Analysis of development status of wave energy development and utilization technology

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***Abstract*—Wave energy has been one of the key directions in the research of marine energy development and utilization, due to its rich resources, green, clean, renewable and other characteristics,. There have been a number of wave energy devices which were commercialized. In contrast with tidal current energy technologies, the development of the wave energy field has slowed down over the past few years. The confidence of investors have been reduced by technological drawbacks of wave energy . At the end of 2016, the situation of the wave energy development field has improved significantly.. At present, there are 21 commercialized pre projects or pre commercialization projects running in the world and several array projects have been moving forward; current installations have a power rating of 1MW. In this paper, firstly, a comprehensive survey of the current situation of wave energy technology in global has been given; Secondly, sorting of wave energy devices and comparing the advantages and disadvantages of various types of devices have been combed and the technical difficulties and challenges have been analysed. Finaly, combined with the characteristics of wave energy resources distribution of China, the future development trend of wave energy devices and the direction suggestions for wave energy development work have been given.**

***Keywords*—Wave energy technology; development and utilization; technology status; development trend**

I. INTRODUCTION

In recent years, ocean energy, as a green low carbon renewable energy, has attracted wide attention from scholars and investors all over the world. Wave energy has always been one of the key directions of marine energy development and utilization technology because of its large resources, green, clean and renewable. Key to the success of the sector will be the improvement of current technologies and the identification of novel financial instruments to sustain the critical phase of moving to demonstration projects [1]. Although the development has slowed down in the past few years, policies for ocean energy are emerging one after another. Wave energy technology has higher technology maturity in marine energy. Following the setback of development in 2014, the industry urgently needs to reduce investment risks through technological progress.

In this paper, it has a comprehensive survey of the current situation of wave energy technology in global; sorting of wave energy devices and comparing the advantages and disadvantages of various types of devices; analysis of technical difficulties and challenges. Combined with the characteristics of wave energy resources distribution in China, the future development trend of wave energy devices and the direction suggestions for wave energy development work are given.

II. CURRENT SITUATION OF DEVELOPMENT AND UTILIZATION OF WAVE ENERGY

A. *Technical status*

There are variety different forms of wave energy devices. But these devices are derived from the following basic principles: Utilized the oscillations and wobble motion of objects under wave; Utilized the wave pressure difference; Utilized the wave energy is converted into potential energy by the rising of the waves.

The classification of wave power generation devices is different according to different criterion, as shown in Table 1.

TABLE I

CLASSIFICATION OF WAVE ENERGY GENERATING DEVISES

Classification	Type
By Fixed Form	Fixed device, Floating device
By Energy transfer force	Pneumatic, Hydraulic, Mechanical device
By Energy conversion force	Direct conversion, Indirect conversion
By Influence on energy flow	Cut-off, Consumable
By structure	Attenuator, Point absorber, Oscillating Water Column Turbine(OWC) , OWSC, Overtopping，SPD， Rotating mass

Wave energy technology research has been carried out for several decades. In recent years, due to technical bottlenecks, the progress has been slow. In 2012 and 2013, some companies withdrew from the wave energy field. In 2014, only Aquamarine Power had been awarded a EUR 0.8 million Horizon 2020 (H2020) grant [2]. Since 2016, the industry has shown signs of recovery.

By the end of 2017, there were 21 projects in the European Union and the Americas, the devices of which have been put into the sea. Several array projects are moving forward, of which CETO project in Australia is the most representative., it is good news for the sector that the three CETO5 devices installed in Australia have achieved a cumulative 14000 hours of operation in the Perth Project which increased the confidence of the developer. In Europe, key developments are expected from the deployment of the first 1 MW Penguin developed by Wello Oy as part of the H2020 CEFOW project. Furthermore, the first full scale Waveroller device is currently being manufactured in Finland, for deployment in Portugal.

The JRC[4] has identified 57 companies active in developing wave energy, 40 of which are still in the early phase of development. But with more and more companies joining, the overall level of wave energy development is expected to increase substantially.

Since 2016, the information on wave energy equipment that has been put into operation is very limited.

In 2015, Eurostat released an overview of the energy generated by wave energy devices[3]. To date, the class of devices that has delivered the most electricity to the grid is the OWC.

Through data collection, the 400 kW Pico OWC plant has delivered more than 70 MWh to the grid during 3100 hours of operation [4]. The 500 kW OWC at Limpet has produced about 600 MWh from 2006 to July 2013[5]. The OWC installed in Mutriku produces about 300 MWh annually[6]. In July 2016, it was announced that Mutriku had surpassed the 1.3 GWh mark a key milestone for the wave energy industry [7]. Aquamarine Power installed the Oyster 2 device (800 kW) at EMEC in 2012 and it fed about 12 MWh of electricity to the grid between February and November 2013[5]. The first BOLT device from Fred Olsen was installed and tested at Risør in Norway and produced about 3.4 MWh between June 2009 and December 2010 [4,8]. The following model, the 240 kW BOLT Lifesaver was subsequently installed in 2012 at FabTest in the UK and has delivered about 4.6 MWh to the grid [8,9]. The 1:2 WaveStar prototype at Roshage device has produced about 70 MWh from September 2009 to April 2013 [4].

From now on, no wave energy converter has thus far been able to deliver electricity to the grid on a continuous base (i.e. in more than twelve consecutive months), aside from OWC. At the same time, the published information shows that the capacity factors achieved are low, reaching 25 % in the case of OWC and 10 % for other device types. Capacity factors of WECs need to reach 30 % to 40 % for the technology to become economically viable.

The wave power generation device can be divided into three parts: energy capture system, PTO system, power transformation and detection system according to the structure function. As an important component of wave energy generation device, PTO is one of the key technologies of wave energy and the key to achieving cost reduction. Three of the four EU funded Horizon 2020 projects under the Research and Innovation Actions (RIA) call addressing specifically the development and optimisation of wave energy PTO. Horizon 2020 funds directed to wave energy specific R&D accounted for a total of EUR 30.1 million. WES has funded 16 different projects addressing issues related to Power Take Off for wave energy converters, for a total of GBP 7 million (EUR 9.5 million). Other R&D priorities of funded projects are the optimisation of mooring configurations, and increasing the survivability of the structures.

B. *TRL analysis*

Compared with tidal current energy development, the development of wave energy development technology has slowed down in the past few years, and technical defects have reduced investor confidence in wave energy technology. In order to improve the investor's confidence, the researchers focus on the research of verification technology, including the

technical verification of wave energy technology in each test and development stage.

In the Ocean Energy Forum [10], the focus for the wave energy industry is to build on the demonstration of existing prototypes, and to improve the performance of key subsystems and components to in-crease the overall device reliability and survivability During 2014-2016, a limited number of wave energy devices have reached TRL8. As of now, the range of TRL for wave energy devices is shown in Figure 2.

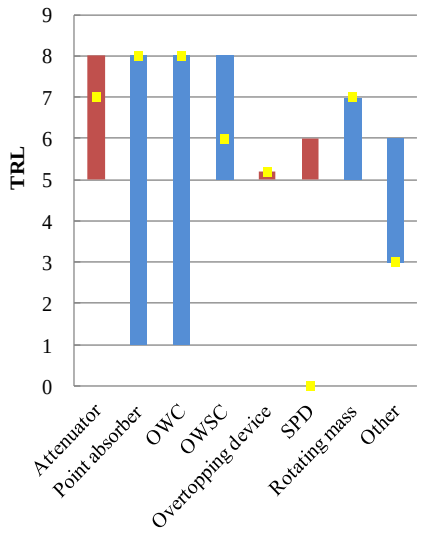

Figure 2 the range of TRL for wave energy devices

The most advanced device types are oscillating water column (OWC) and point absorbers, whit some specific devices have been extensively tested at TRL 8. Oscillating wave surge converters (OWSC) and rotating mass devices have reached relatively high TRL, and are expected to follow through to higher TRL.

No significant progress was witnessed for some specific wave energy technologies such as attenuators, overtopping and sub-merged pressure differential devices (SPD).

Despite the high TRL reached by some devices, their commercial readiness is still to be proven.

III. WAVE ENERGY MARKET STATUS

A. Research institutions and market prospects

The wave energy related projects which being carried out abroad are listed in Appendix 1. The 21 projects are expected to run for a long time in the future. 15 of these projects are located in Europe, and the installed capacity of existing devices is less than 1MW. But with the improvement of technology, the capacity of wave energy array can be reach to 10MW.

Currently，45% of the wave energy device research institutions are distributed in Europe, which also laid the foundation for the advanced position of European wave energy.

Despite the leading technology, the number of devices that have been full-scale tested in the water is still limited. There are 57 installations approved by JRC[4] for wave energy development. Compared with 2014, the number of developers has declined, and many developers have withdrawn from the wave development field due to their lack of confidence in the industry's development prospects.

In these 57 installations, the full scale test of its wave energy device has accounted for about 44% of the total. 64% of the wave energy devices have been installed at sea for testing, but most of them are offshore 10km [26]. In 2014, the two WEC devices, built by Seatricity Company, installed at the Wave Hub test site in the south of the United Kingdom and successfully connected to grid, were at the distance of 16km from onshore, which is the farthest distance to date [27].

The ocean energy system (OES), the Scotland wave energy (WES), the Sustainable Energy Agency of Ireland (SWAI) and the United States Department of energy (DOE) have launched a good policy to make breakthrough progress in the key technology of wave energy. Some projects with commercial prospects have been supported by a certain amount of funds. For instance, the NER 300 plan, the European Investment Bank (EIB) innovfin program, and the European Regional Development Fund (ERDF) [11]. Most of these projects are in the European Union, two in Australia and one in Garner.

In general, under the guidance and support of the policy, the confidence of the developers is greatly enhanced which will help promote the development of the wave energy industry to commercialization.

B. Research institutions and market prospects in China

Wave energy research in China is relatively late, but it develops very fast.Powerful research institutes have developed wave energy devices and achieved excellent results, such as Guangzhou Energy Research Institute and national marine technology center, Chinese Academy of Sciences. The buoy lamp with symmetrical wing turbine is developed by the Guangzhou Energy Research Institute of the Chinese Academy of Sciences. After many years of development, many kinds of products of 10W to 450W have been developed, and have been widely used in navigation lights (ship) buoys in Bohai, the Yellow Sea, the East China Sea and the South China Sea. The developed rear bend

buoy power generation device has been exported to Japan.

Overall, China's micro wave power generation technology has matured and has entered the world's advanced ranks. However, limited by wave resource conditions, the scale of wave energy development in China is far smaller than that in Europe and the United States. So far, more than ten kilowatt class wave power generating devices have been designed and built in China. As shown in Appendix 2.

The 100kW "Wanshan" wave power plant developed by the Guangzhou Energy Institute of the Chinese Academy of Sciences is a typical representative of China's wave energy device.

During the open water test, the daily generation capacity can reach 1087kWh under the condition of 1.5 M wave height, and the conversion efficiency will reach the international leading level. At present, it has accumulated 37210 kWh of power generation, and has been transported to power in April 2017. It has more than 3000 kWh transmission capacity for Wanshan island power grid.

Since the establishment of special funds for marine renewable energy in May 2010, it has promoted the rapid promotion of the overall level of ocean energy work in China, and has achieved remarkable results. It has fully played the central financial funds in supporting the adjustment of the national industrial structure, fostering strategic emerging industries, and exploring the adjustment of energy structure and so on. By the end of April 2017, special funds actually supported 103 projects (6 other projects were terminated), and the total actual investment amounted to nearly 1 billion RMB.

According to the statistics issued by the official website of the National Natural Science Foundation, in 2016, the National Natural Science Foundation supported 18 marine related basic research projects, including 7 projects on the surface, 7 Youth Science Foundation projects, 3 International (regional) cooperation and exchange projects, 1 emergency management projects, and total funds Nearly 6 million RMB.

IV. SUMMARY AND SUGGESTION

A. Summary of the current status

Since 2016, wave energy technology has returned to the researchers' vision and gained new attention. Wave energy technology has become a key direction for the future development of ocean energy because of its high TRL and many successful commercialization cases. However, the cost is still one of the important factors that restrict the development of the wave energy industry. It is an effective way to carry out the study on the array arrangement of wave energy devices, which is an economical way to realize the wave energy generation field.

The OWC device is one of the most successful forms of wave energy technology. At present, the wave energy devices that are successfully connected to the grid and run continuously for more than 12 hours are only OWC devices. Therefore, it can be predicted that OWC wave energy devices will be the focus of developers in the long term. Point absorber device is the first choice for small scale electricity consumption at sea, such as marine lighthouse, buoy lamp, underwater production device control system, etc. The class of attenuator, OWSC and Rotating mass devices had been successfully operated in the past, but because its environmental conditions are very harsh, it is restricted by the objective conditions such as wave energy density, terrain and wave channel. The development cost is extremely high, and it is difficult to popularize in the short time. In recent years, few new devices have emerged and fade away. With the passage of time, the form of such devices may be phased out without major technological breakthroughs.

Besides, wave energy, as a green, low carbon, renewable energy, has attracted wide attention and has been supported by funds from various organizations in the world, including funds and investment banks. The injection of capital has greatly promoted the commercialization of the industry.

B. Suggestions on development and utilization of wave energy in China

Compared with the wave energy resources which are more advantageous abroad, China's wave energy resources are obviously "congenital deficiency". The waves in China's coastal areas are formed by the influence of monsoon. The windy period is short and the wind strength is small. Although the coastline of mainland China is 18 thousand km long, the best areas for wave energy are concentrated in Zhejiang, Fujian, Guangdong and Taiwan Province. The annual average power density of China's coastal wave energy is about 1kW-7kW/m^2, the average power density of a better European country can reach 20kW-100kW/m^2.

According to the current situation of China's resources and the characteristics of various types of devices, the advantages and disadvantages of the 5 classes of wave energy devices used in China are given, as shown in Table 2.

TABLE II

APPLICATION PROSPECTS OF 5 DIFFERENT DEVICES

Device type	Application	Prospect
OWC	Applicable to sea area with heavy waves.	It can be used as a large power plant; suitable for many typhoon days in China.
Attenuator	Applicable to sea area with large wind and waves; combined with breakwater; floating body pendulum is suitable for less waves areas.	The wave period and wave height of China's sea area are small, which can be combined with breakwater, and its application prospect is general.
Point absorber	Applicable to sea area with less waves.	Power supply for lighthouse and buoy, and power supply for island and seashore area by array.
OWSC	Applicable to sea area with large wave energy density	The wave energy density of China's sea area is small, so it is not suitable to install the raft type wave energy device.
Overtopping	Suitable for narrow terrain	Restricted by terrain, wave path and other objective conditions, it is not easy to popularize.

According to the advantages and disadvantages of each device in the above table, combined with the actual conditions of China's wave energy resource conditions, considering the development maturity of the existing equipment technology and the current situation of application and popularization, it is suggested that China should give priority to the development of the OWC device at the same time in consolidating the power generation technology of the miniature wave energy device based on the point absorber device. At the same time, continue to track the new information about the development of OWSC, Attenuator and overtopping wave energy devices.

It is suggested that PTO system should be paid more attention in the research of the key technology of wave energy. The design and optimization of PTO system is the decisive factor for the efficiency improvement of the whole device, and it is also one of the important factors to determine the cost of development. At the same time, it is suggested to carry out the related research on the electric field of wave energy, and to carry out the study on the array arrangement of wave energy devices. This will effectively expand the size of the assembly machine, further reduce the cost of wave energy development, and make the wave energy generation technology move into commercialization faster. In addition, wave energy can not only provide power for various monitoring instruments, underwater mining systems, underwater robots, marine military facilities and offshore platforms, but also can improve the ability of comprehensive application of wave energy. For example, direct drive seawater desalination technology to solve the serious shortage of freshwater resources in China.

Multi energy complementation is a hot spot in recent years. It is also an important field of future energy Internet development. The exploration of the complementary utilization of wave energy and other energy sources can maximize the development of wave energy resources.

In view of the successful experience in the development policy of wave energy resources in European and American countries, based on the current development and main distribution characteristics of the development and utilization of wave energy in China, the development of wave energy in China needs to cultivate and introduce professional talents, follow up the new industry technology in time and enhance China's level and position in the field of wave energy technology research. In the field of wave energy technology research level and status, according to the current situation of uneven distribution of wave energy resources in China, formulate different development policies to make the development of wave energy development differently in different regions, develop wave energy resources according to local conditions, draw lessons from the development experience of wind power industry and develop wave energy resources in China It needs to broaden the financing channels and formulate preferential policies and management policies for the development of wave energy resources so as to attract more investors and promote the commercialization process faster.

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APPENDIX 1 WAVE ENERGY PRE COMMERCIALIZATION AND DEMONSTRATION PROJECTS

Project	Country	Capacity	Class	Status
40SouthEnergy[12]	IT	100kW	OWSC	Device installed at the end of 2015.
Azura Wave [4]	US	20kW	Point absorber	Half scale prototype. Generating electricity since 2015.
Baby Penguin[4]	ES	N/A	Rotating mass	Reliability for new "mild-climate" device.
Camp Rilea[13]	US	40kW	OWSC	Small project with 2 devices (2017). Water will also be used onshore for desalination.
CEFOW[14]	UK	3MW	Roating Mass	Installation expected in 2017, 2019 and 2019. A device each year within H2020 project.
CET06[15]	AUS	4MW	Point absorber	1 MW device, 3 MW demo array planned.
CET06[15] Wave Hub	UK	15MW	Point absorber	1 MW device in 2017, to be expanded to 15 MW by 2021.
Corpower[4]	UK	25kW	Point absorber	Device built in Portugal. Yo be tested in dry rig in Swe-den before deployment at EMEC.
Eco Wave Power[16]	GI	100kW	Point absorber	Device installed and opera-tive since June 2016.
Fred Olsen[17]	US	23kW	Point absorber	Device grid connected, oper-ating at 30% (6.7 kW).
Ghana[18]	GH	14MW	Point absorber	First 6 converters assem-bled and grid connection installed.
Isle of Muck[19]	UK	22kW	Attenuator	3 WaveNET unit installed.
Limpet[4]	UK	500kW	OWC	Operations suspended.
Mutriku[4]	ES	0.3MW	OWC	Operational since 2011. One of the chamber is used for R&D testing of new type of turbines.
Oceantec[20]	ES	30kW	OWC	Installed in October 2016.
PB3[21]	US	3kW	Point absorber	Installed in July 2016.
Perth[15]	AUS	0.72MW	Point absorber	Three CET05 units were deployed in an small array.
Pico[4]	PT	400kW	OWC	In Operation. To be decommissioned.
Seapower[4]	IE	N/A	Attenuator	1:4 scale model to be tested in 2016 in Galway Bay.
Sotenas[19]	SE	10MW	Point absorber	First devices deployed (1 MW).
Swell[22]	PT	5.6MW	OWSC	Funded by NER 300 (9.1 mEUR), planned for 2018, 16 devices.
Wave4Power [4]	NO	N/A	Point absorber	Device installed in February 2016. Company does not provide information on rated power.
WaveHub [23]	UK	10MW	Point absorber	Currently two devices in-stalled. No grid connection.
WaveStar [24]	DK	0.6MW	Point absorber	Grid connected since 2010, 1:2 scale. Project no longer operational.
Wedge Global[25]	ES	N/A	Point absorber	Reliability testing new PA.
Westwave[4]	IE	5MW	t.b.d.	Project funder under NER 300 (34 mio. EUR), planned for 2018.

APPENDIX 2 WAVE ENERGY DEVICE IN CHINA

Project	Research Institute	Capacity	Class	Status
10W-450W Paros	Guangzhou Institute of Energy Conversion.CAS	10W-450W	Point absorber	It has been widely used in navigation lights (buoys) in Bohai, the Yellow Sea, the East China Sea and the South China Sea.
Drakoo	Hann-Ocean Technology	10kW	OWC	It came out in 2016 and has been commercialized.
30kW device	Marine technology center of the State Oceanic Administration	30kW	OWSC	-
Island independent power generation	Zhejiang University	20kW	Other	6 month testing in 2013, running for more than 20 months, and the daily output of seawater desalination reaches 11.6 tons.
40kWonshor device	Guangzhou Institute of Energy Conversion.CAS	40kW	Point absorber	In 2006, the 40kW onshore device was built, and then the point absorber device was developed.
Wanshan project	Guangzhou Institute of Energy Conversion.CAS	100kW	Point absorber	Under the condition of 1.5 meter wave height, the daily power generation capacity of the sea test was 1087 degrees, the conversion efficiency achieved the international lead. BV certification.
Direct drive wave energy generating unit	Southeast University	1kW	Point absorber	The device has been powered by wave flow observation instruments.
A prototype of wave energy power generation device	Shandong University (Weihai)	10kW	Point absorber	Test in the open sea.
A prototype of magnetic fluid wave energy generation	Institute of electrotechnics, CAS	10kW	Point absorber	Learning the key technologies of reciprocating liquid metal magnetohydrodynamic wave energy generator, low melting point liquid metal power generation material.
High efficiency wave energy generating unit with anti wind and wave	Zhongshan University	20kW	OWC	Since 2014, the open water testing has been carried out for 4 years. The total generating capacity is 2600 Kwh, and the maximum generating power is 19.3 kilowatts. The system has higher engineering popularization value.
A power generation system with other ocean energy coupled with waves [28]	Jimei University	10kW	Other	In July 2014, a 6 month open water testing was carried out. The actual sea condition was running for 5000 hours, with a maximum generating power of 3.6 kilowatts.
10KW device	710th Research Institute of central ship heavy industry	10kW	Attenuator	Repairing.
Wave generation system of horizontal rotor turbine	China Institute of water conservancy and Hydroelectric Science	5kW	Attenuator	Repairing.
Demonstration and extension of wave energy net box power supply system	Rizhao City Wan Ze Feng Fisheries Co., Ltd.	5kW	Point absorber	It provides electricity for offshore cold water cage aquaculture in the Yellow Sea.
10kW combined type hydraulic power plant	Ocean University of China	10kW	Point absorber	Repairing.