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Evaluating the Horizon of Renewable Power: A Comprehensive Review of Floating Photovoltaic Systems' Performance and Technologies

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ABSTRACT

This detailed review underscores the significant potential of floating photovoltaic (FPV) systems in fostering a sustainable energy future. It evaluates the efficiencies, applications, and environmental impacts of different FPV technologies, illustrating that FPVs are a feasible solution to the global energy crisis. The review particularly highlights hybrid floating photovoltaic (HFPV) systems, which excel in maximizing energy production while minimizing ecological impacts. It advocates for the adoption and continuous improvement of FPV technologies, emphasizing that FPVs provide a way to meet rising global energy demands and align with the imperative for environmentally sustainable energy solutions.

1. Introduction

Global resources are being rapidly depleted due to population growth and development activities [1]. This is primarily because global energy demand is surging, driven by population expansion and industrialization [2]. Additionally, the ecosystem has suffered significant damage due to emissions from the combustion of fossil fuels, which are a prevalent source of the world's energy [3]. Fossil fuels are also projected to be depleted by 2030 [4]. Historically, the world has exploited resources to generate energy, creating a habitable environment for humans. However, non-RE sources are not only exhaustible but also contribute to climate change and ecological damage [5]. Thus, relying on non-RE to meet global demand is unsustainable.

Selecting eco-friendly, RE sources is crucial for a sustainable future, particularly to reduce greenhouse gas (GHG) emissions and protect the environment [6]. Key sources include solar [7], wind [8], hydropower [9], geothermal [10], and biomass energy [11]. Among these, solar energy stands out as a prime candidate for global investment [12]. According to the International Renewable Energy Agency (IRENA) in 2023, solar energy accounted for 30% of all renewable energy installations in 2022, as illustrated in Figure 1. In the same year, solar energy reached the second-highest installed capacity among renewable technologies, totalling 1061 GW, just behind

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hydropower at 1392 GW [13]. Figure 2 displays the global installed capacity of solar energy over the past decade, showing a clear upward trend and indicating consistent growth year over year [13].

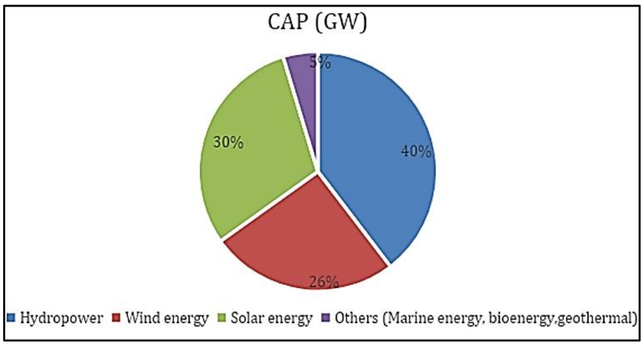

Fig. 1. Capacity RE in 2022

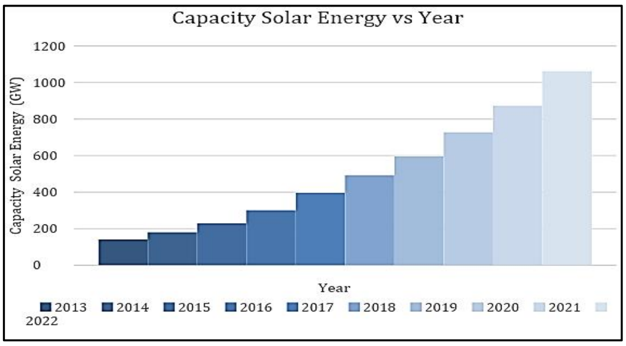

Fig. 2. Global solar energy capacity from 2013 to 2022

There are various factors that contribute to the adoption of solar energy as the preferred choice. Solar energy is the most abundant renewable source, with continuous emission from the sun, making it a sustainable and inexhaustible option [14]. It also has minimal ecological impact, maintaining natural balance [15]. Moreover, solar systems are cost-effective for both industrial and residential applications. Due to these advantages, solar technology has become a major focus of investment, aiming to replenish depleted energy sources and reduce the greenhouse effect caused by fossil fuels. As shown in Figure 3, solar energy has the highest increment compared to other RE sources [16].

PV systems are a notable example of this technology. The Renewables 2022 Global Status Report by REN21 confirms that PV had the highest growth rate in 2021 among RE sources. As depicted in Figure 4, there is a continuous and consistent growth pattern observed in PV over the past decade [13].

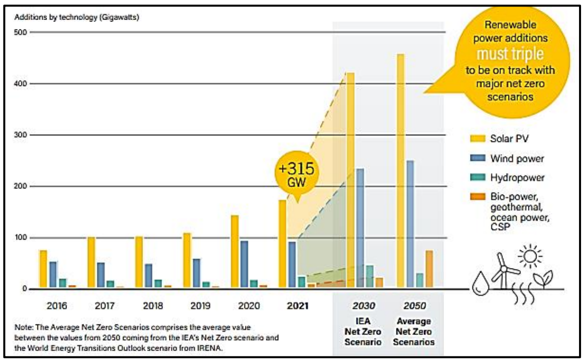

Fig. 3. The growth of RE

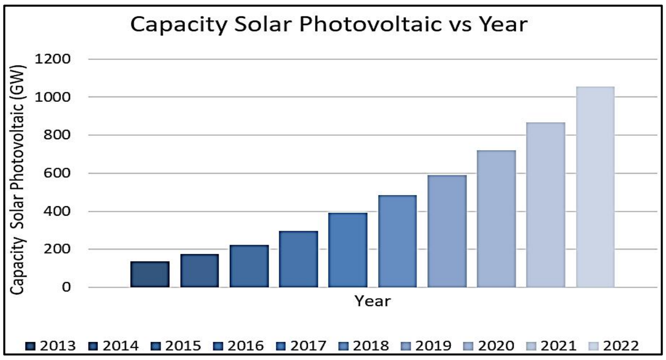

Fig. 4. Global PV capacity through the year from 2013 to 2022

As for Figure 5 [17], it presents a global overview of PV power potential which shows varying intensity of solar resources. According to the data, daily total PVOUT ranges from as low as 2.0 kWh/kWp in regions with minimal sunlight to more than 6.4 kWh/kWp in the most irradiated areas.

On a continental scale, Africa stands out, with the Sahara Desert displaying potential annual totals exceeding 2200 kWh/kWp, underscoring the immense solar energy resources available to African nations. In contrast, Europe shows a wide range, with Southern Europe, particularly the Iberian Peninsula, boasting annual potentials up to 1700 kWh/kWp, while Northern European regions like Scandinavia receive less than 900 kWh/kWp.

The geographic distribution of photovoltaic potential is critical for developing global and regional strategies for solar energy utilization. For instance, countries with high annual photovoltaic power potential values could not only fulfil their own energy requirements but also potentially export solar energy, either through power transmission or manufacturing energy-intensive products.

This paper aims to demonstrate that PV systems are an excellent example of renewable energy capable of meeting global demand. However, traditional PV systems face significant challenges due to extensive land requirements, which has led to the introduction of FPV systems. Hence, this paper examines the efficiencies, applications, and environmental impacts of various FPV technologies, demonstrating that FPVs represent a viable solution to the global energy crisis. In addition, to maximize the energy production and ensure consistence efficiency of FPV system, the implementation of HFPV systems has been suggested.

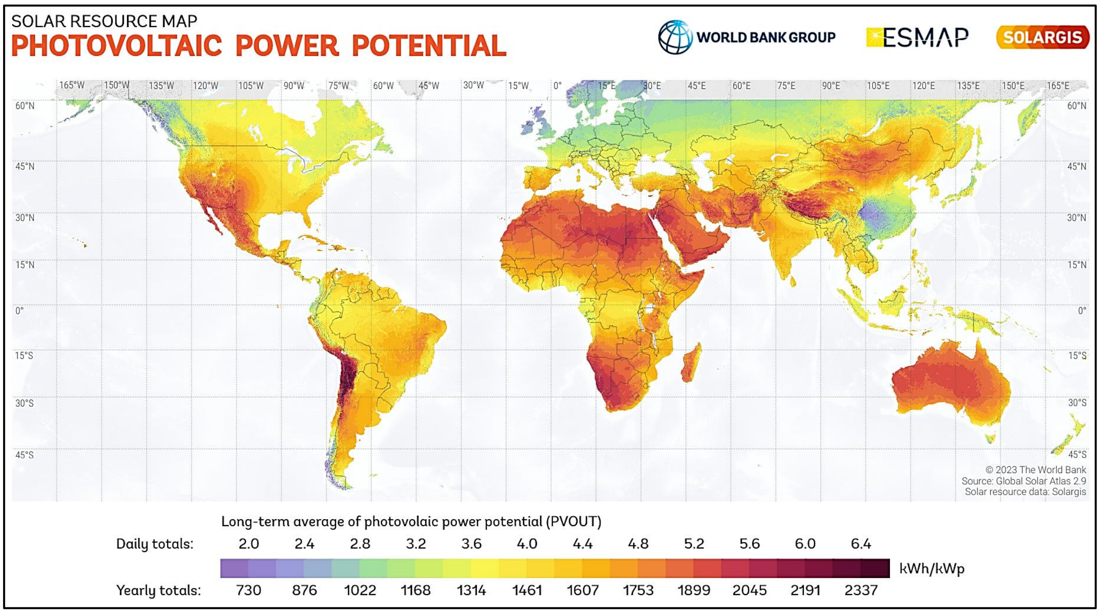

Fig. 5. Global photovoltaic power potential

1.1 PV Systems

PV technology converts solar energy into electrical energy through the PV cells [18]. This effect occurs when photons from light impact a PV cell, transferring energy to the cell's charge carriers [19]. These carriers, comprised of positively charged holes and negatively charged electrons, are separated by the cell's internal electric fields. The creation of an electric circuit by connecting a load to the cell allows for the flow of current. The fundamental mechanism of a PV cell's operation is illustrated in Figure 6 redrawn and adapted from [20].

A PV system incorporates a PV module, Maximum Power Point Tracking (MPPT) techniques, a DC-DC converter, and an inverter. The system's efficiency in converting sunlight into electricity hinges on the integrated functions of these components. The solar panel converts solar irradiation into electrical power, while the MPPT technology optimizes electricity extraction from the panel under certain conditions. The DC-DC converter acts as an intermediary between the PV module and the load. Due to the irregular nature of solar power, these components, along with the inverter, serve as vital elements of energy storage systems, analogous to batteries [20].

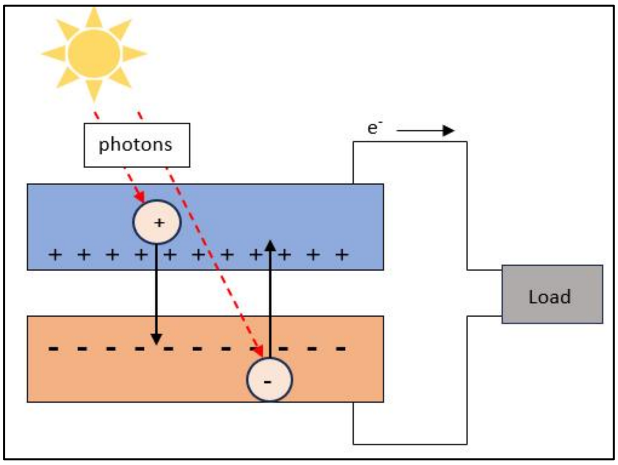

Fig. 6. Basic operation of PV cell

1.2 Type of PV Cells

PV technology is globally utilized due to its efficient energy conversion and simple design. PV devices primarily employ semiconductor materials for electricity generation. These materials are classified into three generations: silicon-based cells (first generation), known for their stability and non-toxicity [21], produced using the Czochralski process [4]; thin-film cells (second generation), which include copper indium gallium selenide (CIGS) and Cadmium Telluride (CdTe) [22], offering benefits like reduced silicon thickness; and organic materials [23] (third generation), comprising polymers, Dye-Sensitized Solar Cells (DSSC), and nano solar cells, noted for their cost-effectiveness. The efficiency comparison of these generations is detailed in Table 1 [20].

Table 1
Comparison of efficiency for three generations of solar cells [20]

Parameters	1st generation		2nd generation		3rd generation		
	Mono silicon	Poly silicon	CIGS	CdTe	Polymer	DSSC	Nano cells
Efficiency	14%−17.5%	12%−14%	10%−12%	9%−11%	~3%−10%	~10%	7%−8%

Silicon-based cells, favoured in PV due to their superior efficiency and abundant material availability, are divided into two categories: monocrystalline and polycrystalline solar cells.

i. Monocrystalline solar cells: Monocrystalline solar cells, known for their high efficiency and spatial economy, are made from single-crystal silicon [24] and have been most widely used in the PV industry [25]. Produced through the Czochralski process, these cells are grown in a laboratory to form cylindrical ingots. These ingots are then processed into thin silicon wafers, enhancing their performance [26]. However, the complexity of their production process renders monocrystalline solar cells more expensive [24].
ii. Polycrystalline solar cells: Polycrystalline solar cells, constructed from multi-crystalline silicon, exhibit lower efficiency compared to monocrystalline cells due to grain boundary-induced crystal defects. Despite this, their lower cost contributes to over half of silicon-based solar cell production [20]. These cells also perform better at higher temperatures, having a greater temperature de-rating coefficient than monocrystalline cells [24].
iii. Bifacial solar cells: Bifacial photovoltaic panels, incorporating both monocrystalline and polycrystalline silicon, are gaining traction for their ability to absorb solar irradiance from both the front and back, thus enhancing energy generation efficiency [27]. Hence, bifacial

PV modules can produce more 20% energy compared to equivalent monofacial modules depending on the installation of PV modules [28].

1.3 Efficiency of PV Cell

The efficiency of power transfer from PV cells is influenced by several factors: solar irradiation intensity [29] , cell temperature [30] , and shading [31] . Optimal solar irradiation is crucial for maximum efficiency, as excessive intensity increases cell temperature, inversely affecting efficiency [32] . According to study that has been carried out by Hamad [33] , it was observed that the efficiency of the PV module decreases as the module temperature increases, resulting in a 9.62% reduction compared to the PV operating under standard conditions. Shading, caused by buildings, trees, or debris like bird droppings, also diminishes panel efficiency. Shading conditions affect the efficiency of a PV panel due to the series connection of its cells [34]. The non-linear voltage-current (V-I) characteristics of solar cells depend on these factors. Therefore, identifying the maximum power point is essential for optimizing power extraction from PV panels [20].

2. Floating Photovoltaic System (FPV)

Traditionally, PV installations are either rooftop or ground-mounted. However, conventional on-ground photovoltaic (OPV) systems face significant challenges due to their low power density and extensive land requirements approximately 15,000 m² per 1.0 MW capacity [35]. This substantial land use competes with other valuable applications like agriculture and commercial development, posing a considerable challenge for PV system expansion [36].

FPV systems emerge as a superior alternative, offering rapid expansion possibilities without consuming land resources. Typically, FPV installations are sited on artificial water bodies such as ponds, reservoirs, and lakes [37] to minimize potential environmental impacts or complications associated with natural water bodies [38]. Research noted in [39], discusses the environmental loads on FPV structures in both freshwater and marine environments, highlighting that FPVs in marine settings must endure greater wind and load pressures than those in freshwater.

Table 2 provides a comprehensive review of literature on FPV systems published over the last seven years, covering topics from the basic materials used in solar cells to advanced HFPV systems. These reviews assess the advantages and challenges of FPV and HFPV systems compared to traditional OPV installations, encapsulating the evolving dialogue in solar energy solutions.

Table 2
Recent 7 years review articles on FPV system

Objectives	Subsections	Year	Ref.
Review the development of marine floating photovoltaic systems.	Summarizes the latest progress in research and applications of FPVs, including design concepts, hybrid usage, structural considerations, and challenges.	2023	[40]
Discuss the recent research of FPV as well as the benefits and drawbacks of the new technology	Advantages and disadvantages of FPV and potential for hybrid with other technologies.	2022	[41]
Provide the benefits and technical potential of HFPV especially for hydropower systems.	Comparing the benefits between FPV and HFPV using global datasets and analysing the technical potential of HFPV.	2020	[38]
Pro Provide an overall overview of the existence of FPV in terms of parts, the advantages and disadvantages and	Discuss the basic components in FPV system and analysis of FPV including benefits, drawbacks and	2020	[42]

Table 2. Continued
Recent 7 years review articles on FPV system

Objectives	Subsections	Year	Ref.
disadvantages and environmental effect.	future scope FPV.		
Present the overview of different technologies FPV by showing advantages and limitations.	Compare difference FPV technologies which are high density polyethylene (HDPE) (Ciel et Terre) and galvanized steel (Solaris Synergy) using PVsyst.	2020	[43]
Review the development of FPV technologies in terms of electrical and mechanical structure.	Discuss the FPV components, important design factors and parameters to compare with OPV.	2020	[44]
Review and analysis factors influencing the efficiency of PV systems.	Overview basic material used for solar cells and various of MPPT techniques in maximize the efficiency of PV system.	2019	[20]
Analysis of different aspects of FPV systems as power generation systems.	Comparison of OPV and FPV in terms of module efficiency and efficiency gain, allocation of FPV system and review of electrical aspects.	2019	[45]
Compare the various cooling techniques for solar panels by analysing the advantages and disadvantages of the techniques.	Basic technique (water and air cooling) and new technique (phase-change materials, heat pipes and nano-fluids).	2018	[46]
Discuss the timeline of concepts and FPV projects that has been established worldwide	Components of FPV system and various FPV installations worldwide.	2017	[47]

2.1 Types of Water Environment of FPV
2.1.1 Freshwater

Examples of freshwater are lake, river and natural basins which have calm waters [48] and low salt concentrations. Freshwater offers numerous benefits compared to marine water for PV applications, including fewer corrosion issues, diminished impact from waves and wind, and restricted algae growth [49].

2.1.2 Marine water

The ocean, with its high salt concentrations, serves as a prime example of a marine water environment. Placing systems in such demanding conditions necessitates a complex design process tailored for marine applications, ensuring sustained and reliable operation throughout their entire lifecycle, especially under extreme conditions like saltwater corrosion and biofouling [39]. The ecological impacts of marine PV systems are influenced by the project design and various environmental factors, such as geography, water depth, distance from shore, and local hydro and oceanographic conditions [50]. Key considerations for these systems include resistance to harsh conditions, reliability, maintainability, overall power performance, modularity, and environmental impact [51].

2.2 Components of FPV System

The components for the FPV system share the same components with the OPV system such as PV panels and measuring station to gather all the data for analysis except the FPV system has additional floating structure and platform to support PV panels on water bodies.

2.2.1 PV panel

The materials selected for the PV cells in a FPV system correspond to those employed OPV. Most silicone-based are extensively employed in manufacturing processes within the solar cell industry. Both types of crystalline silicon wafers are recognized as dominant substrate materials for the fabrication of solar cells [52].

2.2.2 Supporting structure

Usually, the supporting structures for PV panels are made of steel or aluminium. However, for FPV especially in marine water, corrosion factor needs to be considered. Hence, the suitable materials for FPV supporting structure are fibre-reinforced polymer (FRP) which also can withstand extreme conditions such as wind and waves. These FRP have outstanding characteristics which are lower density and high corrosion resistance compared to metallic materials which are heavier and prone to corrosion [39]. However, according to economic feasibility analysis results, FRP is more expensive compared to aluminium and high durability steel. In [53] study, it also shows that for 500 kW FPV installation, the number of high durability steel structural members is less required compared to aluminium and FRP which are 38.19 times lower compared to aluminium and 30.27 times lower than FRP. Hence, it was concluded that the most cost-effective material for a 500 kW FPV power plant is high durability steel. Designated pathways were also built by connecting a series of these platforms that allowed access for maintenance, operation and cleaning of the solar panels [38].

2.2.3 Floating system

The floating system is functioning by ensuring the buoyancy and stability of the electricity-generating system using pontoons [54]. For the floating part, high density polyethylene (HDPE) is usually used for FPV systems [55]. Besides HDPE is a buoyant material that allows it to float on water, it is also known for its durability to high temperature and water exposure. Given prolonged exposure to ultraviolet (UV) radiation, it is crucial to evaluate the impact of UV exposure on the system [56]. The principal limitation in this context is the influence of natural UV radiation, leading to the gradual deterioration of plastic materials over time [57]. Polyethylene is usually made from maintenance-free plastic materials that are resistant to UV light and non-hazardous [58]. In marine applications, the floats are anticipated to endure higher loads and the impacts of corrosion from saltwater as well as biofouling [59]. These characteristics are essential for long term performance of an FPV system.

2.2.4 Anchoring system

In addition, FPV systems also need anchoring systems to prevent drifting and ensure stability [60] The selection of the anchoring system is primarily determined by the geometry of floating structure as well as the direction and intensity of the external actions [61]. Recently, synthetic fibre rope such as polypropylene, nylon and polyester has been used as a mooring line among the FPV industry [43]. As the purpose of the anchoring system is to minimize the movement of floating systems, a proper design needs to be built to find the right balance between the mooring line, neither too tight nor too slack [43].

According to [39], anchoring systems for marine water can be classified into four types which are catenary, compliant, taut, and rigid moorings. The catenary anchoring system utilizes chains that leverage their own weight to offer a spring rate to the anchored float. Compliant anchoring, categorized as catenary anchoring, employs floats and weights to modify the arrangement of mooring lines. A taut anchoring system uses buoyancy surplus to maintain tension in the anchoring lines, restricting vertical motion. This configuration minimizes vertical displacement, a potential concern for significant water level fluctuations, particularly considering the constrained freeboard of FPV structures. A rigid anchoring system comprises an anchored rigid structural component that permits vertical movements while limiting horizontal movements. Although this solution is optimal for maintaining station-keeping, it is economically viable only in shallow waters.

2.2.5 Electrical parts

Solar panels generate electricity in the form of direct current (DC), which is a continuous flow of electric charge in a single direction. However, most household appliances and the electricity grid use alternating current (AC), where the flow of electric charge periodically reverses direction. Hence, an inverter is used to make the electricity produced by solar panels compatible with the AC-based systems. An inverter is an electronic device that converts the DC electricity generated by solar panels into AC electricity.

In addition, a network of cables and electrical elements is necessary to convert and convey electricity from FPV facilities to the shore [62]. The wiring can be conducted either above the water's surface or underwater. Next, the transformer plays a crucial role in converting the high-voltage electricity generated by the PV panel into a usable form. This electricity is then transmitted through the system and distributed to power various industrial or residential appliances. While most electrical components are situated above water to minimize risks, it remains essential to waterproof them. In addition, there is a combiner box in the FPV system which acts as protection from overcurrent, undercurrent and other electrical hazards [62]. Figure 7 shows the schematic FPV system redrawn and adapted from [38].

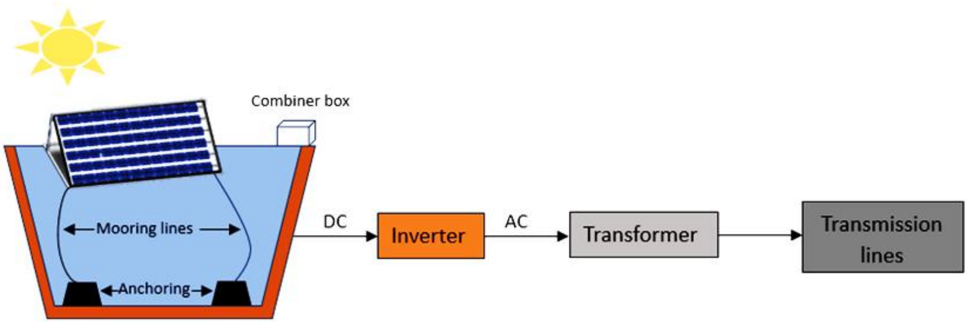

Fig. 7. The schematic of FPV system [38]

2.3 Difference Between FPV And OPV System

Table 3 outlines the differences between FPV and OPV systems in terms of installation, components, performance, and cost. The primary distinction between these two types of PV systems lies in their installation locations. Given the scarcity of land resources, installing PV systems on water bodies is beneficial, offering advantages such as water conservation and a cooling effect that enhances efficiency [63]. For structural support, FPV systems are mounted on floating platforms made of materials such as plastic and stainless steel or galvanized steel, in contrast to the stationary racks used in land-based systems [38]. In terms of cost, FPV systems tend to be slightly more expensive than OPV systems due to the need for additional components like the floating structure. Despite the higher initial cost, FPV systems are financially advantageous in the long run due to their increased efficiency and contribution to water conservation.

Table 3
Summarize difference between FPV and OPV system

Classification	Floating photovoltaic	On ground photovoltaic
Installations and location	Installed on bodies of water. Does not compete with other activities. Easy to find sites.	Installed on land. Compete with other activities such as agriculture, industry and residence.
Platform and fixed structures	Mounted on floating platforms constructed with polyethylene and stainless steel [38].	Fixed structure.
Environmental considerations	Benefits for water conservation by reducing water evaporation and reducing algae growth. Might be affect aquatic life [62].	Smaller environmental footprint but land use considerations.
Cooling type	Cooling effect of water.	Natural air cooling.
Efficiency	Less shade from surroundings will increase the penetration of sunlight to photovoltaic panels	Shading from buildings, mountain and tree will decrease the penetration of sunlight to photovoltaic panel.
Land use	Frees up land for other purposes	Requires land.
Stability and durability	Face of changing water conditions and weather events	Withstand wind, weather and seismic condition.
Costing	Slightly expensive due to additional parts such as mooring and anchoring. However, still financially superior due to water conservation and increasing efficiency over its lifespan.	The cost is less expensive than floating photovoltaic.

2.4 Efficiency Influences Floating Photovoltaic System

As the factors influencing the efficiency of PV cells have been discussed, there are some difference factors that can affect the efficiency between FPV and OPV. Firstly, the cooling effect factor [64]. FPV systems can benefit from the presence of water which will reduce the temperature of solar cells to improve its performance. Meanwhile, OPV systems can rely on natural air cooling which may not be as effective as water cooling in FPV systems. According to the studies, there is an average 10% energy increment in FPV compared to OPV due to the water-cooling effect that increases PV efficiency [65].

Second, the selection of PV materials also impacts the efficiency of FPV systems. High-efficiency solar cells, low-emissivity coatings, and transparent materials can significantly increase power generation by maximizing solar absorption [62]. Additionally, employing an advanced monitoring and control system enhances FPV efficiency, as it allows for regular tracking of energy production and system performance to optimize functionality [62].

Table 4 summarizes journal articles from the past six years that focus on the experimental aspects of FPV systems. These articles cover a broad spectrum of topics, from investigations into the cooling effect and performance enhancements to comparisons between FPV and OPV systems. Various solar cell types, including monocrystalline, polycrystalline, and bifacial, have been studied for their efficiency and electricity generation capabilities. However, research on FPV systems in marine water remains relatively sparse.

Table 4
Recent years journal article on FPV system in experimental parts

Configurations analysis	Type of solar cells	Location of FPV	Results	Research gap	Year	Ref.
Testing and analysing electrical performance and thermal performance on the FPV and OPV systems with different tilt angles, along with the study of water evaporation.	Monocrystalline and polycrystalline	Water basin	FPV systems can help in reduction of water evaporation. Efficiency of FPV is higher compared to OPV due to the water-cooling effect. The FPV system produces the most energy during optimal tilt angle.	Design a measurement station equipped with online data transmission to a database and waterproof sensors to perform year-round experimentation.	2022	[35]
Design, manufacturing and installation of the first FPV systems in Turkey.	Polycrystalline	Lake	System components, wave height calculation and wind climate of the site can be used to design new systems in other parts of Turkey.	Testing should be conduct under marine water.	2022	[66]
Comparing and analysing the electrical and thermal performances of FPV and OPV systems with similar nominal capacities.	Polycrystalline	Water basin	FPVS generates up to 2.33% more daily energy than the OPVS and highest energy at optimal tilt angle.	Implementation of a fully automated measurement. Perform detail financial analysis and the impact of FPV structures on water conservation over the course of a year under real environment.	2021	[67]
Measuring the cooling impact and making comparisons across various climate conditions in the Netherlands and Singapore.	Monocrystalline, polycrystalline, bifacial	Lake and reservoir	The increase in energy output due to the cooling effect of FPV systems compared to reference PV systems is around 3% in the Netherlands and up to 6% in Singapore.	For a fair comparison, panels need to be subjected to the same conditions.	2021	[68]
Comparing the performance of the partially submerged photovoltaic (PSPV) system with different submerged lengths to that of the OPV systems.	Polycrystalline	Water basin	By increasing the submerged length to 10 cm, PSPV generates more daily electricity compare to OPV up to 18.2%.	Use an instrument that is fully automated to avoid any uncertainty in data and testing for a year.	2021	[69]
Comparing two types of FPV (monofacial and bifacial)	Monofacial and bifacial	Lake	Bifacial can produce energy up to 6.75 % compare to monofacial	Compare with OPV under marine water.	2020	[70]
Compare the output power between FPV and OPV	Polycrystalline	Pier	Power generated by FPV is higher than OPV with 51.6 W and 42.9 W respectively.	Conduct the testing over a long time period.	2020	[71]
Investigate the practicality of deploying large scale FPV systems on inland water surface compare to reference system on rooftop	Monofacial and bifacial	Reservoir	Water surface does offer some benefits to increase efficiency of PV panels such as better wind ventilation and cooler ambient	The various risks need to be managed effectively to ensure reliable operation and long lifetime.	2018	[72]

temperature.

2.5 Advantages of FPV

FPV systems are increasingly favoured over OPV systems due to their multiple advantages concerning both performance and environmental impact. A primary benefit of FPVs is that they do not require land for installation, as they are mounted on water bodies like reservoirs, ponds, or lakes [73]. This aspect significantly reduces installation costs by eliminating the need to purchase or lease land [51]. Furthermore, utilizing water surfaces for FPV installations frees up land for other uses such as agriculture or urban development, which is particularly advantageous in regions where land resources are scarce [72]. In essence, FPV systems offer a sustainable alternative by leveraging water bodies under abundant sunlight, thus conserving valuable land resources [48].

As previously mentioned, FPV systems offer benefits in improving efficiency through water cooling, which enhances PV performance [74]. Water cooling is advantageous as it reduces radiation reflection and maintains a lower temperature for FPV panels, enhancing their operational efficiency [64]. A study by Tina *et al.,* [75] revealed that FPV systems yield 10% higher energy than OPV systems. Further research, such as the analysis conducted at Kaylana Lake [76], found that annual energy generation from FPVs increased by 2.48%, while the module temperature decreased by 14.56%. Therefore, FPVs demonstrate higher efficiency compared to OPVs, largely due to the natural cooling effects of water [75, 77]. This cooling mechanism not only lowers temperatures but also helps stabilize PV performance, leading to consistent and reliable energy output [62].

Next, FPV can eliminate the solar panel shading from its surroundings [75]. It is because its installation on water bodies which is an open area compares to OPV where it is usually installed on the ground or rooftop. There will be some obstacles for photovoltaic panels to absorb the sunlight such as buildings and this will affect the efficiency of photovoltaic panels [78]. Hence, the FPV can increase their efficiency by reducing the shading factor.

In terms of environmental benefits, FPV can help in reduction of water evaporation by creating a shading effect on the water surface beneath panel [64, 74, 75]. This shading decreases the direct exposure of the water to sunlight and lowering the temperature along with the rate of evaporation. Hamza Nisar has conducted a small-scale FPV test bench under three different situation pond simulators which are fully exposed, partially covered, and fully covered. According to this study, FPV systems reduce water evaporation by approximately 17% when partially covered and approximately 28% when fully covered [35]. The FPV system at the Kaylana Lake in Jodhpur also estimated that annually, 191.174 million litres of water will be saved from evaporation [76].

As the sunlight penetration to the water has decreased, the growth of algae also has decreased. Hence, the water quality also can improve with reduction of algae growth [79]. As the quality of the water improves, the cost of purification to meet drinking water standards will reduce [80]. However, it is still uncertain whether aquatic life also will be affected with reduction in sunlight penetrating.

2.6 Disadvantages of FPV

While FPV systems offer significant advantages, they also present distinct disadvantages and limitations. One such disadvantage is the potential negative impact on aquatic life; FPV systems can obstruct sunlight penetration into water bodies, potentially affecting the growth of aquatic organisms. As noted by Pimentel *et al.,* [81] the anchoring and mooring systems of FPVs can temporarily harm benthonic communities and alter the lakebed's geomorphology by increasing suspended sediments.

Moreover, FPV systems face challenges with wind exposure. Winds over open water bodies, like seas, tend to be stronger due to the lack of natural barriers such as buildings or trees. Consequently, FPVs require robust mooring systems to withstand heavy gusts, often necessitating numerous mooring points to maintain stability [67].

Financially, installing an FPV system is approximately 15% more expensive than an OPV system due to the additional components required, such as floating structures and mooring systems [82, 83]. These structures must be corrosion-resistant and strong enough to support the weight of PV panels. Maintenance costs are also higher as servicing systems on water is more challenging. Despite these higher initial and maintenance costs, as highlighted by a study conducted at Kaylana Lake in India [76], the FPV systems offer long-term financial benefits through water conservation and enhanced efficiency, outweighing their higher capital investment.

Additionally, FPV systems can be impacted by environmental factors such as dust accumulation and bird droppings, which can obstruct the PV panels and reduce their efficiency [59]. According to previous study [84], the efficiency of a PV panel significantly decreases when dust accumulation covers up to 50% of the panel. While water can wash away some contaminants, consistent maintenance is essential to manage the accumulation and ensure optimal energy production, as emphasized by the Solar Energy Research Institute of Singapore (SERIS) during their evaluation of the world's largest floating solar testbed [85].

3. Hybrid Photovoltaic System

As has been discussed before, the efficiency of a PV cell can be influenced by a few factors, such as the amount of solar irradiation falling on the panels, temperature, and shading. Besides, FPV systems can increase their efficiency by being combined with other existing renewable energy sources to form a HFPV system [86]. The solar PV system itself already has advantages over solar energy, as it is the most abundant source of renewable energy among others. However, solar power has its own weakness, which is that this source is not continuously available for conversion into electricity. This is also known as an intermittent energy source. Usually, solar energy is intermittent during the night or bad weather as the Sun emits less energy compared to the daytime and good weather when the Earth is exposed to direct sunlight.

Therefore, to ensure the constant efficiency of the FPV system, the hybrid system has been suggested [87]. According to Lee *et al.,* [38] hybrid systems can predict the net economic benefits from the combination of multiple generation technologies compared to the cost and/or value associated with comparable independent, stand-alone technologies. HFPV systems integrate solar PV technology with various other renewable energy sources such as wind [88], hydropower [89], biogas [90] and geothermal [91]. This hybrid PV system can help alleviate challenges related to the intermittent and uncertain nature of solar irradiance [92]. Solar irradiance varies across different hours of the day, months of the year, and locations on Earth.

Besides resolving the problem of solar energy intermittency, these HFPV systems have also offered additional benefits in terms of cost, performance, and efficiency compared to stand-alone FPV systems [38].

3.1 Optimizing Efficiency

Enhancing system operation at various time scales is essential for optimizing efficiency. As the solar energy is an intermittent energy, the variability and unpredictability of solar PV generation stem from factors such as changing weather conditions. Meanwhile, hydropower systems, given ample resources, possess the capability for precise generation control and can effectively compensate for shortfalls and balancing intermittent solar photovoltaic generation [93].

At the seasonal or monthly scale, the availability of solar and hydropower resources, however, tends to be asynchronous, posing challenges for coordinated energy generation and distribution. During dry seasons, higher quality solar resources are typically prevalent, whereas the rainy season may bring about the availability of solar resources with lower quality. In contrast with hydropower systems, the high quality of hydropower energy is highest during the rainy season compared to the dry season. Operationally, this means the hybrid system is designed to export power from the PV system when the sun is shining, simultaneously allowing the reservoir to either recharge or store resources for periods when solar energy is not available [38]. Hence, water resources and solar energy can compensate for each other when used in tandem as a hybrid [94].

According to study by [95], the potential worldwide capacity for combining FPV systems with hydropower installations is projected to be between 4,400 to 5,700 GW (equivalent to 6,270 to 8,039 TWh per year of generation). This estimation applies to the installation of FPV systems on reservoirs designated for hydropower and reservoirs with multiple purposes. From Figure 8, it shows that the total for dispatchable energy from the hybrid systems is higher than the total for dispatchable energy from stand-alone systems as it is equal to the total energy generation of the two systems [38]. The projected capacities show an upward trend with an increase in the percentage of the reservoir area covered by FPV systems.

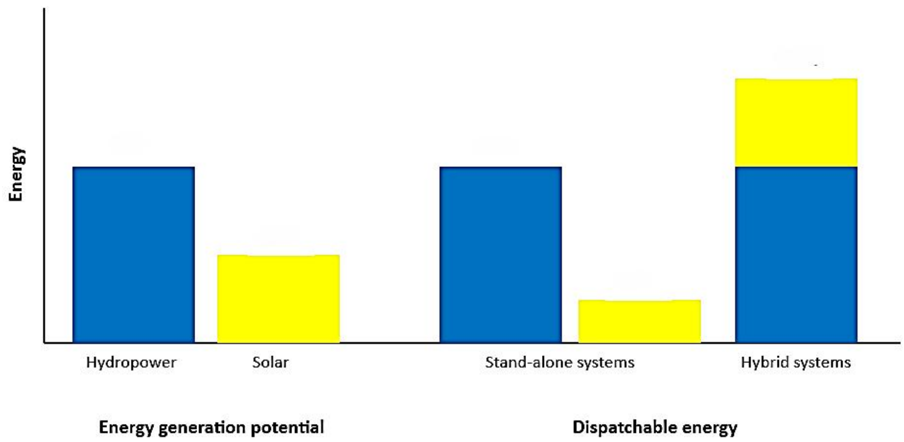

Fig. 8. Energy generation potential and total dispatchable energy for stand-alone systems and hybrid systems redrawn and adapted from [38]

3.2 Reducing the Curtailment of Solar PV

Reducing the curtailment of solar PV means minimizing or reducing the amount of unused or wasted solar energy generated by a PV system. This happens when the generated solar power exceeds demand needed or when grid constraints prevent the integration of the produced electricity. The aim of reducing the curtailment of solar PV is to maximize the utilization of solar energy during peak production periods to ensure the higher percentage of the generated power contributes to the overall energy supply. So, the curtailment of solar PV can be reduced by utilizing solar energy during its peak production hours, thereby preserving hydropower resources for deployment during periods when solar resources are not accessible.

3.3 Reduce Electric Grid Connection Cost

By combining solar PV with other renewable energy such as hydropower, the cost for electric grid connection can be reduced [96]. For example, FPV needs transmission structure to generate electricity. By combining an FPV system with hydropower, it allows for an FPV system to connect with existing transmission structure (transmission lines, transformer and others) [97] and reduce any additional costs [98]. According to the cost evaluation, it has been determined that the additional 35% expenses related to the floating platform in the FPV system will be compensated by the existing grid infrastructure of the HFPV system when compared to both standalone FPV systems and OPV systems [99]. This can be advantageous for both parties since hydropower, solar resources, and appropriate FPV water bodies might not be situated in proximity to load centres or existing transmission systems. Moreover, in the future, expanding FPV capacity within a system is often more feasible and cost-effective through the upgrade of existing infrastructure than creating new interconnections.

3.4 Resource Conservation

Implementing FPV systems on hydropower reservoirs can significantly reduce water evaporation, thereby enhancing the available resources for hydropower generation. The FPV systems shade the water, limiting the amount of sunlight that reaches the reservoir surface, which reduces the solar radiation absorbed by the water which is one of the primary drivers of evaporation [100].

Additionally, the physical presence of FPV panels acts as a barrier, reducing air flow over the water and minimizing wind-driven evaporation. Together, the shading and decreased air movement substantially lower the overall rate of evaporation from the reservoir. Based on study by [95], they estimate that integrating FPV systems with hydropower globally could reduce water evaporation by approximately 74 billion cubic meters, increasing water availability by about 6.3%. This integration is also projected to generate an additional 142.5 TWh of electricity from FPV systems installed on these reservoirs.

Lee *et al.,* [38] proposes three hybridization models with varying costs and performance benefits: co-location hybrid, virtual hybrid, and full hybrid systems. Each of these systems offers distinct approaches to integrating FPV with hydropower technologies.

i. Co-location hybrid systems: These systems integrate two or more technologies, each optimized individually to achieve operational efficiencies. The primary goal of this integration is to realize cost savings.
ii. Virtual hybrid systems: For these systems, two or more technologies are cited separately but the operations are optimized cooperatively to improve the performance.
iii. Full hybrid systems: These systems employ co-optimized planning and operation to enhance both cost efficiency and performance. Typically, these systems consist of a dispatchable technology paired with one or more variable renewable energy sources. Such combinations are designed to optimize benefits in terms of cost savings and improved performance metrics.

Table 5 lists journal articles from the past four years that focus on HFPV systems. It details the methodologies used to analyse these systems, which include both computer-based simulations and experimental techniques. Most commonly, FPV systems are integrated with hydroelectric power, leveraging the plentiful resources available from this type of energy. The articles encompass a variety of research objectives, from evaluating the capacity of hybrid systems to investigating their broader impacts.

Table 5
Recent 4 years journal article of HFPV system

Hybridization	Objective	Method	Location	Year	Ref.
Hydropower reservoir	Analysed the 47.5 MW grid-connected PV plant located on the floatation system at Da Mi hydropower reservoir in Binh Thuan province.	Detail of electrical analysis including DC to DC converters, AC inverters to the transmission network, and PV module connectivity configurations.	Da Mi hydropower reservoir	2023	[101]
Hydroelectric power plants	Examine the 100.74 kW FPV mounted on the reservoir of the 120 MW Santa Clara hydroelectric power plant on impact of atmospheric weather conditions.	Starting with a visual examination of the mechanical condition of the floating modules, followed by a thorough investigation of the anchoring system and computer simulations.	Santa Clara hydroelectric power plant, Brazil	2023	[102]
Wind	Determine the potential to use dam space to build HFPV wind systems in the MENA region.	Design Horizontal Axis Wind Turbines (HAWTS) fitted on the top of dam and analysis using PVSYST simulator.	Wadi Al Mujib dam, Jordan	2022	[103]
Wind	Determine the possibility of combining an offshore floating solar farm into an established Dutch offshore wind farm located in the North Sea.	Combine the FPV solar farm with wind farm by adding cable pooling to increase the efficiency.	Borssele Offshore Wind Farm	2021	[83]
Hydroelectric power plants	Assess the potential impact of implementing the FPV system in the primary hydropower reserves of Egypt.	By using the Helioscope software, the addition of 5 MW FPV for each dam has been analysed.	High Dam and Aswan Reservoir, Egypt	2021	[104]
Hydroelectric power plants	Estimating how much energy and water can be generated by FPV systems in Indian reservoirs and the advantages of HFPV Hydropower Electric Power Plants.	The Helioscope software is used to create a numerical analysis of electrical and meteorological data of the FPV system in the reservoir.	Vaigai reservoir, India	2020	[99]
Wind	To minimize the impact of wind variability on power output through the integration with solar PV systems.	Using Power Smoothing (PS) index to achieve smoother power output between wind and solar energy.	Asturias, Northern Spain	2020	[105]

4. Conclusions

This paper provides an extensive overview of FPV systems, including their components, advantages, and drawbacks. It evaluates the environmental effects and efficiency of FPV systems compared to OPV systems and discusses HFPV systems that integrate solar with other renewable energy sources to enhance efficiency. Key conclusions drawn from the study include:

i. FPV systems are instrumental in advancing renewable energy technologies to meet global energy demands.
ii. According to the Renewables 2022 Global Status Report, solar energy is experiencing the fastest growth among renewable energy sources.
iii. Among solar cell technologies, first-generation cells, including monocrystalline and polycrystalline, demonstrate higher efficiency compared to second and third-generations.
iv. The efficiency of PV cells is influenced by factors such as solar irradiation intensity, cell temperature, and shading.
v. The primary factor enhancing the efficiency of FPV systems over OPV systems is the cooling effect provided by water.
vi. Continued research on factors affecting PV panel efficiency is essential for maximizing energy production.
vii. FPVs are predominantly installed in freshwater environments to minimize corrosion and mitigate the impacts of waves and wind.
viii. The durability of FPV systems in harsh environments must be researched to facilitate further development of FPV technology.
ix. A significant advantage of HFPV systems is their ability to optimize efficiency by exporting power from PV during periods of high solar radiation, while simultaneously allowing the reservoir to recharge or store resources during times of low solar radiation.

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