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Techno-Economic Assessment of Floating Solar Photovoltaics on Inland Water Bodies: Comparative Insights with Land-Based PV Systems and Implications for Sri Lanka

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Abstract: Fast development of solar photovoltaic (PV) has also rendered an important part of the international shift to low-carbon power systems. Nonetheless, the traditional ground-mounted PV systems are currently experiencing more and more difficulties in the form of limited land, being rivaled by agricultural and urban land development, and high cost of land acquisition, especially in the congested areas. As a result, floating solar photovoltaic (FPV) systems have become an effective alternative as they can be placed on water bodies such as reservoirs, lakes, irrigation tanks, and coastal regions. Through leveraging the water surfaces, FPV will minimize the land-use conflict and provide more water-related advantages. This is a systematic review of floating solar PV systems, in terms of techno-economic viability, performance, and the consideration of site selection. It looks into the experiences of FPV technology, the trends of its implementation worldwide and regionally, and compares its performance to the use of traditional land-based PV systems. In line with major technical aspects, such as thermal performance, mechanical loading, mooring systems, and operation and maintenance requirements, the following are examined. Another aspect of efficiency that has been noted in the review is the efficiency that is linked with the cooling effect that water surfaces have. In addition, the paper addresses the FPV as it is applied to the water-energy nexus, especially the possibility of minimizing the evaporation of a reservoir as well as producing renewable energy. There is also the presentation of a techno-economic analysis framework, which takes into account capital and operational costs, levelized cost of energy (LCOE), and the economic performance in the long term. The differences between the inland and seawater-based FPV are presented in the context of technological maturity, cost structures, and deployment issues, which specifically reflect on the tropical and island areas. Finally, the paper suggests a case-study framework which is specific to Sri Lanka and has incorporated technical, economic, grid-integration, environmental, and social factors. It also determines the main gaps in the research, including long-term performance, offshore stability, environmental effects, and regulatory preparedness to inform decisions made on the deployment of FPV in constrained power systems on land and islands.

Keywords- Floating photovoltaic systems, Grid integration, Inland water bodies, Sea-based floating PV, Sri Lanka, Techno-economic analysis, Water energy nexus.

1 INTRODUCTION

Over the past few years, the development of solar photovoltaic technology worldwide has been extremely rapid, making it the most significant source of renewable energy and a key driver of the transition to low-carbon power systems. Nevertheless, when it comes to the massive deployment of traditional ground-mounted PV systems, it is most often constrained, and increasingly so, by issues such as land shortages, competition with other land uses, and rising land purchase costs. These problems are especially severe in densely populated areas with little habitable land and a heavy reliance on agriculture, where it is difficult to set aside large tracts of land solely for energy generation [1], [2]. Therefore, the idea of changing the locations of the PV systems such that they do not consume land, in other words, rethinking how the land is used for the promotion of solar energy, has been increasingly considered as the solar PV industry keeps expanding.

Floating solar photovoltaic (FPV) systems have been proposed as a potential solution to the issues associated with solar PV and land use. With them, solar PV installations can be placed directly on water bodies such as reservoirs, lakes, irrigation ponds, and coastal lagoons [1], [3]. And after some thorough research, it can also be used at sea. FPV systems shown in Fig. 1 below are essentially traditional PV modules that are made compatible with water surface operation by the addition of floating platforms, anchoring mechanisms, and specialized electrical layouts [3]. Technology has evolved very quickly in the last ten years, mainly because of two major advantages: reducing the land area needed for installation and getting water-related benefits as a bonus. These benefits can include reducing water evaporation, controlling algal growth, and possibly enhancing PV performance due to the lower operating temperatures of floating PV systems compared to ground-mounted systems [1], [3], [4].

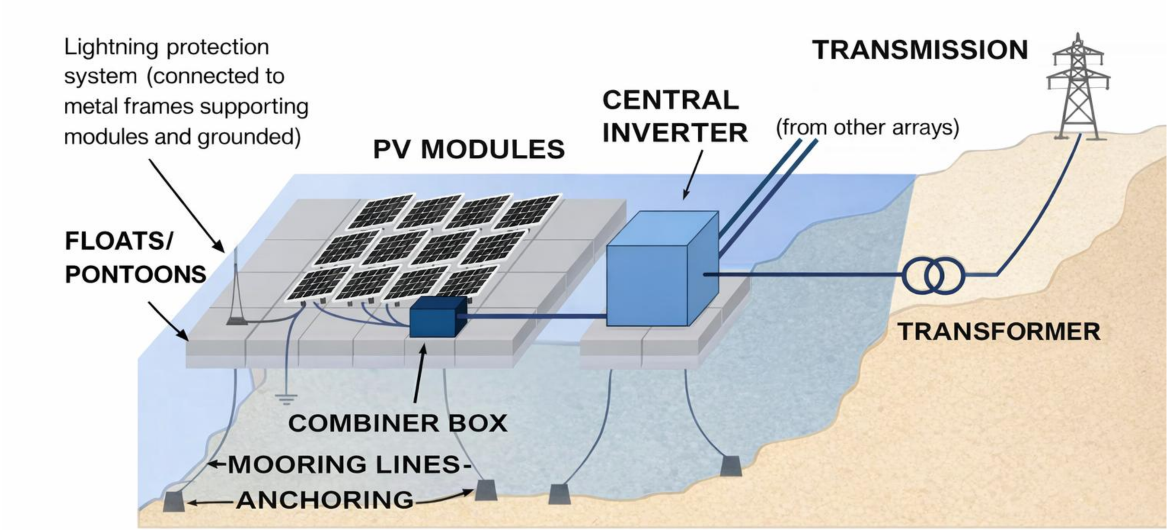

Fig. 1 Typical layout of a floating PV system. Adapted from [1].

Based on performance, FPV systems have been identified in several studies as capable of producing more energy than land-based PV systems with similar configurations, mainly because the natural cooling effect of the surrounding water helps maintain the solar cells at a more optimal operating temperature. The increase in electricity generation reported by the studies mostly falls within the range of 1% to 4%. Nevertheless, the diffusion of the findings is largely dependent on the weather conditions, system layout, and other related variables on the site [1]. Moreover, FPV systems are frequently situated near the existing power systems, particularly when FPVs are deployed on hydroelectric reservoirs, and less difficulty and reduced costs of connecting to the grid may be anticipated [1]. This is because it is these benefits that render FPV an incredibly compelling solar power generation complement, and not a direct alternative, to conventional utility-scale PV.

The rate of the FPV implementation in the world has been astonishing. The cumulative capacity of FPV power generation currently stands at an all-time high of more than 3 GWp in 2021 and is projected to reach approximately 4.8 GWp by 2026, with this being a clear sign that the market had firmly believed in the technology as having a viable future [1]. While the first FPV installations were quite small in scale, recent ones have ranged from tens to hundreds of megawatts, with some of the largest plants exceeding 100 MWp nowadays. Apart from that, the deployment has been significant in Asia, where countries like China, Japan, and South Korea are the main contributors to global capacity additions [2], [3]. However, even with this considerable expansion, most current FPV installations are still on inland freshwater bodies, whereas FPV at sea and offshore remains very limited and mostly at the experimental stage [2].

It is hard to imagine a more suitable beneficiary of floating photovoltaic installations (FPV) than small island developing states and countries with very limited land. A great majority of people in the world live within a few hundred kilometers of the sea. Therefore, the demand for electricity in the marine environment is very high [2]. In such situations, FPV plants, whether constructed on inland reservoirs or at sea just off the shore, can provide a solution for large-scale solar production without further increasing land shortages. Countries with a large reservoir network or a long coastline, such as Sri Lanka, thus have the potential to benefit greatly from FPV technology. Although Sri Lanka is mentioned among countries with FPV activities, the whole of South Asia and Sri Lanka alone haven't seen much implementation of the technology, with few large-scale projects and hardly any locally focused assessments published [2].

There is literature on FPV which indicates its technical capability, although there remain some key gaps in research. To begin with, there are already numerous full-size experiments that have been implemented to examine the performance and test the possibility of FPV in tropical temperatures, where the effect of high temperatures, humidity, and solar radiation may change the behavior of the system significantly [2], [4]. Secondly, the inland FPV systems have been moderately represented in the literature, but no studies have been conducted on the possibility of sea-based FPV systems, especially those that consider wave loading, wind, and corrosion by salt [2], [3]. Third, the techno-economic analysis conducted between FPV and traditional ground-mounted PV systems is yet to take into account every facet of it, more specifically, the aspects that refer to the cost elements, levelized cost of energy (LCOE), and the long-term implications of the operation and maintenance in the economies of the developing countries and islands [1].

Addressing these gaps, this review paper offers a comprehensive, well-structured synthesis of floating solar PV technology, with particular emphasis on techno-economic viability and site suitability. Major contributions of this review are a thorough presentation of FPV system architectures and types of installations, comparative analysis of FPV and ground based PV systems in performance, efficiency, land use and economic indicators, a critical evaluation of the thermal and cooling advantages of water based PV installations and a consideration of the suitability of FPV on inland water bodies vs sea based FPV for Sri Lanka. This review consolidates existing knowledge while highlighting the challenges that remain to be addressed. Hence, it aims to be a useful resource for decision-makers in FPV implementation and to serve as a guideline for research directions in tropical and island settings.

2 OVERVIEW OF FLOATING SOLAR PV TECHNOLOGY

2.1 Global Energy Transition and the Emergence of FPV

This process has compounded the shift to renewable energy systems because of the rapid increase in energy demand in the world and the extreme need to curtail greenhouse gas emissions [5], [6]. A solar photovoltaic power plant uses PV technology, one of the most established renewable energy sources worldwide, and is also cost-effective [5]. According to the latest international evaluation, the installed PV has already exceeded 1185 GW, accompanied by a yearly increase of around 240 GW, which proves the continued growth of the solar industry [5].

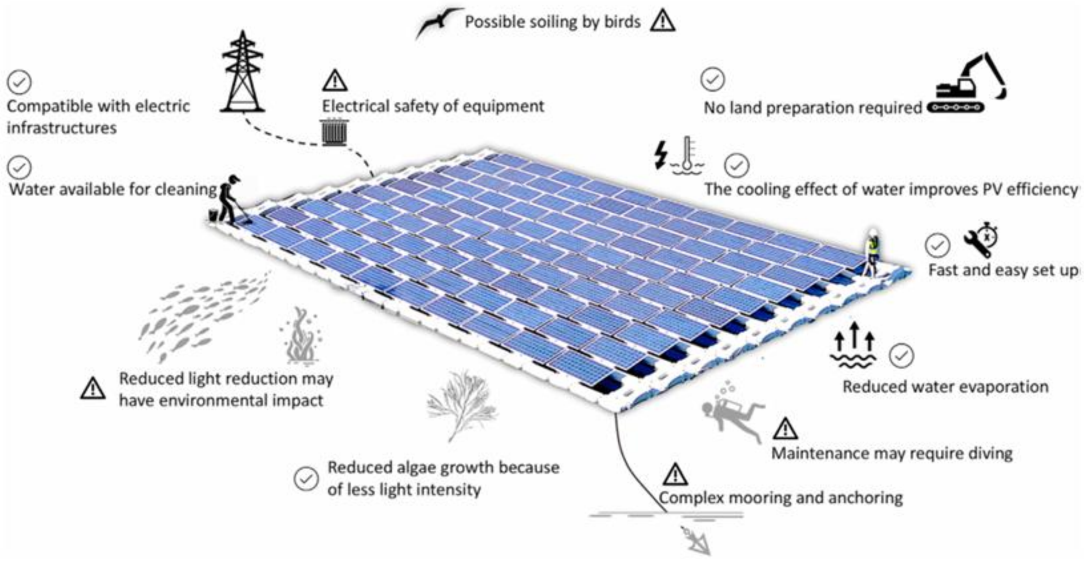

Fig. 2. Schematic representation of the main advantages and potential disadvantages of the FPV systems, adapted from [7].

Floating photovoltaic systems (FPV) have increasingly been mentioned as a strategic direction in the context of this overall transition. As stated above in Fig. 2, FPV is a solution to land scarcity, environmental limitations, and the diversity of installations, especially in places where obtaining vast areas of land for ground-based systems is difficult.

2.2 Definition and Evolution of Floating Photovoltaic Systems

Floating photovoltaic systems are solar PV installations deployed directly on bodies of water rather than on terrestrial surfaces [3], [6]. The technology has continued to advance at a very fast pace since the commissioning of the first FPV installation in 2007, with large-sized projects in operation in Asia, Europe, and North America [1], [6].

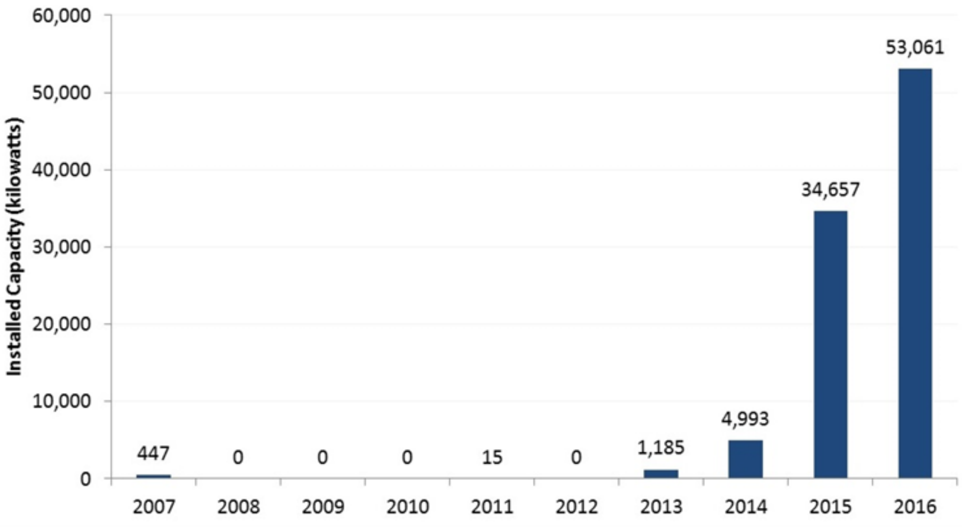

Fig. 3. Floating PV has been a part of the global energy generation system since the first plant was installed in 2007. Adapted from [8]

Initially, FPV deployment was concentrated on artificial water bodies such as reservoirs, irrigation ponds, and wastewater treatment basins. Over time, as shown in Fig. 3, technological advancements and the increasing demand for renewable energy have expanded FPV applications into offshore and marine environments [5], [6]. This evolution reflects both the increasing maturity of PV technologies and the recognition of untapped solar energy potential over water surfaces.

2.3 Comparative Advantages over Ground-Mounted PV

Compared with traditional ground-mounted photovoltaic (GPV) systems, FPV requires structural and operational changes to be buoyant, stable, and capable of withstanding varying water levels [3]. The water-based habitat has several technical and ecological benefits.

- Reduced Land Occupation of FPV substantially reduces land use tensions, where there is a conflict of land use with agriculture and urban growth [3], [2].
- Enhanced Energy Yield Potential is as follows: the propinquity of water can draw the operating temperatures in modules by evaporative cooling, which may speculate to enhance energy conversion performance in similar irradiance conditions [3].
- Water Conservation and Ecological Goods and surface shading can potentially decrease water evaporation and algae growth, which will provide supplementary environmental benefits [2].

All these make FPV a viable competitor in congested areas or within land-inherent regions.

2.4 Technical Configuration and Structural Components

Technically, FPV systems consist of PV modules mounted on buoyant floating platforms that are anchored or moored to maintain positional stability [3], [5]. The pontoons are usually constructed of high-density polyethylene (HDPE) because of their resistance to corrosion, UV stability, and mechanical resistance [5].

Electrical grids, such as inverters and transformers, are typically mounted onshore to facilitate maintenance and improve reliability, and electricity is conveyed via floating or submerged DC/AC cables [3].

For offshore applications, system configurations are more complex and may include,

- Pile-fixed structures
- Modular pontoon-based arrays
- Very Large Floating Structures (VLFS)
- Flexible floating systems designed to withstand dynamic wind and wave loadings

These configurations reflect the increased engineering sophistication required for deployment in high-energy marine environments [5].

2.5 Global Technical Potential and Deployment Outlook

The global technical potential of FPV is considerable. It has been estimated that covering only 1% of the world's reservoirs with FPV installations could yield approximately 404 GWp of additional clean energy capacity [1]. Besides, extensive evaluations of artificial waters suggest that FPV may be a large portion of national electric systems with modest coverage hypotheses [3].

Although this is encouraging, FPV systems are still comparatively more expensive than traditional GPV systems due to the high structural, anchoring, and installation costs. Also, there are unanswered research questions about long-term material durability, environmental effects, survival at offshore locations, and environmental performance lifecycle [1], [6].

3 GLOBAL AND REGIONAL STATUS OF FLOATING SOLAR PV

Over the past ten years, floating solar photovoltaic (FPV) systems have shifted from experimental to utility-scale systems due to land scarcity, rising electricity demand, and the desire to maximize solar energy efficiency. It is a critical analysis of the performance history, world deployment, and current state of affairs of FPV in Sri Lanka and South Asia, considering the inequalities in regions, maturity, and gaps in research.

3.1 Global Deployment Trends of Floating Solar PV

Use of FPV has increased at an alarming rate worldwide because the locations with low land use and high population have largely used it, as seen in Fig. 4. The initial implementations of the FPV systems were small pilot projects that were primarily put on artificial ponds and wastewater treatment basins. However, recent literature has indicated otherwise with the rise of the multi-megawatt utility system, which has demonstrated growing confidence amongst investors and technological maturity [7], [8].

Asia is the current leading continent within the global FPV power capacity, with China, Japan, South Korea, and India leading due to positive policies on renewable energy and high inland water resources in the area [9]. In the case of China specifically, massive FPV-sited power plants in the flooded subsidence regions of coal mines have proven to offer several advantages not only for environmental remediation but also for renewable energy generation [10]. In Europe, FPV deployment remains limited but is gaining attention in countries such as the Netherlands, France, and Portugal, where inland water bodies are increasingly utilized for solar generation [11].

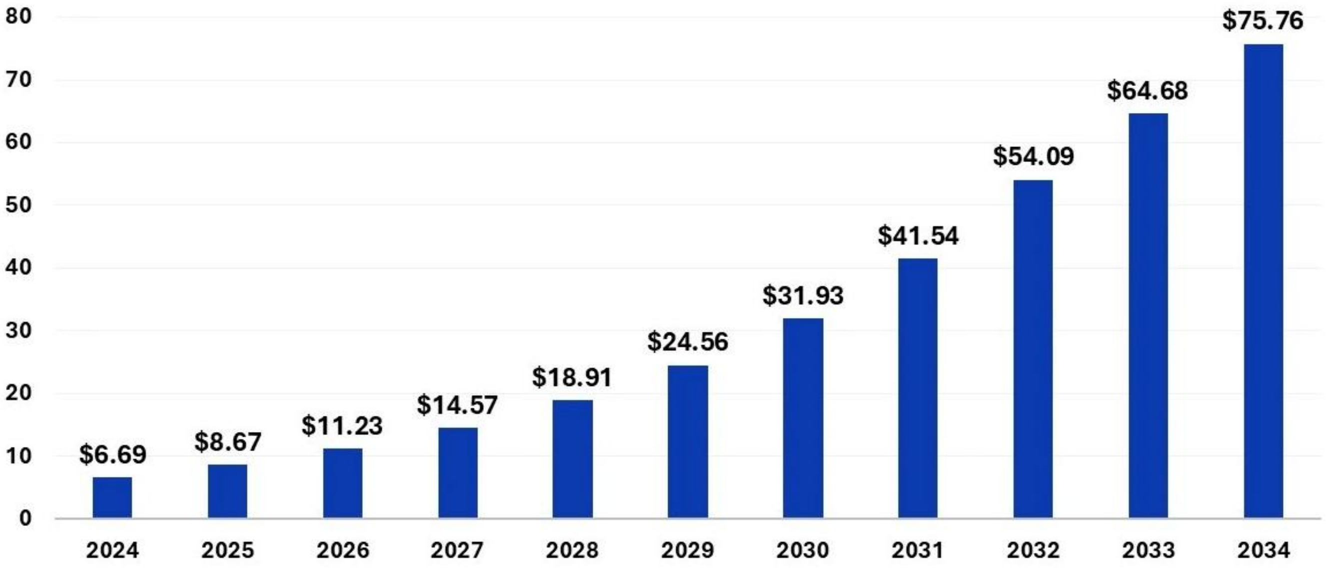

Fig. 4. Global floating solar PV installations market size trend, Adapted from [12].

Technologically, innovations in global FPV systems use high-density polyethylene (HDPE) modular floating systems, regular crystalline-silicon PV panels, and mostly fixed tilts. Being more mechanically complex and expensive, tracking FPV systems have not been widely used [13]. Experiments have almost always demonstrated that FPVs contribute to an increase in energy production compared to land-based PV installations. The main reasons are lower operating temperatures of the modules and a higher reflectivity [14].

3.2 Performance of FPV Systems in Tropical and Coastal Regions

FPV deployment in tropical and coastal regions presents both opportunities and challenges due to high solar irradiance, high ambient temperatures, humidity, and wind. Regular journal investigations carried out in Southeast Asia and South Asia have found that FPV systems in tropical climates outperform similar land-based PV systems in annual calculated yields and under higher-humidity ambient conditions [15], [16].

With reference to the comparison of operational and environmental characteristics shown in Table 1, the radiative cooling of water bodies is crucial for mitigating efficiency losses caused by temperature in a photovoltaic panel. Simulation-based studies and experimental investigations suggest that FPV installations can reduce the average module temperature by 5-15°C and yield a 3-12% efficiency improvement, contingent on climatic factors, water-body properties, and system design [17], [18]. Such advantages are especially pronounced in tropical areas, where land-based PV systems experience severe thermal derating, and high operating temperatures are sustained throughout.

However, it is still a fact that FPV systems built in coastal or near-shore areas experience more technical problems compared to those in inland waters. These problems, such as salt corrosion, higher wind stress, and wave loading, all of which can result in a decrease in the lifespan of the system and may also affect its long-term performance. Although plenty of studies on the FPV systems based on inland reservoirs are available, there are only a few, mostly conceptual or pilot-scale demonstration works on the sea-based FPV systems [19]. Existing journal studies emphasize the importance of advanced material selection, corrosion-resistant electrical components, and robust mooring and anchoring systems to ensure reliable long-term operation in marine environments [20].

Table 1. Comparison of operational and environmental characteristics between floating PV and land-based PV systems [15]-[20].

Parameter	Floating PV	Land-based PV
Average module temperature	Lower by 5-15 °C	Higher
Annual specific yield	Higher	Lower
Temperature-induced losses	Reduced	Significant
Environmental exposure	High humidity, biofouling	Dust, heat
O&M complexity	Moderate	Low

3.3 Status of Floating Solar PV in Sri Lanka and South Asia

A potential target market is South Asia, where FPV has relatively low large-scale implementation with high technical potential. In India and Bangladesh, FPV projects on large-scale reservoirs, irrigation tanks, and hydropower dams have been launched as pilot and commercial projects to expand their renewable energy portfolios [21]. In India, FPV installations integrated with hydropower reservoirs have demonstrated the feasibility of FPV-hydropower hybrid systems, enabling improved grid stability, enhanced capacity utilization, and shared transmission infrastructure [22].

Fig. 5. First Floating Solar PV plant on Chandrika Wewa in the Sabaragamuwa Province, Sri Lanka. Adapted from [23].

Conversely, Sri Lanka is still at the FPV pioneering stage. The first Floating Solar PV plant is Chandrika Wewa in the Sabaragamuwa Province, as shown in Fig.5, although many reservoirs are linked to irrigation and hydropower plans. According to the journal-based tests, FPV can be deployed in Sri Lanka due to the country's tropical climate and the high solar irradiance and inland water bodies, which provide favorable conditions [24]. Nevertheless, the unavailability of demonstration projects at a large scale, the limited support of policy, and the absence of localized and techno-economic feasibility investigations have hindered commercial-scale implementation [25].

The research related to the Sri Lankan situation demonstrates that the principal challenges, including regulatory risks, institutional gaps in understanding the water-based solar systems, long-term performance history, and environmental approvals, are the primary problems [26]. Also, the literature review shows that no peer-reviewed journal-based studies have so far directly compared the techno-economic of FPV and land-based PV systems under the climatic conditions in Sri Lanka, which is an apparent void in the literature filled by the research.

Regional literature typically suggests that the feasibility of various countries should be undertaken country-specifically, particularly in an island state such as Sri Lanka, where land space accessibility, environmental factors, and grid capabilities significantly add strategic value to the floating solar PV systems [27], [28].

4 COMPARISON BETWEEN FLOATING PV AND LAND-BASED PV SYSTEMS

There are common electrical conversion principles between FPV and LPV systems. Still, the thermal environment, mechanical loading conditions, and operating and maintenance (O&M) limitations are different between the two, which show quantifiable variations in performance and reliability outcomes as described in the journal literature [29]-[32]. Specifically, FPV systems are frequently presented as having water-proximate cooling effects and land-use benefits, as well as new risks associated with platform hydrodynamics or mooring integrity, especially in marine/offshore applications [30].

4.1 Technical Performance Comparison

4.1.1 Energy Yield and Capacity Factor

Peer-reviewed research on the comparison of FPV and ground PV indicates that FPV is able to obtain a better performance parameter in specific situations due to cooling and climatic interactions. As an illustration, an analysis of a techno-economic-environmental comparison showed greater performance of FPV compared to ground-based PV and included wind and water temperature effects in its analysis, such as the country of the project, which is northern Iran [32]. It is in addition found in longer review articles, as cooling is listed as an important method in many cases that has been attributed to FPV performance gains, with the authors noting that results are also site and design dependent, and not universal [29],[30],[31].

4.1.2 Thermal behaviour and temperature modelling differences

One major technical difference is that the performance modelling of FPVs needs thermal characterization of FPVs, shown in Fig.6, and not directly applying land-PV temperature coefficients. Multiple (FPV) configurations were characterized in terms of heat-loss coefficients depending on the wind in a one-year study. It has included water temperature as one of the variables, showing that the design and size of the system influence FPV thermal response [33].

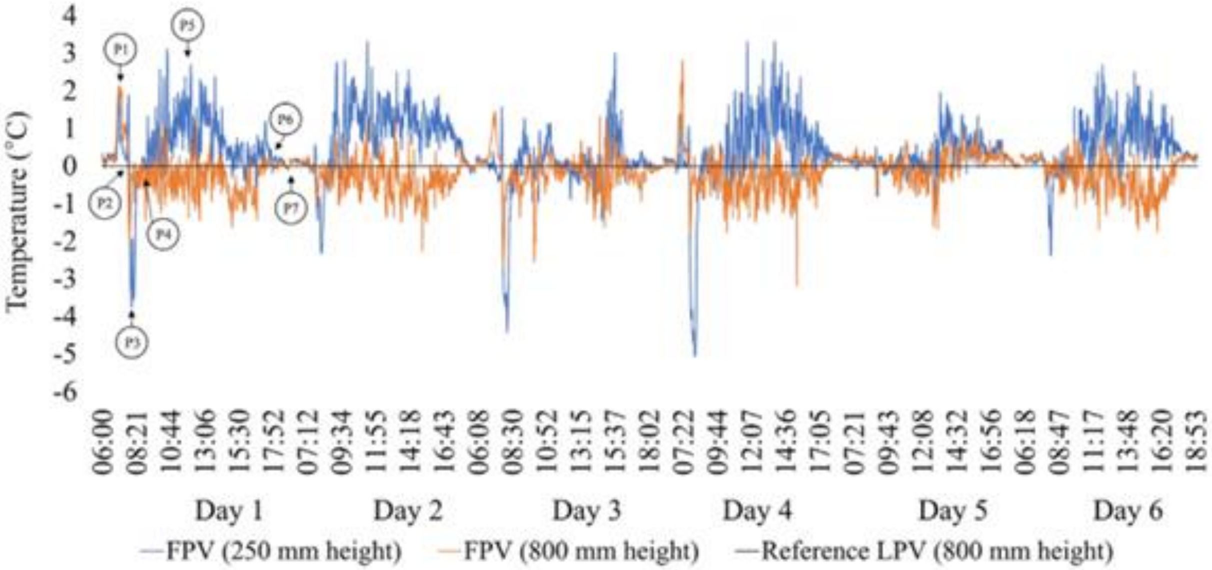

Fig. 6. Thermal behavior of floating photovoltaics, Adapted from [34]

In addition, FPV module temperature estimation has been addressed through thermal/empirical/Computational Fluid Dynamics (CFD) modelling, and by comparison with measured FPV data, reinforcing the need for FPV-specific temperature prediction approaches [35].

4.1.3 Mechanical Loading, Stability, and Reliability

In comparison to LPV, FPV introduces platform movement, and wave/current interaction (where applicable), and mooring dynamics as drivers in designing systems in the coastal/offshore regions. According to marine FPV review literature, survivability, load estimation, wave-structure interaction, and mooring design are of significant importance in the engineering consideration of a mission at sea [36]. Additional assessment of complementary review in fluid mechanics also highlights the problems of wind-wave loading and the imperative to have strong, offshore structural concepts [37]. Detailed proposals on the finer scale, mooring set strategies under joint wind wave current loading display that the mooring set structure can significantly impact the platform movement reaction and mooring tension responses [38].

4.2 Efficiency Enhancement Due to Water-Based Cooling

Lowering the operating temperature is most often recognized as the primary physics basis by which FPV systems can improve their power conversion efficiency in comparison to LPV under the same irradiance level. A number of fundamental FPV literature sources describe not only the cooling effect of water to which floating arrays are close but also other performance-enhancing design measures which result in better efficiency [29], [30]. The Energy enhancement interval for the first four water-based cooling methods is shown in Fig.7 below.

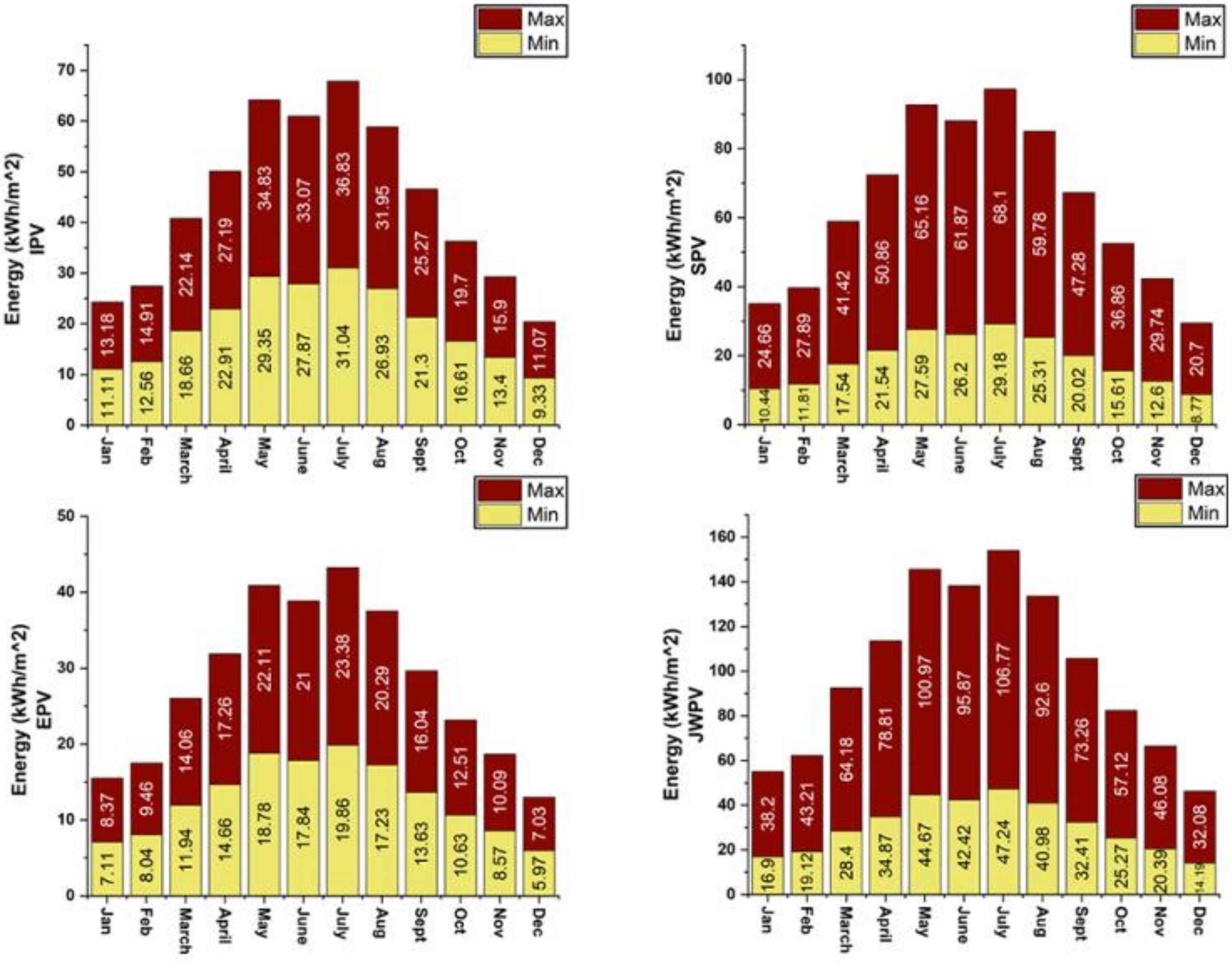

Fig. 7. Energy enhancement interval for the first four water-based cooling methods, Adapted from [39]

Fig. 7 shows how much energy can be generated each month (kWh/m^2) by four types of solar panel setups. Island PV (IPV), Shore PV (SPV), Embankment PV (EPV), and Jetty-based Water PV (JWPV). Minimum and maximum values are also demonstrated. Energy production, in general, goes up from January and reaches its highest levels in late June and July, then slowly goes down to December. JWPV has the highest energy potential, followed in order by SPV, IPV, and EPV. The main reason is the seasonal changes in solar irradiance over the year.

FPV thermal research studies also demonstrate that wind dependence, system size, system configuration, and water temperature have an effect on the heat-transfer behavior, and the inference is that FPV cooling effects cannot be enabled through assumptions, but explicit modeling is required [33],[34],[35]. Techno-economic-environmental work has also been conducted to favor FPV performance when the cooling effects are incorporated into the feasibility test [32].

4.3 Land Use, Water-Nexus Co-Benefits, and O&M Differences

4.3.1 Land-Use Displacement

The FPV systems are systematically placed by journal reviews as a strategic mode to increase the sunlight PV systems in areas where land use is restricted, like in densely populated areas or where reservoirs and hydropower lakes could cover the land, thus blocking the conventional LPV [29],[30],[31]. By exploiting underutilized water surfaces, FPV systems mitigate competition for agricultural land, urban development, and environmentally sensitive land.

The concept of offshore and near-shore evaluation goes one step further to consider the technical capability and cost-efficiency of sea-based FPV operations in appropriate areas, but engineering preparedness, survivability, and environmental limitations are the main focus of large-scale implementations [40].

4.3.2 Water Evaporation Reduction and Water Energy Co-Benefits

Other than land savings, other co-benefits associated with FPVs on reservoirs can be of considerable water nature, thus supporting their applicability in the water-energy nexus. Coupled modelling of hydro-energy Yield and water-energy network of large reservoirs that peer-reviewed experiments have quantified evaporation reduction in large reservoirs in the partial and high surface-coverage case [41]. For example, the study of the Aswan High Dam Reservoir Evaporation loss and water savings due to FPV are mentioned in Table 2 and Fig. 8.

Table 2. Evaporation loss and water savings due to FPV [42].

FPV occupancy[%]	Cumulative evaporation loss[BCM $12a^{-1}$]	Mean evaporation rate[mm d^{-1}]	Total water savings [BCM $12a^{-1}$	Mean annual water savings[BCM a^{-1}]
0 (Reference)	141.6	6.5	-	-
10	134.4	5.96	7.2	0.6
45	107.9	4.55	33.7	2.8
90	71.2	2.93	70.4	59

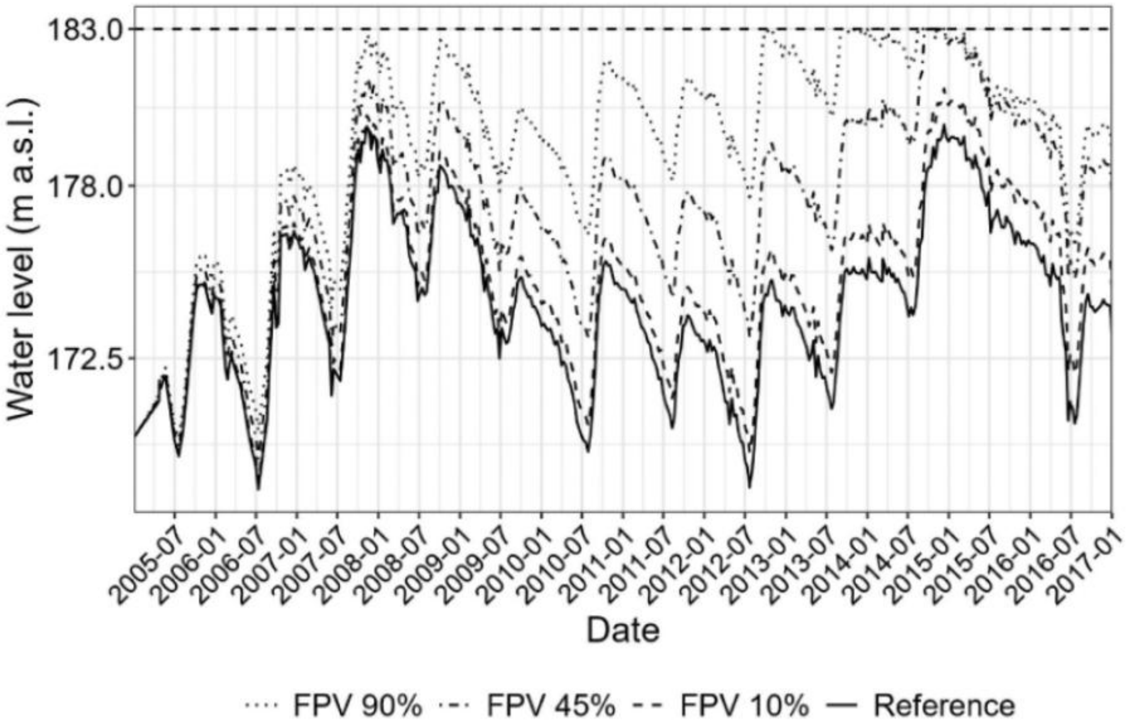

Fig. 8. Effect of different FPV occupancies on the water level of the Aswan High Dam Reservoir, Adapted from [42].

Further theoretical and experimental work provides more knowledge, such as complementary theoretical and experimental results for reservoirs with and without FPV coverage, showing that evaporation is measurably reduced, which can be attributed to surface shading salience and altered heat transfer processes [43]. Another reservoir case study provides savings of water and electricity production with a partial FPV cover, which allows seeing the twin advantage of saving water resources and producing renewable energy [44]. Taking these studies together, it is indicated that FPV is able to perform better in terms of resource efficiency at the water-energy interface, but it is also revealed that the strength of the results of the magnitude of benefits strongly depends on climate conditions, reservoir geometry, and coverage ratio [43],[44],[45].

4.3.3 Operation and Maintenance (O&M) and Monitoring Requirements

The differences in operation and maintenance requirements between FPV and LPV systems are very significant because of the inaccessibility, constant exposure to water bodies, and the requirement of checking floating, anchoring, and mooring systems. FPV systems need periodic checking of floats, electrical, corrosion-prone, and mooring integrity, which brings in an extra logistical and safety challenge compared to ground-based installations.

These problems are identified in peer-reviewed literature on the FPV plant management. It proposes the introduction of new methods of monitoring and surveillance (cost-efficient uncrewed surface vehicles) to aid in routine inspections as well as environmental audits. These works also highlight how complicated FPV systems are when needed in large reservoirs and offshore applications than the traditional LPV systems [46], as indicated in Table 3, Evidence-Based Comparison of FPV and LPV Systems.

Table 3. Evidence-Based Comparison of FPV and LPV Systems

Aspect	Floating PV (FPV)	Land-based PV (LPV)	Key evidence
Comparative performance	FPV can show improved performance in some contexts when cooling effects are considered	LPV baseline of thermal derating can be limiting in hot climates	[32]
Thermal modelling needs	Requires FPV-specific coefficients and water-temperature consideration	Established land-PV temperature models are widely used	[33]-[35]
Mechanical reliability drivers	Mooring/platform dynamics and hydrodynamic loads become critical (esp. marine)	Primarily wind/structural loads on fixed supports	[36]-[38]
Land requirement	Minimal land acquisition (shore facilities mainly)	Requires land	[29]-[31]
Water co-benefits	Can reduce evaporation depending on coverage and site	Not applicable	[43]-[45]
O&M complexity	Aquatic access and monitoring requirements	Generally simpler access	[46]

5 TECHNO-ECONOMIC ANALYSIS OF FLOATING SOLAR PV

The techno economic analysis (TEA) is the analysis of whether FPV could be competitive in its electricity delivery at the additional cost of floating structural, mooring/anchoring, marine-grade electronic elements and intermediate installation amortization and installation administration/OAM to find equilibrium with potential energy gains (cooling-efficient enhancement), energy disadvantages (less soiling in certain locations), and co-benefits (e.g., reduced evaporating), which may generate extra values to the project contingent upon the application. Recent journal reviews have noted that although FPV can enhance energy yield compared to land-based PV, it is usually more costly due to the floating balancing system. The cost difference is, however, shrinking since technology is now maturing and the standardization is now higher [47]. The TEA literature also indicates that offshore-oriented sites tend to make cost competitiveness very site-dependent, such as in those cases where platform and mooring design are driven by wave/wind loading and with logistics and O&M playing a larger role in the lifetime cost [40], [50], TEA literature demonstrates the topic of site-dependence of cost competitiveness of the site even further.

5.1 Capital Expenditure (CAPEX): Cost Drivers and Breakdown

FPV CAPEX may be modeled as PV plants facility core (modules, inverters, transformers, and onshore-to-offshore interconnections) with premium costs (floatation, structural fixing, mooring/anchoring, override, and cabling (that is exposed to water), access, and safety amenities. Published literature in a peer-reviewed article in the IEEE Journal of Photovoltaics notes that the estimates in FPV CAPEX are expected to increase 20-30% over ground-mounted PV, and FPV LCOE by 30% in most cases, mostly due to floating structures and additions to anchor and moor [47]. These results are in line with offshore FPV case-study work, in which the CAPEX and OPEX elements have been explicitly enlisted to calculate LCOE, and conclude that offshore FPV LCOE is greater than a land PV and may remain competitive with other offshore renewables under certain island/offshore limitations [50].

The second CAPEX driver is complexity in site engineering, where mooring design and logistics are the influencing dynamics. Global offshore FPV assessment work models, cost of the system across territorial waters/ Exclusive Economic Zones (EEZs), and demonstrates that the economic feasibility is highly reliant on the regional provisions and assumptions, with significant reliance on sound CAPEX foundations and region-specific inputs to financing in TEA [40]. Offshore structural reviews also reinforce that engineering requirements for survivability (wave and wind loads, connectors, mooring redundancy) can lead to CAPEX escalation relative to sheltered inland reservoirs [36], [37]. The example 480MWp system CAPEX is mentioned in Table 4 below.

Table 4. Capital Expenditure of 480MWp Floating Photovoltaic Plant [51]

CAPEX (480MWP)	US$/ WP	TOTAL (US$)	%
Photovoltaic modules	0.25	120.0×10^6	34.24
Inverters	0.06	28.8×10^6	8.22
Mounting system	0.15	72.0×10^6	20.55
Supervision system	0.13	62.4×10^6	17.81
Design/build/test	0.14	67.2×10^6	19.18
Total	0.73	350.4×10^6	100.00

5.2 Operational Expenditure (OPEX): Maintenance Burden, Downtime Risk, and Lifetime Costs

FPV OPEX is not the same as land PV since both the integrity of electrical assets and floating system integrity (floats, couplers, walkways, mooring tension, corrosion/ biofouling) should be looked after by O&M. According to the review of the IEEE Journal of Photovoltaics, FPV is more expensive than land PV not only is FPV costlier CAPEX-wise but also on other factors such as increased inspection/maintenance costs and operational risk due to water exposure [47]. OPEX is directly a key player in the offshore case-study design work, with the authors indicating that techno-economic competitiveness relies on controlling O&M and launching OPEX under marine driving [50].

Recent journal literature suggests automation and special-purpose monitoring as avenues for cost control. To illustrate the point, there is an example of an O&M-oriented FPV study, which suggests using unmanned surface-vehicle strategies to minimize the obstacles to monitoring and inspection branches in water bodies, which means that O&M innovation is becoming a widely agreed-upon point to minimize the lifecycle costs and enhance the bankability [44]. Simultaneously, marine FPV lists longevity and reliability in the long run as consistent issues that may result in higher OPEX related to more frequent inspections and replacements, and higher risk of downtime, particularly beyond the lee of inland waters [36], [37].

5.3 Economic Performance Indicators and How FPV Compares with Land PV

5.3.1 Core indicators: Levelized Cost of Energy (LCOE), Net Present Value (NPV), Rate of Return (IRR), and Payback

The FPV TEA papers have most quantified economic viability as a factor through LCOE and investor-oriented approaches with NPV and IRR. In the article Energies, FPV economics and performance are compared using the method of a remote-sensing-informed approach. It documents variation in the LCOE and IRR in FPV and ground PV under the study conditions [48]. The FPV versus ground PV payback analysis in Clean Energy reports an improvement of FPV payback against ground PV in the case, where it is shown that the increase in yield can compensate for some of the floating specific cost under specific climatic and financial parameters [32].

To illustrate regional/large-scale TEA, an article in the Journal of Thermal Analysis and Calorimetry has documented LCOE values of FPV in coastal Indian sites, as part of its modelling assumptions, which showed that LCOE can be competitive over a variety of resource and design options [49]. The case study of Discover Sustainability, in its reservoir-oriented report, presents LCOE, IRR, and NPV of various surface-coverage levels using the System Advisor Model (SAM) and Penman-Monteith evaporation modelling, showing how FPV TEA incorporates both energy- and water-conservation value propositions expanded [53].

5.3.2 LCOE variation across contexts (inland, coastal, offshore, hybrid)

A major takeaway from the literature is that the LCOE of FPV can differ greatly not only by the type of location (reservoirs sheltered vs. coastal vs. offshore) but also by the type of panel arrangement (fixed, tilt vs. tracking) and the type of financing (discount rate/WACC). For instance, offshore FPV global assessment studies model LCOE variations across regions systematically and indicate that the choice of location and economic assumptions have a strong impact on the cost competitiveness of the FPV [40]. On the other hand, a multi, disciplinary review in the Journal of Marine Science and Engineering presents extremely wide LCOE ranges for FPV across different offshore/onshore and integrated configurations (aquaculture, hybrid renewables, hydrogen), pointing out that comparisons should be made for system boundaries and financing assumptions [52].

5.3.3 Water-cooling and evaporation: translating co-benefits to economic value

Cooling, induced yield improvements impact LCOE in the first place by raising the annual electricity generation without an equivalent increase in costs. So far, three major pieces of work have been conducted, which also relate to the topic of this paper. A review paper, an evaluation study, and a study of the policy framework of Japan and the Twenty-foot Equivalent Unit schemes. The most comprehensive one is a review paper that summarizes the state of the art of water, air, and other types of cooling for PV applications, as well as their impacts on the performance and environmental footprints. Among others, it also supports, from an energetic point of view, the integration of thermal performance evaluation into TEA of PV designs that make use of water proximity for cooling. [39]. Other thermal FPV systems studies have shown that water temperature, system height/geometry, and environmental parameters affect the module temperature and, as a result, energy yield parameters, which should be taken into account in TEA by yield modeling instead of simply assuming a fixed bonus yield [33], [34], [35]. Conservation of evaporation can create additional economic benefits where water is scarce, or the saved water can be used for monetizable purposes (e.g., irrigation water, hydropower generation, and avoided pumping). Reservoir, scale modeling published in the Hydrological Sciences Journal has quantified reductions in evaporation and water savings associated with high FPV occupancy, thereby providing evidence to support the incorporation of water savings into grander cost-benefit frameworks [41]. Other reservoir studies quantify evaporation reduction through theoretical/experimental methods and reservoir case study analysis, thus supporting TEA monetization routes when local water economics are determined [42], [43].

6 INLAND WATER BODIES VS SEA-BASED FLOATING PV

Floating solar photovoltaic (FPV) systems are versatile in that they can be placed on freshwater bodies or marine environments. Each of the two scenarios has a different set of technical, economic, and environmental issues, which need to be assessed in advance of the installation. Selecting where to put the system has a big impact on the levels of design complexity, uplift of maintenance, and even the overall viability of the project.

6.1 Inland Water Body-Based FPV Systems

In recent years, FPV systems have been mostly deployed on freshwater bodies like reservoirs, lakes, irrigation tanks, and hydropower dams. Apart from the fact that these places usually have calm water with hardly any waves and low wind speeds, they also offer the advantage of making the engineering design of floating structures and anchoring systems much simpler than those for offshore installations. Also, accessibility to the sites is improved and the environment is not as harsh so that it becomes comfortable to perform the maintenance tasks [60].

6.2 Sea-Based Floating PV Systems

On the other hand, oceanic FPV systems provide significantly bigger spaces for solar energy installations, thus making it possible to build large-scale solar power plants in coastal and offshore areas. But marine environments pose serious technical issues such as vigorous wave movements, strong winds, different tides, and saltwater corrosion. These aspects lead to higher structural intricacy, more frequent maintenance, and increased running costs [61].

6.3 Economic Considerations and Relevance to Sri Lanka

Installing and maintaining floating photovoltaic (FPV) systems at sea is usually more costly than establishing such systems on inland water bodies from an economic point of view. Also, a comparison between inland water body FPV and Sea-Based FPV systems is mentioned in Table 5. However, marine FPV could still be a viable option in areas where there are hardly any freshwater resources or where there is a need for a large supply of renewable energy. In Sri Lanka, performing FPV on an inland reservoir is one of the most viable options as the country is marked by a large-scale irrigation and hydropower network, which not only offers the water surface for the FPV system but also the existing power grid connection [62].

Table 5. Comparison Between Inland Water Body FPV and Sea-Based FPV Systems

Aspect	Inland Water Bodies	Sea-Based FPV	Reference
Typical locations	Reservoirs, lakes, irrigation tanks, hydropower dams	Coastal and offshore areas	[60], [61]
Water conditions	Calm waters, low wave activity	Strong waves, tidal effects	[60], [61]
Structural complexity	Lower	Higher	[60], [61]
Maintenance accessibility	Easier	More challenging	[60], [61]
Corrosion exposure	Limited	High (saltwater)	[61]
Installation and O&M cost	Lower	Higher	[61], [62]
Feasibility in Sri Lanka	High	Limited	[62]

7 GRID INTEGRATION AND POWER EVACUATION CONSIDERATIONS

Efficient grid integration is a critical factor for FPV deployment. Electricity generated by floating PV panels must be transferred effectively to the power system for distribution and use [63]. Adequate grid connections and power evacuation facilities should therefore be considered during the planning and design phases. One of the biggest challenges can be the distance between FPV installations and the existing electrical grid, and most likely there are many potential locations which are out of reach and can lack the infrastructure of the grid. Floating solar plants can be linked to the national grid via additional transmission lines and substations [64].

The other factor that should be put into consideration is the stability of the grid. The offline characteristics of solar production include the fact that solar production is based on solar radiation, which varies not only during the course of a day but also during various seasons. There is the likelihood that when a lot of the sources of solar power are linked to the power grid, problems related to the voltage and frequency might occur unless the problems are properly managed and maintained within reasonable limits [65]. Co-location between FPV and hydropower plants can be used to develop hybrid systems. In his instance, the hydro operates as a backup to solar power and uses the already established grid system and makes the overall source of power supply more reliable [66]. Planning and scheduling of the electric power transmission at the FPV systems will need to be conducted electrically [67].

8 CASE STUDY FRAMEWORK FOR SRI LANKAN IMPLEMENTATION

A case study is one method of assessing the practical potential of floating solar photovoltaic (FPV) system in Sri Lanka because of its ability to consider both technical performance, economic and environmental impacts [68]. This organized method allows a thorough checking of the suitability of FPV under the local climate, water, and other infrastructural conditions.

8.1 Site Selection Criteria

Site selection is the first and most important step when you want to create a case study. Different potential locations for floating photovoltaic plants can be compared against each other by changes in solar radiation availability, size and depth of water body, seasonal variations of water level, environmental limitations, closeness to electrical grid, and for ease of installation and maintenance activities [68]. Sri Lanka is endowed with a number of reservoirs and irrigation channels that are technically very well suited for FPV installation. These water bodies were mainly constructed for irrigation and hydropower, and they are very often not fully utilized for electricity generation. Large reservoirs and hydropower dams have the advantage of having relatively peaceful water surfaces and, in most cases, they have electrical infrastructure that can be used for FPV, which makes them very suitable [69].

8.2 Energy Yield and Economic Assessment

After deciding on the location, the possible amount of electricity that the FPV system can generate is calculated by using solar radiation data, efficiency of photovoltaic modules, system capacity installed, and performance forecasts of the system under operation [70]. This evaluation gives the figure of yearly energy production along with the projected system performance according to site-specific conditions.

Economic evaluation focuses on installation, operation, and maintenance costs, expected revenue from electricity generation, and the payback period, enabling an assessment of the overall economic feasibility of FPV deployment in Sri Lanka [70]. The Case Study Evaluation Dimensions for FPV Implementation in Sri Lanka were mentioned in Tables 6 and 7.

Table 6. Case Study Evaluation Dimensions for FPV Implementation in Sri Lanka

Evaluation Dimension	Key Assessment Parameters
Site Selection	Solar radiation, reservoir size and depth, water-level variation, environmental constraints, grid proximity, accessibility [68], [69]
Technical Performance	Installed capacity, PV module efficiency, estimated annual energy generation [70]
Economic Viability	Installation cost, O&M cost, expected revenue, payback period [70]
Environmental Considerations	Use of existing water bodies, avoidance of land use [68]

Table 7. Identified Gaps Addressed by the Sri Lankan Case Study Framework

Aspect	Current Situation	Gap Addressed by Framework
FPV Site Utilization	Reservoirs are mainly used for irrigation and hydropower	Systematic evaluation of reservoirs for electricity generation [69]
Performance Assessment	Limited site-specific FPV studies	Structured estimation of FPV energy generation [70]
Economic Analysis	Few localized feasibility evaluations	Cost, revenue, and payback-based assessment [70]
Decision Support	Fragmented assessment approaches	Integrated technical-economic case study framework [68]

9 CHALLENGES

Even with its various benefits already pointed out, floating solar photovoltaic (FPV) technology is still confronted by several challenges of a technical, environmental, economic, and regulatory nature that are, at present, preventing its large-scale deployment [71]. Overcoming these issues will be a crucial factor in guaranteeing that FPV is operated in a dependable, eco-friendly, and enduring manner, especially in tropical and insular settings like Sri Lanka.

9.1 Technical and Durability Challenges

One of the major initial technical issues of using FPV systems is the long-term durability of floating platforms and electronic components, especially in humid and marine environments [71]. The materials may be damaged more quickly in the future due to the constant moisture, high humidity of the atmosphere, and salt in the air. In fact, the corrosion of metal parts due to seawater can result in the weakening of the main components, electric wiring, and supporting structures, and if left unprotected, can lead to the equipment aging prematurely [72].

9.2 Environmental Considerations

While FPV installations have advantages like less water evaporation and efficient land use, they also result in certain environmental impacts, particularly affecting aquatic ecosystems [73]. FPV systems, by virtue of their coverage, can change the amount of light that gets into the water, aquatic temperature layering, vegetation growth, dissolved oxygen concentration, and aquatic fauna diversity, especially when these systems are installed over natural waterbodies [73], [74]. Due to these reasons, carrying out environmental impact assessments is very important without any doubt, particularly for reservoirs and lakes which are of ecological or social importance.

9.3 Data Availability and Regional Knowledge Gaps

A further drawback is that the detailed long-term performance of FPV systems operating in tropical climates, such as in Sri Lanka, is not available [75]. Most of the existing literature describes the installations in other regions, which may not well represent the local environmental and operational features. Therefore, more experimental studies and pilot-scale FPV projects will be necessary to collect reliable operational data under Sri Lankan conditions [75].

9.4 Future Research Needs

Future research is yet to optimize the design of floating constructions, adopt cost-effective deployment methods and mechanisms, and determine the ecological impact of FPVs deployment in the long term [76]. The fulfilment of these research requirements will be a key element to enhancing of the technical capabilities, environmental friendliness, and cost-effectiveness of FPV systems. Accordingly, Table 8 and Table 9 provide a summary of Key Challenges Associated with FPV Deployment and identified gaps respectively.

Table 8. Summary of Key Challenges Associated with FPV Deployment

Challenge category	Key issues identified	References
Technical	Working life of floating platforms and electrical equipment which are subjected to humid environment and marine environments.	[71], [72]
Environmental	Effects on water ecosystems, water temperature and aquatic algae as well as aquatic and marine biodiversity.	[73], [74]
Data availability	Limited long-term performance data in tropical climates	[75]
Research gaps	Suggestion of better designs, cost cutting, and environmental evaluation.	[76]

Table 9. Identified Gaps and Required Actions for FPV Development

Identified Gap	Implication	Required Focus
Limited tropical performance data	Uncertainty in system reliability and output	Pilot projects and experimental studies [75]
Corrosion and durability risks	Reduced system lifetime	Improved material selection and design optimization [72], [76]
Environmental uncertainty	Potential ecological impacts	Comprehensive environmental assessments [73], [74]

10 CONCLUSION

FPV is a strategic defense and a very important supplement to land-based PV, especially in areas where land availability is limited, in environmentally sensitive areas, and when there are other competing land uses. The worldwide growth of this sector is being driven in part by FPV's ability to use water bodies, even as it helps address land scarcity. It is most likely that the FPVPS is technically advantaged over conventional PVs, especially through cooling effects that lower module temperature and thus improve power output. However, the extent of these benefits is very site-specific as it depends on climatic conditions, wind, water temperature, and system design. This is why there is a need for dedicated thermal and mechanical models instead of relying on land-based PV assumptions. Besides energy production, FPV is also a solution for the water-energy nexus as it can contribute to reservoir evaporation reduction and better water resource utilization. However, such advantages depend on the characteristics and coverage of the site. On the other hand, in terms of economics, FPV systems these days involve higher capital and operational costs due to floating structures and maintenance requirements. Integration with existing hydropower infrastructure through shared grid access and coordinated operation can be one of the ways in which these costs can be partly recovered. Inland reservoir-based FPV is the most feasible option in the near term, and marine or offshore FPV is a longer-term option at the moment and will require further engineering developments.

In the case of Sri Lanka, the availability of large reservoirs/weathered solar potential, along with a hydropower infrastructure, sets the stage favorably for FPV Deployment. Yet, these efforts on a mega scale would be limited due to issues such as uncertainty in the regulatory framework and a lack of local techno-economic and long-term performance data. The present framework, based on the reviewed case studies, serves as a starting point for assessing the technical-economic grid and the environmental suitability of the project. In brief, the article gathers existing information on FPVs (Floating photovoltaic panels) and highlights major obstacles for large-scale adoption. Further research should include tropical performance over long periods, land-based PV comparison, offshore systems resilience, etc. Environmental impact work pr If FPV is to be a sustainable energy source in regions like Sri Lanka, which are land constrained.

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