Journal of
Marine Science
and Engineering

MDPI

Review

A Comprehensive Review of Floating Solar Plants and Potentials for Offshore Applications

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Abstract: Fossil fuel consumption has progressively increased alongside global population growth, representing the predominant energy consumption pattern for humanity. Unfortunately, this persistent reliance on fossil fuels has resulted in a substantial surge in pollution emissions, exerting a detrimental influence on the delicate ecological balance. Therefore, it is imperative to find new renewable energy sources to replace fossil fuels. Solar energy is a clean energy source and has become the most preferred option for human day-to-day needs. Since the construction of the world's first floating photovoltaic power station, humanity has been continuously advancing the technology of power generation by floating photovoltaics. This review comprehensively elucidates the progression of offshore photovoltaic technology and illustrates the composition of the floating photovoltaic system. Each section meticulously contrasts the advantages and drawbacks of various photovoltaic systems. In addition, an in-depth analysis of the offshore photovoltaic application potentials is conducted based on fundamental theories, thereby offering valuable insights for future research. Finally, an encompassing summary of the potential challenges associated with deep-sea floating photovoltaic systems is presented.

Keywords: floating photovoltaic (FPV); clean energy; system stability; high-density polyethylene (HDPE); pontoon; offshore

Citation: Huang, G.; Tang, Y.; Chen, X.; Chen, M.; Jiang, Y. A Comprehensive Review of Floating Solar Plants and Potentials for Offshore Applications. *J. Mar. Sci. Eng.* **2023**, *11*, 2064. https://doi.org/10.3390/jmse11112064

Academic Editor: Eugen Rusu

Received: 5 October 2023
Revised: 20 October 2023
Accepted: 26 October 2023
Published: 28 October 2023

1. Introduction

As the world's population continues to surge, the demand for energy continues to increase, leading to a sharp rise in the use of fossil fuels. The continuous emission of greenhouse gases has caused more and more serious problems such as global warming and sea level rise. The task of finding and developing renewable new energy is imminent [1]. In the past two decades, the greenhouse effect caused by rising temperature has become the primary concern of the world. Countries have adopted several initiatives to combat climate change, such as the Paris Agreement, the Kyoto Protocol, the United Nations Framework Convention on Climate Change (UNFCCC) and the 26th United Nations Climate Change Conference (COP26) in Glasgow, Scotland, in 2021 [2]. Delegates from approximately 200 countries reached a consensus during the COP26 summit to find and develop suitable energy sources in order to fulfill the demands of consumers, simultaneously reducing environmental damage. Moreover, they pledged to accelerate the execution of the Paris Agreement, thus leading the world towards a more sustainable and ecologically balanced trajectory characterized by reduced carbon emissions. At present, the strategy of using low-carbon energy such as natural gas, wind energy and hydrogen energy for sustainable development is constantly advancing. Among the burgeoning renewable energy sources, solar energy emerges as the foremost candidate, given its unparalleled safety, environmental friendliness and natural cleanliness [3]. The International Energy Agency

(IEA) reports that in order for the world to achieve the Net Zero Emissions by 2050, solar power generation will have to grow at an average annual rate of 25% in the period 2022–2030 [4]. It is a significant trial not only for the production and installation efficiency of photovoltaic enterprises but also for the formidable challenge of achieving technological breakthroughs and optimizing innovations in the field of photovoltaic research. From 2004 to 2011, cumulative worldwide photovoltaic power generation dramatically increased from 4 GW to 70 GW, with an average annual growth rate of over 58% [5]. Moreover, under the breakthrough of manufacturing technology promoted by scientific innovation and competition among companies, the expenses of research and installation in the PV field are progressively decreasing, a trend that is anticipated to drive a substantial rise in the capacity of new PV stations to exceed 125 GW annually starting in 2020. By 2050, the global installed capacity is expected to reach 4500 GW [6]. This development not only signifies the endorsement and support of various countries for the direction of photovoltaic power generation but also establishes a foundation for the scientific research of new energy development. Figure 1 compares estimated installed PV capacity growth in numerous countries from 2007 to 2024 [7]. As evident from the figure, China has vast opportunities for growth in the domain of photovoltaic power generation. It mitigates environmental pollution through rational utilization of renewable energy and creates a comfortable living environment while simultaneously providing solutions to the increasing demand for electricity and thereby guarantees the safe and orderly life quality of residents.

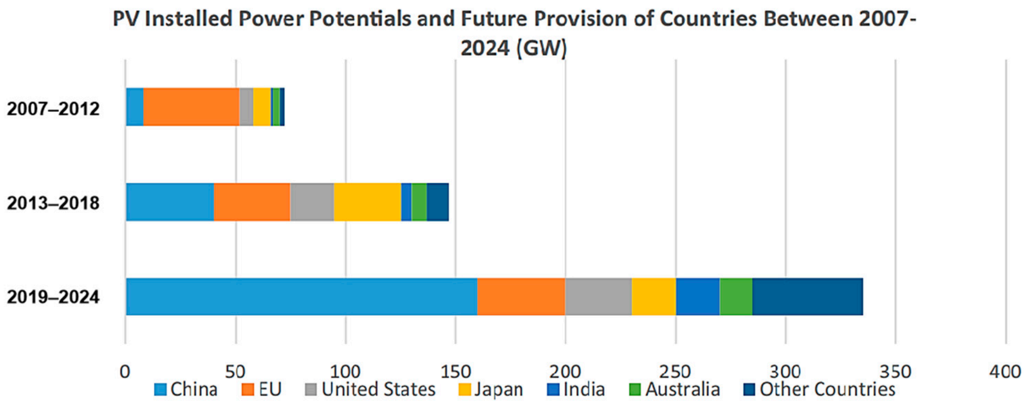


Figure 1. The capacity of planned and installed PV worldwide from 2007 to 2024 [7].

At the United Nations General Assembly in September 2020, China, as the world's largest developing country, coal consumer and carbon emitter, will be guided by the new development concept. While propelling comprehensive green transformation and fostering high-quality development in economic and social development [8], China committed to embarking on emission reduction measures over the next decade, with the aim of reaching the peak of carbon emissions by 2030 and achieving carbon neutrality by 2060 [9]. For China to attain that objective, electricity production needs to more than double, encompassing a 16-fold increase in solar power generation, which should gradually replace coal-fired electricity generation [10]. After the "dual carbon" goal was defined, China attached great importance to the evolution of renewable energy and utilized distributed photovoltaics (PV), which has broad applicability and high cost-effectiveness, to effectively solve the problems stemming from uneven distribution of energy resources and significant differences in power loads across different regions [11]. Last year, 240 GW of PV systems were installed worldwide, bringing the cumulative installed capacity to 1185 GW, according to the statistical report of the IEA [12]. Figure 2 clearly illustrates that China has established a remarkable lead over other nations in both the annual installed capacity and cumulative installed capacity of solar PV systems. Last year, the newly added capacity was 106 GW, accounting for 44% of the global new capacity, and the cumulative installed capacity reached 414.5 GW. The growth trend follows the growth of previous years—54.9 GW of new installations in 2021 and 48.2 GW in 2020. The European Union (EU) installed 38.7 GW of solar capacity last year, up from 27 GW in 2021 and 20 GW in 2020 [13], with Spain (8.1 GW), Germany (7.5 GW), Poland (4.9 GW) and the Netherlands (3.9 GW) following. The EU is the second largest market for the global PV systems industry, with a cumulative installed capacity of 209.3 GW. By conducting an analysis of previous project studies, we aim to provide a detailed assessment of the advantages, disadvantages and development status of both land-based and offshore PV systems. Additionally, we outline the main conceptual characteristics of offshore PV systems and highlight their potential and challenges for offshore applications. Offshore PV systems include pile-fixed PV systems, module pontoon PV systems, very large floating structure (VLFS) PV systems and very flexible floating (VFFS) structure PV systems.

Annual Installed Capacity			Cumulative Capacity		
1	China	106 GW	1	China	414.5 GW
(2)	European Union	38.7 GW	(2)	European Union	209.3 GW
2	USA	18.6 GW	2	USA	141.6 GW
3	India	18.1 GW	3	Japan	84.9 GW
4	Brazil	9.9 GW	4	India	79.1 GW
5	Spain	8.1 GW	5	Germany	67.2 GW
6	Germany	7.5 GW	6	Australia	30 GW
7	Japan	6.5 GW	7	Spain	26.6 GW
8	Poland	4.9 GW	8	Italy	25 GW
9	Australia	3.9 GW	9	Korea	24.8 GW
10	Netherlands	3.9 GW	10	Brazil	23.6 GW

Figure 2. Top 10 countries for installations in 2022 and total installed capacity.

This review is divided into the following sections: the first part briefly discusses the global photovoltaic installed capacity and the necessity of developing offshore photovoltaic power generation technology. The second part shows the current situation of the PV industry and the large-scale projects planned for the future, including the application of land-based PV and four common offshore PV systems. The third part introduces the composition, transportation and installation of offshore floating photovoltaic (FPV) components. Finally, the development direction and application challenges of FPV systems are summarized.

2. Development of Photovoltaic Technology

Over the past decade, the solar photovoltaic industry has experienced rapid growth and expansion, with developments in photovoltaic and wind technologies allowing the renewable energy market to overtake fossil energy sources in the mid-2020s, and is expected to fulfill more than half of the world's electricity demand by 2040. With the COP26 conference in 2021, nations reiterated their commitment to the objectives of the Paris Agreement, which aims to constrain the global average temperature rise to below 2 °C above pre-industrial levels, while striving for efforts to limit the increase to 1.5 °C above pre-industrial levels [14,15]. As nations fervently advance the utilization of renewable energy and actively foster the construction of an ecological civilization, photovoltaic power generation technology has gradually matured. Moreover, countries now possess the capability to deploy photovoltaic power stations at gigawatt scales, which will contribute significantly to short-term emission reduction efforts. Today, solar power stands as the most cost-effective source of electricity in numerous regions across the globe [16]. Haegel et al. [17] discuss the consequences and challenges of complementary technologies (e.g., energy storage, grid integration, etc.). In addition, they summarize the necessity for research pertaining to PV manufacturing, reliability, power generation efficiency and recovery to reach the milestone of cumulative capacity exceeding 1 TW by 2023. Victoria et al. [18] reviewed the factors of the reduction in solar PV costs and identified appropriate policies that could promote elevated installation rates and the challenge of perpetually expanding solar PV capacity over the forthcoming decade. Shi et al. [19] recently summarized some innovative photovoltaic design concepts and emphasized the importance of wave-structure interaction analysis and mooring systems.

Utility-scale PV installations are different from distributed PV systems in their operational characteristics. Distributed PV systems are typically installed on existing structures in close proximity to the user site, such as rooftops. These distributed PV systems follow the principles of adapting to local conditions, cleanliness, efficiency, distributed layout and proximity to utilization sites. Under the circumstance of land utilization remaining unaffected, it makes full use of local solar resources, reducing and replacing fossil energy consumption [20,21]. Utility-scale PV plants are located on agricultural land, as the deployment of land-based PV systems accelerates and the industry expands unprecedentedly through decarbonization programs. Growing apprehension is emerging regarding the land requirements and associated impacts on land use pertaining to utility-scale PV installations [22,23]. Therefore, the development of offshore FPV comes at an opportune juncture as the industry progresses; it has the advantages of strong adaptability to water level changes and less influence on water quality and is conducive to reducing sea water evaporation [24]. In comparison to pile-fixed photovoltaic power stations, floating PV systems offer advantages such as simplified installation, lower layout cost, more convenient maintenance and an increased power generation efficiency of approximately 10–12% [25–29], becoming the world's favorite object. In Norway, Japan, the Netherlands and many other countries, the photovoltaic panel in inland rivers, lakes and other waters has become a practical alternative solution. Next, this article elucidates the solar PV power generation technology, including centralized utility-scale PV systems, distributed PV, offshore pile-based stationary PV systems and floating PV systems, as well as introduces a selection of pertinent projects that have been implemented and some forthcoming large-scale projects.

2.1. Ground-Mounted Photovoltaic (GPV)

As a result of the progressive enhancement in solar photovoltaic power generation efficiency and the rapid reduction in installation costs [30], by dramatically increasing the use of renewable energy and helping to mitigate global warming, photovoltaics have become a previously underestimated force. Green et al. outlined the current photovoltaic market conditions, technological developments and the prospect of effectively reducing carbon dioxide emissions [31]. Following is an introduction to utility-scale PV versus distributed PV systems and an analysis of the advantages and disadvantages of land-based PV, reference to previous research work, application scenarios and ways to improve power generation efficiency.

2.1.1. Utility-Scale Photovoltaic Power Systems

Utility-scale PV plants are defined as ground-mounted installations with a capacity exceeding 5 MW and using diverse solar technologies to generate electricity, including primary PV or concentrated solar (CSP). The fundamental distinction between the two main solar technologies lies in their operational mechanisms. Primary PV technology directly converts solar energy into electricity through the utilization of solar cells. On the other hand, CSP harnesses the thermal effect of solar radiation to produce high-temperature steam. Then, this steam is employed to drive a turbine generator, which in turn generates electricity. The technologies currently used by CSP are divided into the following four types [32,33]: parabolic trough collectors (PTC) [34,35], linear Fresnel collectors (LFC) [36–38], solar towers (heliostat field collectors) [39] and parabolic dish reflectors (PDR) [37,40].

For decades, utility-scale PV systems have been delivering dependable and environmentally clean electricity at a consistent supply price through the utilization of various features, including repurposing abandoned land and ensuring ease of transportation and installation. According to the Solar Energy Industries Association (SEIA), the development of utility-scale PV systems is considered one of the most rapid and effective approaches to curbing carbon emissions and positioning the United States on a trajectory towards a clean energy future [41]. According to statistics, the United States already has more than 37,000 MW of utility-scale solar projects in operation, with plans to arrange 29.1 GW of utility-scale PV systems and 9.4 GW of energy storage in 2023 [42].

The installed capacity of utility-scale photovoltaic power plants has experienced significant growth in the past decade, rising from 1 GW in 2011 to 50 GW today, while there are outstanding and planned large-scale photovoltaic power plant projects in many countries. Therefore, we have summarized the following four advantages of utility-scale PV plants:

1. Cost effective

The cost of solar power has experienced a decline due to advancements in research and development technology. Utility-scale photovoltaic power plants are conducive to satisfying the large energy needs of local residents and enterprises with stable and low electricity prices through large-area efficient power generation and energy storage. Utility-scale photovoltaic plants generate energy on-site, exhibiting a minimal environmental footprint and enabling locations closer to towns, which minimizes power transmission losses [43]. In addition, utility-scale photovoltaic plants cost half as much per megawatt as rooftop solar installations.

2. Store for later use

Utility-scale PV plants require system balancing (BOS), which encompasses the essential equipment and services required to guarantee the safety and optimal functioning of the system besides PV modules. Solar panels can only convert thermal energy to electricity for a few hours when there is sunlight. Therefore, batteries are used to store energy and distribute it when needed. Battery storage increases the flexibility of the grid to distribute electricity and improves the reliability of utility-scale PV systems. Bullich-Massagué et al. [44] analyzed the most suitable energy storage technologies that can be used to provide different services in large photovoltaic power stations, then summarized the characteristics of various energy storage technologies.

3. Environmental impact

Utility-scale photovoltaic power stations possess higher energy efficiency and superior environmental friendliness compared to conventional power stations. Burning fossil fuels releases carbon dioxide into the atmosphere, which results in the greenhouse effect, and nitrogen gas from such fuels may also affect human health [45]. Cities and towns with limited access to electricity can take advantage of solar power, keeping the grid clean and carbon-free. At the same time, there are usually large areas of uninhabited deserts in many tropical climate regions and undeveloped deserts, where large-scale photovoltaic power generation projects rely on long-term and high-intensity sunshine to increase power generation.

4. Improve the quality of local life

Large-scale PV projects necessitate the involvement of various service providers, which can effectively stimulate the development of the local energy industry and the establishment of a sustainable and low-carbon energy economy. Additionally, large-scale PV plants are characterized by extended service lives and reduced maintenance costs. Furthermore, the substantial growth in the development revenue ratio leads to significant tax revenue for the local treasury [46].

Solar projects could also enhance the overall quality of life in the town. As far as farmland is concerned, replacing land with these solar projects could eliminate the use of fertilizers and chemicals, thereby improving local water supplies and soil erosion. The project also requires conducting an assessment of wind, wave and snow loads to ensure the system's safety under severe weather conditions such as storms, floods or heavy snowfall.

A large number of studies have verified that the technology of cleaning dust deposition, adjusting the tilt angle of photovoltaic panels and reducing the operating temperature of the module can significantly improve the power generation performance of photovoltaic cells. Yazdani et al. [46] evaluated the margin of error based on measuring short-circuit current to predict power loss due to PV module contamination and proposed simple experimental models to estimate the effect of dust on PV power generation. Finally, optimal cleaning schedules are designed for utility-scale power stations located in semi-arid environments. Mousavi et al. [47] designed and tested the performance of a suction robot named MFv01, which was designed specifically for cleaning solar panels. The robot demonstrated enhanced cleaning effectiveness and a higher cleaning speed, leading to reduced cleaning time for the solar panel surfaces. Sharaf et al. [48] reviewed and analyzed common methods used to cool PV panels and summarized all studies involving cooling PV solar cells with PCMs and porous structures. Zhao et al. [49] implemented spray cooling as a method for cooling photovoltaic cells and established a mathematical model suitable for solar photovoltaic power generation systems on the basis of considering the power consumption of the cooling system.

Undoubtedly, the rapid growth of utility-scale photovoltaic power stations also presents several challenges, including the following:

1. Large land occupation

Currently, solar modules' photoelectric conversion efficiency remains relatively low, and there are challenges related to transmission and energy storage losses. Consequently, the deployment of large-scale photovoltaic power stations may require substantial land areas, potentially leading to land degradation or the loss of wildlife habitats. Moreover, in certain countries, limited land resources pose constraints on the establishment of large-scale photovoltaic power stations. While solar PV systems can be anchored to existing structures, large utility-scale PV systems may require 3.5 to 10 acres per megawatt, compared to 4 to 6.5 acres per megawatt for CSP facilities [50].

2. Material hazard

The production of solar panels and related technologies may produce some chemical elements that are not friendly to the environment. Nitrogen trifluoride is a common by-product of electronics manufacturing, and many solar cells contain minute quantities of toxic heavy metals. Similarly, energy storage cells encompass large amounts of metals such as indium, gallium and selenium [51,52]. Hence, there is a hopeful anticipation for manufacturers to innovate eco-friendly materials as substitutes for these potentially hazardous substances in the future.

2.1.2. Distributed Photovoltaic Power System

A distributed PV system is a kind of non-centralized control of grid-connected solar power system, usually divided into residential, commercial and industrial applications, with flexible installation, easy maintenance, outstanding environmental advantages and power generation and consumption [52,53]. Residential PV systems are typically installed with a capacity of less than 10 kW. The majority of PV panels are deployed on the roof of a building or on their own structure to reduce transmission losses in a self-sustaining manner and provide a portion of the consumer's domestic electricity. Commercial distributed PV systems are primarily installed on the rooftops of large structures such as hospitals, schools or railway stations. The installed capacity is between 10 kW and 100 kW. Vacant rooftops offer a valuable opportunity for harnessing solar power generation, thereby alleviating the strain on the urban power supply and ensuring the stability of the transmission system of public facilities. Given the substantial and sustained electricity demands of industrial operations, industrial PV systems are strategically installed on roofs of factories or carports of parking lots to circumvent challenges associated with land occupancy, grid connection and power transmission. These systems typically have an installed capacity of 100 kW to 30 MW.

Distributed PV systems generally are small-scale deployments and involve cost-effective installation and maintenance. As a consequence, these systems have contributed significantly to the rapid growth of installed photovoltaic power generation capacity, characterized by decentralization and widespread adoption. Globally, distributed PV system installations are expected to grow by more than 250% during the forecast period, reaching 530 GW by 2024 [54]. In contrast to the previous six years, the increase is more than double, with distributed applications accounting for an increased share of total solar PV capacity expansion, rising from 36% to 45%, as shown in Figure 3 [55]. Commercial and industrial systems continue to dominate as the most rapidly expanding segment, owing to their lower cost and consistent load profile during the day. This is in contrast to large-scale centralized photovoltaic power stations, in which electricity is generated from expansive arrays of solar photovoltaic panels. The electricity produced is subsequently distributed and delivered to consumers through a grid network. Distributed solar systems are typically constructed by individual owners primarily for their own consumption. However, any surplus power can be sold back to power companies or integrated into the grid. Properly planned and installed distributed solar power has several advantages:

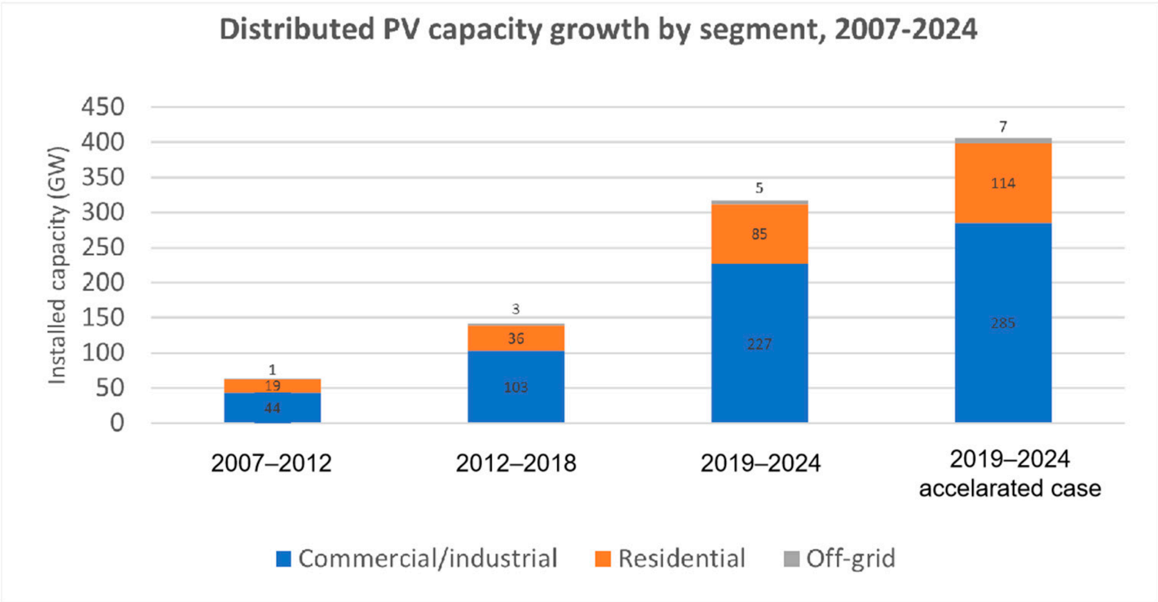


Figure 3. Share of distributed photovoltaics in total global solar photovoltaic capacity growth (green dots in the figure) [55].

1. Cheaper electricity prices

The utilization of distributed PV plants alleviates the burden on grid generation, transmission and distribution facilities, resulting in reduced deployment costs of the overall infrastructure. The generated electricity is primarily consumed by the system owners, leading to lower electricity costs for them. This solves the problems of challenging and heavy electricity consumption in remote rural areas, improves the quality of life of residents and ensures the safety of households.

2. More efficient and easier to maintain

Distributed PV systems reduce or eliminate the "line loss" (energy waste) that occurs during transmission and distribution of the transmission system by transmitting power over short distances [56], decreasing the probability of transmission failures in the system that contribute to reducing the overall lifespan of the system. Due to their relatively small scale, distributed PV systems provide greater flexibility in array layout and module inclination design. The maintenance and cleaning of the PV system are more convenient. Furthermore, replacing photovoltaic modules and electrical equipment is easier in such systems.

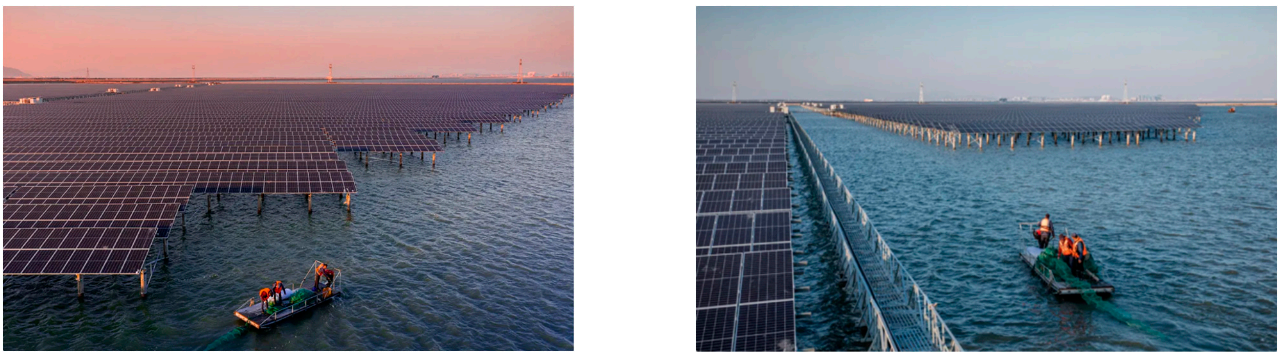
Researchers mainly discuss the maintenance and grid-connected power generation schemes of distributed PV systems. Fan et al. [57] proposed a new water-free cleaning robot suitable for panel dust removal in distributed PV systems in water-poor areas. Furthermore, they tested the effectiveness of the negative pressure adsorption system and the robot's obstacle clearing ability on the 2 kW distributed PV system on the roof of a university in northeast China. The results show that the water-free cleaning robot can obviously remove the dust on the panel. The average dust removal rate is 92.46%, and the photoelectric efficiency increases from 11.06% to 49.53%. Simultaneously, the reverse current of the PV module may exceed the carrying capacity of the device, resulting in a rise in the temperature of the photovoltaic panel. Therefore, how to supervise and manage distributed PV systems in large numbers so that they can generate electricity stably, safely, efficiently and in an environmentally friendly manner is a difficult problem to be overcome by relevant energy enterprises and researchers in the future.

2.2. Offshore Photovoltaic Systems

Nonetheless, despite the utilization of high-efficiency N-type monocrystalline silicon solar cells, the extensive deployment of utility-scale PV systems necessitates a substantial land area due to their relatively low photoelectric conversion efficiency and power density and the duration of sunshine. This, in turn, diminishes the availability of land resources for other developmental purposes. It has seriously affected the economic development of agriculture, tourism and other industries in some areas and the construction of some available ecological environments. In contrast, distributed PV systems are characterized by their smaller scale and lower power generation capacity, often limited to specific facilities. Consequently, this may pose a constraint on the future expansion of the photovoltaic industry. Numerous countries worldwide possess extensive coastlines and ample freshwater resources in the form of reservoirs and lakes, such as Canada, Indonesia, China and Japan. Floating PV installations have emerged as a viable alternative to large-scale centralized PV systems, which not only make rational use of abundant water resources to reduce land development but also effectively reduce water evaporation through the shading effect of photovoltaic panels [58]. The cooling effect of water circulation can prevent high temperature overload of photovoltaic modules, greatly enhancing the performance of photoelectric conversion [59–61]. Many researchers have studied the effect of wind cooling on FPV systems' power generation efficiency [62]. This aspect of research includes wind speed, wind direction and the angle of photovoltaic panels. Tina et al. [63,64] proposed a model to analyze the effect of wind. They found the difference between land-based photovoltaic systems' and FPV systems' temperatures dropped about 5 °C and 6 °C at wind speeds increasing from 0.5 to 10 m/s. Leonardo [65] gathered data on the thermal behavior of FPV systems and discussed the recently available experimental result. Finally, He concluded that wind also has excellent cooling effects on FPV systems. Furthermore, the combination of floating PV with other industries maximizes the utilization of water resources, such as offshore wind power and marine ranching. This integrated approach promotes renewable energy generation and sustainable development in multiple sectors. Currently, Singapore, Japan, the Netherlands and other countries have taken the lead in conducting research on offshore photovoltaic technology. In the following sections, we discuss in detail the offshore PV systems including pile-based fixed and multi-array FPV systems, then summarize the advantages and disadvantages of land-based PV systems and the future challenges of offshore PV systems.

2.2.1. Fixed Pile-Based Photovoltaic Systems

After the experience of deploying land-based stationary pile-based PV systems, the researchers attempted to build large-scale pile-based PV systems in shallow waters. Prestressed high strength concrete (PHC) pipe pile is generally used in the photovoltaic support foundation of pile-based photovoltaic power stations. As a result, offshore PV systems are commonly implemented in waters with depths less than 5 m, where there is no risk of site subsidence or other geological hazards and where water levels exhibit minimal fluctuations. Examples of suitable locations include aquaculture ponds, salt ponds and drainage ponds. When workers are sinking piles, attention should be paid to improving the bearing capacity of the foundation to prevent the uneven settlement of the foundation from threatening the pile foundation. Advanced positioning technology and water level elevation control methods can be employed to enhance the precision and control of key design parameters, including the pile core accurate position, precise pile driving depth and optimal verticality throughout the installation process in offshore PV systems. When applying horizontal force to the pile foundation, the difficulty of construction can be reduced by controlling the pile body with a clamp [66]. The pile driving equipment is capable of swift and precise movement along the guide rail positioned between the pipe piles. This allows for efficient positioning of the pile body and rapid movement of the pile sinking vessel. Consequently, it significantly improves the construction efficiency of offshore pile sinking operations. In order to facilitate the passage of fishing boats and inspection vessels, the lower end of the photovoltaic module should be at least 1 m away from the highest water level, and the optimum installation angle of the photovoltaic panel should be calculated according to the latitude of the location, so as to achieve the highest power generation efficiency. As depicted in Figure 4, this project stands as the largest offshore pile-based photovoltaic power generation and marine farming project in China to date. It encompasses the installation of approximately 1.4 million monocrystalline silicon solar modules, with each module having an output power of 450 W. The project is estimated to generate around 650 million kWh of electricity per year. In April 2023, the initial phase of the offshore pile-based fixed photovoltaic projects in Shandong Province, China, was formally contracted. This undertaking announced an installed capacity of 1000 MW, with a site characterized by water depths ranging from 1 m to 4 m and at a distance of 8 km from the coastal center. The project intends to utilize high-performance monocrystalline silicon photovoltaic modules with a power rating of 550 W. A total of 2.36 million components will be deployed, employing a block power generation strategy and a centralized grid connection approach. The project is expected to be completed and put into operation in 2026. It will generate 1.652 billion kWh of electricity annually, meet the electricity demand of about 550,000 households for one year and reduce carbon dioxide emissions by 1.3447 million tons [67]. Aiming at a pile photovoltaic power station of aquaculture ponds in Jiangsu Province, China, Li et al. [68] studied its influence on the local near-surface meteorological, environmental temperature and solar radiation at different heights, so as to provide reference for the development of offshore pile photovoltaic projects.



(**a**) (**b**)

Figure 4. 550 MW solar farm in China's Zhejiang Province [69]. (**a**) Staffs drove the boat to check the system. (**b**) Staff are conducting inspections.

The rational utilization of marine resources and the advancement of the marine economy represents a prevailing trajectory. In this direction, there are endeavors to construct a comprehensive marine energy system and bolster research and development in core technologies pertaining to marine engineering equipment. Offshore pile-based fixed photovoltaic power stations benefit from a wider sea area, effectively improving photovoltaic power generation and speeding up the construction of offshore renewable energy systems. Such systems have been widely used in reservoirs, fisheries farms, coastal waters and other shallow water depths. We summarize the following advantages for offshore pile-based power generation systems:

1. Wide range of applications

The global coastline spans over 1.63 million km, with nearly half of it deemed suitable for offshore facility installation and aquaculture purposes. In contrast to land-based pile-based PV systems, offshore installations offer a broader expanse of water and a wider range of viable scenarios, encompassing aquaculture ponds, lakes and even areas affected by coal mine subsidence. The deployment of PV modules and equipment in offshore settings is more adaptable, allowing for potential synergies with offshore fish farming to enhance the economic gains derived from marine activities.

2. High system stability

The pile-based PV system utilizes PHC pipe piles. Through accurate pile positioning and pile driving depth calculation, the stability of the overall pile system is improved. Even if it is located in the coastal area affected by the wave load at high tide and low tide, it can still adapt to the impact force of sea water well and maintain secure operation of the system [70].

3. More suitable for fish farming

The pile-based PV system constructed along the coast and fish farms also provides excellent shading effects, leading to a significant reduction in water surface temperature, decreased water evaporation and maintenance of an ecosystem suitable for the growth of aquaculture organisms. These positive factors contribute to the improved survival rate and healthy development of the organisms [71], ensuring a sustainable and stable income for farmers. This approach supports the promotion of an energy system that integrates photovoltaic power generation, complementary fishery and photovoltaics for enhanced sustainability and economic benefits.

On the contrary, the risks associated with the construction of offshore pile-based PV systems may also be higher, and the technical challenges are mainly related to the following four factors:

1. Anti-corrosion and anti-rust design

Due to the submersion and burial of most of the piles under water and in the foundation soil, the presence of complex and diverse aquaculture organisms in sea water leads to their attachment and corrosion on the piles. This can result in issues such as pile cracking and tilting, significantly reducing the service life of the PHC piles. Moreover, these problems can further impact the stable operation of the photovoltaic power generation system [71]. On the other hand, wind and sea water contain high concentrations of salt, which can cause rusting of photovoltaic modules and electrical equipment under bad wind and wave conditions. In serious cases, the photovoltaic modules may be damaged, and the overall circuit of the system may fail. Therefore, strengthening anticorrosive and rust-proof design is the primary technical problem of offshore pile-based PV systems.

2. Environmental issues of using PHC piles

The use of PHC can effectively improve the stability of piles under harsh wind and wave conditions, but there are a lot of carbon emissions in the production process of pipe piles, of which 50–90% are generated by the processing of raw materials. When the photovoltaic modules reach their service life or the pile is damaged, a large number of abandoned pipe piles need to be crushed and recovered, during which there are also a lot of pollutants and carbon emissions, leading to air pollution and serious damage to the ecological environment.

3. Difficulty in transportation and maintenance

PHC pipe piles are typically manufactured and processed in designated factories before being transported to the installation site using large trucks. However, if the journey is long or the road conditions are challenging, the transportation process can subject the piles to significant vibrations, potentially resulting in pile damage. At the same time, the maintenance and repair of offshore PV systems can be challenging due to various factors. Firstly, the considerable distance between the pile top and the water surface makes servicing the system more difficult. Additionally, the current offshore photovoltaic operation and maintenance ships are often retrofitted fishing boats, which have limited carrying capacity and are only able to accommodate small maintenance equipment. Furthermore, these modified boats may lack hull stability and seaworthiness, making them susceptible to problems such as hull collisions, especially during severe wind and wave conditions. These challenges can contribute to issues like pile damage.

4. Resistance to snow and sea ice

In the deployment of offshore PV in cold and ice-prone areas in the winter, the wind and snow load capacity of the module should be considered, and the lateral force on the pile is generated due to the influence of sea ice. Therefore, to ensure the stability and adaptability of offshore PV systems, it is essential to conduct thorough calculations and considerations based on the local climate and water surface conditions. Factors such as load requirements, pile diameter and pile depth should be carefully determined. By appropriately increasing the pile spacing and number, the system's adaptability and stability can be improved [72]. This not only enhances the system's power generation income ratio but also facilitates the smooth progress of scientific research related to the offshore environment.

2.2.2. Floating Photovoltaic (FPV)

Currently, countries around the world are vigorously promoting solar power generation in order to deal with climate change and reduce carbon emissions. However, many countries such as South Korea, Singapore and Japan do not have enough land area for land-based photovoltaic power stations and are facing the growing power demand; thus, offshore FPV becomes a better alternative to renewable energy. Benefitting from the rapid development of strategic emerging marine industries and the continuous progress of science and technology, as well as the continuous renewal of the foundation of offshore pile PV systems, the research and development of offshore FPV systems with similar compositions has been carried out rapidly. Moreover, coastal cities continue to expand the depth and breadth of sea area development and utilization. Accelerating the development of offshore renewable energy projects has become a major goal of the green economy. Compared with pile photovoltaic power stations, which are expensive and difficult to apply to deep water areas, FPV systems are characterized by more convenient installation and maintenance, a wider applicable environment, strong adaptability to water level changes and more diverse module design. Therefore, countries began to explore the development of FPV power stations at sea in the early 21st century. In 2007, the world's first FPV power station was built in Aichi Prefecture, Japan. The system was installed by the National Institute of Advanced Industrial Science and Technology and funded by the Ministry of Environment of Japan. The main purpose of the system was to study the conceptual design of FPV systems and the cooling performance of FPV systems [73]. In the same year, California-based SPG Solar partnered with a winery owner to develop the world's first commercial FPV power plant, a 175 kW solar cell set on a pontoon over an irrigation pond [74]. Not only does it provide sustainable energy for the winery, but it does not take up the land needed to grow grapes. This was followed by the installation of the world's second large-scale commercial FPV system (500 kW) in Italy at the end of 2008, which increased power generation efficiency by 20% to 25% due to the cooling effect of water [75]. In 2019, Kyocera's 13.7 MW floating project at the Yamakura Dam was destroyed by the 120 mph winds the typhoon brought to the coastal city of Chiba [76]. Other researchers focused on the negative influence of the destruction by strong winds and waves of FPV systems and how to prevent damage. Kaymak et al. [77] found that warpage of FPV elements as a consequence of harsh wave action is one of the most serious problems that may be encountered.

The FPV system module is placed on the water surface, and the floating module is restricted within a controllable range through a multi-point mooring system to reduce the influence of wave force caused by water flowing through the floating body. The photovoltaic module is installed at a certain height on the floating module to prevent the direct influence of sea waves on it, which can result in accelerated corrosion of the module. Considering the continuous development of innovative research and the development of new synthetic materials and the application design of module structures, we summarize the floating body module design of offshore FPV systems deployed in the market, including in the following categories:

1. Floating pontoon offshore floating modules of multi-array and multi-mooring
2. Tubular floaters offshore floating modules of multi-array and multi-mooring
3. Very large floating structures (VLFS)
4. Very flexible floating structures (VFFS)

The floating body modules of different shapes developed in the above part are sorted out. In the following sections, the above four types of floating body modules are introduced respectively from the aspects of applicable scenarios, discussion of advantages and disadvantages and consideration of planned projects in combination with previous research work, in the hopes to provide practical reference for subsequent relevant research work.

Pontoon Floaters Module

Firstly, we introduce multi-array and multi-mooring Marine floating modules are composed of a buoyancy pontoon, which is also the most widely applicable and relatively mature surface floating structure at present. Japan and other countries are widely applying and strengthening research on this kind of technology. It is composed of several floating pontoon modules connected by rigid supports. The corresponding panel tilt angle is calculated according to the latitude of the location, as shown in Figure 5. An appropriate distance is reserved between adjacent components to increase the light area and radiation intensity and improve the photoelectric conversion efficiency [78,79]. The appropriate light intensity provides the right amount of oxygen to facilitate the photosynthesis of aquaculture organisms. This kind of floating structure is also being studied and applied to aquaculture, forming a new resource utilization technology of cage culture, complementary fish and light.

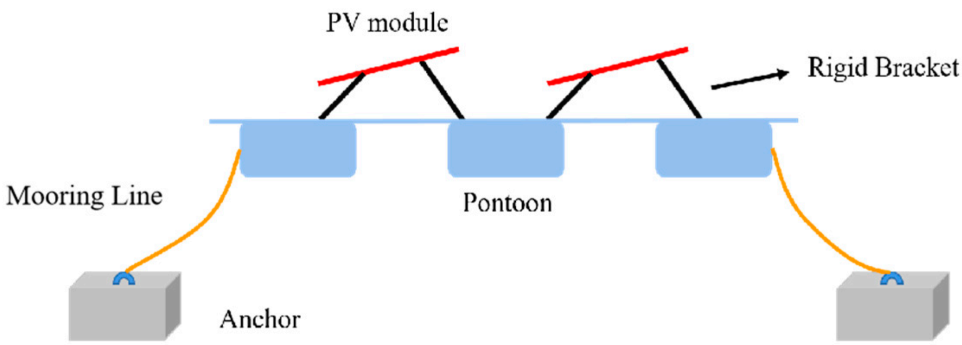


Figure 5. Schematic diagram of the buoy structure module.

In March 2015, a 2.9 MW FPV power station built by Kyocera Solar was located in Hyogo Prefecture, southwest of Japan. As shown in Figure 6, the power station was divided into two sub-arrays of 1.7 MW and 1.2 MW, floating on Nishihira Lake and Higashihira Lake, respectively [80]. In August of the same year, "DREAMSolarFloat1", Osaka Prefecture's first floating 1 MW photovoltaic power plant, was completed on the water surface of Wada City Reservoir, Osaka Prefecture, with an annual generating capacity of about 1180 MWh when put into operation. A total of 4016 solar panels with a power rating of 260 W were installed on the box-type floating structure. The whole system floats on 10,000 square meters of water, forming a multi-mooring array FPV power station [81]. China leads the world in photovoltaic power generation technology, while FPV power generation technology research and development started late. In 2015, China's first FPV power station was built in Xiong River Reservoir, Zaoyang City, Hubei Province [82]. The total installed capacity is 1.2 MW, covering a water area of about 23 square meters. It is also the only FPV power station in Hubei Province. In October 2016, the Tengeh Reservoir in Singapore launched the world's largest FPV test bed (1 MW), with the objective of studying the environmental impact and technical feasibility of deploying large FPV systems on inland waters. Currently, the test stand encompasses eight distinct systems featuring diverse floating structures and photovoltaic modules. Notably, it also incorporates the largest FPV system with active water cooling. It will also examine economic benefits and business models, marking a milestone in the development of Singapore's renewable energy industry [83]. In 2019, the 5 MW offshore FPV plant deployed in the Johor Strait was one of the largest offshore FPV systems in the world. Equipped with 13,312 solar panels and more than 30,000 box floats, the power station is expected to produce up to 6022 MWh of electricity per year and reduce carbon dioxide emissions by around 4258 tons [84].Benefitting from the positive impact of the "two-carbon" target policy and the ongoing efforts to promote low-carbon economic transformation, China's research on FPV technology has experienced significant advancements. In 2021, the Huaneng Dezhou Dingzhuang Reservoir photovoltaic power generation project achieve a remarkable milestone as the world's largest single FPV power station. With a total capacity of 320 MW in a single phase, this project employs advanced technologies such as a high-density polyethylene (HDPE) floating pontoon and scaffolding FPV systems [81]. The research work of the buoy floating module was carried out earlier, and the technology is relatively mature up to now. The large-area laying of the buoy floating module has the characteristics of significantly reducing water evaporation and inhibiting the excessive growth of algae, etc., which has been supported by environmental resources protection organizations of various countries. Over the past decade, it has covered many inland and offshore waters, and its applicability and efficiency have been widely recognized by the industry. Therefore, driven by competition among offshore new energy companies and renewable energy utilization policies, the module design and manufacturing technology of the pontoon FPV system is also being updated and improved. The following is a summary of the advantages of the pontoon floating module systems that have been developed or deployed:

Figure 6. 2.9 MW floating photovoltaic power station in Hyogo Prefecture [80].

1. Various applicable scenarios

The floating module adopts flexible connectors and lightweight and flexible synthetic fiber mooring lines. Even if the water level changes greatly, the power generation system can still easily adapt to different water depth environments, such as lakes, reservoirs, coal mine subsidence areas and other waters, and even the offshore coast. The anchoring system of shore anchor, pile anchor or sinking anchor can be selected according to the topography, geology, wind and wave conditions of the water area. The catenary or tensioned mooring system can be considered and whether the counterweight needs to be increased to improve the anti-wave disturbance ability of the floating module.

2. Lower cost and easy to manufacture

Most of the pontoons are made of HDPE, which is an environmental protection material and can be recycled. It has good characteristics of wear resistance, electrical insulation, toughness and cold resistance. It can resist acid, alkali and all kinds of salt corrosion [85]. Therefore, the production and manufacturing technology of materials is simpler and more environmentally friendly than that of prestressed concrete. With lower production cost and a shorter cycle, it has become the preferred material and the technical object of research and development for the floating body in the current floating module.

3. Easy to install and transport

For the installation of pile-based PV systems, geology should be investigated in advance, the foundation should be stabilized, pile holes should be arranged and pile bodies should be inserted one by one. On the contrary, the FPV system only needs to explore the water depth and terrain and then push the floating body array laid on shore into the water and transport it to the designated position by tugboat for anchorage. As shown in Figure 7, workers install photovoltaic modules on the modules to be transported [86]. In the process of material transportation and installation, PHC pile is prone to crack or damage due to vibration and friction, which increases the difficulty of construction. The HDPE float box has good toughness and wear resistance, effectively reduces the module scrap rate and is small in size and easy to transport in large quantities, and the module connection and deployment mode is simple.

Figure 7. Workers are installing photovoltaic modules on floating modules waiting to be transported to the designated location [86].

4. Prevents excessive water evaporation

A large area of an intensively laid surface photovoltaic power generation system without adverse effects on water quality, nitrate and chlorophyll concentrations was improved to maintain the healthy development of the water ecological environment; Water evaporation was significantly reduced by 60% [87]. This will help save precious water resources, especially in semi-arid regions, and greatly improve the efficiency of agricultural irrigation production [88]. In terms of power generation, FPV is similar to land-based pile PV.

5. Excellent sea water cooling performance

Long-term sunlight intensity and efficient photoelectric conversion cause the surface temperature of photovoltaic modules to rise rapidly, which not only affects the efficiency of power transmission but also damages photovoltaic modules and electrical equipment in serious cases. Fortunately, the proximity of FPV modules to the water surface allows for efficient cooling through the circulation of water flow and the cooling effect of wind gusts. This effective cooling mechanism significantly reduces the temperature of the photovoltaic modules, ensuring optimal performance and longevity [89,90]. It also reduces the failure probability of photovoltaic modules due to heat accumulation, so that the PV system can maintain efficient and durable power generation, which is conducive to energy companies saving maintenance costs and developing photovoltaic modules with higher photoelectric conversion efficiency.

Even though pontoon PV systems are being developed and increasingly utilized, there remain several challenges that must be addressed in offshore research, particularly in relation to the difficulties confronting FPV systems:

1. Anti-corrosion and prevention of aquatic fouling

Suitable underwater environmental conditions will be conducive to photosynthesis of aquatic organisms and improve their reproductive efficiency. A large number of algae and shell aquatic organisms are easy to attach to the floating body of photovoltaic modules with the action of water flow, causing the overall buoyancy change of the module and weakening the anti-sinking ability of the module. On the other hand, the sea water contains a lot of salt and corrosive chemical elements, so the floating module that is in the sea for a long time is vulnerable to erosion and damage. What is more, some aquatic plants and marine garbage with hard and sharp characteristics may puncture the floating body, causing the floating body to crack or even leak, leading to major safety risks in the FPV system. It is necessary to design the surface of the floating body to resist destruction, prevent corrosion and enhance waterproof biological adhesion, which can effectively guarantee the long-term safe and stable operation of the floating power station.

2. Designed to withstand strong winds and waves

Most coastal countries or cities are affected by monsoons and ocean currents. Moreover, the sea surface wind and wave conditions are difficult to predict, which is a great test for the buoyancy, stability and resistance to strong winds of the floating module. For example, some southeastern coastal cities in Japan, South Korea, China and other countries are affected by typhoons almost every year, causing extensive damage to FPV power stations. In addition, the wave force caused by different sea conditions is the main factor affecting the stability of the floating module, and the wave conditions under bad conditions greatly test the bending moment, deflection, shear stress and interfacial strain of the floating body. Researchers need to focus on how to design the shape of the floating body with high wave resistance, connectors with high durability and photovoltaic support. Chen et al. [91] proposed a numerical model to study the hydrodynamic interaction effect on waves of the multiple floating system.

3. Inspection and maintenance

Terrestrial photovoltaic development started earlier, and most uses pipe piles as support, so the related research and development of photovoltaic module cleaning robots and system maintenance strategies are relatively mature. Nevertheless, further research is required regarding the cleaning and maintenance of FPV systems. We encounter several significant challenges, including the analysis of buoyancy variations and hydrodynamics concerning the floating module equipped with cleaning robots. Additionally, certain bodies of water, such as lakes, serve as migratory habitats for birds, and addressing the removal of a substantial amount of guano proves to be difficult. Failure to adequately clean guano can lead to the formation of hotspots on photovoltaic panels and subsequent circuit malfunctions. Secondly, offshore FPV operation and maintenance ships are mostly converted from civilian fishing boats. Compared with offshore wind power special operation and maintenance ships, they are very simple and unable to bear large maintenance equipment. Meanwhile, the swaying of the hull caused by waves poses a threat to the safety of the staff.

Tubular Floaters Module

The essential aspects of the related technologies have reached a relatively advanced stage. However, challenges persist in adapting the floating tube module to offshore waters characterized by unpredictable wind and wave conditions, primarily due to the numerous connections between the floating tubes and the component supports. Presently, the majority of systems are deployed in calm water reservoirs, areas affected by coal mine subsidence, ponds and similar bodies of water. Their production cost is low, and they are vigorously promoted by new energy companies. Such a system is being proposed for a large basin in the Netherlands [92]. This system shares similarities in terms of floating body materials and component composition with a pontoon flotation module. However, its distinguishing features lie in the shape of the floating body and the design of the connecting structure between the floating body and the photovoltaic support. This low-cost solution has garnered significant attention and is being actively promoted by new energy companies. There are many nodes connected to the floating pipe, which makes the stability of the system structure poor and the construction and maintenance difficult. As a result, the number of installed machines deployed in the existing projects is small.

The laying mode of the float tube floating module is similar to that of the float module, so they have many advantages in common, such as short production cycle, easy installation and transportation, prevention of a large amount of water evaporation, etc. Compared with the floating module, the floating tube is used as the floating body, the number of units is less, the manufacturing cost is lower and the anchoring method is more convenient. Therefore, we mainly discuss the shortcomings of the floating tube floating module as follows:

1. Poor stability, less applicable water area

An HDPE floating tube is used as floating body and steel frames are used to fix adjacent floating tubes. As a result, the number of floating tube nodes increases, the degree of freedom decreases and the joints are prone to damage such as bending and breaking. This implies that the application of the floating tube-type floating module is limited to waters with a relatively stable water level and water surface. To ensure the long-term safe and stable operation of the power generation system, it is crucial to minimize the installed quantity. In order to address these challenges, researchers should concentrate on conducting hydrodynamic analyses of the floating pipe as a Morrison rod. This analysis will aid in designing stronger and more durable connections, thereby extending the lifespan of the power generation system.

2. Construction and maintenance difficulties

The connections between floating pipes typically require welding for fixation. Due to the numerous connecting nodes, the floating module needs to be assembled and inspected onshore before it can be transported to the designated position. Additionally, the installation scale of a single project is predetermined, making subsequent splicing of multiple modules impractical. Simultaneously, this approach also poses challenges for routine maintenance and inspections by maintenance personnel. Conducting fatigue tests on connecting nodes, performing component cleaning and maintenance, addressing cracking and damage to the floating body and ensuring the durability of the photovoltaic support all present difficult and time-consuming issues during the construction process.

VLFS

VLFS is a floating module used in the offshore floating photovoltaic project first tried by OceanSun, a new energy company, in recent years. It consists of a flexible film and a circular floating body made of HDPE material. Photovoltaic modules are laid on the flexible film, as shown in Figure 8, and the generated electricity is transmitted to the power grid for distribution through submarine cables. Compared with the pontoon module design, the membrane module has a smaller air gap between the water surface and obtains a better cooling effect, which can increase the power generation efficiency by 5% [93]. The flexible film module possesses properties such as a smaller elastic modulus and material stiffness. The integrated flexible surface allows it to float with the waves, resulting in smaller bending moments and deflections compared to pontoon modules. Consequently, this module is better suited for the floating structures of offshore floating power generation systems located in more remote areas. In recent years, with the continuous improvement of offshore wind power technology, the installed amount is increasing year by year. Researchers try to promote the work related to floating wind turbines to the undeveloped far-reaching sea area and promote the use of far-reaching sea FPV systems to form an innovative renewable energy utilization technology of "the same field of scenery and complementary power generation".

Figure 8. Circular membrane floating platform developed by OceanSun [94].

A circular plastic membrane floating platform was developed in 2019. The advantage of this equipment process is that the flexible plastic film is heavy and elastic, which is more convenient for the staff to install and repair the equipment module and pull the cable. At the same time, the plastic film is directly in contact with the flowing sea water, so that the PV system operates at a lower temperature, which helps to improve the photoelectric conversion efficiency [94]. The system has launched a total of three versions: 200 kW system at a diameter of 50 m, 500 kW circular water system and one suitable for building in the stream river rectangular 100 kW system, which represent a wide range of applications. In 2020, the Dutch company Solarduck proposed a triangular floating platform structure with edges; each platform can be connected together flexibly and stably to form a large offshore floating power station. The implementation of an efficient triangular layout for mooring systems optimizes the utilization of space, scale and cost, ultimately maximizing the power output within the available area. The platform features a robust triangular structure constructed with a lightweight aluminum frame designed for marine applications. Flexible materials are utilized for the connections, enhancing the seaworthiness of the floating module. Its lightweight design allows for excellent stability, even under the influence of strong winds and currents, withstanding speeds of up to 30 m/s. Furthermore, the platform is designed to protect its height from waves as high as 5 m [95], enabling it to adapt to varying wind and wave conditions in different bodies of water. In 2021, the Norwegian Moss Maritime FPV system, also developed by Norwegian New Energy, was designed for a specific geographical location and weather environment, with a square platform size of about 10 m × 10 m, as shown in Figure 9. The floating platform of the photovoltaic system consists of a number of pontoons on the bottom and a square platform structure on the top, on which solar panels can be placed. The platform is provided with the required buoyancy by multiple cube pontoons, flexible connectors that allow the platform to move with the waves and that, combined with the platform's rigid structure, enable the system to withstand waves of up to 3–4 m for long periods of time. Thanks to its versatile concept and design, the platform is suitable for both inland and offshore applications, making it an ideal choice for large-scale installations in diverse wind and wave conditions. The FPV system underwent extensive testing on the Norwegian island of Froya, allowing for validation of its performance and durability in real-world conditions [96]. In October 2022, China's Shandong Peninsula South No. 3 Offshore Wind Farm, Far-reaching Sea floating 500 kW photovoltaic demonstration project successfully generated electricity, becoming the world's first far-reaching sea "scenery" demonstration project put into operation. The FPV project comprises two circular floating platforms, with each platform having an installed capacity of 250 kW. The project incorporates annular wind-resistant floating platforms, high-strength thin films specifically designed for the marine environment, as well as photovoltaic modules and electrical equipment. A total of 770 photovoltaic panels have been installed on the floating platform with a diameter of 53 m. As Figure 10 shows, the same field power generation of wind and photovoltaics has been realized in the far-reaching sea waters 30 km offshore and 30 m deep, which reduces the project cost and operation and maintenance cost and verifies the wind and wave resistance ability of very large offshore floating bodies, including mooring and power generation components, and the weatherability of the marine environment [97]. It marks the technical breakthrough of China's offshore FPV industry.

Figure 9. Square floating platform developed by the Norwegian company New Energy [96].

As a new large-scale offshore photovoltaic power generation technology that has been actively developed by various new energy companies in recent years, a design method for very large offshore floating platforms with high wind and wave resistance, high stability, a long working life and high efficiency with lower cost is sought for the unpredictable wind and wave conditions in the far-reaching sea area. We promote the development of a far-reaching renewable and clean energy system for marine photovoltaic power generation, wind turbines and photovoltaic power generation. Taking advantage of the abundant marine resources and vast ocean area, China will speed up the building of an economic development path for marine green energy, formulate policies for the development of maritime areas under its jurisdiction and regulations for the installation of offshore power generation equipment and ensure that the new energy industry continues to carry out research on relevant technologies. The technology of very large offshore floating platforms started late and has various structural designs. Therefore, we summarize the advantages of very large offshore floating platform PV systems in operation as follows:

1. Suitable for various wind and wave conditions

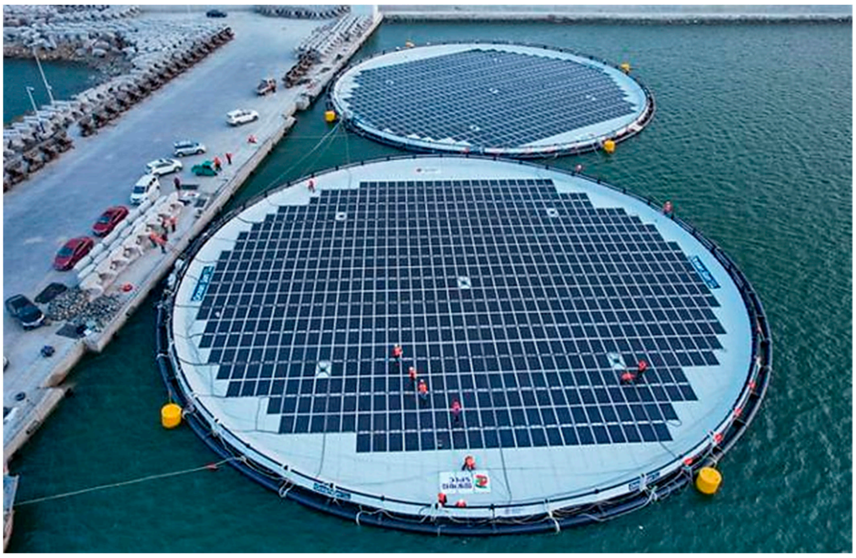


Figure 10. Deep sea photovoltaic power generation project in Shandong, China [97].

The VLFS platform is usually a single modular structure, with few splicing interactions between modules. Floating platforms of different shapes are connected with floating bodies of different styles to provide excellent wind and wave resistance. The flexible thin film floating platform exhibits remarkable elasticity and excellent load-bearing performance. Its thin film structure allows for deformation under various wave conditions, eliminating concerns related to rigid shear stress, fatigue and interaction between the connecting parts of the floating bodies. Moreover, it mitigates structural response issues between floating bodies and supports and facilitates deflection and bending moment analysis [98]. Consequently, this platform is well-suited for challenging wind and wave conditions in deep-sea areas. By addressing the technical challenges associated with the effective utilization of abundant marine resources and responding to the imperative of "energy conservation, emission reduction, low carbon and environmental protection," it actively promotes the development and adoption of innovative technologies within the offshore renewable energy industry.

2 Better cooling effect by the film platform

The floating platform using flexible film as the carrying structure of photovoltaic modules has good elasticity and ductility. Compared with other floating platforms using pontoons, the floating platform is closer to the water surface, and the rapid liquidity of sea water is used to obtain a more significant cooling effect, which is conducive to improving the photoelectric conversion efficiency of photovoltaic modules, improving the revenue ratio of the new energy industry [93], and promoting the long-term and stable development of related industries and the continuous updating of related technologies. Advancing the technology of large-scale offshore renewable energy, with a focus on enhanced power generation efficiency, contributes to the reduction of electricity prices for urban residents. This, in turn, promotes the comfort, safety and stability of residents. Additionally, it uplifts the quality of life for both residents and industrial sectors, while adhering to robust circuit and power grid standards. Through these efforts, we can expedite the sustainable, high-speed and healthy development of cities, fostering a greener and more prosperous urban environment.

3. Diversification of deployment modes

Benefitting from the stability of the very large floating platform, the far-reaching sea photovoltaic power generation technology has been combined with the offshore floating fan to form the complementary power generation application design of "scenery in the same field". In the complex environment with cloudy days and high wind, wind power generation technology contributes most of the electricity production. In contrast, during hot summer weather characterized by sunny days but weak wind, photovoltaic power generation can offer substantial power output, thereby mitigating the issue of significant water evaporation caused by direct sunlight on the sea surface. Following the successful feasibility verification of the far-reaching sea scenery project in Shandong, China, the focus will now shift towards the development of very large floating platforms as the primary research subject for advancing offshore PV system technology. The aim is to enhance the utilization of far-reaching marine resources and improve the efficiency of renewable energy power generation. Furthermore, drawing inspiration from the technology employed in far-reaching sea fan cage culture equipment, there is a growing interest in integrating far-reaching sea culture technology with very large floating platforms. This concept is currently under thorough discussion, and it will require future research and experimental verification to substantiate its feasibility and potential benefits.

The very large offshore floating platform, which is considered to have high research value and potential, is still in the updating and perfecting stage. Researchers will test the system response of various shapes of floating platforms under different sea conditions through numerical simulation analysis and demonstration, so as to promote the offshore renewable energy system to continue to move forward. Chen et al. [99] presented a frequency-time domain model coupled with hydrodynamic-structural with viscous correction, aimed at analyzing the effect of hydrodynamic interaction in very large floating systems. Other researchers also focused on discussing frequency-time domain analysis of multi-body systems with flexible connections to reveal hydrodynamic-structural responses [100–102]. By reviewing and analyzing the large-scale PV systems deployed on very large offshore floating platforms in recent years, we have sorted out the following issues to be solved or considered:

1. The single module is bulky and requires towing

Due to their large size and deployment in deep waters with complex environments, the photovoltaic modules are typically assembled with electrical equipment by professional installers on shore. Subsequently, a specialized offshore tugboat is employed to tow the system to the designated location where it will be securely anchored. The interaction between the floating platform and the tugboat is a problem that needs special attention during the launching stage and the towing process of the module. On the other hand, the influence of the wave damping and friction damping of the floating platform on the maximum horsepower and speed required by the tugboat should also be considered. Moreover, the appropriate tugboat should be selected to ensure the safety of the construction personnel.

2. Design of the anchoring system in the deep sea

The mooring and anchoring methods employed for very large floating platforms in far-reaching sea areas differ from those used for offshore floating modules. These methods can be categorized as shore anchor, pile anchor and sinking anchor. In complex sea areas located far from the coastline and with unknown water depths, sinking anchors are applicable exclusively to the far-reaching sea floating platforms. Additionally, in deep water areas, the material, length and quantity of mooring chains need to be appropriately designed. To prolong the service life of the ultra-large floating platform in far-reaching sea areas and enhance its resilience to withstand wind and waves in unpredictable and extreme weather conditions, corresponding design schemes and improvement measures are proposed.

3. Development of special operation and maintenance equipment

Offshore energy utilization platforms are usually equipped with special operation and maintenance ships and equipment, such as offshore floating fans and offshore oil and gas exploitation platforms. There are various types of special construction and maintenance ships. For offshore floating devices of different sizes, corresponding ship types are used for construction and maintenance. The offshore FPV industry is relatively new, and, as a result, the technology for offshore operation and maintenance equipment supporting FPV systems is not yet mature. Currently, offshore FPV operation and maintenance ships are retrofitted from basic fishing boats, lacking wave endurance and stability. This poses a risk to the safety of maintenance personnel, and their limited carrying capacity restricts the use of large maintenance equipment. Therefore, these ships are only suitable for basic maintenance tasks related to offshore FPV systems. In far-reaching sea conditions, it is necessary to have professional operation and maintenance equipment with improved performance to ensure the stable operation of the PV system and the safety of personnel. Furthermore, the efficiency of maintenance tasks can be significantly enhanced, leading to an extended service life of the system.

VFFS

Very flexible floating structures (VFFS) refer to flexible photovoltaic modules that are directly placed on the water's surface. These structures are characterized by their long length compared to the wavelength, thin and lightweight composition, utilization of ultra-flexible materials and low bending stiffness. As a result of these characteristics, VFFS can effectively adapt to significant local wave heights in long waves. They achieve this through their ability to undergo large vertical deflections and exhibit strong hydroelasticity behavior [103]. As a new research direction of offshore thin-film PV systems, VFFS benefit from lying directly on the surface or submerged water, with excellent water-cooling effect. Elminshawy et al. [89] explored the influence of sea water temperature to maintain the passive cooling effect of photovoltaic modules on power generation efficiency and compared the difference in power generation efficiency between FPV and land-based photovoltaic systems under different immersion ratios in an area of Egypt. The results show that the maximum temperature difference between the two is 12.20°C, and the power generation efficiency of submerged FPV is increased by 23.57%. The VFFS in comparison to other offshore photovoltaic power stations utilizing rigid floating structures offers advantages such as lighter component weight and lower installation costs. As a result, it has emerged as an innovative technology in offshore renewable energy power generation in recent years. Ongoing research efforts have furthered the development of this concept, contributing to the progress of the offshore solar power generation industry. Additionally, this technology provides a conceptual foundation for designing versatile floating platforms suitable for complex sea areas.

The method of VFFS was presented in 2014. Trapani et al. [104] studied the short-term electrical impacts of the floating thin film PV system through 45-day testing. Additionally, they assessed the demonstrable changes that impact such floating system's modulation with significant waves. Other researchers summarized the relation between the efficiency of submerged panels and the depth of the water layer. A test of submerged panels has been analyzed [105]. In 2020, researchers from Michigan Technological University and the School of Electrical Engineering at Aalto University in Finland proposed an immersion flexible photovoltaic design to build a cost-effective floating flexible thin film module [106]. Temperature measurements were conducted using five temperature detectors, capturing data at 15-min intervals. The detectors were utilized to measure the temperature of each individual photovoltaic panel, as well as the surrounding water and air. It is worth noting that the panels can be constructed using specialized materials specifically chosen for this purpose, including neoprene or polyethylene. Neoprene rubber has excellent flexibility, water resistance, heat resistance and high tensile strength [107]. To enhance the tensile strength and flexibility of the structure, synthetic materials are incorporated as additives, aiming to improve the overall performance and durability of the FPV system. In 2021, a new study in the Netherlands was exploring the economic feasibility of deploying thin-film FPV systems offshore. A pilot system was installed at a lake near Rotterdam [108]. The project will also examine the power generation of flexible solar modules, the stability of the flotation system in the face of waves and strong winds and the effects of organic growth on the surface of the device. The project consists of two floats measuring 7 m $\times$ 13 m, with 20 kW solar cells installed above them. Both components and floats are fabricated using flexible materials developed by the consortium, while the holistic system design effectively mitigates wave resistance of the floats and enhances their buoyancy characteristics. This floating power generation approach offers the flexibility to tow the system closer to the shore during winter when certain parts of the sea freeze. This practice minimizes the adverse effects of sea ice on the floating structure and connectors, mitigating risks such as puncture and damage. Moreover, it serves as a valuable reference for the exploration of versatile, multi-scenario, large-scale and high-efficiency floating power generation technologies. Zhang et al. [109] investigated the suitability of theoretical and experimental numerical analysis for studying the hydroelasticity phenomenon in the new floating structure. Their focus was on identifying the commonalities between VFFS, VLFS and sea ice. Based on the research basis of previous work, the characteristics of the studied structure are discussed to provide a theoretical basis and applicability evaluation for the subsequent multi-purpose offshore floating power generation technology. The execution of pertinent demonstration projects and the widespread adoption of FPV power generation technology will expedite the validation of the sustainability of novel offshore floating structures and the results of technological advancements. Currently, this type of floating structure is primarily in the design, research and experimental application stages, with a limited number of development projects and constrained deployment and installation. Drawing from prior research literature and existing construction projects, we have compiled the following advantages:

1. Lower cost and simpler mooring system required

Flexible thin-film photovoltaics eliminates the need for a huge floating body platform structure as a support; the system weight is lighter; the structural tensile strength is higher and can float with wave height and wavelength changes, reducing the influence of waves on the interface strain of the floating body and the bending moment of array connection, making the adopted mooring system lighter; and there is lower development cost and more convenient maintenance.

2. Sea and land dual use, wider scope of application

Given the considerable size of the floating structure, a very large floating platform typically requires the assistance of a specialized tugboat for transportation. In contrast, the lightweight and flexible nature of thin-film photovoltaic modules imposes less stringent demands on the tugboat, resulting in a relatively effortless towing process. The structure is designed for better scheduling and wider applicability in ice-prone waters. The photovoltaic system is towed ashore in the cold winter to reduce the effect of sea ice on the system. In the hot summer, the flexible thin-film PV system immersed in the water uses water cooling to achieve better photovoltaic conversion efficiency.

3. Method

A complete FPV power station is mainly composed of a modular floating structure, a mooring system, photovoltaic modules and electrical equipment. Existing research has tried to analyze the complex floating body material, floating body shape, mooring cable material, photovoltaic panel material, connector design and other aspects, in order to seek a more stable floating structure, more efficient photoelectric conversion and longer service life. In this section, we discuss the design of floating structures, the materials and working principles of photovoltaic panels and the transportation and installation of mooring systems and FPV systems.

3.1. The Design of the Floating Structure

The floating body structure serves to maintain the stability of the system on the water surface. It is designed with flexible connectors or hinges, enabling the formation of an array with modularity. This arrangement facilitates the installation of an appropriate number of parallel-connected photovoltaic modules and allows for the large-scale deployment of offshore FPV systems. Until now, the predominant choice for floats in the offshore photovoltaic industry has been HDPE due to its exceptional qualities such as high UV resistance, corrosion resistance, low maintenance cost, recyclability and excellent tensile strength [59]. The latest research shows that a floating structure composed of lightweight composite material with ultra-high-performance concrete (UHPC) as the material of the upper and lower splints and a soft foam rubber core with a high elastic coefficient can significantly reduce the deflection, shear stress and bending moment peak value of a floating array structure and effectively improve the safety of the floating structure [110]. Another way is to use an UHPC and HDPE mixture, under the premise of increasing a certain manufacturing cost; greatly improving the tensile strength, bending stiffness and surface damage resistance of the floating body structure; and prolonging the service life of the system to improve economic benefits. In the future, more lightweight and high strength composite materials will be applied in the design process of the floating body.

3.2. PV Module

Silicon wafers with a thickness of approximately 180μm have been conventionally employed as the traditional material for manufacturing photovoltaic modules. About 50% of the production cost of monocrystalline silicon solar cells comes from silicon raw materials, of which device processing and module processing account for 20% and 30%, respectively [111]. In addition, there are PV module manufacturers using second-generation CdTe [112], a-Si or CIGS [113]. However, these technologies have not been comprehensively explored in depth. Recent research indicates that Perovskite solar cells (Pero-SCs) exhibit notable advantages, including high power conversion efficiency (PCE) reaching up to 25.7%, abundant reserves of raw materials and a straightforward solution process [114]. An advanced technology called bifacial photovoltaic (bPV) is regarded as a promising alternative. Gu et al. [115] proposed an overview about the development of recent bPV and introduced its working principle, structure composition, cell categories, merits and demerits. Ziar et al. [116] presented two attractive concepts for floating bPV systems and demonstrated their modeling, design and excellent performance monitoring in 2021. Results of this article showed that a bPV system with reflectors and tracking delivers 17.3% more specific yield compared with a PV system installed on land and up to 29% in a clear-sky month. Tina et al. [117] compared the mono-module with bifacial modules in the aspect of the most important geometrical parameters (tilt, pitch and height from the water). The research showed that obtaining energy gains is possible with bPV reaching up to 13.5% compared to mono-facial configurations. Additionally, the utilization of flexible substrate technology offers the potential to reduce production costs. In addition to being lightweight and having high flexibility and lower installation costs, battery treatments with higher processing have low thermal budgets and low material consumption [118]. Therefore, it has a bright future in next generation photovoltaic technology, including single-layer cells, laminated cells, low-light environments and VFFS. Of course, the production process of photovoltaic modules should also comply with environmental protection, safety and efficiency standards.

3.3. Mooring System

The offshore FPV system needs accurate and stable anchorage to prevent the deviation or capsizing caused by complex wind and waves from damaging the power generation system. The anchorage methods with relatively mature technology are mostly shore anchors, pile anchors and sinking anchors. The floating module is restricted by a cable tied to the shore or pile foundation, while the sinking anchor mooring is fixed by a mooring line tied to the anchor block on the sea floor. Based on the material and length of mooring lines, a catenary or tensioned mooring system analysis model was designed to evaluate the feasibility and safety of the system under wind and wave conditions in the deployed sea area [119,120]. At present, most mooring cables are made of nylon rope or polyester fiber rope. However, the length of mooring cables and the need to increase the balance weight of mooring cables should be considered according to the actual water depth and extreme wind and wave conditions. In addition, the anti-corrosion and waterproof biological parasites of mooring cables are also extremely important [121].

3.4. Transportation and Installation

The transportation and installation process of FPV systems is typically more straightforward compared to land-based pile PV systems. HDPE buoys exhibit greater tensile strength and frictional strength, making them less susceptible to damage from vibrations and other transportation-related factors. Moreover, in terms of manufacturing costs, a single HDPE buoy is less expensive than a single PHC pipe pile, resulting in lower economic losses associated with transportation risks. The installation of offshore FPV systems does not require heavy equipment such as pile drivers, cranes, etc., except for the installation of FPV systems in far-reaching waters that require professional tugboats. The installation of offshore FPV systems can only rely on stable mooring and anchoring systems to fix floating platforms. The system is typically assembled onshore and subsequently transported to the water, where it is towed by a tugboat to a designated construction site that meets the installation specifications [122].

4. Conclusions

This review focuses on land-based PV systems and offshore PV systems, discussing their research background, key projects and recent advancements in photovoltaic power generation technology. The paper provides a comprehensive overview of the advantages and disadvantages of various photovoltaic power generation systems, including utility-scale systems based on land piles, distributed systems, offshore systems based on pile foundations, float-type systems, floating tube-type systems, VLFS and VFFS systems. Additionally, the review covers the main components of these different systems. Based on the sustainable development of the renewable energy industry and advancements in solar power generation technology, this paper identifies several key challenges that need to be addressed in the conceptual design of various PV systems. These findings aim to provide guidance and reference for the future development of offshore FPV technology. The following conclusions can be drawn from this study:

1. FPV systems utilize expansive and underutilized bodies of water to establish renewable energy power generation systems. In comparison to land-based pile PV systems, they offer the advantage of conserving valuable land resources that can be utilized for agriculture, mining, tourism and other activities. This utilization of water surfaces for PV installations provides an innovative and sustainable approach to expanding renewable energy capacity while minimizing land-use conflicts.
2. The HDPE floating structure has short lead times, low development costs, strong corrosion resistance and easy transportation. With the exception of very large floating structures in the far reaches of the ocean, all floating platforms can be easily deployed without the need for large equipment.
3. The offshore FPV system applies to more waters and covers a wider range. In undeveloped and far-reaching sea areas, the conceptual design of "same scenery, complementary fishing and light" can be tried. The combination of deep-sea aquaculture and renewable energy power generation has been a hot topic in marine science for a long time and has been studied and applied in the offshore FPV system [123].
4. Large-scale coverage of photovoltaic modules has been proven to effectively reduce water surface temperature, improve the water ecological environment and significantly reduce water evaporation, contributing to the conservation of scarce water

resources. Especially in arid or semi-arid regions, recyclable water resources are more valuable, but abundant solar energy resources are favorable conditions for solar power generation.

5. Offshore PV systems with water-cooled passive cooling have higher photovoltaic conversion efficiency than land-based PV systems, while significantly reducing the probability of photovoltaic module failure due to heat accumulation, providing a guarantee for the development of more efficient photovoltaic cells.

Although offshore FPV systems have many positive effects, there are still questions about their impact on the environment and system stability. In view of the existing deficiencies, the following suggestions are proposed for future research work:

1. The presence of salt and microorganisms in sea water poses a challenge to the durability and functionality of floating structures, photovoltaic modules and electrical equipment. The corrosive nature of sea water can lead to degradation and damage over time. Furthermore, the attachment of aquatic organisms to submerged components and mooring cables can affect the buoyancy of the floating system and the tension of the mooring system. Therefore, it is crucial to prioritize the implementation of robust anti-corrosion measures and develop effective strategies to mitigate biological parasitism and ensure waterproof design. These considerations are essential for enhancing the long-term performance and resilience of offshore FPV systems.
2. Compared to large-scale onshore photovoltaic systems, floating photovoltaic systems have lower average power generation density and energy density. The average power generation density of CSP is 20.33 ± 12.74 W/m^2, and the average energy density is 0.178 ± 0.112 TWh/km^2. However, the average power generation density of floating photovoltaic systems is 9.91 ± 3.28 W/m^2, and the average energy density is 0.087 ± 0.029 TWh/km^2 [124], which is almost half that of terrestrial photovoltaic systems.
3. In the process of photovoltaic panel production and pulverized recovery of PHC pipe piles, there are a lot of toxic raw materials, which seriously affect the health of workers and the balance of the ecological environment. Therefore, safe, environmentally friendly and efficient manufacturing processes should be adopted while improving the efficiency of photovoltaic panel conversion.
4. The development of renewable energy in deep-sea areas has always been a hot research direction. The dynamic response analysis of floating structure and mooring systems is particularly important under complex wind and wave conditions. A multi-scale coupled analysis model of hydrodynamic, structure-material and mooring was designed to evaluate the stability of the system under extreme marine environments and verify the feasibility and sustainability of the system under severe environmental loads. The research and development of very flexible thin-film photovoltaic cells will be accelerated.
5. Unlike terrestrial photovoltaic systems, the cleaning and maintenance of offshore FPV systems present unique challenges that require careful consideration and improvement. The accumulation of bird excrement and sea water stains on the photovoltaic modules can lead to the formation of hotspots and subsequent circuit failures within the system. However, the development and implementation of cleaning robots specifically designed for offshore FPV are still in the early stages of research and verification and have not yet been widely deployed. Additionally, there is a lack of an innovative design for operation and maintenance equipment, such as intelligent detection devices, dedicated maintenance vessels, fatigue warning systems for components and integrated monitoring systems that encompass both land and sea areas. Addressing these issues is crucial for enhancing the operational efficiency and longevity of offshore FPV systems.
6. Currently, the benefits of FPV power generation yield relatively modest returns and low power generation using merely FPV systems. Researchers attempt a combination of multiple power generation methods, such as building fishery complementary

photovoltaic systems or wind turbine and photovoltaic floating power stations. Consequently, sharing power grid systems and mooring systems is essential if floating wind and solar plants are jointly utilized.

Author Contributions: Conceptualization, G.H.; methodology, M.C.; investigation, Y.T. and X.C.; writing—original draft preparation, Y.T. and G.H.; writing—review and editing, X.C., M.C. and Y.J.; supervision, Y.T., M.C. and Y.J.; funding acquisition, M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 52171275.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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