

Floating photovoltaic system

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Case Report

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Floating Solar Photovoltaic Systems: A Review of Technology, Performance, Benefits, and Global Development Trends

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Abstract— Floating solar photovoltaic (FPV) systems mount PV arrays on buoyant structures over reservoirs, lakes, canals and nearshore waters, and have emerged as a land-saving route to scale up solar generation. This review synthesises 29 sources (24 peer-reviewed journal articles) published mainly between 2014 and 2024, searched through ScienceDirect, Scopus, Google Scholar and Web of Science, together with institutional reports. It covers FPV system architecture, governing thermal and electrical equations, performance relative to ground-mounted plants, effects on evaporation and water quality, hybridisation with hydropower, economics, and global deployment trends. The literature indicates that FPV plants generally deliver modestly higher specific yield than comparable land-based systems, with reported gains ranging from about 1% to above 10% depending on climate, module cooling and soiling. Illustrative calculations carried out for this review show that cooling alone accounts for roughly a 1% daily energy gain and that covering 20% of a 10 km² reservoir could save about 2.8 million m³ of water per year. Cumulative installed capacity has grown from tens of kilowatts in 2007 to several gigawatts, led by China, Japan, South Korea, India and Southeast Asia. Remaining challenges include mooring and structural reliability, ecological uncertainty, a capital cost premium and scarce long-term field data. Priorities for future work are standardised testing, offshore designs, bifacial and tracking concepts, and FPV–hydro–storage hybrids.

Keywords: Floating photovoltaics; solar energy; renewable energy; hydro–solar hybrid; water–energy nexus; levelised cost of electricity; energy transition

1. Introduction

Rapid decarbonisation of the power sector depends on scaling solar photovoltaics (PV) to terawatt levels. Utility-scale PV, however, needs several hectares of land per megawatt, which brings it into competition with agriculture, forests, settlements and industry, particularly in densely populated countries [1], [2]. Floating photovoltaic (FPV) technology addresses this constraint by placing PV modules on floats that rest on the surface of reservoirs, lakes, irrigation canals, industrial ponds and sheltered coastal waters. The first demonstration was a small plant of about 20 kWp commissioned in Japan in 2007, and the sector has since moved from pilot projects to plants of hundreds of megawatts [1], [3].

The Indian context makes the technology especially relevant. India has set a target of 500 GW of non-fossil capacity by 2030 and a net-zero goal for 2070, and solar PV is expected to supply the largest share of the additions [4]. At the same time, land is scarce and costly, while the country has a large inventory of reservoirs, hydropower impoundments, canals and thermal-plant cooling ponds with existing grid connections.

Early feasibility studies for Indian sites suggested that FPV is technically attractive where evaporation losses and land prices are high [1], [5], and several large plants have since been commissioned, as summarised later in this paper.

The motivation for FPV extends beyond land saving. Water cooling can lower module temperature and raise conversion efficiency, shading reduces evaporation from the covered surface, and co-location with hydropower allows shared transmission infrastructure and complementary generation profiles [6]–[8]. These claimed benefits are balanced by concerns about structural reliability, ecological side effects, higher capital cost and limited operating history [9], [10]. Several earlier reviews have addressed parts of the topic, including system configurations [2], [3], general technology status [11] and challenges [9]. The present review integrates technology, performance, benefits and global development trends in one narrative and adds simple quantitative analyses (Section 3) to make the comparisons with ground-mounted PV explicit.

The review is aligned with Units 2 and 5 of the Energy Technology syllabus (renewable energy technologies for India; global energy transition and advanced systems). Section 2 presents the technical fundamentals and governing equations. Section 3 reviews the literature under five themes: technology evolution, yield and thermal performance, water–energy nexus and environmental effects, hybrid and advanced configurations, and economics with global trends. Sections 4–6 discuss applications, challenges, and research gaps, and Section 7 concludes.

2. Fundamentals and Theoretical Background

2.1 System architecture

An FPV plant comprises PV modules, a floating support structure, a mooring and anchoring system, electrical balance-of-system equipment (cables, combiner boxes and inverters, which may be floating or shore-based) and a grid interface (Fig. 1). Most commercial plants use high-density polyethylene (HDPE) floats arranged as modular pontoons on which standard crystalline-silicon modules are mounted at a low tilt of roughly 5–15° [6], [12]. Table 1 summarises the principal technology classes identified in the literature.

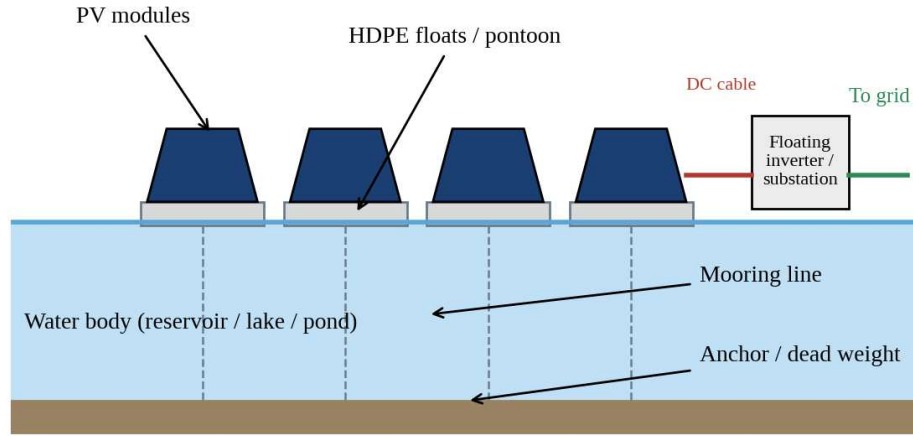


Fig. 1. Schematic of a typical pontoon-type floating PV system with mooring and shore interconnection.

Table 1. Main floating PV technology classes.

Class	Description	Typical use / remark
Pontoon (rigid float)	Modular HDPE floats carrying modules at fixed low tilt	Dominant commercial type on inland waters [6], [13]
Membrane / flexible mat	Modules on a flexible floating membrane in contact with water	Strong cooling and low wave loading; durability still under study [13]
Metal-frame / hybrid float	Steel or aluminium truss supported on separate buoys	Allows higher tilt and trackers; heavier and costlier [6]
Tracking FPV	Rotating platform or single-axis tracker on floats	Higher yield, extra mechanical complexity [14]
Offshore / nearshore	Wave-resistant, flexible or semi-submersible platforms	Early stage; high structural loads [15], [16]

2.2 Electrical and thermal behaviour

The DC power delivered by a PV array depends on incident irradiance G , module area A and conversion efficiency η :

$$P = \eta \cdot A \cdot G \quad (1)$$

Efficiency falls almost linearly with cell temperature T_c , so that

$$\eta = \eta_{ref} [1 - \beta (T_c - T_{ref})] \quad (2)$$

where η_{ref} is the efficiency at the reference temperature $T_{ref} = 25^\circ\text{C}$ and β is the temperature coefficient, around 0.35–0.45 %/°C for crystalline silicon. Cell temperature is commonly estimated with the Faiman steady-state model,

$$T_c = T_a + G / (U_0 + U_1 v) \quad (3)$$

in which T_a is ambient temperature, v is wind speed, and U_0 and U_1 are the constant and wind-dependent heat-loss coefficients. FPV plants are expected to exhibit larger effective U -values because of convective and evaporative exchange with the water surface and the cooler microclimate above it, a point examined by field measurements and heat-transfer analysis [17], [18]. Because the tilt angle of floating arrays is generally low, the

transposition of irradiance onto the module plane, and the soiling rate, also differ from land-based systems.

2.3 Evaporation and economics

The volume of water conserved by a floating cover can be approximated as

$$V_s = A_w \cdot c \cdot f \cdot E_0 \quad (4)$$

where A_w is the water-surface area, c the coverage fraction, f the fractional reduction of evaporation under the cover and E_0 the uncovered evaporation depth per year; experimental work has demonstrated significant reductions in evaporation under floating covers [8]. Project economics are normally compared through the levelised cost of electricity (LCOE):

$$LCOE = (CAPEX \cdot CRF + OPEX) / E_{yr}, \quad CRF = r(1 + r)^n / [(1 + r)^n - 1] \quad (5)$$

with r the discount rate, n the project life, OPEX the annual operating cost and E_{yr} the annual energy yield. Equation (5) shows that a modest yield gain can offset a capital premium, which is the basis of most techno-economic comparisons of FPV with ground-mounted PV [12], [19].

3. Literature Review

3.1 Technology evolution and structural design

Early reviews framed FPV as a simple transfer of land-based PV onto pontoons, emphasising its cooling and land-saving potential [2]. Later reviews recognised that floating structures, moorings and electrical components introduce unique design problems and classified FPV into rigid-float, membrane and hybrid concepts [3], [6]. Comparative case-study work indicates that the platform concept strongly influences both energy yield and structural cost, and that no single design is optimal for all water bodies [13]. The design of structures for marine conditions is a particular concern, since wave, wind and current loads, fatigue of connectors and mooring dynamics govern survival and cost offshore [15]. There is broad agreement across the reviews that standardised design rules and certification are still lacking, and that most experience comes from sheltered inland waters [9], [11].

3.2 Energy yield and thermal performance

Field and simulation studies consistently report that FPV modules operate at lower temperatures than ground-mounted modules, but the magnitude of the benefit varies. A Korean pilot comparison reported appreciably higher generation than a land-based plant, attributing it to cooler modules and the absence of shading [20], and a Chinese-Nordic analysis reached a similar conclusion for efficiency [21]. Side-by-side measurements in the Netherlands and Singapore found a cooling effect that depended on climate zone and mounting geometry [17], while heat-transfer work showed that water temperature, not

just wind, controls how much cooling is achieved [18]. Simulations of offshore versus land-based arrays suggest additional gains from wind and wave cooling, partly offset by wave-induced tilt variation [16]. Overall, reported energy gains range from about 1% to above 10%, and disagreements between studies largely reflect differences in climate, reference system, soiling and measurement uncertainty rather than fundamental contradictions [16], [17], [20].

To illustrate the cooling contribution, Eqs. (1)–(3) were evaluated for $T_a = 30^\circ\text{C}$ and $v = 2\text{ m/s}$ with a temperature coefficient of $-0.35\text{ \%}/^\circ\text{C}$ and assumed heat-loss coefficients of $U_0 = 25\text{ W/m}^2\text{K}$ and $U_1 = 6.84\text{ W}\cdot\text{s/m}^3\text{K}$ for land, versus $U_0 = 29$ and $U_1 = 8.0$ for FPV (Table 2). At 1000 W/m^2 , cell temperature falls from about 55.9°C to 52.2°C (Fig. 2a), raising normalised power by about 1.3% (Fig. 2b). Over a clear day with a sinusoidal irradiance profile, the cooling-only energy gain is about 1.1% (Fig. 3). This is lower than many field reports, which implies that a large share of observed gains must come from other factors such as lower soiling, lower ambient temperature over water and differences in tilt and albedo, a point that deserves dedicated measurement campaigns.

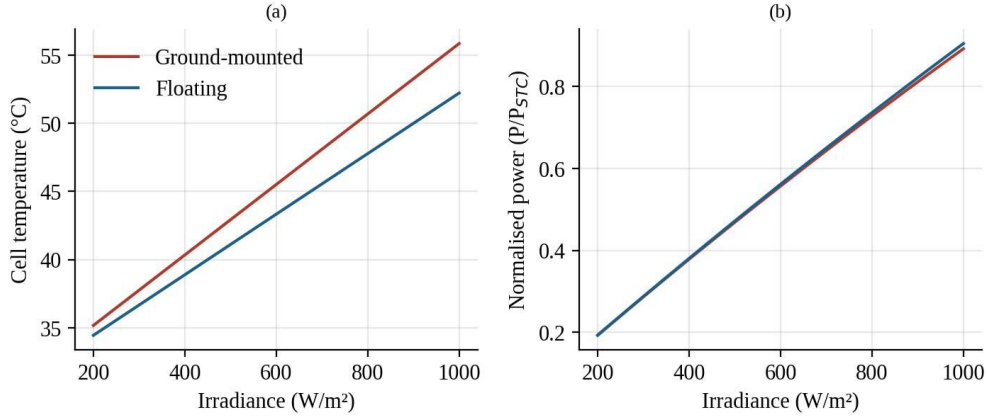


Fig. 2. (a) Cell temperature and (b) normalised power versus irradiance for ground-mounted and floating PV (Eqs. (1)–(3); assumed parameters in Table 2).

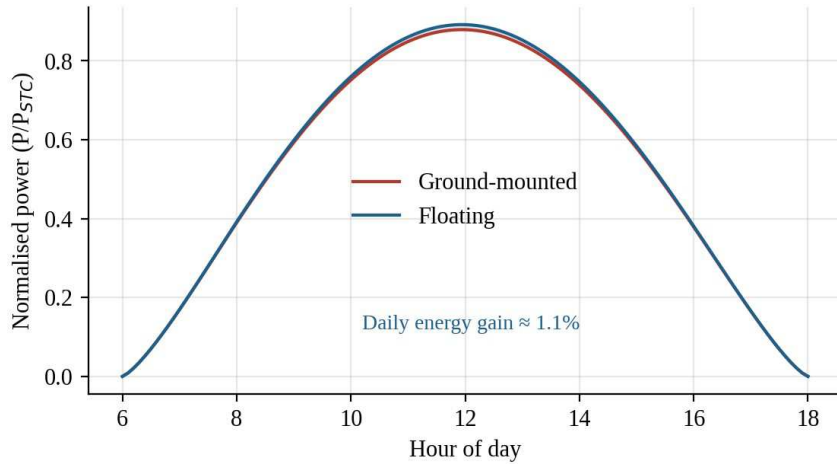


Fig. 3. Normalised daily power profile for ground-mounted and floating PV considering only the cooling effect ($T_a = 26\text{--}35^\circ\text{C}$).

Table 2. Assumptions and results of the illustrative analysis performed for this review.

Parameter	Ground-mounted	Floating PV
Heat-loss coefficients U_0 ; U_1	25; 6.84	29; 8.0 (assumed)
Cell temperature at 1000 W/m ²	55.9 °C	52.2 °C
Daily energy gain (cooling only)	Reference	≈ 1.1%
CAPEX (USD/kW)	700	850 (assumed premium)
O&M (USD/kW·year)	12	14
Capacity factor	19%	20.5%
LCOE at $r = 8\%$, $n = 25$ y, 0.5%/y degradation	≈ 48.8 USD/MWh	≈ 54.6 USD/MWh

3.3 Water–energy nexus and environmental effects

Reduced evaporation is among the most frequently cited co-benefits of FPV. Experimental and modelling work on a covered water body showed that floating covers cut evaporation substantially [8]. Applying Eq. (4) for an illustrative 10 km² reservoir with 2 m/year of evaporation, covering 20% of the surface with an FPV array that reduces evaporation by 70% would conserve about 2.8 million m³ per year, and the saving rises linearly with coverage (Fig. 4). In arid regions, the water saved can be of comparable economic value to the electricity generated, which strengthens the case for dual-purpose reservoirs [22].

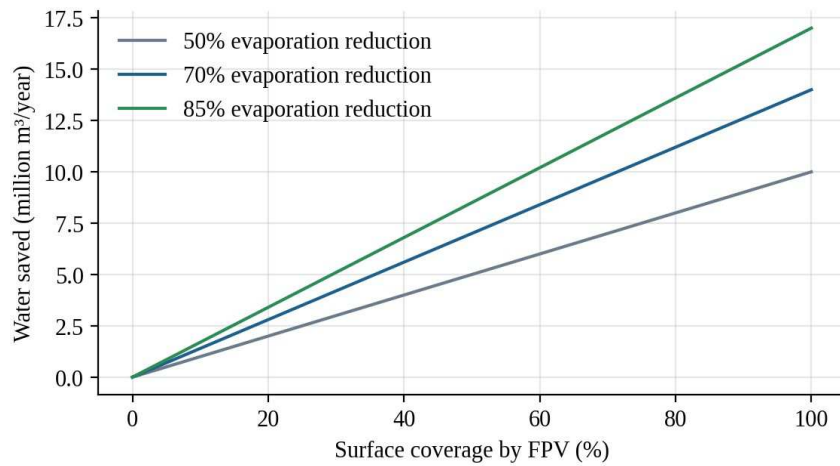


Fig. 4. Estimated annual water saving versus FPV coverage for a 10 km² reservoir with 2 m/year evaporation (Eq. (4)).

The environmental literature is less uniform. Modelling suggests that partial shading could moderate lake temperature and stratification under a warming climate [23], and could reduce algal growth by limiting light. Conversely, reduced light and wind mixing may lower dissolved oxygen, alter phytoplankton communities and affect fish and birds, and these effects are strongly site dependent [24], [25]. A widely cited commentary warns that rapid expansion is running ahead of empirical evidence and calls for monitored deployment and conservative coverage limits [10]. Social acceptance is a further factor:

stakeholder research in the Netherlands identified concerns about recreation, landscape and fishing that can be decisive for permitting [26]. Studies therefore agree on the need for site-specific environmental assessment, but disagree on the sign and magnitude of ecological impacts because long-term data are sparse [22], [24].

3.4 Hybrid and advanced configurations

Co-locating FPV with hydropower is widely seen as the most promising hybrid. Floating arrays on hydropower reservoirs can share grid connections and allow the hydro turbines to compensate for solar variability, effectively storing solar energy as reservoir water [7], [27]. A global assessment indicated very large technical potential for such hybrids [7], while an analysis of ecological versus operational trade-offs concluded that coverage should be tuned to each reservoir's flexibility and ecosystem [25]. Optimisation studies for on- and off-grid hybrid systems showed that floating-tracking arrays can improve system performance compared with fixed floating arrays, albeit with higher complexity [14]. Bifacial modules exploit rear-side irradiance, but the relatively low albedo of open water limits the gain unless the design adds reflective surfaces or optimised tilts, and bifacial floating concepts have been proposed for inland waters [28]. Recent work therefore points towards integrated systems that combine FPV with hydropower, batteries and possibly hydrogen production, which also connects to Units 4 and 5 of the syllabus.

3.5 Economics and global development trends

Cost comparisons generally find that FPV capital cost is somewhat higher than for ground-mounted PV because of floats, moorings and specialised installation, with the gap narrowing as volumes grow [1], [19]. In our illustrative calculation (Table 2), the LCOE of FPV is about 12% above that of ground-mounted PV at an 8% discount rate (Fig. 5), even after allowing a 1.5-point higher capacity factor. Project value therefore depends on benefits not captured in LCOE, namely avoided land cost, water saving and the use of existing hydropower grid infrastructure. A Korean assessment, for example, showed that reservoirs can host substantial FPV capacity relative to national fossil-fuel dependence [29].

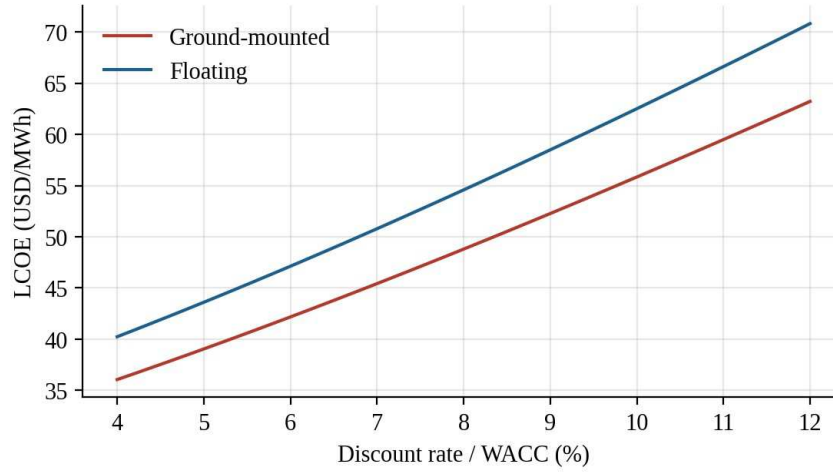


Fig. 5. LCOE of ground-mounted and floating PV versus discount rate (assumptions in Table 2; land cost not included).

Deployment has accelerated since 2015. Cumulative capacity was only tens of kilowatts in 2007, passed roughly 1 GW around 2018 and has reached several gigawatts in recent years, with China, Japan, South Korea, Taiwan, India and Singapore leading installations (Fig. 6) [1], [3]. The curve in Fig. 6 is indicative and compiled from the cited market report and subsequent public announcements; exact figures differ between sources. India's FPV pipeline now includes several tens to hundreds of megawatts at individual sites, as shown in Table 3.

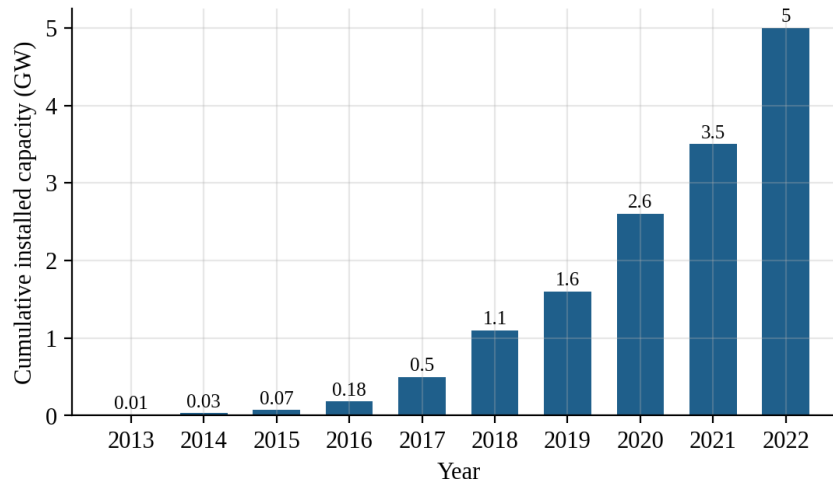


Fig. 6. Approximate cumulative global FPV installed capacity, 2013–2022 (indicative values).

4. Applications in the Energy Sector and Industry

Power generation is the principal application. Large utility plants have been built on freshwater reservoirs and on flooded former coal-mining areas, notably in China, where a plant of about 150 MW operates near Huainan, and in Singapore, where a 60 MWp plant has been placed on a drinking-water reservoir [1], [11]. In India, state-owned utilities have commissioned large floating plants on reservoirs and ponds, including the 100 MW

Ramagundam project in Telangana and the 92 MW Kayamkulam project in Kerala, and a multi-hundred-megawatt FPV park is being developed at Omkareshwar in Madhya Pradesh [4] (Table 3).

Table 3. Representative large floating PV installations (approximate capacities; compiled from [1], [4]).

Project / location	Country	Capacity	Remark
Huainan, Anhui	China	≈ 150 MW	Flooded coal-mining subsidence area
Tengeh Reservoir	Singapore	≈ 60 MWp	Drinking-water reservoir
Ramagundam, Telangana	India	100 MW	Reservoir of a thermal power station
Kayamkulam, Kerala	India	≈ 92 MW	Utility-scale on reservoir
Omkareshwar, Madhya Pradesh	India	Phased, up to ≈ 600 MW	Hydro reservoir hybrid

Hybrid FPV–hydropower systems form the second main application, where the solar plant is connected through the hydropower substation and dispatched with the turbines [7], [27]. Off-grid and island systems combine FPV with batteries and diesel or biomass generators, and optimisation indicates that floating and floating-tracking arrays can lower the cost of such microgrids [14]. FPV is also being applied on industrial and utility water bodies: cooling ponds of thermal power stations, effluent and wastewater ponds, irrigation canals and aquaculture or irrigation reservoirs, where it supplies on-site power and reduces evaporation [8], [22]. Looking ahead, floating plants are a candidate power source for electrolyzers and desalination units located next to water bodies, linking FPV with the hydrogen and storage technologies in Unit 4 of the syllabus.

5. Challenges and Limitations

Technical challenges start with the structure: floats and connectors must resist ultraviolet radiation, humidity, wave-induced fatigue and biofouling for 25 years, while moorings must accommodate seasonal water-level changes of several metres [9], [15]. High humidity and condensation raise the risk of corrosion, potential-induced degradation and connector failures, and bird droppings, algae and wave splash may increase soiling in specific locations [9], [11]. Electrical safety and fire response on a floating platform are more complicated than on land, and standards for design, testing and certification of floating arrays are still emerging [9], [13].

Economic barriers include a capital premium for floats, anchoring and specialised installation, scarcity of long-term operating data for bankability, and in some cases higher insurance and financing costs [1], [19]. The illustrative analysis in Table 2 shows that yield gains alone may not offset the capital premium, so incentives, land-cost avoidance or water-saving credits may be needed in early markets.

Environmental and social limitations are equally important. Effects on stratification, dissolved oxygen, plankton and fauna vary with reservoir type and coverage, and empirical evidence is still scarce [10], [24], [25]. Use of reservoirs for drinking water, fishing, recreation or navigation can create conflicts with stakeholders and delay permitting [26]. Policy gaps include unclear water-use rights, lack of a standard environmental assessment protocol and missing rules for end-of-life recycling of floats and modules [22]. Finally, the reviewed literature shows methodological inconsistency: studies use different baselines, climates and metrics, which hampers direct comparison of reported gains [16], [17], [20].

6. Future Directions and Research Gaps

Several specific gaps emerge from the reviewed literature. First, long-term, openly reported field datasets with matched ground-mounted reference arrays are required to separate the contributions of cooling, soiling, tilt and albedo to yield, since the present analysis and several studies suggest that cooling alone does not explain observed gains [17], [18]. Second, standardised test protocols for floats, anchors and electrical components, including accelerated ageing under humid and wave-loaded conditions, are needed to underpin reliability claims and bankability [9], [15].

Third, design research should explore offshore and nearshore platforms, bifacial and reflective-surface concepts, and tracking systems whose gains justify the added complexity [14], [16], [28]. Fourth, hybrid operation strategies for FPV combined with hydropower, pumped storage, batteries and hydrogen production should be optimised using multi-objective models that include ecological constraints [7], [25], [27]. Fifth, ecological monitoring frameworks with before-and-after control studies are necessary to establish safe coverage limits for different water body types [10], [23], [24]. Sixth, life-cycle assessment and recycling pathways for HDPE floats and mooring materials remain underdeveloped. Finally, for India specifically, systematic mapping of reservoir and canal potential, together with water-saving credits and clear policy on water-body use, would help to scale deployment, and AI-based condition monitoring and digital twins could improve operation and maintenance of remote floating plants [5], [22].

7. Conclusions

This review examined the technology, performance, benefits and global development of floating solar photovoltaic systems based on 29 sources. FPV has progressed from small demonstrations to utility-scale plants in a decade, and pontoon-type systems on sheltered inland waters now dominate the market. The literature agrees that water proximity cools modules and that floating covers reduce evaporation, but the reported energy gain varies from about 1% to more than 10% and cannot be attributed to cooling alone, as the illustrative calculations here also suggest. Under the assumptions used, FPV

has a somewhat higher LCOE than ground-mounted PV, so its attractiveness rests on avoided land use, water conservation and synergy with hydropower infrastructure. Environmental effects are site specific and insufficiently documented, and structural reliability and standardisation remain open issues. Hybrid FPV–hydro systems, bifacial and tracking concepts, and ecological monitoring represent the most promising directions. For countries such as India, with abundant sunshine, limited land and extensive water bodies, FPV offers a practical complement to ground-mounted solar and an important contribution to the energy transition, provided that deployment is accompanied by careful environmental assessment and transparent data sharing.

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