (54-70 kW IG with rotor diameters 3-5 m.) mounted on the Triton S, summing up to 2.5 MW total capacity. This grid-connect Triton system, also called Triton S40 (see FIGURE 33), was specially designed for the high flow speed, and powers 1000 Nova Scotia homes. This device was originally planned for deployment in the autumn of 2016, and delayed to 2017. However, according to [94]–[96], the Triton deployment was delayed again to another year.

K. OTHER COMPANIES

Some other companies who focus on the marine current energy also should be mentioned, such as Tocardo Tidal Power and Nova Innovation Ltd.

Tocardo is a Netherlands found and based company, who is the leader in the tidal energy solution. In July 2016, International Marine Energy (IME) and Tocardo Tidal Power formed Minas Tidal Limited Partnership (MTLP, Minas Tidal) to extract the bay's powerful marine current energy by a floating turbine system starting in 2017. It plans to deploy three Tocardo floating UFS (Universal Foundation Systems) platforms at FORCE by catenary mooring systems, each with four 250 KW T2 bi-directional Tocardo turbines (see FIGURE 36) [97]. Moreover, Tocardo brings innovative technology to a whole new level with UFS. This new UFS is an integrated with five Tocardo T2 turbines on a semi-submersible U-shaped floating platform, up to 1.5 MW (see FIGURE 37) [92].

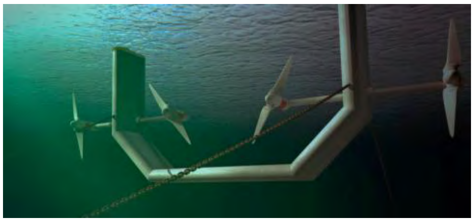


FIGURE 36. UFS with 1 MW [92].

FIGURE 37. UFS with 1.5 MW [92].

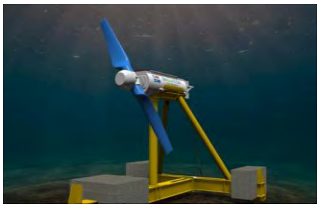


FIGURE 38. Nova M100 turbine [98].

Edinburgh-based Nova Innovation (Scotland) is a tidal energy generation company. In 2014, the world's first community-owned tidal turbine, which was developed by Nova Innovation and North Yell Development Council has begun exporting electricity to the local grid. Then, it installed the world's first fully-operational, commercial, grid-connected offshore tidal array with ELSA (Belgium) in Shetland. Phase 1 of this project is just completed: in March 2016, the first 100 kW Nova M100 turbine was deployed in the Bluemull Sound; the second one was in August 2016; the third one was in February 2017 [98]. Some more turbines will be installed in the following phases of this project. In July, 2017, Nova Innovation and the Crown Estate have signed an agreement of lease. They will plan to deploy a 2 MW tidal turbine array at Bardsey Sound, off the Llyn Peninsula in Cyngor, Gwynedd, Wales.

VIII. CONCLUSION

This paper mainly summarizes the attraction and the challenges of the extracting energy from marine current, and as well as the latest information about some famous tidal projects. Marine current is the horizontal movement of the ocean, which is just one form of ocean energy. However, it is a very attractive choice for the renewable energy due to its significant energy, the distinct advantages and technological and economical consideration. The mature WECS technologies have been already partially transferred to MCECS as their similar system structures; however, MCECS obviously still lacks of deep knowledge of the environmental and social impacts and confronts many problems. The physical impacts, ecological impacts and pollutions must be solved to minimize impacts of the marine life and environment nearby. Moreover, the technical challenges must be put more and more attention, such as: blade designs, installation, fouling, support structure, etc. Then, the famous marine current companies and their technologies and some projects undergoing recently are presented at the end of the paper. According to these large scale turbines or tidal array projects, many of them are belong to the UK-based companies, which indicate that the UK is currently leading the industrial process of tidal power generation. Moreover, the Europe also shows a very strong capability of research and production-manufacturing in this field as nearly all of these famous companies mentioned above are located in this continent. What also should be mentioned, according to the relative literature, other countries such as the USA and Canada as well as Korea and Japan, and possibly China and Indonesia, are also poised to become important players in marine current energy markets.

In recent years, many kinds of turbines (horizontal axis turbines, vertical axis turbines and oscillating hydrofoil) are proposed for MCECS application. It's true that the companies prefer different turbine technologies and there is no overall agreement for which type of turbine is the best solution for MCECS. However, with the development of the MCECS scale, only the horizontal axis turbine still appears some vitality. Certain horizontal axis technology has even reached 2 MW capacity. Many of the technologies have undergone one or two generations. For OpenHydro, it has even realized its seventh generation in 2014.

The support structure is a very important part for MCECS. Although there are many kinds of different support structures, the gravity structure is always preferred by the larger scale project. Recently, some other companies have proposed and achieved the different innovative floating platforms for the energy extraction. The capacity of the system is also up to 2 MW. These mooring structures can surely capture more energy and have the ability of easy deployment and accessibility. But their reliability and anti-interference performance still need to be investigated and tested in the future tidal array project.

In order to reduce the unnecessary maintenance of the system under the seawater, fixed-pitch blade is more appropriate than the variable one. Based on the larger scale turbine presented above, nearly half of the turbines choose the fixed-pitch one. The other point, which should also be mentioned, is the generator. All the machine topologies seem to be exploitable for MCECS. However, due to the particularity, certain machine may be not suitable for operating under the water as it would highly increase the possibility and difficulty of maintenance. Right now, the mainly kinds of the machines are IG and PMSG. More than half of the projects above use PMSG, or even DDPMSG. IG is normally a high speed machine, and always needs the gearbox; while for DDPMSG, it can eliminate this component. This difference will certainly influence the regular maintenance and the possibility of failure. Until now, there is no consensus worldwide, which one is the most suitable choice for MCECS. It can be researched continuously based on the operating condition of the system in the complex marine environment for a long time.

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