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Floating Photovoltaics: Assessing the Potential, Advantages, and Challenges of Harnessing Solar Energy on Water Bodies

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ABSTRACT

The worldwide transition to a future with net-zero emissions depends heavily on solar energy. However, when land prices rise, and population density rises, the need for large land expanses to develop solar farms poses difficulties. Floating Photovoltaics (FPV) has come to light as a viable remedy to this problem. FPV, which includes mounting solar panels on bodies of water, is gaining popularity as a practical choice in many nations worldwide. A significant capacity of 404 GWp for producing clean energy might be attained by using FPV to cover only 1% of the world's reservoirs. This review shows that FPV has several benefits over conventional ground-mounted PV systems. On the other hand, there is a large study void regarding the effects of FPV on water quality and aquatic ecosystems. This review looks at the most recent FPV research, including its advantages, disadvantages, and potential. It looks into the compatibility of various bodies of water, worldwide potential, system effectiveness, and the possibility of integrating different technologies with FPV.

Keywords: photovoltaic, solar energy, water bodies

INTRODUCTION

The need for energy is rising along with the global population, which leads to more people utilizing fossil fuels that produce greenhouse gases (Azni et al., 2023). The globe seeks the strategies to minimize greenhouse gas emissions as climate change worsens (Donaghy et al., 2023), resulting in a climatic problem on the planet. According to the International Energy Agency (IEA), there must be a 24% increase in annual average solar energy generation for the globe to achieve net zero emissions by 2050 (Liang et al. 2023). Due to a 23% rise in solar power in 2020, the IEA classified solar photovoltaics (PV) as requiring "more effort" (Qureshi et al., 2023).

Power sources in the future are anticipated to include PV (Rauf et al., 2023). Nowadays, PV costs about the same as traditional energy sources, owing to a sharp decline in price (Muhammad et al., 2023). According to the IEA, PV has historically been the least expensive source of electricity (Vartiainen et al., 2020). Although the amount of installed PV is expected to increase, large-scale ground-mounted photovoltaic (GPV) farms are having trouble locating land to install on (Essak and Ghosh, 2022). About 15,000 m^2 of land is required for a 1MW PV farm (Essak and

Ghosh, 2022). It is becoming increasingly harder to find land to build a PV farm because of the enormous land requirements and growing land prices. PV installations must also contend with issues including cooling and keeping the panels dust-free to boost energy efficiency (Kazem et al., 2020). Placing PV panels on water bodies, such as wastewater treatment facilities, oceans, lakes, lagoons, canals, ponds, reservoirs, or irrigation ponds, is one way to solve the problem of land use regulations for solar energy projects. This technique enables the use of water surfaces for solar energy generation, potentially solving the lack of available land and the high land cost. Floating photovoltaics (FPV) systems can help in increasing the solar energy capacity while reducing the requirement for substantial land resources by utilizing the available water bodies (Lee et al., 2020). This research on Floating PV explores solar energy generation and integration in water bodies. It focuses on optimizing energy systems, drawing on a previous study on energy storage systems and their impact on grid peak load shaving (Makahleh et al., 2023). The study aimed to determine the optimal placement and capacity of energy storage and establish a charge-discharge strategy for these systems. Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) techniques were used to calculate the minimum and maximum loads in the network considering the energy storage systems.

This review aimed to assess the present state of FPV as well as its advantages and disadvantages. The first FPV factory was established in Japan in 2007 (Vo et al., 2021a), making it a relatively young technology. The installed FPV capacity is currently doubling annually and is anticipated to continue doing so (Cazzaniga and Rosa-Clot, 2021). Currently, FPV is more expensive than GPV, with a 4–8% increase in project break-even costs (Essak and Ghosh, 2022); this is an important and timely assessment, because this industry has significant global growth but little understanding of the potentially harmful effects of FPV.

THE TECHNOLOGY OVERVIEW

The installation of solar panels over water uses floating platforms, which has potential advantages over conventional installations on land. Recent years have seen an increase in interest in this novel strategy (Banik and Sengupta, 2021). Figure 1 depicts a standard FPV system comprising PV panels and a floating structure securely anchored to the ground.

Floating photovoltaic systems

Floating platforms

A pontoon construction keeps the apparatus afloat in the water (Edwards et al., 2023), where the floats are connected to form pontoons to support the structure weight on top of the water (Jiang et al., 2023). High-density polyethylene (HDPE) that is maintenance-free, UV-resistant, recyclable, corrosion-resistant, and has excellent tensile strength, is utilized to make the bulk of floats used in the industry (Natarajan et al., 2019). Fiber Glass-reinforced plastic is another, albeit less typical, material used for floats (Abdurohman and Adhitya, 2019). These systems typically feature fixed panel inclinations that are difficult to change after installation. The floating structures have the advantage of being simpler to decommission than a GPV system (Rosa-Clot, 2020). Additional possibilities for floating structures comprise one- or two-axis tracking platforms and galvanized steel stands (Cazzaniga, 2020). There are numerous types of floating platforms available for FPV systems which can be broadly categorized into:

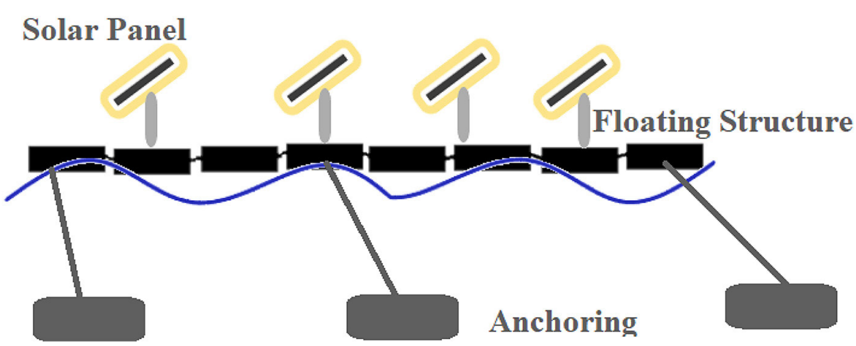

Figure 1. The FPV structure

Buoyancy-based platforms

The most popular FPV platform comprises several buoyant modules that are joined to create a stable floating platform, where the platforms that based on buoyancy are often affordable, modular, as well as simple to install and disassemble (Solomin et al., 2021a); however, they are less stable in choppy water, and because of their low freeboard height, flooding may be more likely.

Semi-submersible platforms

These platforms can partially submerge in water, increasing stability and lowering the risk of floods (Li et al., 2022), as shown in Figure 2. Semi-submersible platforms cost more than buoyancy-based platforms, in addition to having more intricate installation and maintenance requirements.

Tension leg platforms

Tension leg platforms allow for larger FPV systems and are highly stable because they are anchored to the seafloor using tensioned cables (Schreier et al., 2022), as shown in Figure 3. They are more difficult and expensive to deploy and maintain than other kinds of platforms.

Floating rafts

Solar panels installed on a series of pontoons anchored to the ocean floor make up floating rafts (Refaai et al., 2022), as shown in Figure 4, where they are easy to install and maintain but may be

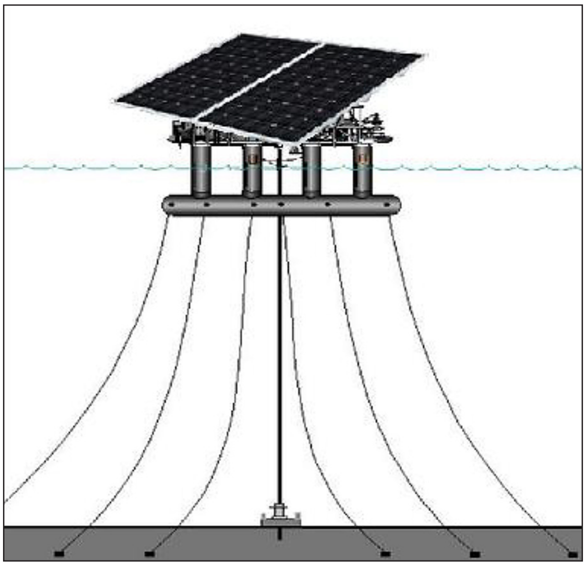

Figure 2. Design of semi-submersible platforms

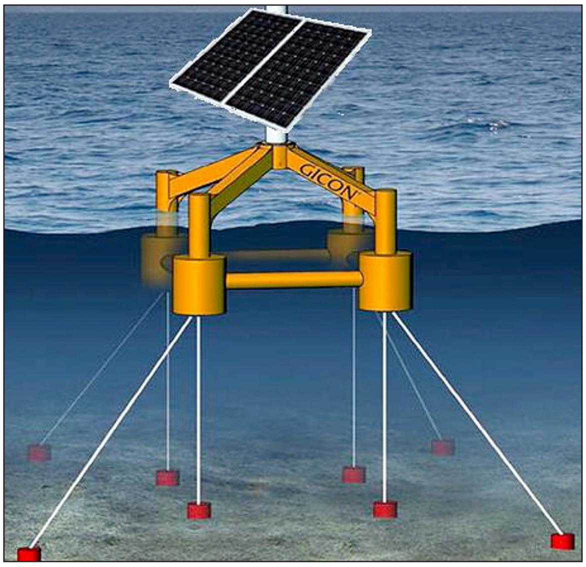

Figure 3. General view of tension leg platform

Figure 4. Floating rafts with solar panels installed

prone to capsize in choppy waters because of how wave conditions affect their stability.

PV Module

Crystalline Silicon is the most usually used FPV system module type (Luo *et al.*, 2021). Crystalline modules function fine in freshwater settings, but because the industry turns its attention to marine settings, modules must be built to survive the salty conditions. As a result, an alternate material will need to be used in place of traditional metal frames. Indeed, second-generation solar panel technologies such as cadmium telluride (CdTe), amorphous Silicon (a-Si), and copper indium gallium selenide (CIGS) are practical choices for floating PV systems.

Second-generation CdTe

A thin coating of cadmium telluride serves as the light-absorbing layer in CdTe solar panels. CdTes are popular for large-scale installations due to their high conversion efficiency and low manufacturing costs. Moreover, CdTe panels are also less susceptible to high temperatures and low light levels compared to certain other technologies (Kaliyannan et al., 2023).

Amorphous Silicon (a-Si)

Non-crystalline Silicon creates a-Si solar panels, allowing flexibility and a lightweight design. A-Si panels operate better in diffuse lighting conditions, such as on overcast days or in shadowed regions, despite having lower conversion efficiencies than other technologies. Due to reflections and ripples on the water's surface, this trait may make them useful for floating PV applications where light conditions may vary (Mayville, Patil and Pearce, 2020).

Copper Indium Gallium Selenide

Thin copper, selenide films, gallium, and indium, comprise Copper Indium Gallium Selenide (CIGS) solar panels, as they work well in low-light situations and have excellent conversion efficiencies. Additionally noted for its flexibility, CIGS panels can adapt to curved or uneven surfaces. The flexibility can be useful for floating PV installations that may need to change to fit the curve of the water body (Wijewardane and Kazmerski, 2023).

Currently, 3rd generation PV technologies are not used for FPV systems due to their relative infancy in development and deployment (Jin *et al.*, 2023).

Mooring system

A mooring system is necessary to stop FPV systems from tipping over or drifting. The apparatus is firmly fastened to the ground or the seafloor using anchors (Ndumnu et al., no date). The mooring lines are commonly made of nylon ropes, enabling the system to adjust to wind and water depth changes. Depending on the project budget, the water depth, the state of the seabed, and other parameters, the anchoring method may be gravity-based, drag embedment, suction, or tension-based. It is essential to consider the long-term performance and dependability of the anchoring mechanism to ensure the safety and stability of the FPV platform in challenging marine environments.

Cables

Cables are essential to the operation of FPV systems, as they link the solar panels to the power inverter atop the platform. Underwater cables convey the system's electricity and can move the power to an onshore substation (Kumar, Mohammed Niyaz and Gupta, 2021); moreover, the wires are frequently elevated above the water's surface. The cables must be carefully built when used in floating PV systems to withstand the harsh marine environment, which includes exposure to saltwater, waves, and wind.

Finally, the cables installed for FPV systems must be able to adjust for water and wind levels in order to move platforms and send data to monitoring stations, where aluminum, copper, or a mix of these materials are utilized.

Electrical safety

For achieving reliable, secure, and safe FPV systems, electrical safety standards are essential, mainly because the electric shock and corrosion may be avoided with the help of adequate grounding, insulation, and training. The electrical system of FPV is shielded from overloads and dangers by the installation of safety devices like surge protectors and circuit breakers. Worker safety is guaranteed via lockdown/tag-out procedures, appropriate instruction, and personal protective equipment (PPE). In addition, regular maintenance, such as component replacement and corrosion tests, ensures the system's integrity (Kumar, Mohammed Niyaz and Gupta, 2021).

During the design process, the factors related to electrical safety, such as component location, cable management, and grounding requirements, should be taken into account. FPV systems may operate securely and productively when abiding by all relevant laws and regulations.

Installation and location

As long as the mooring and anchoring mechanism is not unduly complex, installing FPV systems is frequently easier than installing GPV systems (Solar Energy Institute of Singapore, 2018). FPV systems are typically built on land before being transferred to water; where they can be simply pulled to the desired installation area without the need for complicated machinery.

Several factors need to be considered when choosing a location for FPV installation. Table 1 lists the key factors that must be evaluated before deciding on a site for FPV. Weather, location, terrain, and water conditions, among others, can all impact an FPV system. The system's location is crucial, since solar irradiation levels fluctuate depending on the latitude and longitude of the site. Solar radiation levels are higher in the regions near the equator than in those near the poles. The efficiency of the anchoring system in providing stability and safety in challenging marine situations can be impacted by ground and water conditions. The floating platform style picked out must be appropriate for the water where it will be installed. Additionally, meteorological elements like clouds, rain, and fog can impact the amount of solar irradiation, affecting how well the FPV system performs.

Table 1. Suitability of the site (Solar Energy Institute of Singapore, 2018)

Feature	Criteria
Water conditions	Limited wave activity Freshwater with low hardness Low salinity
Ground conditions	Compact soil suitable for anchoring Consistent terrain
Location	Absence of shadowing caused by surrounding buildings or mountains Convenient transportation Proximity to electrical connection Easy installation and maintenance
Weather	Low occurrence of rain or fog Abundant sunlight Wind speeds not exceeding 30 m/s

FPV performance and efficiency

Temperature effect

The performance, energy output, efficiency, and high temperatures have an adverse effect on the lifespan of PV modules as high temperatures convert sunlight into heat instead of output power, making module temperature the most significant factor impacting efficiency (Grant et al., 2020). To mitigate the impact of high temperatures on PV modules, various cooling techniques have been explored (Dwivedi et al., 2020). An effective approach involves using FPV systems, which take advantage of placing PV modules on water bodies to benefit from the cooling effect. This cooling effect enhances the efficiency of the modules, resulting in a higher annual energy output. Studies have indicated that this cooling effect can result in an efficiency increase of 1.5% to 12.5% for FPV systems compared to GPV systems, depending on the specific climatic conditions of the location. The cooling effect, facilitated by the circulation of cool air beneath the PV modules, is a significant advantage of FPV systems over GPV systems (Micheli, 2022).

Humidity

An increase in module humidity is another consequence of placement near water. Compared to GPV modules, FPV modules endure increased humidity. The performance of a module may be negatively impacted by an increase in surrounding humidity (Kaplanis et al., 2023).

FPV systems can be impacted by humidity in several ways:

- Reduced efficiency: High humidity levels can impair the efficiency of PV panels by raising the cell temperature, which can decrease the output voltage and current. Consequently, the output power of the solar cells decreases as the temperature rises.
- Corrosion: Because FPV systems are frequently installed in humid areas, such as those close to water bodies, the exposure to excessive humidity can shorten the lifespan of the metal components of the PV panels.

- Condensation: Excessive humidity can result in condensation on the PV panel surfaces, reducing the quantity of sunlight that reaches the cells, resulting in decreasing harvested power at the output.
- Salt deposition: In coastal regions, high humidity levels combined with air rich in salt content can cause salt to accumulate on the PV panel surfaces, decreasing their efficiency over time.

Designing and installing FPV systems resistant to corrosion and moisture is crucial (Claus and López, 2022), as is routinely cleaning the panels to eliminate any salt buildup or other impurities that could lower their performance.

Evaporation of water

One of the economic benefits of utilizing FPV is their capacity to mitigate water evaporation from bodies of water, such as reservoirs (Farrar et al., 2022). By creating shading, solar panels decrease the amount of sunlight that reaches the water, thereby decreasing the amount of water that evaporates and improving water quality. It becomes even more crucial for the nations experiencing a water crisis. It was determined that installing FPV had a significant positive impact in central and southern Asia's water-scarce regions (Abid et al., 2019). In India, the state of Maharashtra installed a 1 MW FPV system on the Ujjani reservoir, generating 1.6 million units of electricity annually and reducing water evaporation by 1.3 million cubic meters per year, resulting in an estimated cost savings of INR 30 million (approximately USD 400,000). Another study examined the environmental impact, economic viability, electricity production, and water evaporation reduction of deploying FPV on Iran's five largest reservoir lakes. By implementing FPV systems on 10% of the five major reservoir lakes, it is possible to conserve a significant amount of water from evaporation. FPV systems can significantly reduce water evaporation, benefiting Iran due to its current water and energy crises. This can meet the domestic water requirements of around one million individuals, reducing water evaporation and salinity and improving water quality. Studies show that FPV systems can reduce water evaporation by up to 70% (Fereshtehpour et al., 2021).

By conserving water resources and improving water quality, FPV systems can help address the growing demand for water while reducing the environmental impact of energy production.

Impact on water quality

Due to the paucity of available information, the rapid growth of the FPV industry has sparked concerns about how it would affect water quality. The greatest danger posed by FPV systems is the potential impact they may have on the quality of water. In spite of FPV operators' claims that they have little impact on water quality, the study conducted by Exley et al. indicated that only 15% of them actively monitor and analyze water quality, with the majority relying exclusively on visual examination (Exley et al., 2021). The impact of FPV installations on nine ecological services was also investigated in the study. In a separate study that conducted an experiment using two nearby farm ponds, one equipped with FPV and the other left uncovered as a control, no detrimental effects on water quality were observed due to the presence of FPV. However, the study of (Abdelal, 2021) did report elevated nitrate and chlorophyll levels, along with a significant 60% reduction in water evaporation. Various research studies indicate that FPV systems can contribute to the reduction of algae growth and improvement of water quality (Al-Widyan et al., 2021). The extent to which FPV affects algae growth depends on the coverage of the water body. Research on the impact of FPV on water quality suggests that a small coverage area of a reservoir with FPV may not be sufficient to prevent algae blooms (Haas et al., 2020). An important concern raised in a study examining the impact of FPV on water quality is the limited number of comprehensive studies and models available to accurately identify any potential negative effects.

Reduced and protection of agricultural land

High population density nations encounter difficulties in locating suitable land for solar PV farms, resulting in potential conflicts with other land users and environmental harm, such as soil erosion and habitat destruction (Gadzanku et al., 2021). FPV provides a solution to this issue by enabling the installation of solar panels on water surfaces that are otherwise underutilized. FPV systems offer the flexibility to be installed on various water bodies such as lakes, ponds, canals, reservoirs, lagoons, wastewater treatment facilities, irrigation ponds, and even in small island communities that have limited available land space (Cazzaniga et al., 2019). Particularly in urban areas where land is scarce and expensive, FPV systems can help mitigate conflicts over land use and alleviate the demand for land by utilizing water resources for solar energy generation. In comparison to GPV systems, FPV installations often incur lower costs as there is no need to purchase or obtain land approvals (Gadzanku, Beshilas and Grunwald, 2021a). A techno-economic study conducted in Islamabad exemplified this advantage, where a GPV system had a payback period exceeding 15 years, while a floating system installed on NUST Lake, an urban lake, had a significantly shorter payback period of 5.37 years.

FPV can aid in preserving agricultural land, which is essential for food production. FPV can aid with sustainable land management and food security by reducing the usage of agricultural land for solar energy production (Nagananthini and Nagavinothini, 2021).

Minimized harm that solar energy generation causes to ecosystems and natural habitats

Additionally, FPV can lessen the harm that solar energy generation causes to ecosystems and natural areas. Water quality, wildlife habitats, and the condition of the soil can all be negatively impacted by land-based solar PV installations. The impact of FPV systems on water bodies and aquatic species, on the other hand, can be reduced by careful design and installation (Giles Exley et al., 2021).

Last, using aquatic bodies for FPV has extra advantages, including lowering water evaporation, raising water quality, and algae blooms, which may be especially important in dry and semi-arid areas with limited water supplies.

To sum up, reduced land use is a significant economic and environmental factor for FPV, where FPV can lessen land-use conflicts, protect agricultural land, lessen the impact on natural habitats, and provide additional environmental benefits by utilizing water bodies for solar energy generation.

Shading and soiling

Due to FPV location on level terrain, FPV rarely has performance issues due to nearby shading (Nisar et al., 2022). One advantage of FPV is the absence of shading. A significant problem that lowers the power output of a PV system corresponds to soiling losses caused by deposited dust building up on PV systems. In addition to providing renewable energy, FPV can also provide shading for aquatic plants and fish, creating a more favorable environment for aquaculture operations. For example, in the Netherlands, a 2 MW FPV system was installed on a lake, providing electricity for a nearby dairy farm and creating a shaded area for fish farming (Vo et al., 2021b).

Soiling losses that decreased electricity generation by 3% to 4% in 2018 resulted in a loss of income of EUR 3–5 billion (Enaganti et al., 2022). It is predicted that soiling losses will cause a loss in income of EUR 4–7 billion by 2023. By 2040, 7200 TWh of solar energy will be produced globally, making soiling losses more crucial than ever. Utilizing anti-soiling coatings on the PV system is a typical way to prevent soiling losses. Another option to lessen soiling losses is FPV. Because water bodies are frequently less dusty than the arid regions where GPV is typically installed, using FPV reduces the likelihood that the panels will become soiled. Cleaning FPV systems is typically easier compared to GPV systems in the cases where soiling occurs because the water on the site can be utilized to clean the modules.

Hybrid FPV with hydropower plants

Hydropower is a major source of electricity globally, accounting for 16% of global electricity generation and 70% of renewable electricity generation in 2019. However, future hydropower projects face obstacles, including environmental concerns and potential political conflicts. To maximize the potential of hydropower and reduce carbon emissions, researchers are exploring the combination of FPV systems with hydropower plants (Solomin et al., 2021b).

There are various benefits to FPV and hydropower combination. By restricting algal growth, it can decrease water evaporation, boost hydropower effectiveness, and enhance water quality. FPV systems can be set up in places where there are already grid connections, which lowers the cost of installation. The intermittent nature of solar energy can be handled by combining FPV and hydropower because the reservoir can store water even when the FPV system is not producing electricity. According to studies, FPV-HPP hybrid systems can improve the co-production of food, energy, and water.

The installation of FPV on HPP reservoirs in various locales has been the subject of numerous studies. For instance, installing FPV on 1% of the HPP reservoirs in Africa can boost electrical generation by 58% while lowering water evaporation. In Australia, Bangladesh, and Pakistan, FPV has also demonstrated promise of boosting electricity production and promoting sustainable development,. In Brazil, the switch from hydropower to thermoelectric power facilities has increased greenhouse gas emissions (Lima et al., 2020). To counteract this, Brazil needs to look into alternate energy sources like renewable energy.

The Alto Rabagao reservoir in Portugal, shown in Figure 5, has successfully used FPV and HPP together, demonstrating the coupling systems' potential on a worldwide scale. Academic studies have outlined the benefits of FPV-HPP hybrid systems, which make them an appealing option for solving both environmental issues and energy needs.

Ponds for irrigation

Ponds used for irrigation are a potential area for FPV installation, because the obtained electricity can be advantageous for farms that installed by the irrigation ponds, which are expected to be located in nearby. Indeed, Muñoz-Cerón et al. (2023) showed that many agricultural areas require irrigation, ponds or other water storage facilities where installing FPV systems is recommended, as these bodies of water can also be used to produce solar power. As it avoids additional land acquisitions or clearances, this can be a cost-effective alternative that lowers the cost of establishing a solar power system. Additionally, using FPV can have a double benefit by lowering the amount of water that evaporates from the pond, which can help conserve water resources in expensive or limited places. As a result, establishing FPV on irrigation ponds can be an effective approach to producing renewable energy while preserving water supplies. In Brazil, an agricultural irrigation pond has been covered by a 305 kW FPV system, accounting for 45% of its surface area (Cuce et al., 2022). Most installed FPV farms in Japan are on irrigation ponds (Vo et al., 2021b). In addition to minimizing water evaporation from ponds, the installed FPV can power farms (Abdelal, 2021; Nagananthini and Nagavinothini, 2021).

Marine vs. freshwater

Since freshwater habitats are the primary focus of FPV research and installations, saltwater water is regarded less targeted to install FPV systems, mainly because FPV systems in saltwater are susceptible to elements like tides, currents, and waves in maritime regions. Moreover, it is important to properly take into account the complex ecology of maritime ecosystems, including biofouling and coral effects (Ghosh, 2023). The creation of artificial reefs and integration with other marine energy sources may result from FPV sites in marine settings. Figure 6 depicts the installation of a marine FPV system in the Maldives. Diverse pontoon designs are employed for marine areas, such as Ocean Sun's innovative

Figure 5. The first FPV-HPP hybrid system, established in 2017

Figure 6. A marine FPV system in the Maldives

design for protected marine environments and Swimsol's floating SolarSea in the Maldives. In contrast to freshwater installations, marine settings also offer difficulties and knowledge gaps.

The economy of floating solar plants

The installation of PV systems on water bodies offers a viable alternative, especially in the locations where usable land is limited, such as islands. When evaluating the economic viability of energy plants, the levelized cost of energy (LCOE) plays a crucial role. LCOE takes into account various operating expenses, including fuel, maintenance, and operations. Since FPV plants do not rely on fossil fuels, they are impervious to fluctuating fuel prices (Patil et al., 2022).

It is important to highlight that PV technology has witnessed rapid advancements, making it one of the most accessible and cost-effective sources of energy. Currently, the prices for PV systems are below $50 per megawatt-hour (USD/MWh) (Goswami et al., 2019).

It is crucial to consider the expenditures associated with floating construction, which include buoys, anchoring, floaters, and mooring linkages, and raise the total cost. Anchors can be set on the dry sides or bottom of lakes. Inverters can be placed alongside a body of water on dry ground or, more frequently, on floaters for larger installations. The challenge arises when dealing with the reservoirs that experience substantial fluctuations in water levels or even complete drying up, as the floating structures need to remain operational under such conditions. An illustration of this situation is Lac des Toules, an artificial reservoir situated at an elevation of 1810 meters above sea level in the Swiss Alps, which is known to be drained during the winter season. The reservoir's summit has an FPV installation that was constructed in 2019. It must be able to function in cold climates and after the reservoir has been depleted. Other instances of FPV are running in highly cold environments where snowfall is likely (Kaymak and Şahin, 2021), such as Harbin Heilongjiang, China. A strong FPV plant constructed by Sungrow is another illustration; it was located in Taiwan and managed to withstand typhoon season without suffering harm, while submerged in water, the behavior of PV modules is interesting, where the effectiveness is stronger because of the chilling impact, which also relies on depth. Additionally, the issue of cleaning the modules has been resolved (Piana et al., 2021).

According to a 2018 analysis, the total capital expenses for FPV systems range from 0.8 to 1.2 USD/MWp (Vidović et al., 2023). With a capital cost of 0.69 USD/MWp, the Tata Power Solar facility in India's West Bengal region illustrates how costs for large FPV plants are falling, where the lowest price is 0.59 USD/Wp for an Indian 100 MW plant. Asian nations rule the FPV market in terms of capacity (Gadzanku et al., 2021b), where the largest FPV facilities will be built in South Korea and have a combined capacity of 2.1 GW. The largest FPV facilities are currently found in China (Rosa-Clot and Tina, 2020). Worldwide, in 2020, FPV produced 2.6 GW, so, with an anticipated yearly growth of more than 20%, it is predicted that FPV will continue to expand and that more than 100 GW of FPV installations will be made by 2025 (Vidović et al., 2023).

CASE STUDIES AND APPLICATIONS

Due to its ability to circumvent land constraints and increase energy efficiency by lowering water evaporation, FPV have recently grown in popularity. Some FPV case studies and applications are as follows:

The Tengeh Reservoir in Singapore

An outstanding illustration of a successful FPV use is Singapore's Tengeh Reservoir, where adding a floating solar PV system, the reservoir, which was initially designed for flood control and water delivery, has now been transformed into a renewable energy source. Figure 7 illustrates the Tengeh Reservoir floating solar farm (Yang et al., 2022).

With a 60 MWp capacity, the Tengeh Reservoir Floating Solar PV system is an amazing floating solar power plant and one of the largest of its kind globally, as it has more than 122,000 solar panels and covers 122,000 square meters (which is equal to 45 football fields).

When compared to conventional solar power plants, the Tengeh Reservoir Floating Solar PV system has a number of benefits such as the following:

- Eliminating the need for priceless land resources, which is especially important in Singapore, where land is expensive and rare,
- By providing a cooling effect, the water beneath the solar panels increases its effectiveness and durability, and
- The technique aids in lowering carbon emissions and water conservation initiatives.

Success stories like the Tengeh Reservoir Floating Solar PV system show how FPVs may produce renewable energy while maximizing land exploiting and reducing environmental effect. As a result, other nations and areas are already thinking about establishing comparable floating solar PV systems.

Together with assistance from the Economic Development Board and the Energy Market Authority, Sembcorp Industries, the Singapore Public Utilities Board (PUB), and others, the project was built, where the system was expected when firstly designed to produce enough electricity after completing the project in 2021 to power more than 16,000 Singaporean houses for a whole year. Among other environmental advantages, the technique reduces carbon emissions by substituting fossil fuel-based electricity sources and promotes water conservation by lowering reservoir evaporation.

The Tengeh Reservoir Floating Solar PV system can generate energy; in addition, it has

Figure 7. Tengeh Reservoir floating solar farm

educational and recreational amenities including a tourist center and a walking track that provides a panoramic view of the solar panels and the reservoir.

An important step forward in the development of renewable energy is represented by the installation of the Tengeh Reservoir Floating Solar PV system, mainly for other nations and areas looking to lessen their reliance on fossil fuels and fight climate change, it serves as a model.

Yamakura Dam in Japan

Yamakura Dam in Japan serves as a great case study for the application of FPV as a renewable energy source. The dam is situated in the Chiba Prefecture, which is well-known for its high levels of solar radiation and scarce land availability, making it the perfect place for FPV installations. Figure 8 illustrates the floating solar farm located at Yamakura Dam in Japan (Abbasnia et al., 2022).

With a total capacity of 13.7 MW and a completion date of 2018, the Yamakura Dam FPV project was one of the largest FPV installations in the world at that time, which had started in 2016. The project made use of a modular floating platform architecture that made installation and maintenance simple and less disruptive to the marine environment.

Additionally created specifically for FPV applications, the solar panels utilized in the project had great durability and were resistant to water and UV rays. To increase energy output and lessen the impact of shadowing from surrounding modules, the modules were positioned at an angle. The project offers a number of advantages, such as:

- Energy production: The Yamakura Dam FPV project generates clean energy that is equivalent to the annual electricity needs of about 4,700 families while also lowering carbon dioxide emissions by about 7,800 tons.
- Land usage: By utilizing the dam's surface area, the project avoids the requirement for land use, which is crucial in Japan due to the country's limited land supply.
- Water conservation: The project lessens water evaporation from the dam, assisting in the preservation of the scarce water supplies in that area.
- Environmental impact: The modular construction of the floating platforms reduces the negative effects of the project on the local marine ecosystem and enables it to cohabit with other water-based activities.

Due to the success of the Yamakura Dam FPV project, similar initiatives have been undertaken throughout Japan, including the 2020 installation of a 2.6 MW FPV system at Kyoto's Higashihirauchi Reservoir. These initiatives show how FPV has the potential to be used as a renewable energy source in the locations with a shortage of available land and offer a long-term answer to securing enough electricity while minimizing environmental damage.

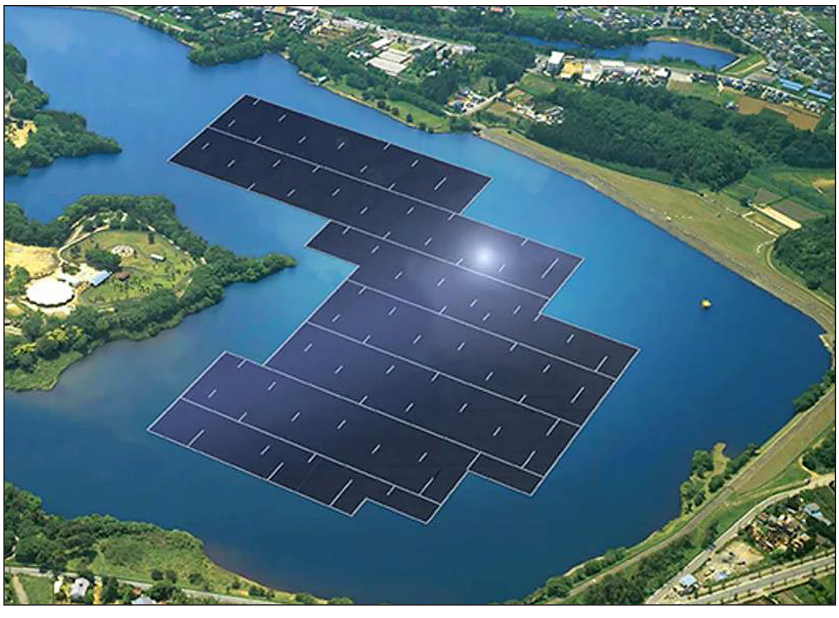

Figure 8. Floating solar farm at Yamakura Dam in Japan

CHALLENGES, RESTRICTIONS, AND PERSPECTIVE

Challenges and restrictions

There are several constraints and challenges to FPV that must be taken into consideration, where the lack of accessible bodies of water for FPV installations is one possible challenge; moreover, due of the extra design requirements for water exposure and anchoring, installing and maintaining FPV systems may be more difficult than maintaining land-based PV systems (Banik and Sengupta, 2021; Kumar, Mohammed Niyaz and Gupta, 2021).

FPVs provide numerous potential advantages for the economy and the environment, but there are also certain drawbacks that must be considered, resulting in the following difficulties and restrictions:

FPV systems have a high initial investment cost, including the floating platform price, anchoring mechanism, and solar panels, which may be more expensive to manufacture and install than conventional land-based solar PV systems, resulting in possible prevention of widespread use of FPV.

Limited installation space; while floating platforms provide a solution to the issue of constrained land availability for solar PV installations, there is also a constrained area of waterbodies that may be used for FPV. This restriction can make it difficult to scale up FPV systems and fulfill the rising demand for renewable energy.

Environmental impact; by shading the water's surface, altering the water's temperature, and reducing water quality, FPV systems can harm marine ecosystems. These effects may have an impact on fish and other aquatic animals' behavior as well as the development of aquatic vegetation. Environmental monitoring and careful planning are needed to mitigate these effects.

Maintenance and operational issues; because FPV systems are exposed to the weather and could be harmed by waves and currents, they must be regularly inspected and maintained. Maintaining large-scale installations in remote or offshore areas can be difficult logistically.

Limitations on efficacy; water quality, temperature, and solar radiation are some variables that impact how effective FPV systems can be. These elements may impact the efficiency of solar modules and lower energy production.

Continuous research and development are required to increase the effectiveness and lower the cost of FPV systems to overcome these difficulties and restrictions. The environmental impact of FPV installations can also be reduced with appropriate planning and environmental monitoring. Finally, frameworks for policy and regulation that support the expansion of FPV systems can assist in addressing the financial issues and promoting investment in this promising technology.

FPV is a desirable choice for fulfilling the rising demand for clean energy while simultaneously lowering the environmental effect of power generation because of its economic and environmental advantages. FPV systems are set to play an increasingly significant role in the shift to a more sustainable energy future as technology develops and costs continue to fall.

Perspective

The potential of FPV systems on the global market has been emphasized by research. The first FPV development guidelines were released by DNV in 2021 and offered instructions for designing, using, and decommissioning FPV stations. In densely populated places with scarce land availability and high expenses, FPV is especially attractive. Lowering reservoir evaporation may also be advantageous for nations with a water shortage. HPP reservoir space and the grid connection can be used to generate power by integrating FPV. More study is necessary to comprehend how FPV affects habitats and water quality fully. While GPV is now more common, FPV can handle several restrictions. Studies have calculated the considerable power-generating potential of FPV in artificial bodies of water and global HPP reservoirs. As it avoids the need for land purchase and permission expenses, FPV can also be financially advantageous in urban locations with high land prices. FPV adoption faces obstacles like requiring specialized equipment, potential storm damage, and environmental concerns despite its benefits.

CONCLUSIONS

The evaluation of floating photovoltaic systems reveals their many benefits, which make them a potential choice in the field of renewable energy. The advantages of FPV systems near water bodies include reducing water evaporation, lessening solar panel soiling, and preventing algae blooms. This benefit is especially important in the areas where there is a shortage of available land since FPV enables the use of water surfaces for the production of renewable energy without depleting terrestrial resources.

The study does, however, note several difficulties with FPV systems, including the possibility of ecological effects on water quality and humidity influencing PV modules. When used in artificial bodies of water like industrial ponds, irrigation reservoirs, and man-made lakes, FPV systems work at their best. Hybrid systems that successfully combine FPV and hydropower sources benefit from greater water conservation and improved grid access, among other synergistic benefits.

FPV systems have a lot of potential for producing green electricity and preserving water supplies. To identify and handle potential environmental impacts, particularly in maritime environments, more research is necessary. The economic analysis shows that FPV systems can be an affordable alternative, particularly in the areas with expensive or limited land resources. The economic viability of FPV is revealed by the levelized cost of energy analysis, making it a desirable alternative for environmentally friendly power production and a contribution to international efforts to battle climate change.

The review indicates that FPV systems provide a variety of advantages, but it also stresses the need for more research and development to realize all of their potential and handle any environmental issues. With continual developments and a focused research effort, FPV systems are ready to play a significant part in the global transition to a greener and more sustainable future.

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