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Floating Solar Photovoltaic: A Critical Review of Improvements in Thermal Competence, Cost-Effectiveness, and Hybrid System Integration

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Abstract

This paper provides a critical review of the design, performance, and integration opportunities of Floating Photovoltaic (FPV) systems in accordance with the growing need sustainable and land-efficient renewable energy systems to overcome land-use constraints and enhance energy production through floating deployments. The methodology is based on the PRISMA principles and entails a systematic review of peer-reviewed articles published between 2020 and 2026, and the findings are categorized into three key themes: performance and efficiency analysis, technical and economic feasibility, and hybrid system integration. Key results show that FPV systems have a consistent and consistently better performance over ground-mounted PV, with a range of temperature reductions of 2-11°C and energy yield improvement between 2-28%, with such variability being attributed to the changing of local climatic conditions (tropical vs. temperate) as well as the system design (tilt angle, mounting height, and inter-row spacing) and testing conditions (wind speed, irradiance, and water temperature differentials). Other advantages are evaporation cuts of up to 49%, even payable cost of electricity (LCOE) of 0.036-0.10 \$/kWh, payback periods of 4.7-8.4 years, and reductions in water of up to 105000 kL per year. The review concludes that the FPV technology is a potential and feasible source of renewable energy in various climates, especially when used in combination with hydro power or offshore wind energy.

Keywords: Floating photovoltaic; Performance analysis; Techno-economic feasibility; Hybrid energy systems; Renewable energy integration.

1. Introduction

In recent years, the process of moving to renewable energy worldwide has gained impetus, and this is due to the pressing necessity to eliminate climate change and ensure that fossil-based fuels are not relied upon [1]. It is against this backdrop that the selection of hydrokinetic and renewable energy sites has become mature, and researchers have devised elaborate methodologies for assessing potential sites [2]. The floating photovoltaic (FPV) systems have become one of the most discussed examples of emerging renewable energy technologies that can be implemented to overcome the problem of land shortage and provide certain opportunities that ground-mounted solar plants do not offer [3].

Floating photovoltaic systems are developed with great consideration of the plethora of technical and environmental issues, especially when they are implemented in harsh marine conditions. Among the design factors, there are structural integrity, resistance to waves, corrosion resistance, and anchoring system that should withstand the harsh oceanic conditions [4]. In determining the sustainability and security of such installations in the long term, researchers have established advanced methodologies of gauging on the dynamic response and structural integrity of floating photovoltaic installations under different loads of the environment, such as wind, waves, and currents [5]. These evaluation systems play a significant role in streamlining the system guidelines and structural breakdowns.

Levelized cost of energy (LCoE) methods have been widely used to investigate the economic feasibility of floating renewable energy systems, which can be used to make investment and policy decisions [6]. Certain area analyses have shown great promise of optimised floating photovoltaic systems, with some studies in the Northern Lakes of Egypt showing high potentials of electricity generation when systems are designed in accordance with the local weather conditions [7]. Additionally, FPV systems have been noted through elaborate technical and economic analysis to hold some synergies in the water-energy nexus that can help to produce electricity, minimise water evaporations, and enhance water quality at the same time [8].

Inclusion of floating photovoltaic systems within wider energy planning is now a matters of concern, especially in areas where water shortage and energy needs are imminent. Urban and rural planning efforts are starting to use FPV technology in water-energy-food nexus systems, as the systems have multifunctional opportunities [9]. Offshore floating solar farms have been economically feasible to study in several geographical locations, with some works in the Levantine-Balearic region of Spain showing positive economic payoffs under good conditions [10]. These studies have cost-efficient methodologies, which take into account capital expenditure, operational cost, and the production of energy potential [11].

The approach to holistic site selection has been designed to single out the best location to set up hydrokinetic and floating renewable energy schemes, taking into account the environmental, technical, and socioeconomic parameters [12]. Recent developments are the innovative methods to apply the complementarity criteria by the process of resource assessment, especially hybrid power plants that include offshore wind and floating photovoltaic systems [13]. Thorough analyses of floating

photovoltaic systems and energy storage options have offered essential findings of system designs maximization of performance, as well as integration plans [14].

With globalization heading towards the decarbonization agenda, there is a need to adopt diverse and pragmatic approaches to the green energy change that account for the regional differences in resources, infrastructure, and development imperatives [15]. Knowledge on floating solar power plants has been interdisciplinarily reviewed in literature that has offered extensive frameworks of what constitutes the multidimensional nature of this technology [16]. Studies have investigated the possibility of novel solar installations and their role in the achievement of zero-energy buildings even in high-latitude cities with scarce solar resources [17].

The spatial variations in economic feasibility have been determined by the levelized cost of energy of floating solar photovoltaics in particular regions, including the Mediterranean Sea, and optimal deployment areas have been defined by detailed mapping and sensitivity analysis of the cost of energy [18]. Other tests involving the European Atlantic, the North Sea, and the Baltic Sea have increased our knowledge about the FPV capacity in different marine conditions [19]. Niche uses of floating solar technology, such as floating solar stills and solar-powered membrane systems, have shown that this method can be used extensively to meet water purification requirements in addition to energy production. Systematic reviews of the siting factors have established important aspects that define the success of FPV implementations, such as environmental effects, regulatory mechanisms, and stakeholder consultation [20]. The technological reviews of FPV systems have included the development of the technology, with emphasis on the latest innovations in the inventions, materials, and strategies of operation [21].

Figure 1 shows a bibliometric network visualization of the floating solar photovoltaic (FPV) research published from 2020 to 2026, which shows the mutual connectivity between the main themes, authors, and publications in this new area. The network probably emphasises the main clusters of research like performance analysis, techno-economic feasibility, hybrid system integration, and environmental effects, and fatter lines give the impression of co-citation or collaboration. This map highlights the multidisciplinary aspect of FPV research that connects engineering, environmental science, energy policy, and economics, and can be considered an aesthetic way of identifying the most influential publications, promising trends, and research gaps that can be used to determine the direction of future research.

Although the available FPV reviews tend to address rather fragmented issues like thermal performance or cost-efficiency in different climates, a systematic review that concurrently measures the performance gains, cost-effectiveness in various climates, and the potential of hybrid integration in a systematic meta-analytical framework has not been developed yet. This is a big gap since in the absence of an integrated, evidence-based synthesis, policymakers and system designers would have no such benchmarks as they could use to direct deployment strategies and investment decisions across different geographic and operational contexts. As such, we have reorganized the final paragraph of the Introduction so as to bring out this gap clearly and show how it directly drives the triple goal of the paper, which is to critically

review performance, economic feasibility, and hybrid integration within a single PRISMA-directed methodology.

Whereas current Floating Photovoltaic (FPV) literature review often considers individual elements of performance, such as thermal performance or cost-effectiveness, this paper offers a synthesis based on PRISMA, which simultaneously measures performance improvements on a wide scale in a wide variety of climates and examines the potential of hybrid integration critically, which is a crucial void in the literature. We also indicate that the integrated framework provides operational benchmarks to policymakers in energy and water resource planning, guidance in practical design to engineers and system developers, and a consolidated evidence base to those researchers engaged in sustainable deployment of renewable energy.

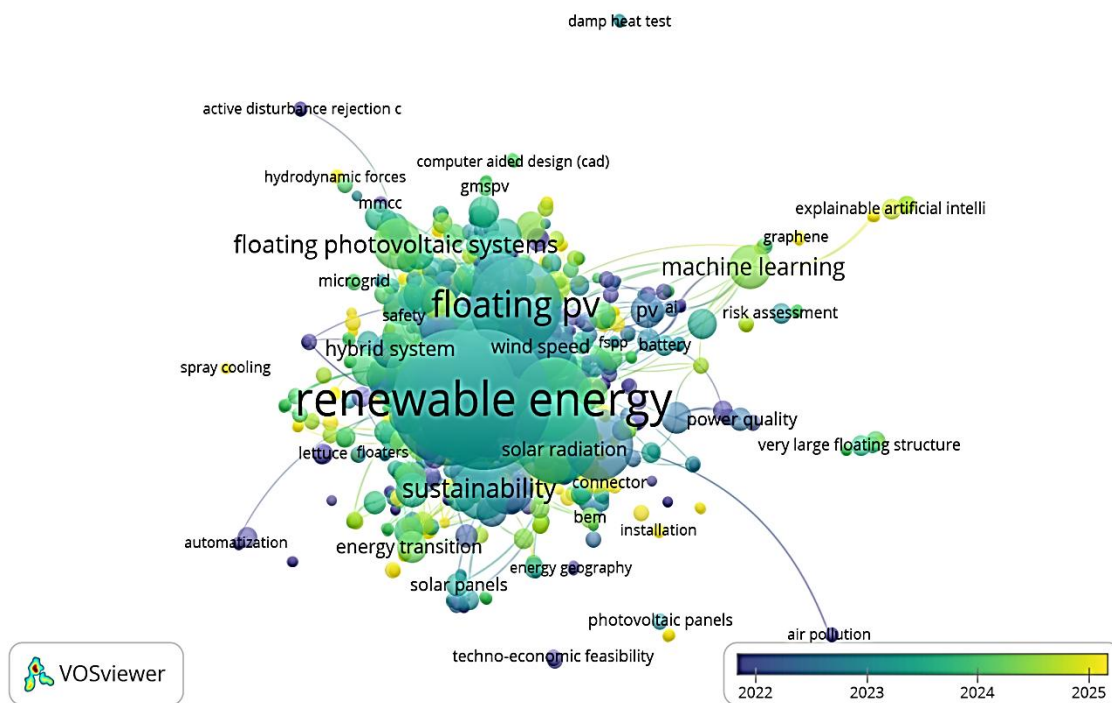


Figure 1. Bibliometric Network of Floating Solar Photovoltaic Research (2020–2026).

2. Methodology

The literature review of this review paper is based on a systematic review of recent and pertinent research on FPV systems with an overview of the survey period between 2020 and 2026 to ensure capturing of the current research and technological developments. To achieve methodological rigor, transparency, and reproducibility, the review is based on the guidelines of Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA). It entailed a methodical search, screening, and selection of peer-reviewed literature in the scientific databases, after which thematic synthesis of the results was carried out and categorized into three broad areas: performance and efficiency analysis, technical and

economic feasibility, and hybrid systems and integration. Critical evaluation was conducted of each of the studies, and important data, including exergy efficiency, levelized cost of electricity, capacity factor, water savings, and environmental impact data, were extracted and summarized in comparative tables to make a meta-analytical evaluation of the performance trends and cost-effectiveness of various FPV architectures and geographical locations.

2.1. Performance and Efficiency Analysis

In their study, Kumar et al. (2020) [22] used an exergy-based parametric method to examine the realistic performance and energy conversion mechanism of a PV module based on amorphous silicon thin-film closely installed as ground-mount PV (GMPV), floating PV (FPV), and submerged PV (SPV) in water and land conditions, as shown in Figure 2. The submerged design is the creation of panels that have been placed below the water to use the cooling effect to achieve the desired efficiency, but the design has some challenges associated with the light attenuation and sealing of the structure. The floating technique affixes panels to water bodies on floating platforms, which save land area and instead make use of a natural cooling effect of water and is susceptible to strong mooring mechanisms. Conversely, the ground mount is a traditional method, that has fixed racks on the ground, which are fairly easy and simple to maintain but subjected to greater temperatures of operation and limitation of land use. Figure 3 above represents the values of thermal exergy, with GMPV recording the highest thermal exergy at 16 W (because the operating temperature is greater and because the cooling effect of the surrounding water is limited), FPV, and SPV demonstrating a thermal exergy of 10.22 W and 6.38 W, respectively. Conversely, Figure 4 shows the electrical exergy output, and FPV has the highest electrical exergy output (47 W) compared to GMPV (37.22 W) and SPV (32.24 W), which means that the floating set-up is the best balance between thermal control and effective electrical power conversion. All of this illustrates that, whereas ground-mounted structures have a thermo-loss and submerged structures have a reduced electrical yield, floating photovoltaic structures provide a better trade-off by exploiting the cooling afforded by water to increase their exergetic efficiency.



Figure 2. An experimental configuration of a solar module using submerged, floating, and ground-mount installation techniques [22]

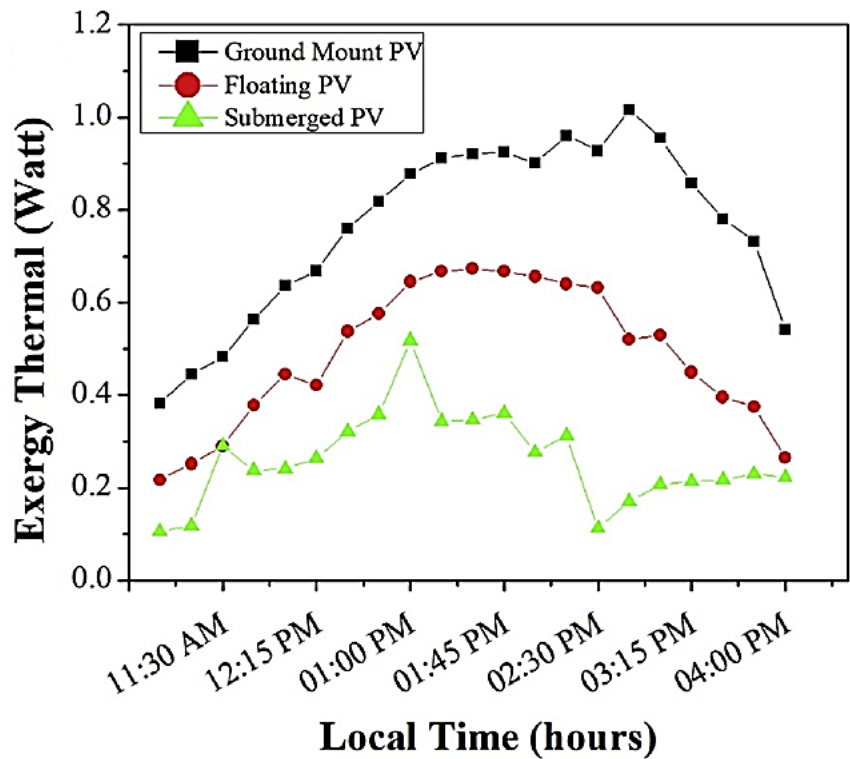


Figure 3. Exergy thermal [24]

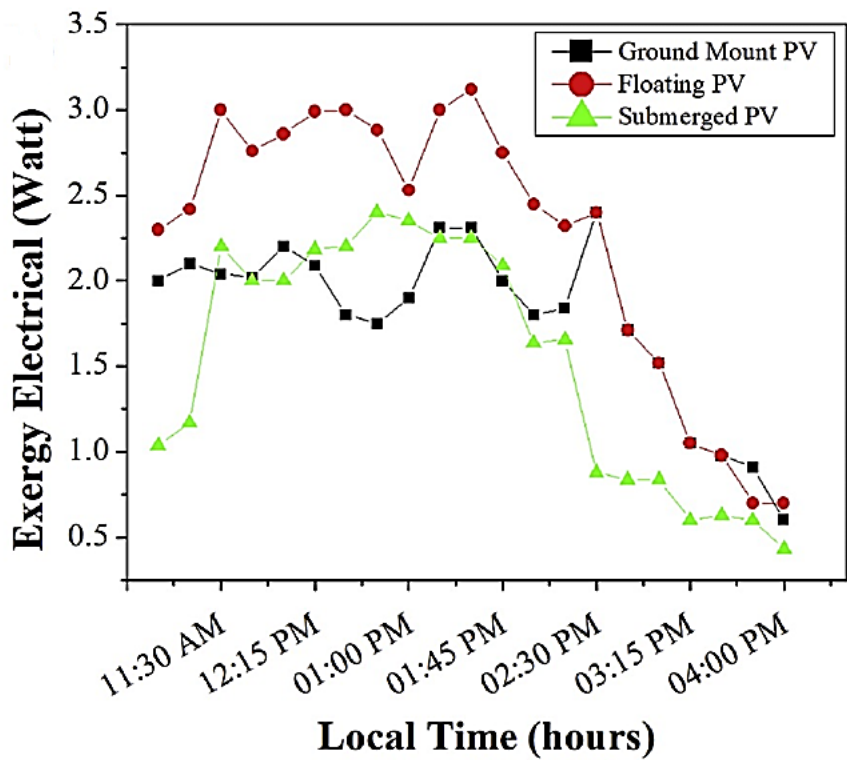


Figure 4. Exergy electrical [22]

According to Elminshawy et al. (2021) [23], an improved superiority of floating photovoltaic (PV) technology was developed through an original partially floating system (FPVWS) to maximize the energy capture via the underwater portion that allows stable temperature control in the PVs by exchanging heat with the ambient water, and high efficiency of electricity generation was achieved. A test system was designed to test the new FPVWS system in real windy conditions, and the findings indicated that the operational temperature of the FPVWS decreased by 11.60%, the output power experienced an increment of around 20.28 percent, and the electrical efficiencies increased by 32.82% as the wind speed increased by 49%. The submerging technique and the good direction of the northerly-westerly wind flow also added to the performance of the FPVT module, and that formed the biggest part of its gains. Moreover, with the same increase in 49% wind speed, the cost of energy became leveled by 17% and the average CO₂ emissions over the world were cut by 69.51 kg CO₂/summer.

El Hammoumi et al. (2021) [24] provided an experimental study of a small-scale Floating Photovoltaic System (FPVS) as illustrated in Figure 5 that was aimed at a preliminary effort to examine this concept in Moroccan conditions. The experimental design and measurement station, and the design and the experimental setup of the FPVS were described, with the authors comparing the electrical and thermal performance of the FPVS with an overland PV system (OPVS) of the same capacity. The findings revealed that the average temperature of the FPV modules was found to be 2.74 °C lower than the OPV modules because of the cooling effect of water, which increased the efficiency and caused 2.33% more energy to be generated on a daily basis. Further experiments on comparing FPVS energy production at the various angles indicated that when the string was tilted at the optimal angle of 30°, the highest power was generated, and the lowest power was generated at 0° as shown in Figure 6.

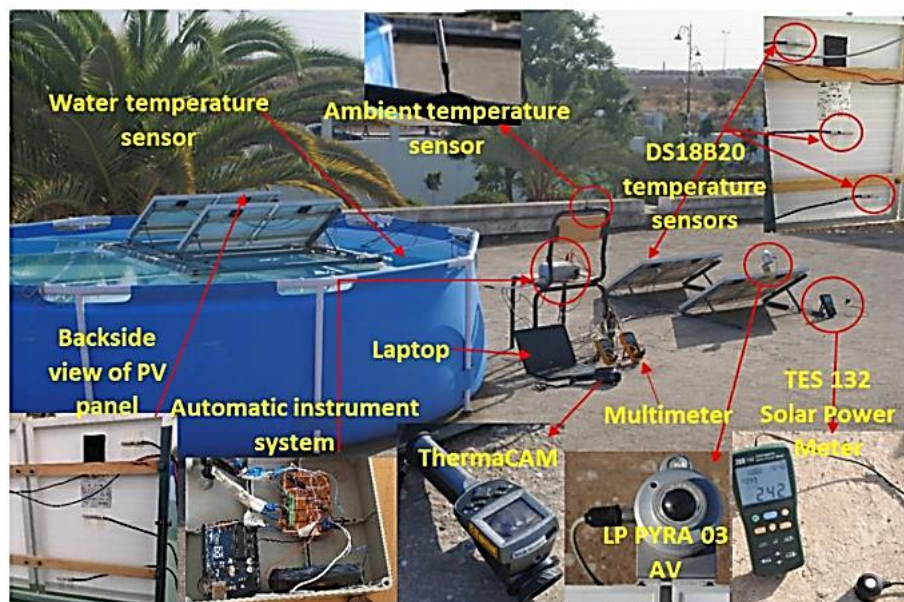


Figure 5. Test bench setup for the experiment [24]

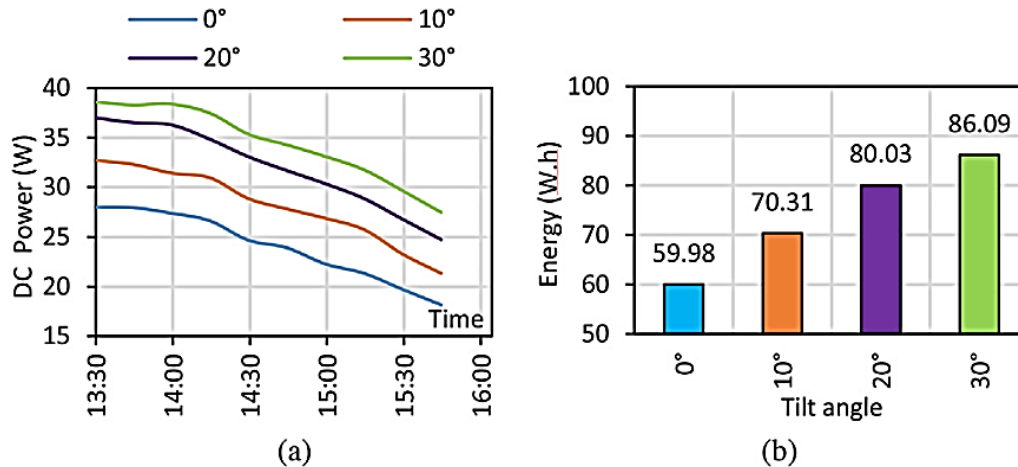


Figure 6. The FPVS's instantaneous DC power (a) and generated energy (b) at various tilt angles throughout the test period [24]

In Figure 7, Goswami et al. (2021) [25] presented their experimental data using the techno-economic feasibility and reliability study of a floating solar photovoltaic (FSPV) power plant over 17 months. They have analyzed a mean performance ratio and degradation rate of 71.58 percent and 1.18%/year of the FSPV module with respect to a land-based system of 64.05 percent and 1.07/year. Applying this 1.18% per year degradation to a modeled 5 MW FSPV plant means that the average generation per year should be 8604.5 MWh, and the levelized cost of electricity (LCOE) would rise by 2.5 % to 0.041\$/kWh. Significant environmental benefits were also measured by the study, as the FSPV plant will save 105,000 kL of water per year through evaporation reduction, and a lifetime CO₂ saving 183,493.24 ton will be achieved. In the performance analysis, certain loss factors were broken down: 1% due to irradiance, 13.3% due to temperature, 1% due to module array mismatch, 1.1% due to DC ohmic losses, 1.6% due to inverter, loss and 0.1% due to AC ohmic loss, all as listed in Figure 8.

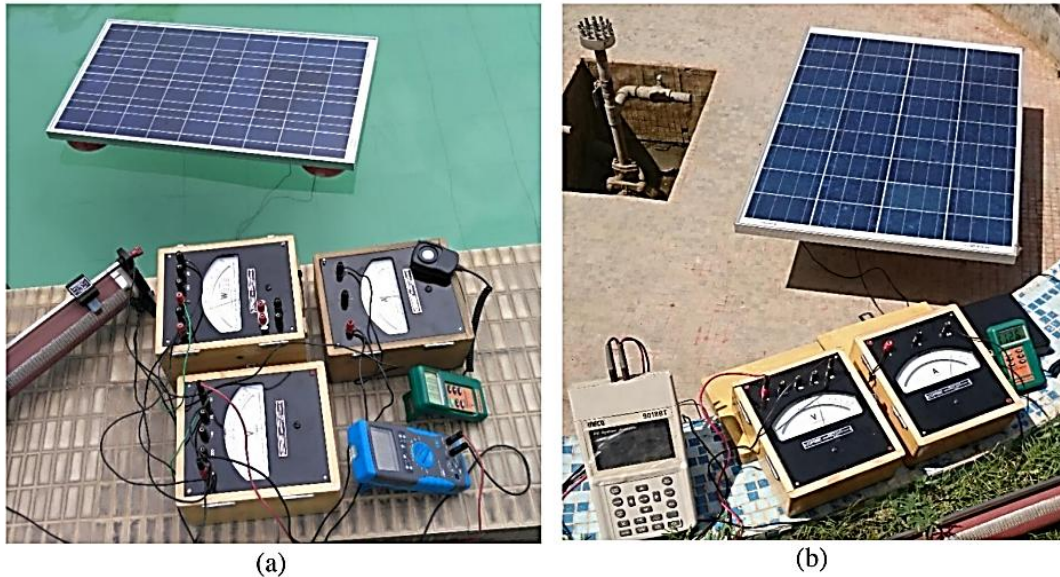


Figure 7. FSPV system experimental setup (a) (b) System based on land [25]

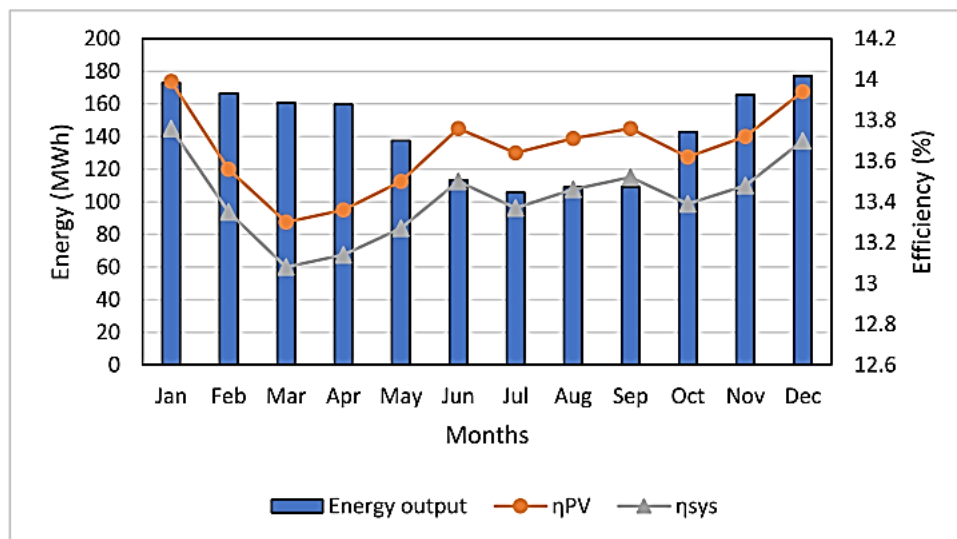


Figure 8. The FSPV system's energy output and efficiency [25]

Nisar et al. (2022) [26] published experimental results of a small-scale FPV system's thermal and electrical performance of mono and polycrystalline FPV modules were compared to comparable On-Ground PV (OPV) systems using a custom test bench; their results showed that, with partial FPV coverage, water evaporation decreases by 17% and with full FPV coverage, evaporation decreases by about 28%, with the water body providing a cooling effect, and the front temperature of the FPV Thermal images indicated that there was a uniform temperature on the front at 0° tilt, but both the bottom and middle of the modules indicated a variation in temperature as the tilt increased. Further experimentation of power generation under varying tilt angles showed that the FPV system generates the highest power at the annual optimum tilt angle, which caused the suggestion that optimum tilt angles should be adjusted

to FPV panels, interestingly although the FPV system at 0° is generating 20 to 28% more energy than the OPV system at 0° , the optimum tilt angles still give better results.

Hafeez et al. (2022) [27] estimated the potential of a floating photovoltaic (FPV) system on an urban lake surface to determine its scale and compare it with a similar photovoltaic system on the ground using the System Advisor Model (SAM) based on an example in Pakistan. The technical analysis was based on monitoring the impact of a temperature decrease in real time and estimating the efficiency of water reduction in the FPV system, and economic feasibility was evaluated based on such parameters as net present value (NPV) and payback period. It should be mentioned that in an urban location, the deployment of the FPV is liable to soiling, and the cleaning water price of a traditional system is at a one-time extraction price of \$1435, in comparison with the FPV system at an estimated price of \$1.35. Based on a temperature decrease of 10°C , the capacity factor of one year under standard temperature conditions (STC) is 0.70% higher in the lake case to yield an extra amount of energy of 64 kWh/kW. The overall power potential of the whole NUST Lake is 4.47 MW, and a 1 MW FPV system in the location would reach a water reduction efficiency of 11.6%\$/year.

To compute U-values of common FPV technology, Lindholm et al. (2022) [28] used Computational Fluid Dynamics (CFD) to assess temperature profiles in the wafer layer, and our findings revealed that a float with a large water footprint produces a significantly non-uniform temperature field in the wafer layer. Researchers supported the fact that cell temperature rises as a result of reduced wind velocity and high solar radiance and air temperature, whereas we discovered that water temperature does not considerably affect cell temperature. Radiative heat transfer between the rear of the module and the water was estimated to generally reduce cell temperature by less than 1°C . Since the technologies, although dissimilar, nevertheless characterize systems with a high water footprint, the U-values provided by the authors were considered to be in good agreement with the literature values obtained in the FPV field research in Singapore and in the Netherlands.

A feasibility study in Ghana by Alhassan et al. (2023) [29] on a 420 MWp floating photovoltaic (FPV) system on a $4.66\text{ kWh/m}^2/\text{day}$ solar-irradiated area of the Akosombo Dam reservoir, in the article, recommends building a 500,000 panel plant yielding 520,233 MWh of electricity each year with a 14.1% capacity factor. This project would conserve a total of 73,327 cubic meters of water that would otherwise evaporate per year to generate approximately 10 MWp of hydroelectric energy annually, and an economic analysis indicated a low levelized cost of energy (LCOE) of US\$0.10/kWh, annual revenue of US\$52, 238,576.00 and a simple payback period of 12 years, a good economic payback. Moreover, it would reduce the emission of greenhouse gases by 308,904.5 tCO₂ per year, showing that the FPV-hydropower hybrid plant is viable and it can make Ghana achieve its goal of adding 10% more renewable energy, as shown in Figure 9.

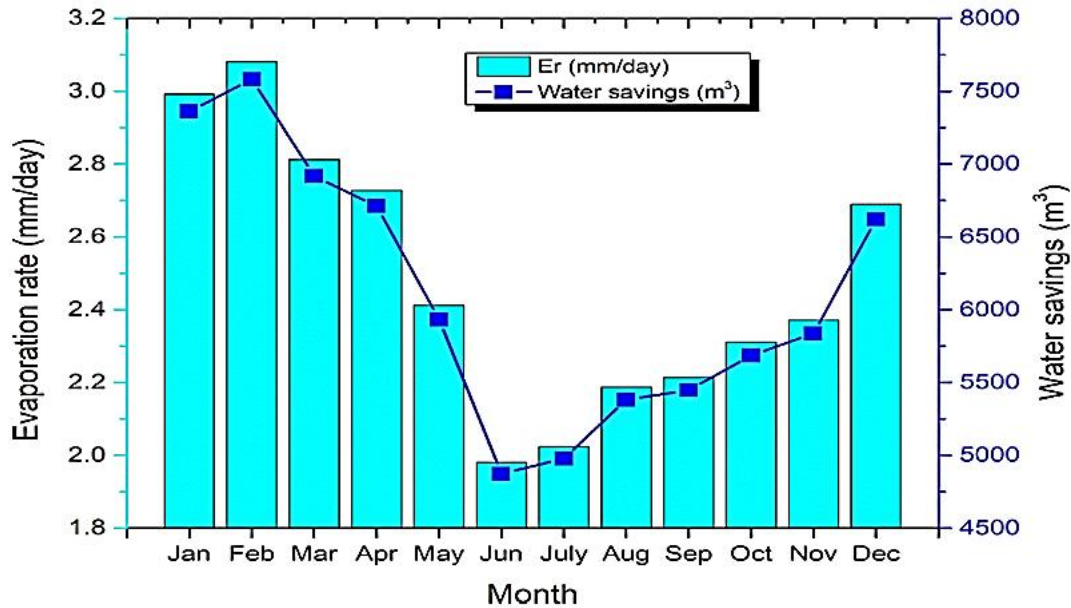


Figure 9. Hybrid FPV-hydro systems' potential to reduce evaporation and save water [29]

Yakubu et al. (2023) [30] in their study (50 MW and 400 kW) compared the potential energy output of 50 MW and 400 kW bifacial photovoltaic (PV) systems on land versus existing monofacial PV systems of the same size and design in Bui, Ghana, through ground weather files and PV configurations to simulate the system yields based on capacity factor, performance ratio, and monthly/annual energy. The specific yield of the 50 MW land-based monofacial system was 1533.96 kWh/kWp annually and 1544.40 kWh/kWp of the bifacial system, as presented in Figure 10. The findings showed that land-based and floating systems were bifacially gaining 2.51 and 4.57%, respectively, where the capacity factor and performance ratio of the bifacial technology were higher; thus, the extra energy was not considered worth the new installations, as shown in Figure 11. The research therefore suggests the optimization of parameters such as albedo (0.5), tilt (15°), and ground cover ratio (0.3) to improve the performance and bifacial gain.

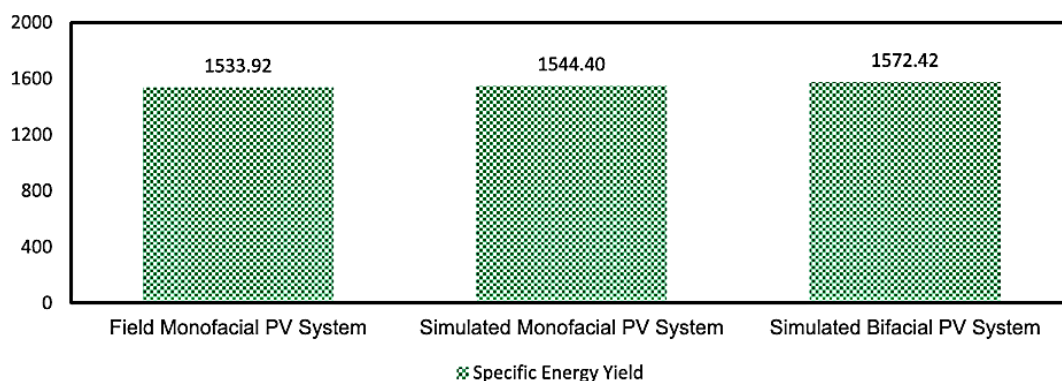


Figure 10. Land-based photovoltaic system final energy yield [30]

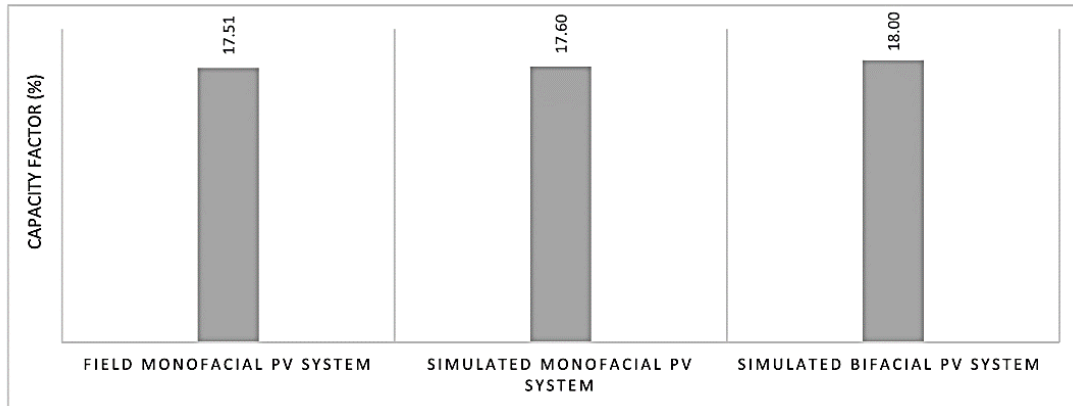


Figure 11. Land-based monofacial and bifacial photovoltaic systems' capacity factor [30]

Ground-mounted and floating solar photovoltaic systems in the Ghanaian Bui Generating Station (Dzamesi et al., 2024) [31] revealed that tests conducted on floating PV systems indicate that they are more profitable in performance, such as the low operating temperatures, ability to produce more energy, and efficient land use; nevertheless, they are more prone to corrosion in aluminum frames and other metallic mounting elements, which can be resolved by making changes in the design. The study has shown the feasibility of FPV systems being used as a strategic instrument to achieve the renewable energy goals, and as the technology advances, the systems will help create a more sustainable and environmentally friendly energy environment.

Ramanan et al. (2024) [32] tested the effect of wind, ambient temperature, water temperature, height, and tilt angle on an FPV system and compared the outcome temperature drop caused by the wind and water cooling to a free-standing module cooled solely by the wind in NOCT conditions. They conducted numerous studies in the form of parametric studies to optimize the design of FPV using CFD simulations with a finite volume approach of a 2D PV module and concluded that a minimum temperature difference of 5 °C between wind and water is necessary to be able to have good heat transfer in FPV. As shown in Figure 12, their results show that at a lower height and at a lower tilt, FPV cooling is preferable, but at a higher tilt, above 55 degrees, the NOCT PV module is colder; in FPV, the highest possible PV cell cooling is obtained at a 0° tilt and a height of 1500 mm, and the NOCT at a higher height and tilt is 6 °C more. The temperature that the FPV solar cell would be subjected to was simulated within the range of 49.73 °C to 51.30 °C which is depicted in Figure 13. It shows that mounting height as well as the tilt angle of floating photovoltaic (FPV) panels are important factors that affect cell temperature. A higher tilt angle tends to lower cell temperature as more heat is convectively removed, but especially at a lower height of mounting since the nearness to a cooler water surface gives an added cooling effect. An increase in the panels, on the contrary, decreases the positive impact of water-cooling, thus increasing the cell temperatures of all the tilt angles, with the maximum cell temperatures being recorded when the panels were mounted at a high height and with a low tilt angle.

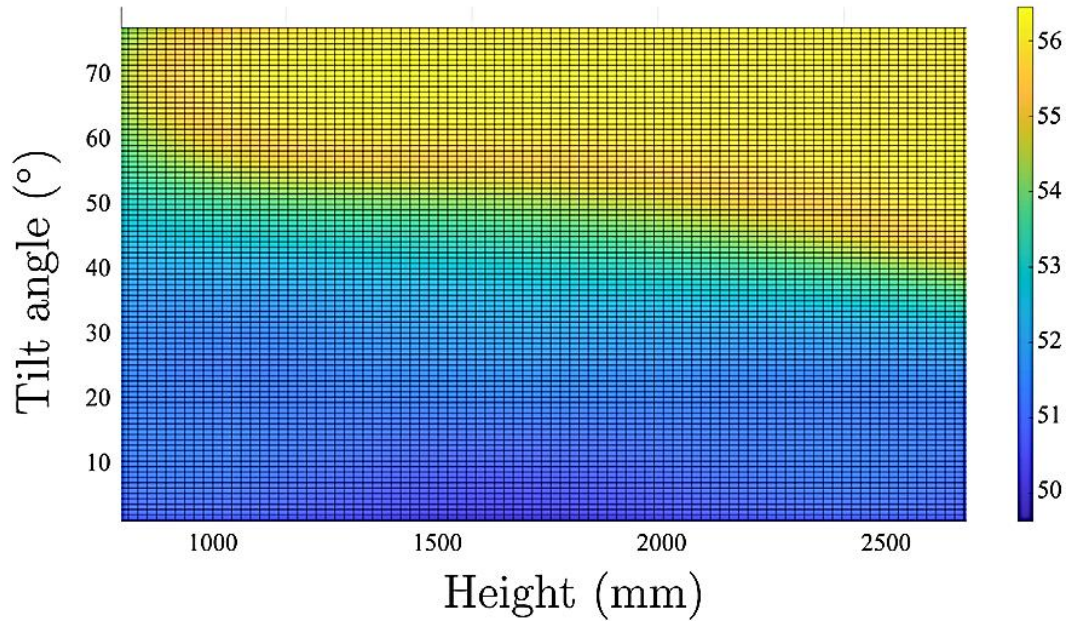


Figure 12. The temperature difference in solar PV cells caused by different tilt angles and heights for FPV at 1 m/s wind speed, 800 W/m² solar irradiance, 30 °C wind, and 20 °C water temperature [32]

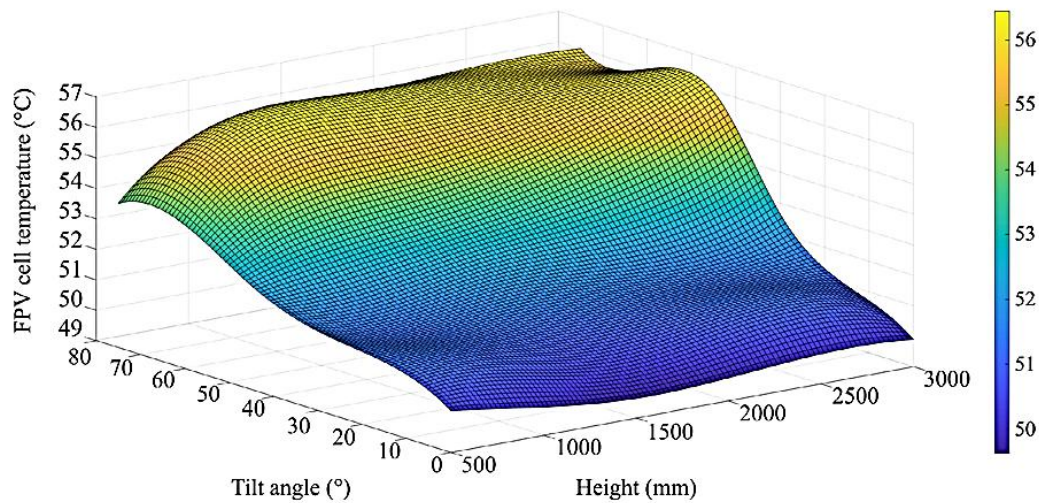


Figure 13. Effects of height and tilt angle on FPV cell temperature at 1 m/s wind speed, 800 W/m² solar radiation, 30 °C wind, and 20 °C water temperature [32]

The study by Ramzan et al. (2025) [33] involved the evaluation of the feasibility of a Floating Solar Photovoltaic (FSPV) system installed on Dal Lake in Kashmir using the System Advisor Model (SAM) and technical assessment with respect to the performance of PV panels under temperature change and economic analysis based on net present value (NPV) and levelized cost of energy (LCOE) and payback period. The comparison of a 100 kWp FSPV system with a land-based photovoltaic (LBPV) system of equal size revealed that the FSPV system operating at a 5° tilt produced 0.14 GWh each year, 4.7% higher than the 0.1 GWh of LBPV and 25% higher than the capacity factor. The paper has also established that with an increment of 4 °C in the module temperature, the yearly output reduced by 1

MWh and the yield of energy reduced by 5 kWh/kW in both systems. The FSPV system had a payback period of 4.7 years as opposed to 6 years in the LBPV system, economically. Table 1 shows a summary of studies outlining that are related to performance and efficiency analysis.

Table 1. A summary of studies outline that are related to performance and efficiency analysis.

Authors (year) reference	Configuration	Studied parameters	Highlighted results/findings
Kumar et al. (2020) [22]	GMPV, FPV, SPV installation methods	Exergy efficiency, thermal and electrical exergy	SPV had 3.07% higher exergy efficiency than FPV and 43.65% higher than GMPV; FPV recorded the highest electrical exergy (47 W)
Elminshawy et al. (2021) [23]	Partially floating FPV system (FPV~WS~)	Temperature, output power, efficiency, wind speed, LCOE, CO ₂ emissions	Temperature reduced by 11.60%, power increased by 20.28%, efficiency increased by 32.82%; LCOE reduced by 17%, CO ₂ reduced by ~69.51 kg/summer
El Hammoumi et al. (2021) [24]	Small-scale FPVS vs. OPVS	Temperature, energy yield, tilt angles	FPV modules cooler by up to 2.74°C; FPVS generated 2.33% more daily energy; optimal tilt angle = 30°
Goswami et al. (2021) [25]	FSPV vs. land-based PV	Performance ratio, degradation rate, LCOE, water savings, CO ₂ savings	FSPV PR = 71.58%, degradation = 1.18%/year; LCOE = \$0.041/kWh; water saved = 105,000 kL/year; CO ₂ saved~ 183,493.24 tons lifetime
Nisar et al. (2022) [26]	Small-scale FPV vs. OPV	Temperature, evaporation reduction, tilt angles	Evaporation reduced by 17% (partial cover) and 28% (full cover); FPV modules cooler by 2–4% front and 5–11% back; optimal tilt improves energy yield
Hafeez et al. (2022) [27]	FPV on urban lake vs. on-ground PV	Temperature drop, water reduction efficiency, NPV, payback	Additional yield = 64 kWh/kW with 10°C drop; water reduction efficiency = 11.6%/year; FPV more economical

Lindholm et al. (2022) [28]	CFD modeling of FPV with large water footprint	U-values, temperature field, wind, irradiation, water temperature	Cell temperature is affected by wind, irradiation, air temperature; water temperature had a minor effect; U-values comparable to field data
Alhassan et al. (2023) [29]	420 MWp FPV on dam reservoir	Capacity factor, water savings, LCOE, revenue, CO ₂ ~ reduction	Capacity factor = 14.1%; water saved = 73,327 m ³ /year; LCOE = \$0.10/kWh; revenue = \$52.24 M/year; CO ₂ reduced~ 308,904.5 t/year
Yakubu et al. (2023) [30]	Bifacial vs. monofacial PV (land and floating)	Capacity factor, performance ratio, energy yield, bifacial gain	Bifacial gain: land = 2.51%, floating = 4.57%; bifacial PR and CF higher; optimization of albedo, tilt, ground cover ratio recommended
Dzamesi et al. (2024) [31]	FPV vs. ground-mounted PV at Bui Generating Station	Temperature, energy generation, area efficiency, corrosion	FPV cooler, higher energy yield, better area use; corrosion risk noted; design modifications recommended
Ramanan et al. (2024) [32]	CFD simulation of FPV under varying environmental conditions	Wind, ambient/water temperature, height, tilt angle	A minimum 5°C difference between wind/water needed for heat transfer; optimal: low height and tilt (0°, 1500 mm) for cooling
Ramzan et al. (2025) [33]	FSPV vs. LBPV in temperate region	Energy output, capacity factor, temperature effect, payback	FSPV produced 0.14 GWh/year vs. 0.1 GWh for LBPV; capacity factor 4.7% higher; payback = 4.7 years vs. 6 years

2.2. Technical and Economic Feasibility

In a study by Rauf et al. (2020) [34], a floating solar photovoltaic (FSPV) plant is considered to be located at a small reservoir in Pakistan and evaluated the grid interconnection at 500 kV, 132 kV, and 11 kV voltage parameters and developed a hydro-solar optimization framework of an efficient use of energy. Their findings indicate that the systems of 200 MWp FSPV and hydro together produce a power

that is greater than that of hydro at over 3.5% with the added advantage that the generation of FSPV happens at the same time as the national grid's midday peak load, thus can serve as a peaker plant.

Recently, Shyam and Kanakasabapathy (2022) [35] have investigated the possibility of a small-scale floating solar photovoltaic (PV) integrated Pumped Storage Hydroelectric (PSH) system in India under a subsidized Time-of-Day tariff by highlighting the imperative to explore and consider new reservoirs and water bodies in hilly areas to store energy and integrate renewable energy. They developed a system operation-based objective function and constraints, approximating the levelized cost of solar energy and stored energy to evaluate the economics of system, and created a linear programming-based solver algorithm to optimize system scheduling. Their findings validated the feasibility of the methodology. The analysis provided a levelized cost of 0.8518₹/kWh of floating solar PV and 4.2713₹/kWh of stored energy with the help of existing cascaded reservoirs, whereas the proposed system resulted in lower costs per day of operation and loss of load probability than a grid-only system, which proves economically viable even under an established system with subsidized static tariffs.

In a work by Agrawal et al. (2022) [36], the authors simulated the technical potential of FPV power generation, assessing the sustainability of the technology in terms of its potential energy generation, water savings, and its capacity to conserve farmland. The authors calculated the maximum power of 6513 MWp of 25% coverage of the entire covered area of submergence at the Rajghat dam in south Uttar Pradesh, India, to produce an annual power of 10,623,501 MWh. Authors also record one extra advantage of minimizing yearly evaporative losses by 1395 cubic meters per MWp (or 0.9 liters per kWh). To measure economy, Levelized Cost of Energy (LCOE) is reported to be 0.036\$/kWh (INR 2.61/kWh) with an internal rate of return (IRR) of 8.55%, which is a very promising parameter in the context of large-scale implementation of a Floating Solar PV (FSPV) plant.

Farrar et al. (2022) [37] simulated different FPV setups on a possible installation on an already existing irrigation reservoir through their study of a dry and water-stressed desert area in Jordan based on real-world consumption data. They concluded that the best design was fixed-tilt 300 kWp FPV, which was a compromise of conserving water, generating energy, and being economically viable, as well as reductions in CO₂ emissions compared to ground-mounted PV or FPV with tracking and active cooling. The recommended system will require a payback period of 8.4 years, cut down the amount of greenhouse gas emissions (per year) by about 141 TCO₂ and save about 12,700 m³ (42%) of water per annum relative to the uncovered reservoir, with the best payback cost in terms of net present value being 20°, as shown in Figure 14.

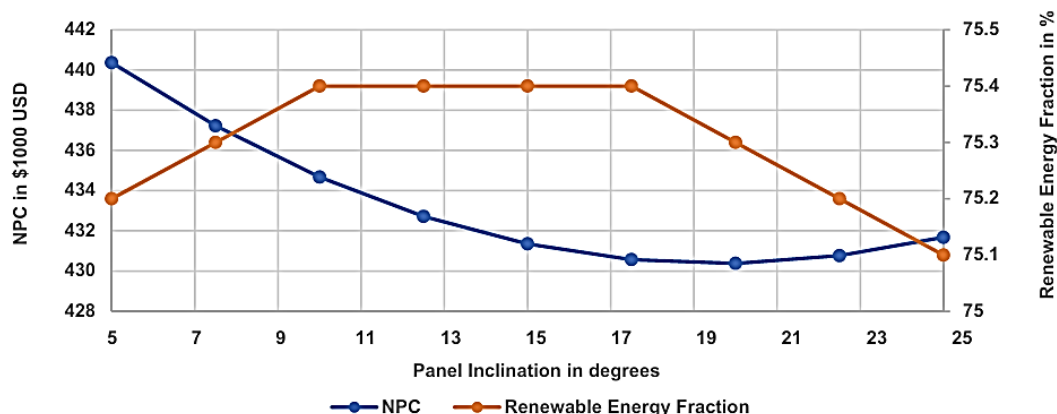


Figure 14. Panel inclination effects on NPC and the percentage of renewable energy [37]

Nasir et al. (2023) [38] evaluated a lower-cost and sustainable approach to enhance the water, energy, food, and ecosystem nexus in dry regions and proposed a hybrid system of 200 MW Paras pumped storage hydropower, 30 MWp floating solar photovoltaic, and 300 MW Balakot conventional hydropower to store energy given to the grid. The authors identified the cost of energy storage at the level by considering the conventional hydropower resources, water stream dynamics, and floating solar PV installation. The innovation of the study shows a reduction of the levelized cost of energy storage by 28%, an increase in the benefit-to-cost ratio by 56%, and a cut in the installed costs by 25% of a greenfield closed-loop pumped storage hydropower project. This mixed structure has the ability to produce an additional 3693 GWh of clean energy, which translates to a 30% increment in revenue over a 30-year period when compared to the green field closed-loop alternative.

The cost analysis of a lifetime study of an exemplar floating PV farm was given by Martinez and Iglesias (2024) [39], considering site-specific, such as the depth of water and the distance to the shore, and estimation of the energy production based on local reanalysis data. Their findings emphasize the main role of solar resources and distance to shore, the latter since it affects the costs of installation, though the role of water depth is secondary. The authors establish southern nearshore locations, especially in Spain and Portugal, as the lowest LCOE of about 250 EUR/MWh, and LCOE rises with latitude to about 650 EUR/MWh in Norway, the North and the Baltic Seas with, LCOE of about 400 EUR/MWh and 440 EUR/MWh, respectively. In addition, the LCOE of different floating platforms and PV technologies was analyzed in order to identify possible cost savings. These LCOE values are expected to go down with technological improvements in the future, supply chain maturity, and economies of scale, although at the following stage, these LCOE values would remain non-competitive in the absence of subsidies or feed-in tariffs.

The design that offers a full-fledged technical, environmental, and economic analysis of designing a PV water pumping system is presented in al-Smairan et al. (2024) [40], where the author suggests the installation of PV panels on a water lake to enhance efficiency and aesthetics, and the system consisted of a 165 kW PV array and three 55 kW inverters with the initial cost of 54696.92 JD, a reduction in CO² emission by more than 5000 tons, and the findings were that two sizing approaches, i.e., an equations-based approach and a PVsyst simulation tool, gave the same results, and the cost of energy production of FPV is 30 \$/MWh (0.0300 \$/kWh) in Cairo (Egypt) and 25 \$/MWh (0.0250 \$/kWh) in Dubai (UAE), as shown in Figure 15.

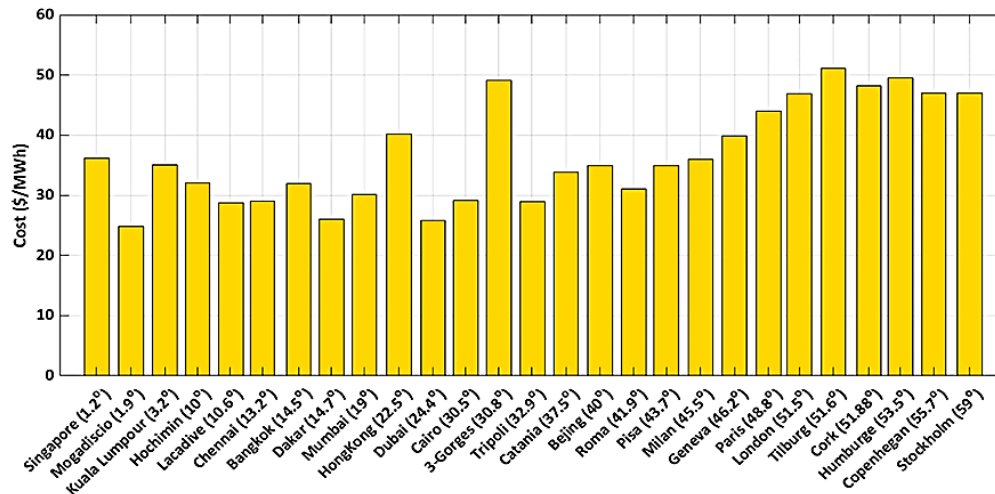


Figure 15. The price of manufacturing FPV in 27 different northern hemisphere locales [40]

Islam et al. (2024) [41] have evaluated the feasibility of a 6.7 MW floating solar plant located on the lake of Hatirjheel in Dhaka, Bangladesh, using Meteonorm 8.1 software to calculate climatic conditions (temperature, humidity, rainfall, sunshine hours, solar radiation, and wind speed) and data (Bangladesh Meteorological Department archive). It used the local grid energy demand data of the Dhaka Power Distribution Company to specify the architecture and capacity of the plant, and the technical analysis and simulation of the plant were conducted in PVsyst 7.3 software to measure equipment, DC energy production, and the energy injected into the grid in MWh. The economic analysis estimated the Levelized Cost of Energy per kilowatt-hour and payback period of the system, which proved that the system is economically feasible, and the dataset that had been compiled was mentioned to be an important resource that could be used to plan the construction of different types of solar power plants, including floating power plants, in any part of the Dhaka Metropolitan region.

A logical study and overview of the state of the art on Floating Photovoltaic (FPVT) systems as a source of electricity is presented by Panda et al. (2024) [42], where they delineate the multiple features and elements of the systems and provide a comparative analysis of the merits and demerits of each of them. Although the typical way of harnessing solar energy is to install the solar arrays on the roof of the home (400 kW), most of the business (100 kW) on the roof sign on with these panels to generate an average of 11% more energy than a ground-based array. Also, since the research has shown that around 40 % of the water in open reservoirs is lost through evaporation, covering only 30 % of the water surface will cut down the level of evaporation by 49 %. The solar panel market of 104 GW is estimated to grow by a compound annual rate of 6%, and global photovoltaic capacity grew by 27% to 512 GW in 2018, which is approximately 55% of the total capacity.

The challenges and hints of the technological, financial, and other parameters required to ensure the at-scale deployment of floating photovoltaic (FPV) systems were taken up by Jindal et al. (2025) [43], who created a new selection framework with references to particular prerequisites and conditions that are necessary and favorable to find appropriate reservoirs in India. The researchers used this framework on a dataset of 130 reservoirs and found 17 appropriate sites. The researchers then came up with a reservoir,

ranking framework to rank these 17 reservoirs showing that the Almatti reservoir is the most suitable and Maharashtra has the largest number of suitable reservoirs, followed by Odisha. As a financial feasibility measure, a levelized cost-based economic evaluation will be done and the results indicate that the LCOE of FPV systems is between 3.16-3.80 INR /kWh with the lowest LCOE of 3.16 INR /kWh at the Tungabhadra reservoir.

Rahmot Ullah et al. (2025) [44] performed a techno-economic optimization of a proposed 200 MW grid connected floating photovoltaic (FPV) plant at Kaptai Lake (22.63°N, 92.24°E) by positioning 100 configurations of PVs into PVsyst software (Version 7.4.7) by spinning the tilt angle (18 to 27) and inter-row spacing (0.2 to 2 m). A combination of 22° tilt and 0.8 m separation generates the highest 399.8 GWh/year with 83.21 PR, low shading loss (1.71%), and 0.804% and 0.077% array/system losses, respectively. Commercial analysis establishes good viability, which includes the Net Present Value (NPV) of USD 226.23 million, Levelized Cost of Electricity (LCOE) of USD 0.0433/kWh, 5.81-year payback period, 149.2% return on investment (ROI), and 19.25% internal rate of return (IRR). Although a greater tilt or separation will slightly boost output, it will significantly impact the cost of installation (up to USD 190.62 million), which compromises cost-effectiveness. Figure 16 indicates that there is an evident monotonically upward trend in which the cost of installation increases with increased inter-row spacing. Figure 17 demonstrates that a dense layout and reduced balance-of-system (BOS) requirements result in a minimum LCOE of 0.0427 USD/kWh when the tilt is 18°, and the spacing between the layers is 0.4 m. The research paper proves that FPV is not land-efficient and environmentally sustainable alone, not emitting 4,740,316.3 tons of CO₂, but also cost-effective to use in large-scale applications in Bangladesh.

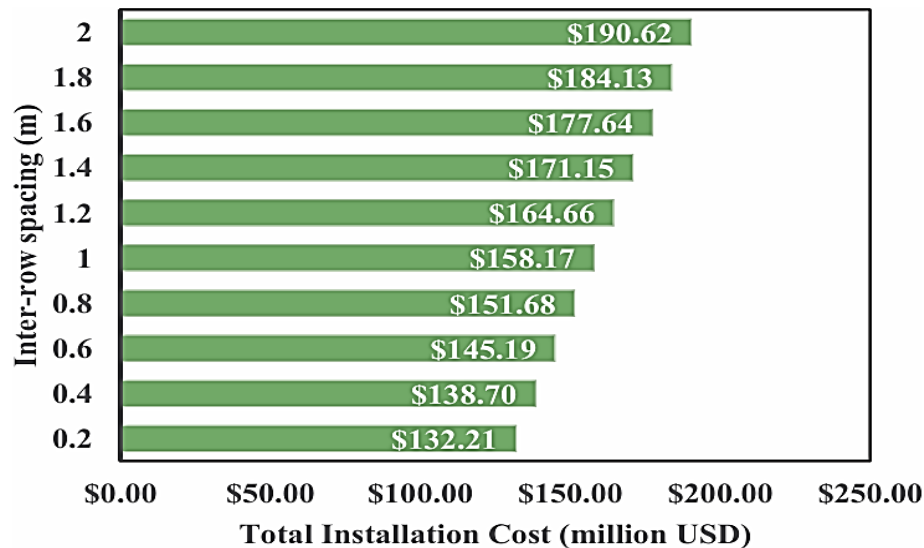


Figure 16 Shows how the inter-row spacing affects the total installation cost [44]

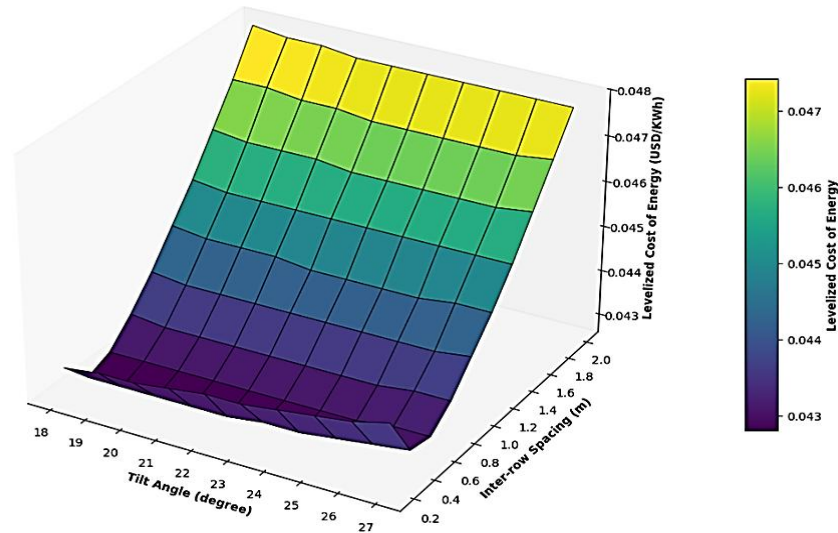


Figure 17. Higher tilt angles are associated with higher LCOE, according to an illustration of the levelized cost of energy as a function of tilt angle and inter-row spacing [44]

The integrated system of electric power and green hydrogen generation analyzed in the research by Rehman et al. (2025) [45] is a combination of offshore wind turbines (OWT) and floating solar photovoltaic (FPV) technology. This system with OWT farms, FPV arrays, a water electrolyzer, and a hydrogen storage tank was optimized to achieve minimum levelized cost of energy (LCOE), probability of loss of power supply (LPSP), and unnecessary energy. The researchers employed a new Dung Beetle Optimization (DBO) algorithm whose performance is compared to the Grey Wolf Optimizer (GWO), and identified the DBO-optimized FPV/OWT hybrid configuration to be less expensive, with the OWT contributing 45.96% to the total expenses. This hybrid system had a lower LCOE of 0.5797 \$/kWh than the standalone OWT system with a LCOE of 0.8190 \$/kWh and also had a competitive levelized cost of hydrogen (COH) of 1.205 \$/kg at large-scale production.

Lodhi et al. (2025) [46] evaluated the photovoltaic performance of building rooftops and inland water bodies in Pakistan to calculate their contribution to the national solar sufficiency and used machine learning regression and geospatial tools at the grid resolution of 1 km², which is used in analyzing rooftop and 30 m pixel resolution corresponding to FPV. The involved authors estimated the annual potential of solar on rooftops, examined the trends in electricity consumption, calculated the required rooftop size to achieve solar adequacy, performed multicriteria decision-making with respect to FPV systems, and quantified the benefits of carbon mitigation. The study determined that the current electricity consumption in Pakistan was 132.6 TWh/yr, with a maximum rooftop PV (RPV) and FPV capacity of 310.1 TWh and 59.23 TWh, respectively; the potentials would save 192.3 MtCO₂e and 36.7 MtCO₂e of emissions annually. Even though it might not be easy to fully be self-sufficient with the implementation of PV on the roof alone, the study provides crucial information to consider whether it is viable or not and its role in the energy mix in Pakistan. Table 2 shows a summary of studies outlining that are related to technical and economic feasibility.

Table 2. A summary of studies outline that are related to technical and economic feasibility

Authors (year) reference	Configuration	Studied parameters	Highlighted results/findings
Rauf et al. (2020) [34]	FSPV integrated with hydroelectric power station	Voltage levels (500 kV, 132 kV, 11 kV), hydro-solar optimization	Combined system produced >3.5% more power; FSPV acts as peaker plant during mid-day peak load
Shyam and Kanakasabapathy (2022) [35]	FPV integrated with Pumped Storage Hydroelectric (PSH)	LCOE, operating cost, loss of load probability	LCOE of solar = 0.8518₹/kWh, stored energy = 4.2713₹/kWh; reduced daily operating cost and loss of load probability
Agrawal et al. (2022) [36]	FSPV on dam reservoir	Power potential, evaporation reduction, LCOE, IRR	Potential = 6513 MWp; generation = 10,623,501 MWh/year; evaporation reduced by 1395 m³/MWp; LCOE = \$0.036/kWh; IRR = 8.55%
Farrar et al. (2022) [37]	Fixed-tilt FPV on irrigation reservoir	Water savings, energy yield, economics, CO ₂ ~ reduction, tilt angle	Water saved = 12,700 m³/year (42% reduction); payback = 8.4 years; CO ₂ reduced ~141 t/year; optimal tilt = 20° for NPC
Nasir et al. (2023) [38]	Hybrid FPV with pumped storage and conventional hydropower	LCOE storage, benefit-cost ratio, installed costs, revenue	LCOE storage reduced by 28%; benefit-cost ratio increased by 56%; installed costs reduced by 25%; additional clean energy = 3693 GWh
Martinez and Iglesias (2024) [39]	FPV farm cost analysis across European waters	LCOE, solar resources, distance to shore, water depth	LCOE ranges from ~250 EUR/MWh (South) to 650 EUR/MWh (North); distance to shore major cost factor; water depth secondary

Al-Smairan et al. (2024) [40]	FPV water pumping system	Efficiency, cost, CO ₂ ~ emissions, LCOE	FPV efficiency 5% higher; CO ₂ reduced~ >5000 tons; LCOE = 0.028 JD/kWh; energy cost in Cairo = \$0.030/kWh, Dubai = \$0.025/kWh
Islam et al. (2024) [41]	6.7 MW FPV plant on urban lake	Climate data, energy demand, LCOE, payback period	Feasible design using PVsyst; LCOE and payback calculated; dataset useful for other sites in Dhaka
Panda et al. (2024) [42]	Review of FPVT systems	Energy yield, evaporation reduction, market growth	FPV produces 11% more energy than ground-based; covers 30% of water surface reduces evaporation by 49%; CAGR = 6%
Jindal et al. (2025) [43]	Reservoir selection framework for FPV in India	Suitability ranking, LCOE, economic assessment	17 suitable reservoirs identified; LCOE range = INR 3.16–3.80/kWh; Tungabhadra reservoir had lowest LCOE (INR 3.16/kWh)
Rahmot Ullah et al. (2025) [44]	200 MW FPV plant optimization	Tilt angle, inter-row spacing, PR, LCOE, NPV, ROI, IRR	Optimal: 22° tilt, 0.8 m spacing; PR = 83.21%; LCOE = \$0.0433/kWh; NPV = \$226.23M; payback = 5.81 years; CO ₂ reduced~ 4.74M tons
Rehman et al. (2025) [45]	Hybrid FPV/offshore wind with green hydrogen production	LCOE, LPSP, excess energy, COH	Hybrid LCOE = \$0.5797/kWh vs. \$0.8190/kWh for OWT alone; COH = \$1.205/kg; optimized with DBO algorithm
Lodhi et al. (2025) [46]	Rooftop and FPV potential in Pakistan	Solar potential, consumption, carbon mitigation, machine learning	RPV potential = 310.1 TWh/year; FPV potential = 59.23 TWh/year; CO ₂ ~ reduction = 192.3 Mt/year (RPV) and 36.7 Mt/year (FPV)

2.3. Hybrid Systems and Integration

Choi et al. (2022) [47], in their experimental study, measured local pressure distribution on a solar panel array (Figure 18) and an economic analysis of the reduced manufacturing costs and concluded that the first and last rows of the panels had the highest drag and lift coefficients because of direct exposure to

wind and gradually decreased in other rows because of the shelter effect. The sideways flow of the wind offered shelter to the leftmost and rightmost columns, which brought drag and lift coefficients in the center of the array relative to 45%-86%, which may likely make the middle areas of floating bodies use cheaper materials, and bigger systems may result in even higher economies. Also, the final row had the same maximum lift coefficients in the columns, whereas in other rows, the maximum lift coefficients varied between the columns, as shown in Figure 19.

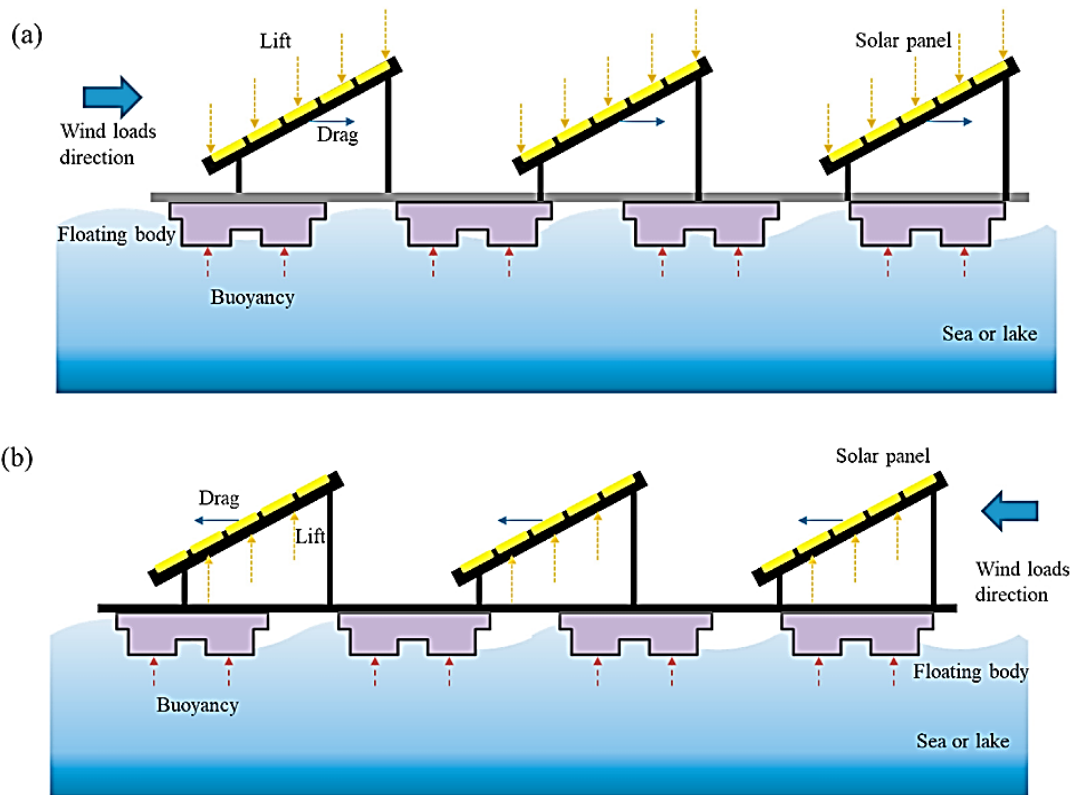


Figure 18. Wind loads have two effects on a floating PV system's solar panel array: (a) forward and (b) backward [47]

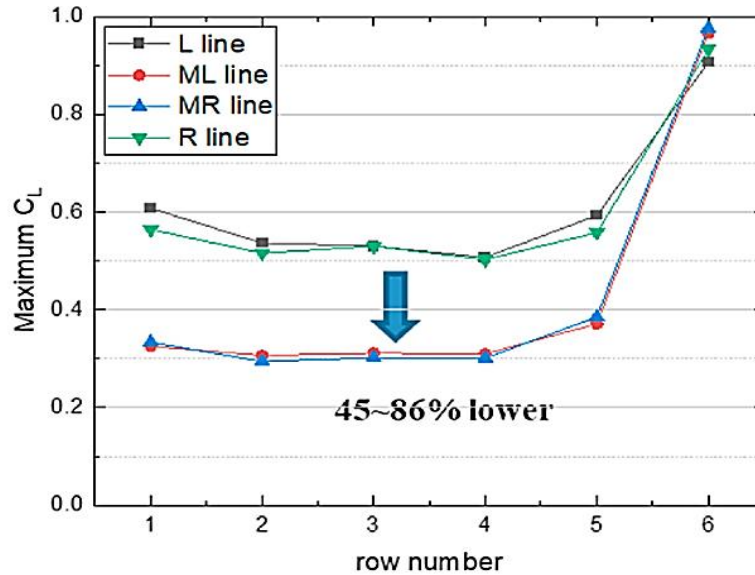


Figure 19. Maximum coefficients of lift [47]

Evidence from Gomis et al. (2026) [48] measured the hydrodynamic behavior of a floating photovoltaic (FPV) platform, created by ISIGENERE, in 107 experimental runs in a wave tank at the Cantabria Coastal and Ocean Basin (CCOB, IHCantabria) by using a system of interconnected floating units joined with fiberglass-reinforced nylon plates under both regular and irregular waves in an effort to understand the interactions between waves and structures. Their findings indicate that the dynamic regime of the platform mainly depends on the wave period, longer periods make it act as a wave follower and shorter ones make it act as a wave leader as it dissipates more energy, and energy dissipation is most effective during perpendicular waves (90°). There was also an evaluation of the mooring system by authors who determined that the mooring system mainly responded to surge and heave motions, and the energy is concentrated at the same frequencies as the waves. Table 3 presents a summary of studies outlining that are related to hybrid systems and integration.

Table 3. A summary of studies outline that are related to hybrid systems and integration

Authors (year) reference	Configuration	Studied parameters	Highlighted results/findings
Choi et al. (2022) [47]	Solar panel array under wind loads	Drag and lift coefficients, manufacturing cost	First/last rows had highest drag/lift; sheltering effect reduced coefficients by 45–86%; cost reduced by 19% for 2.5 MW system
Gomis et al. (2026) [48]	Hydrodynamic behavior of FPV platform	Wave period, direction, mooring system, motion amplitudes	Platform acts as wave follower for long periods; perpendicular waves (90°) most efficient; surge and heave motions dominant

3. Meta-Analysis of Cost-Effectiveness across Floating Photovoltaic

An extensive meta-analysis of the cost-effectiveness of the FPV system shows a definite trend of economic feasibility and competitiveness on comparison with the traditional ground-mounted photovoltaic (GMPV) installations due to increased energy production, water conservation, and minimized land-use tensions. The levelized cost of electricity (LCOE) of FPV systems is always between around 0.036\$/kWh and 0.10\$/kWh in various geographical and climatic conditions, and in some cases, it is lower than the conventional PV systems with a reduction of evaporation, advantage of cooling, and integration with hybrids considered. It is important to note that FPV systems show better financial performance, such as shorter payback time (e.g., 4.7 to 8.4 years), better performance ratios (to 83.21%), and positive net present value (e.g., 200 MW plant net present value of 226.23 million), and other potential environmental co-benefits such as up to 105,000 kL in annual water savings and over 300,000 ton per year in CO₂ reductions. Site-specific elements, including solar irradiance, wind conditions, water depth, and distance to shore, however, do affect economic performance, with LCOE varying between about 250 EUR/MWh in southern Europe and 650 EUR/MWh in northern latitudes, and hybrid designs involving hydropower or offshore wind further reducing costs because of their properties to store energy and provide stability to the grid. The summary of noteworthy economic indicators of specific studies (Table 4) is used to demonstrate the cost-effectiveness and financial appeal of the FPV deployments in various countries.

Table 4. Key economic indicators from selected studies

Study (Year)	Location	System Size	LCOE (\$/kWh)	Payback Period (Years)	NPV (\$)	Key Economic Findings
Goswami et al. (2021)	India	5 MW FSPV	0.041	N/A	N/A	LCOE 2.5% higher than standard degradation scenario; annual water savings of 105,000 kL
Alhassan et al. (2023)	Ghana	420 MWp FPV	0.10	12	52,238,576 (annual revenue)	Positive economic indicators with annual CO ₂ reduction of 308,904.5 t
Farrar et al. (2022)	Jordan	300 kWp FPV	~0.028 (JD/kWh)	8.4	N/A	Water savings of 12,700 m ³ /year;

						optimal tilt angle of 20° minimizes NPC
Agrawal et al. (2022)	India	6513 MWp (potential)	0.036	N/A	N/A	IRR of 8.55%; evaporation reduction of 1395 m ³ /MWp annually
Rahmot Ullah et al. (2025)	Bangladesh	200 MW FPV	0.0433	5.81	226,230,000	ROI of 149.2%; IRR of 19.25%; CO ₂ reduction of 4.74 million tons
Al-Smairan et al. (2024)	Egypt/UAE	165 kW FPV	0.030 (Cairo), 0.025 (Dubai)	N/A	N/A	FPV efficiency 5% higher than land-based; CO ₂ reduction >5000 tons
Jindal et al. (2025)	India	Various reservoirs	0.038–0.046 (INR 3.16–3.80/kWh)	N/A	N/A	LCOE below national average; Tungabhadra reservoir lowest at INR 3.16/kWh
Martinez and Iglesias (2024)	European waters	Variable	0.25–0.65 (EUR/kWh)	N/A	N/A	LCOE increases with latitude; distance to shore major cost driver
Rehman et al. (2025)	Hybrid offshore	FPV + Wind	0.5797 (hybrid) vs. 0.8190 (wind only)	N/A	N/A	Hybrid system reduces LCOE by 29%; COH of \$1.205/kg for hydrogen production

4. Conclusions

The FPV is a recent technology that has become a viable solution to overcome the issue of land-use, which is also beneficial in terms of energy output and water saving in the renewable energy system. This paper is a review article to assess the literature on the performance measures, cost-benefit, and integration plans published between 2020 and 2026. The following conclusions are a synthesis of the results of the experimental studies, simulations, and techno-economic evaluations, providing the actionable information to policymakers, engineers, and researchers.

1. The FPV systems are always superior to ground-mounted PV, with temperature decreases of 2-11 °C and energy yields of 2 to 28%, where this broad scale is an indication of variation in the local climatic conditions (tropical versus temperate), system design (tilt angle, mounting height, and inter-row spacing), and the testing (wind speed, irradiance, and water temperature differentials).
2. FPV systems are sensitive to design parameters, including the tilt angle, height above water, and the inter-row spacing. The best configurations (low tilt angles 0-30°) and minimum module height are those with the highest cooling and energy production, whereas CFD models indicate the significance of wind and water temperature differences (minimum 5 °C) to enhance heat transfer.
3. FPV installations help save a lot of water, evaporation in reservoirs is minimised. Partial coverage can lower the evaporation by 17%, and total coverage can be as much as 49%. This comes in very handy, especially in arid and water strained areas, and helps in energy as well as water security.
4. Levelized Cost of Electricity (LCOE) of FPV is priced between 0.036-0.10\$/kWh, which is competitive with ground-based and conventional solar. Obtaining systems in favorable locations (e.g., India, Ghana, Spain) has payback periods as minuscule as 4.784 years with robust financial metrics, including positive NPV and appealing IRR (up to 19.25%).
5. FPV systems are also good at helping to reduce carbon and lifetime CO₂ reduction is up to 183,493 tons per plant. Hybrid FPV-hydro also enhances these advantages, which support national goals in renewable energy use and minimize the use of fossil fuels.
6. FPV can operate in diverse geographical and climatic areas, including tropical (Ghana, India) and temperate (Kashmir, Europe) areas. Specific conditions of the location, like the sun radiance, the wind patterns, the water depth, etc., do impact it, yet, in general, FPV is flexible and robust.
7. Combining FPV with that which already exists, includes hydropower, pumped storage, or offshore wind to provide synergistic systems that enhance grid reliability, serve as peaking plants, and decrease the probability of power supply loss (LPSP). FPV systems integrated with hydropower, pumped storage, or offshore wind enhance grid reliability, reduce the probability of loss of power supply, and improve overall system economics through synergistic operation.
8. Research on wind loads and hydrodynamic characteristics is used to guide cost-efficient design changes, i.e., inexpensive material in the sheltered part of large FPV arrays. This has the potential of cutting down the manufacturing expenses by up to 19% on multi-megawatt installations.
9. FPV eliminates land-use antagonism, and thus it is appropriate in high-density urban areas, farmlands, and ecologically sensitive regions. The technology helps in high-density energy production per square meter and can potentially be applied on dam reservoirs and lakes on a gigawatt scale.

5. Further Enhancements and Accompanying Challenges

With the FPV technology still in its developmental stage, it provides enormous prospects of innovation and integration in the world of renewable energy. Its adoption must, however, be conditional upon dealing with deep-rooted technical, economic, and environmental problems. This section provides major aspects of additional improvements and the relevant challenges that need to be addressed to achieve the full potential of FPV systems. The fast development of FPV technologies provides a wide range of possibilities in the form of performance, cost-cutting, and integration of the system. Development of hybrids, economic and policy support, and the environment are some of the broad areas where future improvements can be made.

1. Materials science and engineering can make a substantial contribution to the FPV systems. Anti-reflective, hydrophobic, and self-cleaning coatings on PV modules can minimise soiling losses and retain significant optical efficiency even in moist and dusty conditions. Also, floats, mooring systems, and mounting structures having corrosion-resistant materials, including fiber-reinforced polymers, coated aluminum, and stainless-steel alloys, would be used to improve durability in freshwater and salty environments.
2. The concept of dynamic tilt and tracking adapted to the aquatic conditions can be used in future FPV deployments to obtain high energy yields. Although single- and dual-axis trackers are used in ground-mounted systems, a floating platform adaptation of these trackers needs a strong but lightweight design that can handle hydrodynamic forces. Optimisation of float geometry, float spacing, and mooring can be optimised using Computational Fluid Dynamics (CFD) and finite element analysis to reduce the stresses caused by waves and optimize energy capture.
3. FPV can be adopted more effectively to be used in synergistic hybrid networks with other renewable energy sources and storage systems. Coupling FPV and hydropower reservoirs will not only minimize evaporation but also allow complementary power generation solar at the peak time of day, and hydro at night or low-irradiance times. Equally, grid stability and energy time-shifting can be achieved by integration with pumped hydro storage (PHS). Multi-source marine energy platforms can be built with offshore and nearshore FPV systems, and floating wind turbines, and wave energy converters.
4. The innovative business and financing models are required to speed up the deployment of FPV. The initial capital expenditure can be minimised through the use of public-private partnerships (PPP), green bonds, and climate funds. Project bankability can be enhanced by performance-based incentives, which include feed-in tariffs and renewable energy certificates (RECs).

5. FPV systems may be developed to aid aquatic ecosystems and biodiversity. As an example, floating platforms might include porous or vegetated areas to permit penetration of light and gas exchange, which reduces effects on underwater life. FPV over irrigation ponds could minimize water loss as solar pumps operate in agricultural areas to achieve the water-energy-food nexus.
6. The development of standardized regulatory frameworks and long-term environmental monitoring protocols remains essential to support the sustainable large-scale deployment of hybrid FPV systems.

Although it has potential, FPV suffers a number of technical, economic, regulatory, and environmental issues, which it needs to overcome to realize sustainable and scalable implementation.

1. FPV systems will be subjected to severe aquatic conditions such as waves, currents, water-level variability and biofouling. When these factors are not effectively controlled, they may cause structural fatigue, corrosion and electrical failures. The mooring and anchoring systems should be made in such a way that it can endure the weather conditions that are hostile like storms and floods without any breakage in the systems.
2. Despite the fact that the LCOE of FPV is competitive, the increased initial costs are still a challenge, especially in third-world countries. The capital cost can rise 15-25 % more than ground-mounted PV because of the costs of floating structures and marine resistant components, as well as marine grade electrical systems.
3. The regulatory framework on FPV is either not well developed or fractured, particularly on water surface rights, environmental permitting, and grid interconnection. In most countries, FPV projects are subjected to jurisdictions of several officials who work in energy, water resource, environment, and maritime projects and create bureaucratic hurdles and uncertainties.
4. FPV decreases land use, but it can affect water ecosystems by changing the quality of the light penetration, temperature, and oxygen in the water. Panel shading may have an impact on the phytoplankton productivity and aquatic food webs. Furthermore, other water uses might come into conflict with this use as other uses like fishing, recreation, navigation, and irrigation could be experienced, especially in highly populated or multi-use water bodies.
5. Long term data on the performance of FPV systems in various weather types and climatic conditions still does not exist. The majority of available research is location-specific, short or simulation research, which restricts the extrapolation of results. Models should be tested more in

the field, in pilot projects, and in monitoring programs which would help to test models, measure the degradation rates, and measure the ecological impacts.

- 6. FPVs should be able to withstand the effects of climate change, such as the increase in water temperature, changes in the precipitation patterns, and the compound rise of extreme weather patterns. The water level and water quality can change and impact the performance and the life span of the system.

Although this synthesis is rather complete, the review has some drawbacks, among them the natural heterogeneity of the experimental conditions in the studies analyzed, i.e., different climate zones, system configurations, and measurement procedures, which restricts the direct applicability of the performance measures. Also, the fact that most of the research is done using simulation in the short term, and the fact that FPV deployments are more concentrated in a limited geographic area, restricts the ability to generalize the results of the study to a wide range of environmental settings. To fill these gaps, the focus of future research must be on standardized performance reporting systems, long-term monitoring of the field across various climatic regions and systematic life-cycle assessment systems that will measure the effects on the environment and ecology as a whole. Additionally, there will be a need to promote hybrid integration policies with hydropower and offshore wind as well as to create adaptive regulatory measures that would help to enable the deployment of FPV in the world in a more scalable and sustainable manner.

Declaration of generative AI and AI-assisted technologies in the writing process

-None

Disclosures

The authors have no conflicts of interest to declare in relation to this report.

Abbreviations

Symbol	Definition
Roman Letters	
<i>FSPV</i>	Floating Solar Photovoltaic
<i>FPV</i>	Floating Photovoltaic
<i>GMPV</i>	Ground-Mounted Photovoltaic

<i>SPV</i>	Submerged Photovoltaic
<i>OPVS/OPV</i>	Overland / On-Ground Photovoltaic System
<i>LCOE</i>	Levelized Cost of Electricity
<i>NPV</i>	Net Present Value
<i>IRR</i>	Internal Rate of Return
<i>PR</i>	Performance Ratio
<i>CF</i>	Capacity Factor
<i>COH</i>	Cost of Hydrogen
<i>LPSP</i>	Loss of Power Supply Probability
<i>NPC</i>	Net Present Cost
<i>ROI</i>	Return on Investment
<i>U-value</i>	Thermal transmittance coefficient
<i>MWp</i>	Megawatt peak
<i>kWh</i>	Kilowatt-hour
<i>MWh</i>	Megawatt-hour
<i>GWh</i>	Gigawatt-hour
<i>TWh</i>	Terawatt-hour
<i>tCO₂</i>	Tonnes of carbon dioxide
<i>m³</i>	Cubic meter
<i>kL</i>	Kiloliter
<i>°C</i>	Degrees Celsius
<i>W</i>	Watt
<i>kW</i>	Kilowatt
<i>MW</i>	Megawatt
<i>GW</i>	Gigawatt
<i>EUR</i>	Euro
<i>USD</i>	United States Dollar
<i>INR</i>	Indian Rupee
<i>JD</i>	Jordanian Dinar
<i>CAGR</i>	Compound Annual Growth Rate

Greek Letters

θ	Tilt angle
α	Reflectivity coefficient
η	Efficiency
ΔT	Temperature difference
ρ	Density
ν	Kinematic viscosity
φ	Angle of wave incidence

Despite the comprehensive synthesis presented, this review is subject to certain limitations, including the inherent d scalable and sustainable FPV deployment world

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الطاقة الشمسية الكهروضوئية العائمة: مراجعة نقدية للتحسينات في الكفاءة الحرارية، والفعالية من حيث التكلفة، وتكامل الأنظمة الهجينة

الخلاصة: تقدم هذه الورقة مراجعة شاملة تتماشى مع الطلب المتزايد على أنظمة الطاقة المتجددة المستدامة والفعالة في استخدام الأراضي، وذلك من خلال تحليل نقدي لتصميم وأداء وفرص دمج أنظمة الخلايا الكهروضوئية العائمة، مع التركيز بشكل خاص على تجاوز قيود استخدام الأراضي وتحسين توليد الطاقة عبر نشر هذه الأنظمة. ويتبع مبادئ PRISMA، تتضمن المنهجية مراجعة منهجية للمقالات المحكمة المنشورة بين عامي 2020 و2026، وتُصنف النتائج ضمن ثلاثة محاور رئيسية: تحليل الأداء والكفاءة، والجودة التقنية والاقتصادية، ودمج الأنظمة الهجينة. وتشير بعض النتائج الرئيسية إلى أن أنظمة الخلايا الكهروضوئية العائمة تتفوق دائمًا على أنظمة الخلايا الكهروضوئية الأرضية، حيث تُحقق انخفاضًا في درجة الحرارة يتراوح بين 2 و11 درجة مئوية، وإنتاجية طاقة تتراوح بين 2 و28%، وانخفاضًا في التبخر يصل إلى 49%، وتكلفة مُعدلة للكهرباء تتراوح بين 0.036 و10 دولارات أمريكية/كيلوواط ساعة، وفترة استرداد تتراوح بين 4.7 و8.4 سنوات. توجد أيضًا فوائد أخرى مرتبطة باستخدام أنظمة الطاقة الشمسية الكهروضوئية العائمة، مثل خفض استهلاك المياه السنوي بما يصل إلى 105000 كيلولتر. وتتلخص فكرة البحث في أن تقنية الطاقة الشمسية الكهروضوئية العائمة مصدر واعد وفعال من حيث التكلفة للطاقة المتجددة في مختلف المناخات، لا سيما عند دمجها مع الطاقة الكهرومائية أو طاقة الرياح البحرية. ومع ذلك، لا تزال هناك حاجة إلى معالجة قضايا محددة تتعلق باستقرار النظام، والسياسات التنظيمية، والآثار البيئية من خلال البحث وحلول التصميم المبتكرة لجعلها قابلة للتطبيق على نطاق واسع ومستدامة.

الكلمات المفتاحية: الخلايا الكهروضوئية العائمة؛ تحليل الأداء؛ الجودة التقنية والاقتصادية؛ أنظمة الطاقة الهجينة؛ دمج الطاقة المتجددة.