
Perspective

Offshore Renewable Energy Advance

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ABSTRACT: Offshore renewable energy generation has become an important means to address the energy crisis and climate change, which has gained widespread attention in recent years. This article presents classic domestic and international cases that introduce the development and industrial transformation of generation technologies for offshore wind, offshore photovoltaics, ocean wave energy, tidal energy and temperature difference energy. Offshore power generation projects face challenges in design, safety, long-term operation and economic feasibility. Offshore renewable energy generation is gradually moving towards industrialization, and is expected to become a key component of global energy supply in the future with technological advancements and policy support, providing strong support for tackling climate change and achieving sustainable development goals.

Keywords: Offshore renewable energy; Offshore wind power generation; Offshore photovoltaics; Hydrogen energy



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1. Introduction

The global energy landscape has undergone profound changes from the end of the 20th century to the beginning of the 21st century. Traditional fossil energy sources, such as oil and coal, are facing challenges such as resource depletion and rising extraction costs, while the imbalance between global energy supply and demand has become increasingly prominent. At the same time, the widespread use of fossil fuels has led to severe environmental problems, particularly growing concerns over climate change and air pollution [1–3]. In response to the energy crisis and environmental pressures, countries worldwide have adopted various measures to promote energy transition and develop clean energy to reduce dependence on fossil fuels.

Offshore renewable energy generation, as an emerging technology, has gained significant attention and rapid development globally in recent years. Due to its advantages, including high energy density, minimal land occupation and low carbon emissions, offshore renewable energy is seen as a crucial means to reduce greenhouse gas emissions and promote sustainable development. The vigorous development of offshore renewable energy is critical for advancing green and low-carbon development, enhancing the competitiveness of the marine economy and supporting the "dual carbon" strategy [2]. Offshore renewable energy primarily includes offshore wind power, offshore photovoltaic power, offshore wave energy and tidal energy, all of which are undergoing intensified research, and development. The optimization of the global energy structure, continuous technological innovation and increased policy support and will enable offshore renewable energy to play an increasingly important role in the future energy landscape.

2. Offshore Renewable Energy

2.1. Offshore Wind Power Generation

Offshore renewable energy generation technologies have made breakthroughs with technological advancements continuously. The maturity of offshore wind technology, the development of prototypes and the establishment of testing platforms have laid a solid foundation for the application of offshore wind power. In particular, in the field of offshore wind power, with the increase in turbine capacity, innovations in floating platform technology and improvements in

offshore installation and maintenance technologies, the cost of offshore wind power generation is steadily decreasing. Offshore wind power has become one of the most competitive clean energy sources, attracting significant investment and research [3].

The concept of offshore wind power dates back to the 1980s when the world's first offshore wind project was experimentally installed in Denmark's waters [4]. Throughout the 1990s, Denmark, Germany and the Netherlands led numerous experiments and technological research in this area. Offshore wind power has evolved into a global market, driven by increasing collaboration and competition among multinational companies since the mid-2010s, spurring rapid technological innovation. As a clean and renewable energy source, offshore wind power will play a pivotal role in the global energy transition. Governments and international organizations are ramping up policy support to accelerate the scaling and industrialization of offshore wind power [5].

With the development of technology, deep offshore wind power is gradually becoming commercialized and seen as a key direction for the future development of the industry. Its main advantage lies in richer and more stable wind resources, providing higher power output with higher wind speeds and greater energy density in offshore areas. As floating wind turbine technology develops, wind turbines can be deployed in deeper waters, overcoming the limitations of the traditional fixed infrastructure and providing technical support for the expansion of deep offshore wind power. However, deep offshore wind power still faces challenges such as high construction and maintenance costs, harsh marine environments and power transmission issues. With the maturity of the global offshore wind power supply chain and technological advancements, related costs are decreasing. It is expected that deep offshore wind power will become a key component of the global energy transition and play an important role in addressing climate change and achieving carbon neutrality goals with continued policy support and technological breakthroughs.

2.2. Offshore Photovoltaic Power Generation

Offshore photovoltaics has become an application for the next generation of photovoltaic power generation projects with its unique characteristics and advantages. Currently, offshore photovoltaic project development mainly focuses on research and demonstration applications, testing equipment and exploring models for large-scale deployment.

Fixed and floating photovoltaics are the two main forms of offshore photovoltaics, and they differ significantly due to geographical locations and application scenarios. Fixed-pile photovoltaics are typically deployed in tidal flats or nearshore areas. They offer strong resistance to wind and waves, making them suitable for shallow seas or tidal flats with a robust foundation structure. Their equipment and operational management are relatively mature, ensuring high system reliability and making large-scale centralized power generation feasible. However, fixed-pile photovoltaics have higher construction costs, especially in deep-water areas, where the complexity and duration of pile foundation construction significantly increase. Additionally, fixed-pile photovoltaics may cause significant environmental disruption, affecting marine habitats, and their durability presents long-term challenges in harsh offshore conditions, such as high temperatures, humidity, and salt fog [6].

In contrast, floating photovoltaics, as an emerging technology, enhance photovoltaic efficiency through reflection and cooling effects, which is suitable for deep-water areas and reduces impacts on the marine ecosystem. However, floating photovoltaics still face numerous challenges, such as salt crystallization on panels, high environmental loads and the reduction in photovoltaic efficiency due to platform movement. Breakthroughs are urgently needed in material science and engineering technologies. Furthermore, there is an increasing demand for automation, visualization and intelligence in offshore photovoltaics. Addressing these critical issues will be the key driver for the sustainable development of floating photovoltaic technology [7].

Currently, floating photovoltaics adopt various technological approaches. Typical structures include semi-submersible platforms, flexible membrane structures, large-module floating arrays and small-module floating arrays.

Floating photovoltaic technology is gradually becoming a key direction for offshore photovoltaic development due to its potential for deep-sea deployment and synergy with other renewable energy sources [8]. The technology, which is supported by policies and international cooperation, is expected to achieve broader commercialization through large-scale deployment and standardized construction, providing essential support for achieving carbon neutrality and the sustainable development of marine resources.

2.3. Offshore Wave Energy Generation

Wave energy generation is a clean, renewable energy technology that converts the kinetic and potential energy of ocean surface waves into electricity through energy conversion devices. Ocean waves are mainly formed by wind and

atmospheric pressure, making wave energy one of the most promising sources of renewable energy with high energy density and good predictability and continuity. Compared to other renewable energy sources, wave energy is less affected by weather conditions, providing stable energy support for coastal and island areas. Additionally, nearly all coastal countries have some potential for development due to the widespread distribution of wave energy resources, which makes it highly scalable globally [9].

Although wave energy technology has made progress, it still faces challenges such as poor durability, low energy conversion efficiency and high costs. Marine wave devices are exposed to harsh ocean environments for extended periods, requiring designs that can withstand extreme weather and minimize disruption to marine ecosystems. These issues limit the widespread adoption and economic viability of wave energy. However, the fatigue resistance and conversion efficiency of wave energy devices are expected to improve, making them a potential source of green energy in the global energy transition with breakthroughs in materials science, mechanical design and control technologies.

2.4. Tidal and Temperature Gradient Energy Generation

2.4.1. Tidal Energy Generation

Tidal energy generation harnesses the kinetic energy of water flow generated by tidal movements and converts it into electricity through devices such as water turbines. Due to the regularity and high energy density of tidal movements, tidal energy is highly reliable, especially in areas with significant tidal ranges. Additionally, tidal energy is not affected by climate change or seasonal variations, making it a reliable and clean renewable energy source, particularly suitable for coastal and island regions with high energy stability demands.

Internationally, the "Seagen" tidal energy generator in the UK is a successful example of commercialization. Its efficient dual-rotor design has provided technical insights for further development of tidal energy. In China, the Zhoushan tidal energy demonstration project has made significant progress in improving equipment stability and efficiency and has explored the potential for joint development with offshore wind power. Moreover, Chinese universities and research institutions have made important achievements in tidal energy numerical simulation and equipment optimization design, though challenges remain, including high maintenance costs and ecological impacts.

2.4.2. Temperature Gradient Energy Generation

Thermal gradient energy generation utilizes the temperature difference between surface and deep ocean waters to convert thermal energy into electricity through a heat cycle. It is a clean energy technology with low environmental impact, particularly suitable for tropical and subtropical regions. Common technologies include open-cycle, closed-cycle, and hybrid-cycle systems. Open-cycle systems directly use seawater as the working fluid, closed-cycle systems use low-boiling-point working fluids to improve heat exchange efficiency, and hybrid-cycle systems combine the advantages of both but are structurally more complex.

The coordinated development of tidal energy, temperature gradient energy, wave energy, wind energy, and other marine energies can effectively enhance the stability and diversity of energy supply [10]. Combined with other renewable energy sources, this diversified marine energy system will provide significant support for global energy transition and carbon neutrality goals, contributing to the sustainable development of a green and low-carbon economy.

3. Challenges of Offshore Renewable Energy

The development of offshore renewable energy is moving towards more diversified and integrated solutions with the global energy transition underway, improving resource efficiency and providing strong support for achieving carbon neutrality by integrating multiple energy sources such as wind and solar power. For example, renewable energy powers the electrolysis of seawater to produce hydrogen, which is then used to synthesize ammonia or alcohol-based fuels, creating an "electricity-hydrogen-ammonia/alcohol" system. This not only addresses energy supply challenges in remote offshore areas but also reduces the volatility of offshore wind power. Additionally, ammonia, as a high-density energy carrier, can be used for power generation, ship fuel or international energy transport, significantly expanding the application scenarios for offshore renewable energy. These models, like "complementary collaboration and diverse integration" provide directions for the comprehensive use of offshore energy and create conditions for the large-scale application of renewable energy. By promoting the coordinated development of multiple energy sources, energy utilization efficiency can be increased, and the challenges related to offshore energy production and supply can be effectively addressed, paving the way for more sustainable and low-carbon development of offshore renewables.

Despite the enormous development potential of offshore renewable energy, there are several designs, operational and economic challenges in the complex marine environment. Firstly, the safety and stability of platform design are key issues for offshore energy systems. Due to the harsh marine environment, factors such as waves, storms and corrosion can severely impact equipment. Platform designs must ensure structural strength and stability to withstand long-term marine conditions and extreme weather. Secondly, the long-term operation of offshore renewable energy projects also faces challenges. The harsh marine environment demands higher durability from equipment, and maintenance and repair cycles are longer. Finally, cost reduction is crucial for the widespread application of offshore renewable energy. Although offshore energy has advantages in environmental benefits and long-term sustainability, initial construction and operational costs are high, particularly in deep-sea areas. Therefore, scaling up and the use of innovative materials are needed to effectively reduce costs.

In summary, offshore renewable energy still faces technical challenges that need breakthroughs in design, operation and economics. The offshore energy industry is expected to overcome these challenges and move toward a greener, low-carbon and sustainable development path with further technological innovation and policy support.

Author Contributions

Conceptualization, J.L. and L.C.; Methodology, L.C.; Writing – Original Draft Preparation, Q.F.; Writing – Review & Editing, J.L. and L.C.; Supervision, J.L. and L.C.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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