

Floating Photovoltaic Plant: A Review

Cahyaningsih Wilujeng¹, Sigit Tri Wicaksono¹

¹Magister Inovasi Sistem Teknologi, Institut Teknologi Sepuluh Nopember

Abstract. Floating photovoltaic (FPV) systems have emerged as a promising alternative to traditional land-based solar energy solutions, offering a sustainable and efficient approach to harnessing solar energy. The discussion of the topic provides a comprehensive review of the technical, economic, and environmental aspects of FPV technology. It examines the performance ratio, levelized cost of electricity, and compares FPV systems with ground-mounted, rooftop, and canal-top, offshore solar installations. The potential advantages of FPV systems, such as higher energy yields and reduced environmental impact, are discussed, highlighting their ability to conserve land and minimize water evaporation when deployed on water bodies. The review also explores the economic feasibility and technical parameters of FPV systems, including design requirements, energy demand, weather forecasting, and temperature and heat transfer coefficients. The results of this study conclude some of the need for further research to optimize FPV system performance, assess environmental impacts, and enhance economic viability. It calls for future studies to focus on data analysis and the development of innovative solutions to overcome current limitations.

Keywords: *FPVT, LCOE, Technology*

1 Introduction

The growing awareness of the environmental impact of fossil-fuels including air pollution and climate change has led to a shift towards cleaner and more sustainable energy sources. The increasing global demand for energy and the depletion of fossil fuels, along with the rise in global warming and greenhouse gas emissions, necessitate the development and implementation of renewable energy sources as viable solutions to meet energy needs. The expenses associated with renewable energy technologies, including solar and wind, have notably declined over the years, enhancing their competitiveness against fossil fuels. The technology's rapid development is further supported by the global shift towards renewable energy sources, aiming to reduce greenhouse gas emissions and mitigate climate change [1].

Solar Photovoltaic (PV) technology is a rapidly advancing field within the renewable energy industry that harnesses abundant solar energy, converting sunlight directly into electricity using solar cells. The efficiency of these plants has improved considerably because of technical advances and increasing

production volumes. The price of solar cells and modules has decreased markedly, rendering solar photovoltaic technology more economical and competitive [2]. Solar PV systems can be installed in various configurations, including ground-mounted, rooftop, offshore, and floating systems. All the methods, floating photovoltaic (FPV) systems are becoming increasingly popular due to their ability to use water surfaces to save land and reduce evaporation. Although a relatively new concept with limited commercial implementation, demand for FPV is increasing in countries with limited land availability [2].

The global floating solar photovoltaic (FPV) market has seen remarkable growth over the last few years, and it's showing no signs of slowing. By December 2018, the total installed capacity of floating solar reached approximately 1.3 gigawatts peak (GWp), effectively doubling the overall installed capacity to around 2.6 GWp. Based on Wood Mackenzie report, the global FPV market will reach 16,3 GWp in 2025 and this market will be growing exponentially [3]. According to Figure 1, the solar technology market, which encompasses FPV, is anticipated to expand by 7.38% by 2025, contributing an additional 485.4 GW to the existing global installed power capacity [4]. The expanding global solar market presents an opportunity for FPV to significantly contribute to the worldwide transition towards renewable energy sources. FPV has been implemented in various countries including Japan, the United States, South Korea, Australia, Brazil, Canada, Portugal, Spain, the Netherlands, and others. Currently, China stands as the largest player in the FPV sector.

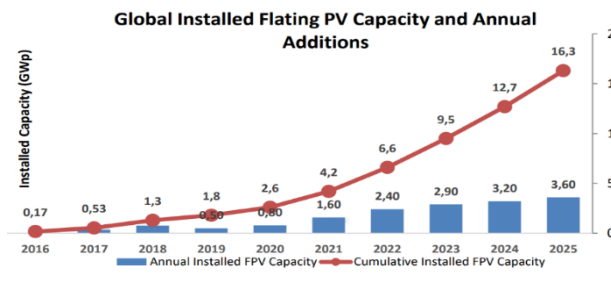


Figure 1 Global Installed FPV Capacity and Annual Addition [2][3]

Among the various solar energy harvesting methods, Floating Photovoltaic Technology (FPVT) has emerged as an innovative and promising approach. This burgeoning interest is driven by the technology's potential to mitigate land costs, reduce specific energy costs and better cooling system compared to another solar PV systems. The natural cooling effect of water enhances the efficiency of solar panels by mitigating overheating caused by elevated temperatures, which may result in increased energy yields and reduced costs throughout the lifespan of the floating photovoltaic system.

Numerous studies have been conducted on FPV systems. However, the promising advancements and rapid adoption of FPV technology, there remains a significant gap in comprehensive understanding and data regarding its long-term performance and environmental impacts. The economic viability and cost competitiveness of floating photovoltaic (FPV) systems relative to conventional land-based solar and other renewable energy sources remain inadequately determined, as financial feasibility is affected by numerous factors such as geographical location, capital expenditures, and electricity market prices [6].

This study looks at the current state of FPVT implementation. As FPVT continues to gain popularity in the renewable energy space, more research is essential to maximise its performance and assess its cost-effectiveness using data from completed projects. Through these comprehensive analyses, FPVT reviews aim to advance the knowledge base, support the scaling up of FPVT projects, and help realize the full potential of this emerging technology in the global transition to renewable energy.

2 The Booming of Floating Photovoltaic

The booming interest in floating photovoltaic (FPV) systems is propelled by a confluence of environmental, geographical, and efficiency factors. By harnessing even one percent of artificial reservoir surfaces, floating photovoltaic (FPV) installations might add almost 400 GWp to the global energy portfolio, with potential increases if marine surfaces are included. In the region of Jaén, Spain, there exist about 3,000 ponds utilised for agricultural irrigation. Should 25% of their surface area be utilised, a minimum capacity of 490 MWp can be established, fulfilling 251% of agricultural electricity requirements[6]. Moreover, the technology is becoming increasingly popular because to its capacity to minimise land usage, presenting a considerable benefit over conventional land-based solar arrays [7].

Unlike ground-mounted systems that require significant land space, FPVT conserves land by utilizing water bodies, making it particularly beneficial for regions with limited land availability[8]. Initially FPVT was not widely commercialized, with only a handful of demonstration projects worldwide. However, China has also made significant strides, with more than 950 MWp installed by 2018, which accounts for approximately 73% of the world's total FPV capacity at that time signaling the rapid increase in floating PV installation capacity[9]. Governments and investors globally are increasingly acknowledging the advantages of FPVT, especially in nations with underdeveloped electrical infrastructure. The technique enhances productivity and is vital for water conservation, rendering it an appealing choice for areas experiencing water scarcity [10]

3 Types of Photovoltaic Setups

The categories of different PV installations are shown in Figure.2 these are classified according to how they're used and where they're located.

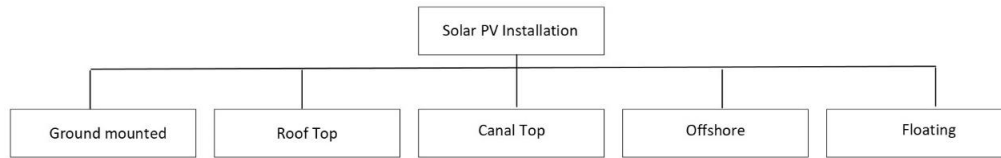


Figure 2 Classification of Solar Installation [11].

3.1 Ground Mounted

Ground-mounted photovoltaic (PV) systems, also known as land-based PV, are a prevalent form of solar energy generation, where solar panels are installed directly on the ground. Although ground-mounted photovoltaic systems are a dependable source of renewable energy, they may pose obstacles, including land use disputes, particularly in areas where land is limited or holds significant value for agricultural or conservation objectives [12].

3.2 Roof Top

Roof top photovoltaic (PV) systems are a sustainable and space-efficient approach to generating solar energy, especially in urban environments where land is limited. The study revealed a discrepancy between simulated and actual energy performance, highlighting the importance of accurate modeling tools for system design and performance prediction[13]. Rooftop photovoltaic systems not only diminish a building's carbon footprint but also possess the capacity to minimise energy expenses and enhance energy autonomy. Moreover, rooftop solar installations are less obtrusive than ground-mounted systems, mitigating land use conflicts and conserving the natural landscape [14].

3.3 Canal Top

Canal-top photovoltaic (PV) systems present an innovative approach to integrating solar energy generation with existing water infrastructure. By installing solar panels over canals, these systems capitalize on the synergy between water management and renewable energy production. The dual benefits include generating clean electricity while reducing water evaporation from the canals, thus conserving a precious resource[15]. India pioneered the implementation of canal-top PV systems, with notable projects such as the 1 MW plant stretching over 750 meters of the Narmada canal [16]. The project has inspired other countries to explore similar applications, recognizing the dual benefits of energy production and water conservation. A study on the Tajo-Segura

canal in Spain demonstrated that canal-top photovoltaic (PV) systems could conserve substantial amounts of water while reducing PV losses. The system payback period was less than 15 years [17].

3.4 Offshore

Over 70% of the Earth's surface is enveloped by seas, which absorb a substantial quantity of solar radiation. Offshore floating photovoltaic (FPV) systems signify a notable progression in renewable energy technology, providing a viable solution to the increasing demand for sustainable energy sources. The amalgamation of floating photovoltaic systems with offshore wind farms and aquaculture offers a complex strategy for energy production, potentially enhancing efficiency and economic feasibility [18]. The economic viability of Floating Photovoltaics (FPV) has been examined; a 2020 investor presentation by Ocean Sun claims that their systems are 25-30% more cost-effective than traditional FPV systems and 10-15% more economical than ground-mounted photovoltaic (PV) systems [19].

3.5 Floating Photovoltaic System

Floating photovoltaic (FPV) systems are an innovative method of solar energy generation, wherein photovoltaic panels are mounted on buoyant structures that float in aquatic environments such as reservoirs, lakes, and canals. The overall configuration of a floating photovoltaic (FPV) system resembles that of a terrestrial photovoltaic (PV) system, with the primary distinction being the floating infrastructure. Electricity produced by photovoltaic modules is gathered by combiner boxes and transformed from direct current (DC) to alternating current (AC) by inverters. The FPV platforms are outfitted with anchoring and mooring devices to maintain their stability against wind and wave forces, as seen in **Figure 3**.

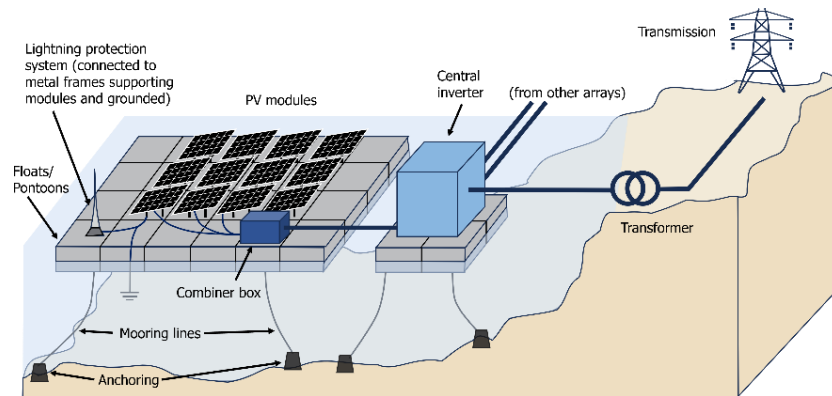


Figure 3 Floating PV Installation [20]

FPV systems have garnered attention for their efficiency advantages over traditional land-based solar installations. The natural cooling effect of water bodies can lead to a lower operating temperature for the solar panels, which is beneficial since photovoltaic cells typically operate more efficiently at cooler temperatures[21]. Studies have shown that FPV systems can maintain stable performance, with one analysis revealing that the mean performance loss rates (PLRs) of FPV systems in the tropics were around 0.7%/year, comparable to rooftop systems and within the performance warranty of PV module manufacturers[22]. This suggests that FPV systems can potentially offer higher energy yields than their land-based counterparts. The principal criterion for assessing FPV performance is the photovoltaic system's capacity to efficiently convert energy under operational conditions. This exerts an immediate influence on energy output and constitutes the module's most significant attribute. The efficiency of energy conversion is dictated by the correlation between energy generation intensity and total solar radiation. It is stated,

$$\eta_{el} = \frac{P_{max}}{S \times A_{PV}} \times 100\% \quad (1)$$

Where η_{el} represents the efficiency of electricity production (%), P_{max} denotes the maximum power generated by the photovoltaic (PV) system (W), S indicates the intensity of solar radiation incident on the PV module (W/m^2), and APV signifies the area of the PV module exposed to that solar radiation (m^2).

4 Design and Technical Parameters Floating Photovoltaic

FPV systems have several design and technical requirements that must be met to ensure their effective operation and efficiency. These requirements include:

4.1 Design Floating Photovoltaic System

FPV systems are mounted on plastic floats or pontoons, functioning as either standalone or hybrid systems. The floats interlock to form a raft, with power cables linking the panels to onshore equipment and transmission lines.

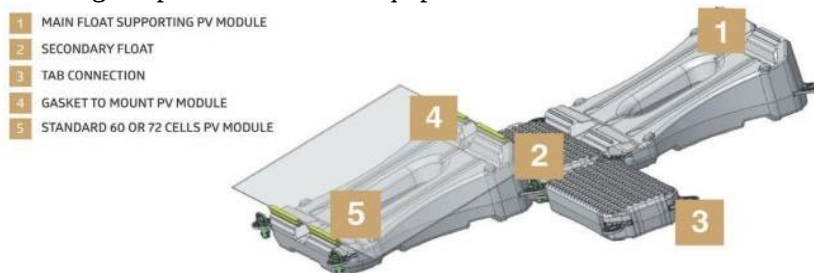


Figure 4 Floating PV design, Ciel & Terre's [23]

- **Pontoons**

Pontoons are a fundamental component of floating photovoltaic (FPV) systems, serving as the buoyant foundation upon which solar panels are mounted. These structures have been utilized in various small to medium-sized FPV installations, drawing on the extensive experience of those who manage ports and wharves, shown in **Figure 4**. Typically constructed from durable materials like high-density polyethylene (HDPE), pontoons are known for their robustness, UV resistance, and corrosion resistance, providing a balance between cost-efficiency and structural integrity [24]. Innovations in pontoon design, such as the introduction of curved shapes, have been developed to enhance performance in rough water conditions, promising better stability and resilience against wave action [25]. Furthermore, the integration of buffering systems between FPV modules on pontoons can help mitigate the risk of damage from collisions, ensuring the structural integrity of the FPV installation.

- **Mooring System**

Mooring systems are essential for the stability and positioning of floating photovoltaic (FPV) installations, ensuring that the platforms remain anchored at their designated locations despite environmental forces such as wind and water movement [26]. The design of mooring systems can range from simple shore anchoring to complex arrangements, depending on factors like the depth of the water body, soil properties of the reservoir bed, and wind loads.

- **Solar PV Module**

Solar photovoltaic (PV) modules are fundamental components of solar energy systems, turning sunlight directly into electricity via the photovoltaic effect. These modules consist of several solar cells, often fabricated from silicon, which are interconnected in series and encased for protection against environmental factors. Monocrystalline photovoltaic modules, identifiable by their consistent dark hue and rounded edges, are constructed from single-crystal silicon and are esteemed for their superior efficiency and longevity, frequently selected for optimal performance in constrained areas [27]. Thin-film modules, composed of diverse materials such as cadmium telluride (CdTe) and amorphous silicon (a-Si), are lightweight and flexible, facilitating numerous applications including building-integrated photovoltaics (BIPV). Bifacial photovoltaic modules, an advanced technology, are engineered to harness sunlight from both their front and rear surfaces, thereby enhancing energy generation and rendering them appropriate for ground-mounted and floating photovoltaic systems [28].

4.2 Technical Parameters Floating Photovoltaic Systems

- **Energy Demand**

Energy demand across the globe is on a continuous rise, driven by factors such as population growth, economic development, and technological advancements. In Southeast Asia, countries like Malaysia are exploring the potential of solar photovoltaic (PV) as a renewable energy source to meet their growing energy needs, with national policies and installations of solar PV in both urban and rural areas [29]. Similarly, Vietnam has experienced a significant boom in solar PV installations, becoming the largest installed capacity in the region, largely due to supportive policies and a generous feed-in tariff (FIT) [30]. Meanwhile, Indonesia is assessing pathways to achieve 100% renewable energy by 2050, with solar PV utility-scale playing a crucial role in this transition. Myanmar, still heavily reliant on traditional energy sources, is implementing energy policy guidelines to emphasize renewable energy use, though conventional domestic sources fall short of meeting the country's demand. The Philippines, with its numerous off-grid islands, is considering the transferability of smart energy systems, with photovoltaic-battery systems emerging as a favorable option for renewable energy-based systems [31]. As these countries grapple with the challenges of energy supply and sustainability, the adoption of FPV is increasingly seen as a viable solution to meet the escalating energy demand.

The initial stage in generating the energy necessary for the installation of FPVs in these countries is to determine the total daily energy requirement (kWh/day). This can be determined by multiplying the power consumption of each electrical device by the operational duration and the quantity of items.

$$E = P \times n \times t \text{ (kWh/day)} \quad (2)$$

Where E represent energy demand, P denote the power in watts (W) of each electrical device, n signify the number of items, and t indicate the time necessary for operation in hours (h).

- **Temperature and Heat Transfer Coefficient**

The operational temperature of a photovoltaic module is influenced by various elements, including incident solar radiation, ambient temperature, wind speed and direction, as well as the properties of the cell and module materials and the installation framework. Both radiative and convective heat transfer affect the module temperature. Various models have been suggested for simulating module temperature. The IEC61853-2 standard offers instructions for assessing the influence of the angle of incidence of irradiance on the output power of

photovoltaic modules and for calculating the module's operating temperature under defined environmental and mounting circumstances. The electrical efficiency, η , is assumed so that the portion of the incident irradiance converted to electrical energy does not contribute to the rise in module temperature, although this is not addressed in the standard. The module temperature, T_{mod} (K), is determined when electrical efficiency is considered.

$$T_{mod} = T_{amb} + \frac{G(\alpha - \eta)}{U_0 + U_1 v} \quad (3)$$

In this context, T_{amb} (K) denotes the ambient temperature, α represents the absorbed proportion of the incident irradiance, fixed at 0.9, G (W/m^2) signifies the incoming irradiance, and η indicates the electrical efficiency of the module. The heat loss coefficient of the system, $U_0 + U_1 v$, comprises a constant value and a wind component. In the absence of wind component data or reliable wind observations in meteorological data, a singular value for the heat loss coefficient, U ($\text{W/m}^2\text{K}$), is typically employed and designated as the U-value. However, the optimal values of U_0 and U_1 for different mounting arrangements remain a subject of contention. The variability in optimal fit values for different systems is anticipated, as heat transport is influenced by module features, outside conditions, and installation structure.

- **Performance Ratio for Floating Photovoltaic**

The system's total performance is evaluated using the performance ratio (PR), defined as follows.

$$PR = \frac{\sum_t E_t / P_{STC}}{\sum_t H_{i,t} / G_{STC}} \quad (4)$$

In this context, E_t (kWh) represents the energy production of the array at a specific moment, P_{STC} (kW) denotes the nominal power under standard test circumstances (STC), $H_{i,t}$ (W/m^2) indicates the incident irradiation at that time, and G_{STC} equals 1000 W/m^2 .

- **Levelized Cost of Electricity**

The Levelized Cost of power (LCOE) is a commonly utilised tool for assessing the economic viability of different power producing systems. Research on floating photovoltaic (FPV) systems indicates that although the levelized cost of electricity (LCOE) for FPV typically exceeds that of onshore wind and terrestrial

photovoltaics, it remains competitive with fossil gas and can yield profitable returns in areas characterised by advantageous conditions such as low capital expenditures, elevated energy yields, or high market electricity prices. The economic viability of FPV systems differs by region and is affected by various aspects, including as installation costs, solar irradiation levels, and market conditions. This analysis highlights that FPV installations provide several advantages compared to terrestrial systems, notwithstanding the extra problems and expenses they entail. **Table 1** shows a thorough comparison of the two system types.

Table 1 Comprehensive comparison of both type of system.

Parameter	Floating PV	Land-based PV
Surface use	• Does not vie for land with agricultural, industrial, or residential developments. • Frequently more accessible to locate sites in proximity to densely populated regions. • The permitting procedure is typically less complex, as water bodies usually have a singular owner. • Reduced leasing expenses. • Prospective integration with aquatic ecosystems. • Can preserve water resources by minimising water evaporation.	• Appropriate and economical land for renewable energy initiatives may be situated at considerable distances from load centres, necessitating expensive transmission infrastructure. • Furthermore, alterations in land usage can be a protracted process. • Compete for land with urban dwelling, industrial development, and agricultural use.
Performance/ energy yield	• Reduced module temperatures (the effect varies with climate). • Minimal shading. • Reduced accumulation of dust. • Initial performance ratio is 5–10 percent greater overall (specific to climate). • The long-term degradation, such as possible induced degradation, remains unknown.	• Can gain advantages from tracking, bifacial technology, and optimal tilt angle. • Experiences increased temperature losses in elevated temperatures.
Installation and deployment	• Generally straightforward assembly, however significantly contingent upon location and staff availability. • The transportation of floats to the site presents challenges, hence favouring local production. • A proper launching area is required.	• Efficiency fluctuates based on geographical location and labour availability. • Requires substantial machinery and land cultivation. • Contingent upon soil quality.

Power system benefits	• Harmony with the current electrical infrastructure. • Potential hybrid operation utilising hydropower.	• The expenses associated with grid connectivity are often borne by the project developer and can be prohibitively high.
Environmental	• The long-term impacts on water quality remain inadequately defined. • Capability to diminish algal proliferation. • Capability to diminish water evaporation. • Possible effects on aquatic ecosystems	• The investment and financing sector is firmly established owing to the substantial installed capacity. • Expenses persist in declining.
Investment	• Average costs are somewhat elevated due to floats, anchoring, mooring, and system design. • Increased perceived risk is linked to the reduced level of maturity	• The investment and financing sector is firmly established owing to the substantial installed capacity. • Expenses persist in declining.
Operation and maintenance	• Accessing and replacing specific components is more challenging. • Biofouling. • Visits by animals and excrement from birds. • More challenging to sustain anchoring. • Convenient access to water for sanitation purposes. • Reduced likelihood of theft and vandalism.	• Accessible. • More influenced by vegetative proliferation. • Simplified implementation of cleaning protocols.
Durability	• Typically, a warranty period of 5 to 10 years is provided for floats.	• Essential system components are designed to last over 20 years.
Regulation and permits	• More challenging for natural lakes and simpler for artificial ponds. • Absence of specified laws.	• Enhanced permitting procedure. • More explicit regulations.
Experience	• Four years of experience with extensive projects.	• Thousands of projects constructed. • 10–30 years of experience.

5 Conclusion

In conclusion, Floating Photovoltaic (FPV) systems present a viable solution for solar energy production, especially in regions where land is scarce or expensive. The cooling impact of water on solar panels enhances the efficiency of these systems, potentially resulting in increased energy generation. Environmentally, FPV systems can diminish water evaporation and exert a reduced impact on land

utilisation compared to conventional land-based PV systems. However, challenges such as the risk of panel warping due to wave movement and the need for robust designs to withstand harsh conditions must be overcome. Economic studies indicate that FPV systems can be a cost-effective option, with lower levelized costs of energy (LCOE) and quicker payback periods in certain circumstances. The financial viability of FPV depends on factors such as initial capital costs, energy output, and local electricity prices. In general, adopting FPV systems could significantly reduce carbon emissions by increasing the share of renewable energy in the grid.

6 Suggestion

Given the promising potential and rapid growth of floating photovoltaic (FPV) systems, future research should focus on several key areas to further enhance the technology's efficiency, sustainability, and economic viability:

- **Optimizing Performance:** Continued studies on the thermal regulation of FPV systems are vital. Researchers could look into new materials and innovative platform designs to maximize cooling effects and reduce vulnerability to environmental challenges like wave impact.
- **Economic Feasibility:** Comprehensive economic assessments are important to determine FPV's cost-effectiveness in different locations. These analyses should include capital and operating costs, as well as levelized costs of energy (LCOE), comparing FPV systems with traditional solar systems. Additionally, evaluating FPV's financial benefits in areas with limited land can help validate investment in this technology.
- **Policy and Regulatory Support:** Research into social and technical obstacles such as regulatory uncertainties and limited environmental data can help smooth FPV adoption. This work should aim to guide policymakers and stakeholders in creating policies and regulations that support FPV growth.

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