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Marine renewable energy in China: Current status and perspectives

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Abstract: Based on a general review of marine renewable energy in China, an assessment of the development status and amount of various marine renewable energy resources, including tidal energy, tidal current energy, wave energy, ocean thermal energy, and salinity gradient energy in China's coastal seas, such as the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea, is presented. We have found that these kinds of marine renewable energy resources will play an important role in meeting China's future energy needs. Additionally, considering the uneven distribution of China's marine renewable energy and the influences of its exploitation on the environment, we have suggested several sites with great potential for each kind of marine energy. Furthermore, perspectives on and challenges related with marine renewable energy in China are addressed.

Key words: *renewable energy; tidal energy; tidal current energy; wave energy; ocean thermal energy; salinity gradient energy*

1 Introduction

Over the past three decades, China's economy has been developing rapidly, and resultant energy demands have also increased rapidly (IEA 2013), while the domestic energy supply has become more and more constrained. Since 1997, China has become a net energy importing country. In recent years, because of the growing global energy crisis and environmental problems caused by consuming fossil fuels, such as the greenhouse effect, numerous studies, e.g., Edenhofer et al. (2011) and references therein, have been carried out on renewable energy with the aim of reducing the emissions of greenhouse gases.

The energy consumption structure of China in 2009 was as follows (Yan 2011): the natural sources of coal, oil, and natural gas accounted for 70%, 17.8%, and 3.9%, respectively, while the renewable resources of hydropower, nuclear power, and other types accounted for 6.7%, 0.8%, and 0.8%, respectively. The proportion of renewable energy in China's annual

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total energy consumption increased from 7.2% in 2006 to 8.3% in 2009 (Yan 2011; Wang et al. 2011). According to the target set by the State Council of the People's Republic of China at the end of 2009, the proportion of China's total energy consumption that is made up by renewable energy consumption will reach 15% by 2020 (IOSC-PRC 2007). Therefore, it can be deduced that the proportion of renewable energy consumption will increase by 0.61% per year. Although such a proportion of renewable energy in 2020 is not large, in consideration of prospective energy demand growth in China, it is still challenging to realize such a target. China's energy structure must be adjusted, and the development of renewable energy must be sped up, particularly the abundant marine energy, solar energy, and wind energy resources. Among these resources, marine energy potentials have been given much attention because oceans store a great amount of energy in various forms, such as wave, tidal, thermal, salinity gradient, and current energy, which can meet the total demand of electricity worldwide many times over (Pelc and Fujita 2002). As is well known, marine renewable energy is inexhaustible in supply and always available for use (Wang et al. 2011). Practical experiences in the commercial application of marine renewable energy, such as tidal energy, have proven that, in the long term, these technologies can compete with conventional power plants (Andre 1978).

An assessment of marine energy potential can help in the selection of available sites and suitable capacities for marine energy exploitation and utilization, as well as in determining the most appropriate type of energy converters. In this context, a systematic estimation of China's marine energy resources and the prospects of their development were performed based on a survey of their reserves, density, distribution, and exploitability from 2004 to 2009 (Wang et al. 2011). These marine energy resources are distributed along 32 000 km of the coastline of more than 3×10^6 km^2 in China. To date, the marine energy potentials in China have been partially assessed by various research projects and field observations (Shi et al. 2011).

In this study, we classified marine renewable energy into tidal energy, tidal current energy, wave energy, ocean thermal energy, and salinity gradient energy. We limited our attention to reviewing these five kinds of marine renewable energy in China in terms of their reserves, distributions, and development status. Based on this review, we presented some suggestions and perspectives, and highlighted the challenges.

2 Tidal energy

2.1 Resources and distribution

Tidal energy is one of the most available types of marine energy, and is created by the gravitational forces of the moon and the sun and the rotation of the earth. It is the potential energy of the water level difference caused by ebbs and flood tides and extracted mostly by constructing a barrage across an estuary or the mouth of a bay in coastal waters with a large tidal range to form a basin. The water level difference on both sides of the dam is used to drive turbines installed in the barrage wall. The tidal energy is directly proportional to the square of the tidal range and the basin area. It is estimated that there are around 110 GW of tidal power exploitable in China's four coastal waters, i.e. the coastal waters of the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea, and 426 potential tidal energy dam sites along China's coast with a total installed capacity of 21.8 GW and an annual energy output of 6.24×10^4 GW·h (Shi et al. 2011).

Table 1 presents the tidal energy resources in China's four coastal waters. The theoretical tidal energy capacity and the annual energy output of coastal waters of the East China Sea are the largest, followed by those of the South China Sea, the Bohai Sea, and the Yellow Sea. Theoretical tidal energy capacities off the coast of Fujian and Zhejiang provinces, located on the coast of the East China Sea, are the largest, i.e., 10 333 MW and 8 914 MW at 88 and 73 dam sites, respectively. In these waters, the average tidal range is 4 to 5 m, and the maximum tidal range is 7 to 8 m.

Table 1 Distribution of exploitable tidal energy resources in China (Shi et al. 2011)

Site province	Tidal energy capacity (MW)	Annual energy output (GW·h)	Number of dam sites	Site province	Tidal energy capacity (MW)	Annual energy output (GW·h)	Number of dam sites
Liaoning①	597	1 640	53	Fujian③	10 333	28 413	88
Hebei①	10	21	20	Taiwan③	56	135	17
Shandong①②	124	375	24	Guangdong④	573	1 520	49
Jiangsu②	1	6	2	Guangxi④	394	1 112	72
Shanghai③	704	2 280	1	Hainan④	91	229	27
Zhejiang③	8914	26 690	73	Total for China	21 797	62 421	426

Note: The superscripts ①, ②, ③, and ④ mean that the corresponding province is located on the coast of the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea, respectively.

2.2 Development status

China is one of the leading countries in harnessing tidal energy. The utilization of tidal energy resources and construction of tidal power plants can be traced back to the 1950s when 42 tidal power plants were built. From then into the 1970s more than 10 tidal power plants were built. However, not long after being put into use, most of these tidal power plants were abandoned. This is mainly attributed to the following factors: dam site defects, insufficient technology, insufficient maintenance of generator sets, low ratio of benefit to cost, conflict between irrigation and water transportation, and inconvenience in operation (Li 2008; Chang et al. 2003). Until the 1980s, eight plants were still in service or in testing: the Jiangxia, Haishan, Baishakou, Shashan, Yuepu, Liuhe, Xingfuyan, and Guozishan tidal power plants (Li 2008), as listed in Table 2. The total installed capacity for these eight plants was 6000 kW, and the total annual power output was 10^7 kW·h. Now, however, only two plants, the Jiangxia and Haishan power plants, are in service.

Table 2 Tidal power plants in China (Cai and Li 1996; Lü 2001)

Plant	Location	Installed capacity (kW)	Mean tide range (m)	Reservoir capacity (10^4 m^3)	Reservoir area (10^6 m^2)	Commissioning date	Operation scheme
Jiangxia	Wenling, Zhejiang	1 × 500+1 × 600+4 × 700	5.08	490.0	137.00	May 1980 Jun. 2007	Single-pool two-way system
Xingfuyan	Pintang, Fujian	4 × 320	4.54	167.0	–	May 1989	Single-pool ebb system
Baishakou	Rushan, Shandong	6 × 160	2.36	220.0	3.20	Aug. 1978	Single-pool one -way system
Yuepu	Xiangshan, Zhejiang	4 × 75	3.60	40.0	0.02	Nov. 1971	Single-pool ebb system
Haishan	Yuhua, Zhejiang	2 × 125	4.91	28.0* 5.9**	0.25* 0.03**	Dec. 1975	Two-pool one -way system
Liuhe	Taicang, Jiangsu	2 × 75	1.20	–	3.84	Aug. 1976	Single-pool two -way system
Shashan	Wenling, Zhejiang	40	–	5.0	0.05	Aug. 1959	Single-pool ebb system
Guozishan	Qinzhou, Guangxi	40	1.30	–	–	Feb. 1977	Single-pool one-way system

Note: The superscripts * and ** mean the upstream and downstream reservoirs, respectively.

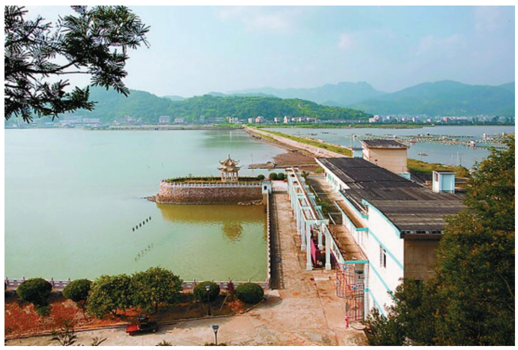

Fig. 1 Jiangxia Tidal Power Plant

The Jiangxia Tidal Power Plant (Fig. 1) located at the north end of Yueqing Bay, Zhejiang Province, is the largest one in China, and the fourth largest one in the world, ranking after the Sihwa Tidal Power Plant in South Korea, the Rance Tidal Power Plant in France, and the Annapolis Tidal Power Plant in Canada (Xie et al. 2009; Kim et al. 2012). Its construction began in 1974 and was completed in 1985. It had an original total capacity of 3.2 MW, with one set of 500 kW units, one set of 600 kW units, and three sets of 700 kW units. The first set of 500 kW units began generating electricity in 1980. In June 2007, the fourth set of 700 kW units was successfully developed and integrated into the electric grid. Since then the total installed capacity of the Jiangxia Tidal Power Plant has reached 3.9 MW (Zhu 2009). Even though the Jiangxia Tidal Power Plant currently operates in good condition, it is still not economical from the point of view of electricity generation. Actually, the operation of the Jiangxia Tidal Power Plant is well integrated with the comprehensive utilization of its reservoir, including land reclamation, aquaculture, and shellfish farming in the reservoir. Therefore, based on the comprehensive evaluation of the

Jiangxia Tidal Power Plant, a great profit is obtained from its electricity generation, land reclamation, aquaculture, and shellfish farming. Additionally, abundant experience for optimization of eco-environment has been accumulated.

Since the Jiangxia Tidal Power Plant was put into operation in 1985, progress in the development of tidal energy in China has been made. For example, the Xingfuyan Tidal Power Plant, which is the second largest one in China, was constructed and integrated into the electric grid in May 1989 (Cai and Li 1996). With the technological advancement of tidal power generation, the tidal energy industry still faces multiple challenges from financial, technical, and environmental aspects as it evolves from research and development towards extensively commercial-scale deployment (Shi and Guo 2012).

Site selection is very important in the utilization of tidal energy. Thus, 426 potential sites for utilizing tidal energy have been preliminarily selected in China, of which 242 sites are suitable for tidal energy dams with installed capacities from 200 to 1000 kW (Shi et al. 2011). Of these sites, Sansha Bay, with a tidal range of 8 m, and Xiangshan Bay, with a tidal range of 6 m, situated in Fujian and Zhejiang provinces, respectively, have been considered the best candidate sites (Wu 1999). In Sansha Bay there are two water areas, Dongwuyang Bay and Sanduao, which could comprise two reservoirs with their dams extending 3.9 km and 5.7 km, and confining two areas of $1.44 \times 10^8\ m^2$ and $2.33 \times 10^8\ m^2$, respectively (Shi et al. 2011). This would allow Sansha Bay to form two reservoirs with large capacities and short barrages. All these factors could meet the requirements of an ideal candidate site. However, it is strongly recommended that further synthetic investigations and studies be carried out if Sansha Bay is chosen as a development site.

In order to realize the goal that tidal power plants with a total installed capacity of 100 MW be built by 2020 (NDRC-PRC 2007a, b; Liu et al. 2007a), preliminary work is being done, including investigation, planning, design, and a feasibility study of the Daguanban Tidal Power Plant, with a capacity of 14 MW, and the Bachemen Tidal Power Plant, with a capacity of 36 MW, in Fujian Province, as well as the Jiantiaokong Tidal Power Plant, with a capacity of 20 MW, and the Huangdungang Tidal Power Plant, with a capacity of 24MW, in Zhejiang Province. Preliminary comprehensive studies of sites are also needed for construction of large tidal power plants, with capacities of 704 MW, 5360 MW, and 550 MW in the North Branch of the Yangtze Estuary, Hangzhou Bay, and Yueqing Bay, respectively (Shi et al. 2011).

3 Tidal current energy

3.1 Resources and distribution

Tidal current energy utilizes kinetic energy available in currents and can be converted into renewable electricity with tidal current devices placed directly in streams rather than with a previously mentioned dam structure. The power of currents is proportional to velocity cubed and flux. Generally, currents in water channels with a maximum flow velocity of more than

2 m/s are of high significance in practical application (Wang et al. 2011).

The statistical results in Table 3 show that there are about 13.95 GW of tidal current energy technically available in 130 channels in China (Li 2008; Wang and Lu 2009). Tidal current energy potentials in some channels are given in Table 4. Based on the tidal current energy density and its impacts on the environment, tidal current energy resources in the Jintang Channel, Guishan Channel, and Xihoumen Channel in the Zhoushan Archipelago, as well as in the Hangzhou Bay Channel, are worth being exploited preferentially. In these channels, the maximum flow velocity exceeds 5 m/s.

Table 3 Distribution of tidal current energy resources in China (Li 2008; Wang and Lu 2009)

Site province	Theoretical capacity (MW)	Number of channel	Site province	Theoretical capacity (MW)	Number of channel
Liaoning	1 130	5	Fujian	1 280	19
Hebei	–	–	Taiwan	2 282	35
Shandong	1 178	7	Guangdong	376	16
Jiangsu	–	–	Guangxi	23	4
Shanghai	305	4	Hainan	282	3
Zhejiang	7 090	37	Total	13 946	130

Table 4 Tidal current energy potential in some channels

Channel	Site province	Site sea	Average power (kW/m^2)	Channel	Site province	Site sea	Average power (kW/m^2)
Laotieshan	Liaoning	Bohai Sea	17.4	Hangzhou Bay	Zhejiang	East China Sea	28.9
Jintang	Zhejiang	East China Sea	25.9	Sandujiao	Fujian	East China Sea	15.1
Guishan	Zhejiang	East China Sea	23.9	Channel southwest of Yuwong Island	Taiwan	East China Sea	13.7
Xihoumen	Zhejiang	East China Sea	25.9				

Similar to the tidal energy resource distribution, tidal current energy resources along the coast of China are also not evenly distributed. Current velocities in most of the coastal waters of the Bohai Sea are less than 0.77 m/s, except in water channels (such as the Laotieshan Water Channel). Current velocities are 0.5 to 1.0 m/s in the Yellow Sea, and can reach 1.5 to 3.0 m/s at the Yangtze Estuary, the mouth of Hangzhou Bay, the water channels in the Zhoushan Archipelago, and mouths of some rivers in Zhejiang and Fujian provinces along the coastline of the East China Sea. Marine current velocities in coastal waters of the South China Sea are the lowest, less than 0.5 m/s. The theoretical capacity of tidal current energy off the coast of Zhejiang Province located on the coast of the East China Sea is the largest and reaches 7 090 MW, which accounts for 50.8% of the total tidal current energy capacity in China.

3.2 Development status

Tidal current energy utilization in China can be traced back to the 1980s. Up to now, four tidal current power stations have been constructed (Table 5). The newly commissioned Haineng I Tidal Current Power Station, with a capacity of 300 kW, uses a vertical-axis tidal turbine and has become the world's largest tidal current power station. This indicates that China has stepped into the demonstration stage in the utilization of tidal current energy. The further promotion and large-scale commercialization of vertical-axis tidal turbine technology will drive further development of related machinery manufacturing as well as material processing industries and promote regional economic development and employment.

Table 5 Tidal current power stations in China

Power station	Year of operation	Capacity (kW)	Location	Type of turbine
Wanxiang I	2002	70	Guishan Channel, Zhejiang Province	Vertical-axis
Wanxiang II	2005	40	Gaoting Bay, Zhejiang Province	Vertical-axis
Haiming I	2011	10	Xiaomentou Channel, Zhejiang Province	Horizontal-axis
Haineng I	2013	2 × 150	Guishan Channel, Zhejiang Province	Vertical-axis

Tidal current turbines can be categorized as either axial-flow turbines or cross-flow turbines. Axial-flow turbines can be divided into vertical-axis turbines and horizontal-axis turbines. Vertical-axis turbines can work in bidirectional flow without pitching blades, and the generator can be loaded on a ship, avoiding a strict sealing requirement. They are easy to operate and maintain. Development of vertical-axis turbines in China has a history of about 30 years, with rapid development over the last decade. Efforts have mainly been devoted to improving the turbine efficiency, strength, and stability of the carrier. The 70 kW Wanxiang I Tidal Current Power Station is loaded on a catamaran. It contains two vertical-axis turbines made up of rectangular self-adjusted blades. The collected data show an average output power of 5 to 20 kW, achieved at a current speed of 2 to 2.5 m/s (Wang et al. 2011). To improve the turbine efficiency, Harbin Engineering University has carried out various studies on the variable-pitch mechanism design for vertical-axis turbines (Wang et al. 2007; Zhang et al. 2007; Kong et al. 2010; Nasir et al. 2012). Numerical model optimization of blades and performance assessment of different rotor shroud profiles were carried out. The improved turbine based on the research was used in the 40 kW Wanxiang II Tidal Current Power Station and the recently deployed 300 kW Haineng I Tidal Current Power Station.

Studies of horizontal-axis turbines began later. Research on underwater turbines at Zhejiang University began in 2004. The prototype of a 5 kW horizontal-axis turbine was tested in a water channel in 2006 (Lin et al. 2008), and an upgraded 25 kW prototype was designed and tested in sea trials successively in 2009 (Ma et al. 2010a). During the tests, mechanical transmission showed poor performance without energy buffers, and the sealing failed (Ma et al. 2011). In order to deal with those problems, an electro-hydraulic variable pitch control system was adopted for hydraulic transmission (Ma et al. 2011; Ma et al. 2010b). Additionally, an improved sealing mechanism and a leak-detecting system based on pressure gradients were proposed to solve the sealing problem (Liu et al. 2007b; Zeng 2012).

Recently, researchers at Northeast Normal University have devoted themselves to developing small underwater direct-driven turbines that can supply power to underwater devices. Some special designs were taken to make the device compact, efficient, and reliable. First, the self-lubricating, maintenance-free, and magnetic thrust bearing pack decreases the friction-induced energy loss between the bearings. Second, a sealing of the generator filled with isolative materials guarantees that it can function well even at 300 m underwater (Zhu et al. 2012). Third, a self-adjusted turbine was designed to guarantee that it could rotate in one direction, avoiding wire intertwining and huge impacts on the turbine while pitching (Zhang et al. 2010). Prototypes with capacities of 1 kW and 2 kW have been developed, and a 20 kW prototype is currently under development (Wang et al. 2011; Zhang et al. 2010).

With respect to cross-flow turbines, researchers at Ocean University of China brought up a novel idea to use flexible blade turbines (Wang et al. 2011). The inspiration comes from the sail, which can move forward both with the wind and against the wind. The blade is made of flexible materials that make the turbine easy to manufacture and transport. The turbine rotates under the lift force and drag force without need of a variable-pitch control system. A 5 kW prototype was tested in sea trials, and the results showed that it could start at a current speed of 0.8 m/s, and that the output was about 3 kW at a current speed of 1.5 m/s, with a power coefficient of 28% to 30% (Wang 2009).

4 Wave energy

4.1 Resources and distribution

Wave energy is most difficult to predict among marine energy resources because waves are caused by winds blowing over the surface of oceans, which are highly variable. The energy in waves is proportional to the wave height squared and motion period. Therefore, in ocean waves with periods of 4 to 6 s and amplitudes of 1 to 1.6 m, there are appreciable energy fluxes commonly averaging between 2 and 8 kW per unit width of oncoming waves. It is estimated that there are around 12.85 GW of wave power in the coastal waters of the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea in China. The average wave power in coastal waters of some provinces is given in Table 6. Based on the wave energy density and minor potential impact on the environment, the priority of wave energy resource development should be given to coastal waters of Zhejiang and Fujian provinces, followed by the eastern part of the coastal waters of Guangdong Province, the Yangtze Estuary, and the southern part of the Shandong Peninsula.

Table 6 Distribution of wave energy resources in China's coastal waters (Li 2008; Wang et al. 2011)

Site province	Average power (MW)	Wave energy density (kW/m)
Liaoning	255	
Hebei	143	5.11-7.73 (Bohai Strait)
Shandong	1 610	2.25-2.82 (Southern waters of Shandong Peninsula)
Jiangsu	291	
Shanghai	165	3.63-4.05 (Yangtze Estuary)
Zhejiang	2 053	5.11-7.73 (Central), 3.63-4.05 (Southern and northern)
Fujian	1 660	5.11-7.73 (Northern), 2.25-2.82 (Southern)
Taiwan	4 291	5.11-7.73
Guangdong	1 739	3.63-4.05 (Eastern)
Guangxi	72	
Hainan	563	3.63-4.05 (Xisha Archipelago)
Total	12 842	

4.2 Development status

The oscillating water column (OWC), pendulum, oscillating buoy, and Salter's duck are four types of wave energy converters (WECs) that have been developed and tested in sea trials in China.

Compared to other types of WECs, the study of OWCs in China took quite a long time. So far, the Guangzhou Institute of Energy Conversion has built up three experimental onshore OWCs with capacities of 3 kW, 20 kW, and 100 kW, respectively, and a 5 kW floating backward bent duct buoy (BBDB) OWC. Furthermore, several 10 W BBDB OWCs were exported for navigation illumination (You et al. 2003). The OWC was simply composed of an air chamber, inside of which air was driven by the fluctuation of wave surface, and an air turbine, which turned kinematic energy into electricity. Results from the 20 kW pilot wave power station have shown that the capture ratio of the air chamber is usually 50% to 150%, and sometimes even exceeds 250% (Yu et al. 1996). For the floating BBDB OWC, the ratio is smaller than the onshore one, but the experimental results show that it can still reach 73.3% (Liang et al. 1999). The efficiency of the OWC mainly depends on the efficiency of the air turbine. Performances of the Wells turbine used in the 3 kW and 20 kW OWCs and the 5 kW floating BBDB OWC showed that its efficiency was unsatisfactory, only 10% to 30% (Experts in Advanced Energy Technology Field of National High-Tech Research and Development Program of China 2010). You (2012) pointed out that the large inertia of the turbine impeded its self-starting process and led to the lower output. A laboratory experiment showed that the maximum efficiency of the Wells turbine could reach 32.8%, lower than the impulse turbine and turbines with bidirectional guide vanes (Liang et al. 2001). Thus, impulse turbines were installed in the 100 kW OWC, taking the place of the Wells turbine to improve the efficiency.

The working principle of the pendulum WEC is easy to understand. The wave forces the swing wing of the device to move forward and backward around the shaft, consequently driving the hydraulic system to generate electricity. There are two onshore pendulum WECs in China with capacities of 8 kW and 30 kW, respectively. The later 30 kW pendulum WEC (Fig. 2) was constructed together with wind and photovoltaic energy conversion systems to meet the power demands of Daguan Island, in Shandong Province. Moreover, a floating duck device with a capacity of 10 kW was deployed at the end of 2009, after three years of research, testing, and construction, and an underwater plate was appended to improve the stability and reliability of the floating duck (You et al. 2012).

Fig. 2 Pendulum WEC with capacity of 30 kW at Daguan Island, Shandong Province

At present, the cost of WECs in China cannot yet compete with that of the traditional energy converter. However, their use is promising on islands where supplements of fossil fuels are expensive and will be difficult to access in future. The hydraulic transmission is well suited to achieving stand-alone power generation to meet the power demands on the island. By means of accumulators and the control system, the electrical generator can run smoothly. A test showed that a transmission efficiency of 56% from the mechanical energy of pendulums to output electrical energy could be achieved by the hydraulic transmission (Yuan 1990), and an efficiency of over 60% after optimization was estimated (You et al. 2008). A closed-loop feedback hydraulic transmission circuit composed of variable-displacement pumps and variable-displacement motors was employed to achieve smooth power generation at the 100 kW stand-alone power station in Shanwei City, Guangdong Province. It performed well with an electrical system, which could intelligently distribute currents between users and internal loads in the system, avoiding the water hammer effect in the circuit (Wu et al. 2009). Strategies for adjusting the generator speed according to loads to achieve maximum power were also discussed (Zhang et al. 2011).

5 Ocean thermal energy

5.1 Resources and distribution

Ocean thermal energy conversion (OTEC) utilizes the temperature difference between deep cool waters, which hold 5℃, and shallow warm waters (or surface waters), which typically hold 25℃, to run a heat engine and produce useful work. It is estimated that in China there are about 1.16×10^{18} kJ of ocean thermal energy reserves technically available in waters mainly along the east coast of Taiwan and the coasts of Guangdong and Guangxi provinces, as well as off Hainan Island and islands in the South China Sea (Wang et al. 2011). The distribution of ocean thermal energy resources off the coastlines of China is given in Table 7 (Shi et al. 2011; Wang and Lu 2009).

Table 7 Distribution of ocean thermal energy resources off coastlines of China (Shi et al. 2011; Wang and Lu 2009)

Site Sea	Part of waters	Theoretical reserve (10^{18} kJ)	Technically available reserve (10^{15} kJ)	Technical capacity (TW)	Technically available capacity (GW)
Yellow Sea		0.14	4.92	–	–
East China Sea		2.09	116.00	3.55	35.5
East of Taiwan		–	0.22	–	6.8
South China Sea	Northern part	2.11	163.00	5.17	51.7
	Central part	5.90	481.00	15.25	152.5
	Southern part	4.95	399.00	12.65	126.5
Total		15.19	1 164.14	36.62	373.0

The coastal waters of the South China Sea have the most abundant ocean thermal energy of China's coastal waters (Wang et al. 2011), where the mean temperature difference between the water surface and the location 500 to 800 m below the surface is more than 20℃. Their theoretical reserves of ocean thermal energy are 12.96×10^{18} kJ (Shi et al. 2011). The South China Sea has a vast area and can be divided into three parts, the southern, central, and northern parts, and the theoretical reserve of ocean thermal energy in the central part is the largest. The Xisha Archipelago, located in the western area of the central part of the South China Sea, consists of over 30 islets, sandbanks, and reefs, and the water depth there is 900 to 1000 m. The Xisha Archipelago is suitable for construction of ground-based or continental-type thermoelectric power stations. Yongxing Island, located in the Xisha Archipelago, has a more permanent population than other islands in the South China Sea. The energy and fresh water are supplied to the island from the mainland, and the cost is very high due to long-distance transportation. If ocean thermal energy resources around the island are developed and utilized, not only can electrical power and fresh water be provided, but deep ocean water can also be used for air conditioning and breeding.

In waters along the east coast of Taiwan with steep cliffs, the temperature difference between the top warm layer and deep cold water varies between 20℃ and 24℃. It is estimated that the ocean thermal energy reserves available around Taiwan are about 2.2×10^{14} kJ (Wang and Lu 2009). Based on the energy density, reserves, and exploitation conditions, the ocean thermal energy resources off islands in the central part of the South China Sea (especially the Xishan Archipelago) and off the east coast of Taiwan are those most worth being exploited preferentially.

5.2 Development status

There are only a few studies of OTEC in China. In the 1980s a mist-lift cycle (MLC) experiment was carried out in Guangzhou City (Li 2008). The MLC was invented by Ridgway (1977), and shows little difference from the commonly known thermodynamic cycle. After warm water is atomized and flashed, mist rises up to a certain height and condenses to water again by condensers. After that, the water falls down, driving the water turbine to rotate. The output power is proportional to the lifted water quantity, the lifted height, and the efficiency of the water turbine. With this method, large-scale heat exchangers are eliminated, and the efficiency of OTEC improves with the water turbine, which takes the place of the vapor turbine. While it is a good idea, theoretical analysis shows that a lifting tower of about 100 m in height is required to obtain a net power output (Li 2008; Wu et al. 1991), which is difficult to realize. Research on this method ceased in the early 1990s. It was only in the last decade that OTEC came to wide attention again.

A 200 W saturated ammonia steam turbine was developed by Tianjin University (Zhao 2005). An experimental underwater glider propelled by an OTEC thermal engine was developed and tested in Qiandao Lake in July 2005 (Zhang 2005). The First Institute of Oceanography of the National Bureau of Oceanography has carried out an investigation into closed-cycle OTEC, and now is undertaking a project for developing a 15 kW closed-cycle OTEC system with the support of the National High Technology Research and Development Program (Experts in Advanced Energy Technology Field of National High-Tech Research and Development Program of China 2010).

6 Salinity gradient energy

6.1 Resources and distribution

Salinity gradient energy is available from the difference in salt concentrations between seawater and river water. Its reserves mainly depend on the volume of river water flowing into seas. China has several large rivers, which run into the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea, and have abundant salinity gradient energy resources in estuaries. Table 8 shows salinity gradient energy in major estuaries in China (Shi et al. 2011). It can be seen that there are 3.58×10^{15} kJ of salinity gradient energy along the coastal waters of China with a theoretical power of about 113.5 GW. The salinity gradient energy resources are unevenly distributed along China’s coastline. Its capacities in the estuaries of the Yangtze River and the Pearl River respectively account for 61.8% and 19.4% of the total capacity in China.

6.2 Development status

Though the amount of salinity gradient energy sources is the largest of all marine renewable energy resources (Jones and Finley 2003), it is the least developed marine renewable energy in China. There are few reports on salinity gradient energy conversion (SGEC). In the1980s, a pressure-retarded osmosis device was tested with a maximum output

Table 8 Salinity gradient energy in typical estuaries in China (Shi et al. 2011)

River	Annual runoff (10^8 m^3)	Theoretical reserve (10^{12} kJ)	Theoretical power of each river (10^4 kW)	River	Annual runoff (10^8 m^3)	Theoretical reserve (10^{12} kJ)	Theoretical power of each river (10^4 kW)
Liaohe River①	45.1	11.0	34.7	Oujiang River③	143.0	34.7	110.0
Haihe River①	14.8	3.6	11.4	Jiaoxi River③	65.7	16.0	50.6
Luanhe River①	45.6	11.1	35.1	Minjiang River③	552.0	134.0	425.0
Yellow River①	431.0	104.7	332.0	Jinjiang River③	50.6	12.3	39.0
Yalu River②	81.8	19.9	63.0	Jiulong River③	147.0	35.7	113.3
Huaihe River②	223.0	54.2	171.8	Hanjiang River④	241.0	58.6	185.7
Yangtze River③	9 114.0	2 214.0	7 022.0	Pearl River④	2 860.0	694.9	2 203.0
Qiantang River③	292.0	70.9	225.0	Other rivers	431.7	104.9	332.7
Total	14 738.3	3 580.5	11 354.3				

Note: The superscripts ①, ②, ③, and ④ mean that the river flows into the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea, respectively.

of 1.2 W. Consequently it could hardly be a successful experiment (Wang 1985). Though the device was carefully designed, the vulnerable membrane system and poor performances of the man-made water turbine and primitive generator inevitably led to low efficiency (Ning 1990). A few years ago, an experimental investigation on reversed electro dialysis was carried out (Hu and Ji 2009). However, no follow-up has been published. Chinese salinity gradient energy resources are abundant and mainly distributed in the developed Yangtze River Delta and the Pearl River Delta economic zones. Salinity gradient energy near the economic center can meet the local demand of electricity, and it can be foreseen that there is a good prospect for its commercialization. Currently, salinity gradient energy development is restricted by membrane technology. However, the commission of the world's first salinity gradient power generation plant in Norway in 2009 may encourage more research on salinity gradient energy utilization later on.

The impacts of salinity gradient energy development on the environment have been less studied, even though the influences on ocean economic activities (such as water transportation, fisheries, and marine engineering) and the eco-environment in estuary areas are relatively significant (Shi et al. 2011). Since estuaries in China are usually located in economically developed areas, with relatively advanced industries in water transportation, fisheries, and marine engineering. If a dam is constructed across an estuary to develop salinity gradient energy, water transportation, biological migration, and sediment transport will be highly impacted. Such kind of energy development is clearly not feasible. To solve this problem, river water and sea water could be diverted to the shore through hydraulic pipes, and thus SGEC could be realized.

7 Summary and perspectives

China has abundant marine energy resources unevenly distributed along its coastline of 32000 km, and has significant potential to develop marine renewable energy. The technology for utilizing tidal energy in China is the most mature of the five kinds of marine renewable energies. The development of tidal current, wave, ocean thermal, and salinity gradient energies is still underway. It is expected that such development will contribute considerably to an increase in the proportion of renewable energy in total energy consumption, to environmental protection, and to economic development in China.

For tidal energy, there are around 110 GW of tidal power in China's four coastal waters. With strong tides in the eastern coastal region of China, there are 88 and 73 potential dam sites for tidal power plants, respectively, in Fujian and Zhejiang provinces with an average tide range of 4 to 5 m. Of the 161 sites that have been studied, Sansha Bay, with a tidal range of 8 m, and Xiangshan Bay with a tidal range of 6 m, situated in Fujian and Zhejiang provinces, respectively, have been considered the best candidate sites for tidal power plants in China.

When it comes to tidal current energy, the theoretical tidal current energy capacity of Zhejiang Province in the coastal waters of the East China Sea is the largest and reaches 7 090 MW, which accounts for 50.8% of the total tidal current energy capacity in China. Tidal current energy resources in the Jintang Channel, Guishan Channel, and Xihoumen Channel in the Zhoushan Archipelago as well as the Hangzhou Bay Channel are those most worth being exploited preferentially.

As for wave energy, the east coast of Taiwan, the central part of the Zhejiang coast, the Bohai Strait, and the northern part of the Fujian coast have a maximum wave power potential of 7.73 kW/m. However, the wave power level in the Yangtze Estuary, the southern and northern parts of the Zhejiang coast, the eastern part of the Guangdong coast, and the Xisha Archipelago decreases to 3.63 to 4.05 kW/m. As one moves north from the Yangtze Estuary, it further decreases to values less than 3 kW/m. Accordingly, Zhejiang Province, Fujian Province, and Taiwan are the best places to exploit the wave energy.

As far as ocean thermal energy is concerned, there are about 373 GW of ocean thermal energy technically available, mainly along the east coast of Taiwan and the coasts of Guangdong and Guangxi provinces, as well as off Hainan Island and islands in the South China Sea. However, among these areas, coastal waters off the islands in the South China Sea and the east coast of Taiwan are the most worthwhile areas for preferential use.

Salinity gradient energy capacities in the estuaries of the Yangtze River and the Pearl River account for 46% and 15.3% of the total capacity in China (114 GW), respectively, and could be exploited preferentially.

The importance of marine energy resource development has received extensive attention in China. Since the beginning of this century, China has committed to improving the ability and increasing investment in the development and utilization of marine renewable energy. The prospects for marine energy development and utilization are as follows:

(1) One or two 10 MW demonstration tidal power plants will be built and put into operation in one or two years. After that, the technology of the demonstration tidal power plant will be improved and research and development of the 100 MW tidal power plant will be initiated.

(2) Demonstration tidal current and wave power devices with a capacity of 10 kW are expected to be enhanced to a capacity of 100 kW in one and two years, respectively, and the capacities are expected to reach 1 MW in five years. Wave energy and tidal current energy devices will be further developed.

In addition, lessons from successful experiences of marine energy exploitation in the United Kingdom and other developed countries should be applied to accelerate the technical development of marine renewable energy in China:

(1) Comprehensive observation and assessment of marine energy resources should be performed to obtain sufficient information, and the assessment precision should be improved.

(2) It is necessary to accelerate the development of test facilities to make the prototype marine energy technologies more cost-effective and time-saving in order to undergo sea trials.

(3) In general, the study and exploitation of marine energy in China are still in the primary stage. Researchers specializing in ocean energy development are encouraged to cooperate more closely for further development of related technologies.

(4) Related machinery manufacturing and material processing industries should also be encouraged to meet the technical requirements of marine energy exploitation, including those relating to corrosion resistance, reliable sealing, and high strength for underwater marine energy converters.

Furthermore, we should focus on the policy and legislation of marine renewable energy exploitation and various economic and environmental challenges in our research.

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