Exploration and Development of Marine Renewable Energy in Fujian Province Towards Carbon Neutrality

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Abstract. To achieve peak carbon emission and carbon neutrality, marine renewable energy plays an essential role in energy transition in China’s coastal areas. Fujian Province is not only exposed to a shortage of traditional energy resources, but also urgently needs to change its current coal-based energy structure to reduce carbon emissions. In contrast to the scarcity of fossil fuels, Fujian Province has rich marine energy reserves, with an abundant supply of offshore wind, wave, tidal, and ocean current energy. Therefore, the active development of low-carbon and carbon-free marine energy can increase the energy supply and alleviate energy shortages. Furthermore, it can optimize the structure of the energy sector in this region. This study analyzed the energy structure of the Fujian Province, the effort needed to reach the carbon neutrality goal, the reserves of marine energy resources, the background of marine energy development technology, and socio-economic conditions. We believe that the development of the marine energy is a critical action towards solving the current energy resource limitations in Fujian and subsequently propose relevant suggestions for marine energy industry development in Fujian Province in terms of development ideas and pathways.

1 Introduction

Excessive greenhouse gas emissions caused by human activities have given rise to a series of ecological issues, such as ocean acidification, global warming, glacier melt, and sea level rise, accompanied by frequent extreme weather events such as abnormally high temperatures, dust storms, and high winds [1]. Reducing global carbon emissions and controlling climate-environmental problems caused by global warming have become major challenges for human society [2]. To achieve the long-term temperature targets specified in the Paris Agreement, there is an urgent need to achieve peak global carbon emissions as soon as possible, followed by carbon neutrality [3]. An important way to achieve carbon neutrality and mitigate the effects of climate change is to reduce carbon emissions using renewable energy [4], particularly with emphasis on the use of marine renewable energy in coastal areas. The generous supply of offshore wind energy, tidal energy, current energy, wave energy, energy from thermal gradients, salinity gradients and other marine renewable energies are very important for coastal areas to diversify energy structure, promote energy transition, reduce carbon emissions, control global warming and solve environmental pollution[5-6]. In addition to increasing clean energy supply, the utilization of marine renewable energy also has many other benefits such as the possibility to make a significant contribution to medium- and long-term economic growth and future job creation [7]. The use of marine energy can also alleviate the serious energy security problems faced by many countries with inadequate fossil fuels, particularly island countries [8].

Currently, there is an increase in research on potential assessment and technology of marine renewable energy. With a theoretical production of 2,000 trillion kWh of electricity per year (excluding wind energy), the reserves of renewable energy in the ocean far exceed human energy demand in theory[9], many times the global electricity consumption. By 2050, usable offshore wind energy could reach 16,000 TWha⁻¹ [10, 11]. However, the development of ocean energy is still in early stage, the existing power generation capacity is only 53 × 10⁴ kW [12] and accounts for a very small proportion of the world’s energy system, revealing room for growth [13]. To date, offshore wind energy is the most advanced and promising type of marine renewable energy, and has entered the large-scale development stage[14]. In the short to medium term, tidal energy and wave energy are expected to become commercially feasible technologies, as many tidal energy and wave energy stations have already been built, with more projects planned [15].

China has more than 70 GW usable marine renewable energy resources in nearshore waters, and the open sea wave energy far exceeds that in nearshore waters [16]. In addition, ocean current energy resources in deep water

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are relatively abundant [17]. The total ocean carbon free energy reserves are $15.80 \times 10^8$ kW, with a theoretical annual power generation capacity of $13.84 \times 10^{12}$ kWh, indicating China's huge potential for developing marine renewable energy [18]. Over the past few decades, marine renewable energy research and technology have developed rapidly in China [19].

Fujian Province is located in southeastern China, a region with a relative lack of traditional energy resources, resulting in a serious shortage of coal resources and a high dependence on external energy. Concurrently, Fujian has a coal-based energy structure, and the emissions from large scale coal combustion damage the atmosphere and ecological environment of the region. To meet the carbon peaking and neutrality requirements, Fujian Province needs to change the region’s socioeconomic development model, especially the energy strategy. The use of marine energy for the sustainable development of the region will not only increase the energy supply, alleviate the energy shortage, and reduce the pollution caused by energy consumption, but also optimize the Fujian Province’s energy structure and reduce carbon emissions. Based on the energy structure and carbon emission pressure analysis in Fujian Province, this paper systematically sorts out the availability and reserves of various marine renewable energy in Fujian Province, and finds out the types of marine energy that should be preferentially developed in the future, which will provide a supplement to the research on emission reduction path under the peak carbon emission and carbon neutrality background.

2 Energy Structure and Carbon Emissions in the Fujian Province

2.1 Energy Production and Consumption

The Fujian Province has a low energy supply owing to its supply of nuclear power energy. However, with the rapid economic growth, total energy consumption in this region has been consistently higher than the energy production, showing a rapidly growing trend. From 2011 to 2020, the province’s total primary energy consumption increased by 39.32% (Figure 1). The energy types mainly include coal, crude oil, natural gas, hydropower, wind power, and nuclear power, with coal being the dominant energy source. Over the past three decades, the allocation of coal in total energy consumption has gradually declined, but remains at approximately 50%. The share of crude oil consumption has been relatively stable, at approximately 24%. Owing to limitations in the scale of hydropower, its development has been constrained, and its distribution has dropped to 6.2% in 2020 as the total energy consumption demand has increased. With gradual improvement in wind power generation technology, the share of wind power has been increasing in recent years, but it remains insignificant at 3.3%. The grid connection of the Ningde and Fuqing nuclear power plants has increased the share of nuclear power in the Fujian Province, reaching 13.9% in 2020 (Figure 2) [20]. By 2020, the share of fossil energy consumption was 76.6%.

2.2 Energy Supply and Demand Gap

The lack of conventional energy resources and the continuous rise in energy consumption demand have led to an insufficient supply of energy resources in the Fujian Province, with a relatively low self-sufficiency rate and high dependence on external energy sources. Since 2005, the gap between the production and consumption of energy resources in the Fujian Province has been gradually increasing, reaching 105 million tons of standard coal in 2021 (Figure 3). In 2005, the external energy dependence of the province was 57%, reached 75% in 2015. With the increase in nuclear power production, the dependence on external energy has decreased to 72% in 2021; however, it is still highly dependent on external energy [20].

2.3 Carbon Emissions of the Fujian Province

Carbon emissions generated by various types of energy consumption in the Fujian Province from 2005 to 2020 were calculated (Figure 4) according to the carbon emission factors of China (Table 1) [20]. With the increase in energy consumption and current energy structure in the Fujian Province, total carbon emissions have surged, reaching 50.21 million tons in 2020, which is 2.24 times that of 2005. Carbon emissions caused by coal consumption were the largest among the three fossil energy sources, followed by crude oil and natural gas. These results show that the Fujian Province is still under
enormous pressure to achieve emissions reductions, and the development of sustainable energy and control of carbon emissions are urgently needed.

Table 1. Carbon emission factors for various types of energy

<table>
<thead>
<tr>
<th>Data source</th>
<th>Coal</th>
<th>Crude oil</th>
<th>Natural gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Research Institute of NDRC</td>
<td>0.7476</td>
<td>0.5825</td>
<td>0.4435</td>
</tr>
</tbody>
</table>

![Figure 4. Carbon emissions in the Fujian Province from 2005-2020](image)

3 Feasibility Analysis of Marine Energy Development in the Fujian Province

3.1 Energy Policies

3.1.1 China's Marine Energy Policies

China has put great emphasis on addressing climate change and has issued a series of plans and laws to support the development of marine energy and other renewable energy sources to achieve “carbon peaking and neutrality” [21]. The Renewable Energy Law, which was implemented on January 1, 2006, laid the legal foundation for renewable energy resources development, including marine energy. To promote the research, development, and utilization of marine energy in various aspects, such as the overall framework, development directions, and technical support, China has promulgated the Strategy for Energy Production and Consumption Revolution (2016-2030), the 13th Five-Year Plan for the Development of Marine Renewable Energy, 14th Five-Year Plan for Renewable Energy Development, 14th Five-Year Plan for a Modern Energy System, 14th Five-Year Plan for Energy Science and Technology Innovation, 14th Five-Year Plan for the Marine Economy Development, and 14th Five-Year Comprehensive Work Plan for Energy Conservation and Emission Reduction. Marine energy is officially listed as an important path in China's energy restructuring.

For “carbon neutrality,” China disseminated the Action Plan for Carbon Dioxide Peaking Before 2030, which showed a clear route for the energy structure adjustment: by 2025, the non-fossil energy consumption proportion should reach approximately 20%; by 2030, this proportion should reach approximately 25%, and carbon dioxide emissions per unit of GDP should drop by more than 65% compared to that in 2005, achieving the carbon peak target. Furthermore, it also specifies goals for improving the offshore wind power industry chain, building offshore wind power bases, and advancing the development of new marine energy sources, such as tidal and wave energy, and energy produced by temperature gradients[22]. The overall policy analysis revealed that China's energy restructuring policy tried to address energy shortages using a two-pronged approach: improving energy efficiency while reducing dependence on fossil fuels. Therefore, the energy restructuring policy provided an advantageous opportunity for marine energy to develop rapidly.

In addition, China has introduced green energy certificates, concessional loans for renewable energy, feed-in tariffs, and other policy measures to promote renewable power generation, which provides a reference for further research on policies to develop the marine energy industry.

3.1.2 Fujian Marine Energy Policies

During the period of “14th Five-Year Plan”, the Fujian Province emphasized the strengthening of marine energy development in the plan layout, which was listed as an important direction for energy restructuring. The 14th Five-Year Plan for the Economic and Social Development of Fujian Province and the Outline of Visionary Goals for 2035 proposed building a cleaner energy supply structure to upgrade the offshore wind power equipment industry and develop marine renewable energy. The 14th Five-Year Special Plan for the Development of Strategic Emerging Industries in Fujian Province emphasized the need to accelerate the renewable energy development, fully utilize the offshore wind power resources advantages, and promote the use of offshore wind power in industrial parks construction. The plan also proposed carrying out research and pilot work on marine tidal energy power generation technology, building medium-scale tidal energy demonstration power stations on islands, scaling up the grid connection of tidal energy power stations, and exploring the application of wave power generation devices. The 14th Five-Year Special Plan for the Strong Coastal Province Construction in Fujian proposed focusing on strengthening the marine renewable energy technologies and expanding the industry chain of offshore wind power.

3.2 Marine Energy Reserves in the Fujian Province

The Fujian Province has abundant reserves of major marine energy sources, such as offshore wind, tidal, wave, and ocean current energy, all of which are among the highest in the country. According to the preliminary marine wind energy estimation results of the 908 Special Project Survey and Research on nearshore Ocean Energy in China organized by the State Oceanic Administration, the nearshore wind energy reserve of the Fujian Province was approximately $1.734 \times 10^8$ kW at 10 m height in shallow waters above the 50 m isobath, and the technically available amount was approximately $1.33 \times 10^9$ kW (Table 2). It has the highest reserve of total nearshore marine wind energy and the best utilization...
conditions in China. The average tidal range is large in the coastal waters of Fujian, which are lined with primarily rocky coasts interspersed with multiple bays, providing ideal sites for tidal power stations. This region has the most favorable conditions for tidal energy resources utilization in China. Additionally, the wave energy density in southern Fujian is more than 4 kW/m, with the advantages of shallow water depth in the nearshore region, a large slope, relatively high wave power density, and small seasonal changes, favoring the design and installation of power generation devices and increasing the total conversion efficiency. Moreover, it is an area with ideal conditions for wave energy development and utilization in China [23].

Table 2. Marine Energy Reserves in the Fujian Province [18, 24, 25]

<table>
<thead>
<tr>
<th>Types of marine energy</th>
<th>Reserve</th>
<th>Technically available amount</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theoretical installed capacity (10^4 kW)</td>
<td>Theoretical annual power generation (10^8 kWh)</td>
</tr>
<tr>
<td>Offshore wind</td>
<td>17,335.7</td>
<td>15,154.8</td>
</tr>
<tr>
<td>Tidal</td>
<td>1,361.78</td>
<td>1,192.30</td>
</tr>
<tr>
<td>Current</td>
<td>46.7</td>
<td>40.9</td>
</tr>
<tr>
<td>Wave</td>
<td>291.07</td>
<td>254.98</td>
</tr>
<tr>
<td>Energy from Salinity gradient</td>
<td>294</td>
<td>257.5</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>52.6</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>26.3</td>
</tr>
</tbody>
</table>

3.3 Technical Support for the Use of Marine Energy

Currently, the offshore wind has entered a large-scale development stage, showing rapid improvements in the technology and equipment used [26]. The installed capacity for offshore wind power has been growing rapidly for multiple years and is the most promising marine renewable energy type in the near future [27]. Since 2009, the wind power equipment manufacturing capacity in China has increased rapidly, and it is capable of manufacturing power generation units and major components of various technical types and specifications with or above a level of 1.5 MW. This effectively fulfills the need for land and offshore wind power development. Simultaneously, the cost of wind power generation has also been gradually decreasing, falling to 1/6 of the level during the 1980s, and continues to reduce [28]. This has laid the groundwork for large-scale development of offshore wind power in Fujian Province. At the end of 2021, the cumulative grid-connected capacity of offshore wind power in Fujian has reached 3.14 million kW, which is expected to exceed 5 million kW by 2025 [29].

An adequate theoretical foundation has been formed based on extensive practical experience in the technology, power generation devices, and equipment for tidal energy[25]. There are many sites with high energy density and superior natural environments in the coastal areas of Fujian, which are rich in tidal energy resources with an average tidal range of approximately 4-5 m. Preliminary investigations and surveys, planning and design, and feasibility studies were carried out at the Daguanban and Bachimen station sites, which showed short-term development values [23].

The technology of China’s tidal current energy has undergone rapid development, producing a relatively mature technology for the development of tidal current energy on a large scale. Presently, approximately 20 units have completed sea trials with a maximum power of 650 kW for a single unit, and some units have achieved long-term demonstration operations. Tidal wave energy power generation technology research has a late start, but a swift development is in the early stage of testing and large-scale commercial operation, with many tidal wave energy station sites of large installed capacity under planning and construction [30]. In 2020, the tidal wave energy test power station on Zhairuoshan Island of the Zhoushan Islands achieved a maximum power of 637 kW, furthering China’s tidal current energy development for low-cost and large-scale applications. The coastal area of Fujian has relatively rich tidal energy resources. The nearshore water area around Nanri Island in Putian, Fujian provides usable tidal energy power between 0.5-1.0 MW during high tides, and 0.2-0.4 MW during the low tides [31]. Locations such as the mouth of Sansha Bay and Luoyuan Bay have relatively high current velocities and stable sea conditions, providing a superior development environment [32].

China has been developing wave energy power generation technology for more than 30 years, with certain advantages in the conversion efficiency and stability research of wave energy and a solid foundation for improving reliability. The Guangdong Province, with the support of the Science and Technology Support
Program, has conducted research and built a 100 kW oscillating water column and a 30-kilowatt pendulum type wave energy power generation test power station for conducting research on high-efficiency floating wave energy devices, and has launched the research and construction of two demonstration test power stations with an installed capacity of 100 kW. Currently, certain marine energy power generation technologies are at a critical stage, moving from experimental research and development to engineering applications.

Although the theoretical reserves of temperature and salinity gradient energy in the Fujian Province are relatively high, relevant technologies have not been fully developed. They are at the key stage of technology research, development, and simulation, and are far from practical utilization.

Considering the large reserves of wind energy, tidal energy, and salinity gradient energy in Fujian Province, as well as the advanced technological maturity and economic benefits, this study concludes that offshore wind energy in Fujian Province has the highest development value. Efforts should be made to develop offshore wind energy in nearshore waters and island areas, followed by tidal, wave, and tidal current energy, which currently have relatively helpful technical support and greater development potential in the future. Tidal energy should be developed according to the local conditions. Demonstration and testing of the comprehensive utilization of wave and current energies should be actively promoted. Utilization of energy from the temperature gradient and salinity gradient still requires significant development and will require exploration of critical technical research and development as well as testing.

4 Conclusions
There is a shortage of fossil fuel resources in the Fujian Province, and the demand for energy consumption and total carbon emissions are rising. As per the requirements of China’s new carbon policy, the Fujian Province is under increasing pressure to reduce emissions with a pressing need for renewable energy. The Fujian Province has substantial marine energy reserves, with the most abundant wind, tidal, and wave energy in the country, and a relatively developed technology for the utilization of offshore wind and tidal energy. Therefore, offshore wind energy, ocean waves and tidal energy are expected to play an increasingly important role in the near future. The development of marine renewable energy could not only provide a stable energy supply and effectively alleviate its energy shortage, but also bring forth new means for achieving the transformation of energy structure and reduce carbon emissions. Moreover, it can also structure a new industry with advantages in the region and become a new point for the regional economy growth. Therefore, it is feasible to develop marine renewable energy in Fujian Province. Marine renewable energy will contribute greatly to energy structure adjustment, carbon neutrality and peak shaving.

With current policy and technical support, the following suggestions for marine energy industry development in Fujian Province are proposed:
1) Further investigation and evaluation of the reserves and distribution of marine energy resources are required to determine the current situation of utilization and research, and provide basic information for the construction of demonstration power stations.
2) In the near future, focus on the development of offshore wind and tidal energy, and explore wave energy, tidal current energy, and salinity gradient energy experiments for long-term utilization.
3) Strengthen the construction of the legal system and policy planning for marine energy development, as well as local conditions, formulate relevant policies and plans to stimulate industrial development, and further encourage marine energy research and development.
4) Develop energy storage technology for marine renewable energy and reduce the impact of marine energy development on the environment.

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