Combining Floating PV Power Plant and Hydro Reservoir

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Abstract— The shift toward sustainable energy has generated significant interest in hybrid renewable energy systems that achieve highly desirable outcomes by maximizing resource utilization while minimizing environmental impacts. This paper considers the hybrid integration of Floating Photovoltaic (FPV) power plants with hydro reservoirs, particularly focusing on achieving higher total energy output by utilizing existing hydropower assets. Quite effective in regions with little land availability, FPV systems also create reductions in evaporation losses from the reservoir. When strategically hybridized with a hydropower system, the FPV system uses solar to meet the electricity demand during the day while the hydropower meets the peak load demand or when solar irradiance is limited, providing additional value to the efficiency of the plant while ensuring resilience in power generation across varied seasonal variations. Countries such as India, China, and Portugal have shown that this integration can be effective in increasing annual energy production, providing cost reductions, and achieving greenhouse gas emission reductions while providing more stable water levels in the reservoir and supporting a diverse aquatic habitat. Even with several examples of deployment, challenges still remain with deployment, including, but not limited to, the mooring design, structural durability of floating devices, grid integration potential, and the impacts on sedimentation within the reservoir. This study has identified and discussed both the opportunities and challenges in creating FPV-hydropower hybrid systems that are an efficient and economic solution to enhance clean energy generation.

Keywords: Floating Photovoltaic (FPV), Hybrid Renewable energy, Hydro Reservoir Integration, Solar-Hydro Energy, Grid Stability, Renewable Energy Storage, Climate-Resilient Energy.

1. INTRODUCTION

The global energy transition that is currently happening is largely motivated by the demand for reduced carbon emissions and the need for sustainable and effective energy options to accommodate increasing demands for power applications. Hybrid renewable energy systems, which combine complementary sources such as hydropower and solar energy, are gaining momentum as a practical path toward reliable, affordable, and low-carbon electricity generation [1]. Among these hybrid systems, the coupling of Floating Photovoltaic (FPV) systems with hydropower reservoirs can be characterized as being novel and visionary, while still leveraging existing water infrastructure and limiting land use [2], [8].

While hydropower is one of the most established and controllable forms of renewable generation due to its flexibility of generation and storage, hydropower can be stifled by seasonal rainfall and drought conditions [8]. While it is true that the photovoltaic systems continue to demonstrate increasing modularity and decreasing install costs, intermittency can still make it challenging to maintain reliability on the grid [1],[3]. By co-locating FPV at an existing hydropower plant, the FPV can operate in tandem with hydropower, supplying daytime energy supplies while storing natural flow through the reservoirs for nighttime or cloudy days [4]. This pairing is an effective method to use transmission infrastructure more efficiently with a more stable electricity supplying resource during daily and seasonal cycles with a linear conversion factor for electricity produced [6], [7].

Various studies from around the world have verified both the feasibility and advantages of FPV-hydropower hybrid systems. One study about Ghana's Bui Generating Station, which consists of a 400 MW hydropower plant and a 50 MW solar PV system, reported reduced losses in the grid and improved frequency stability [1], [10]. In Brazil, the Furnas Hydropower Plant reported an increase of total energy production up to 50 % after FPV was integrated over only 3 % of the reservoir area [4]. In Africa, the equivalent of 1 % of all operating hydropower reservoirs with floating solar panels would increase electricity generation by 58 % and save approximately 743 million m³ of water annually [8]. These studies show that hybrid systems can increase electricity production as well as provide important benefits to water resources and the environment.

Environmental benefits are a primary characteristic of FPV-hydropower systems. Our FPV systems shade the surface of the reservoir and help reduce water evaporation losses [8, 9], improve water quality, and decrease algal growth [4]. The water also enhances the PV module efficiency by 5–10 % versus PV located on the ground [8]. By using the same access and low-cost infrastructure and existing high-voltage hydropower transmission lines, FPV projects have reduced project costs and ecological footprints [5]. The hybrid configuration is also an economically attractive prospect: co-located FPV systems reported payback periods of around 12 years, and generation costs as low as 0.10 USD per kWh [10].

However, hybrid FPV-hydro systems have associated engineering and policy problems. Anchoring and mooring systems must experience cyclic water levels, high winds and waves [2]. Electrical safety and interfacing with a utility grid requires superior control methods to respond to the variability of power generation [1],[6]. The long-term ecological impact of partially shading a reservoir on local ecosystems is an area needing further study [8],[9]. Finally, these problems require interdisciplinary designs and intelligent management systems that can coordinate and respond to the hydropower generation and solar generation in real time [2].

Globally, the future for FPV-hydropower systems looks bright. Interest from countries such as China, India, and Portugal is high for large-scale hybrid projects as they realize the potential for increased penetration of renewable energy while maintaining water resources [6],[7]. In tropical areas such as India and sub-Saharan African countries, where solar radiation is abundant and hydropower is established, hybridization presents an effective and climate adaptive pathway to sustainable electrification [8],[10]. Therefore, the goal of our study is to explore coupled operations of floating solar PV with hydropower reservoirs, with regard to technical, environmental, and roles in advancing clean energy globally.

2. LITERATURE REVIEW

Numerous studies have investigated hybrid renewable energy systems that couple solar photovoltaic generation with existing hydropower reservoirs. This literature review summarizes the main findings in terms of system performance, environmental benefits, operational aspects, and barriers to deploy hybrid renewable energy systems.

2.1. Performance Enhancement in Hybrid Systems

There is a substantial amount of literature that demonstrates FPV–hydropower combines for higher annual energy generation and greater dispatch flexibility in energy production. Studies in Ghana have demonstrated that coordinated operation can reduce grid losses and voltage variation even in extreme conditions [1]. Studies conducted at Furnas hydropower complex in Brazil estimate up to a 50% increase in overall energy production after installing FPV on the reservoir surface [4]. Additionally, other studies agree that installing FPV on just 1% of hydropower reservoirs across the African continent yields an estimated total power production increase of ~58% [8]. Therefore, these studies provide significant evidence that FPV can improve performance greater than each system could accomplish alone.

2.2. Grid Integration and Benefits to Power Quality

The hybrid configuration allows hydropower's capacity for performance response to solar variability, which improves the overall voltage regulation and frequency control and minimizes curtailment [1], [6]. Studies in wastewater hybrid grids indicate the coordination of advanced inverters improved energy continuity and power quality [5]. Integrating FPV–Hydro topologies improve renewable penetration consistent with grid stability.

2.3. Environmental and Water Resource Benefits

The deployment of FPV decreases evaporation from the surface by 30–70%, which is particularly noteworthy in regions vulnerable to drought [8], [9]. Shade from FPV also reduces excessive algae growth and provides protection to aquatic life, provided it is well sited [4], [10]. FVP mitigates land-use conflict by not affecting agriculture or habitats for wildlife, and potentially allows for more ecological renewable development [2], [8].

2.4. Cost Feasibility and Reuse of Infrastructure

The reuse of the existing hydropower infrastructure—which includes transmission lines, access roads, and substations—reduces capital costs and shortens construction time [4], [7]. Techno-economic studies in Ghana suggest that hybridization reduces the lifetime costs of operation and improves payback for operation costs as a result of efficiency gained in the energy generated and associated water savings [10]. Models supported by policy indicate FPV–Hydro systems can provide affordable clean power for developing counties [1], [6].

2.5. Design, Control and Deployment Challenges

The literature reviewed in literature notes barriers that require careful design:

- Mooring and anchoring for moving water levels [2], [6]
- Corrosion and fouling for buoyant materials [3], [9]
- Rapid changes in irradiance affecting grid voltage stability [1]
- Lack of standardization for large FPV deployments [7]

Future there is a demand for advances in smart control systems, durable buoyant materials, and regulatory frameworks for the affected environment [3], [8]

2.6. Research Gaps Identified

Although promising, there are gaps in the literature:

- The long-term ecological impacts of aquatic systems [8], [9]
- Global deployment has substantial limitations to pilot, and mid-scale systems [4], [10]

- Ability to scale hybrid floating wind, with battery systems is still in development [3]

3. TECHNICAL OVERVIEW OF FLOATING PHOTOVOLTAIC SYSTEMS

3.1 Working Principles of FPV

Floating Photovoltaic (FPV) systems, otherwise known as floatovoltaics, are solar energy projects installed on floating platforms above surfaces of water (e.g., reservoirs, lakes). FPV systems function in the same way that traditional solar photovoltaics do on land: they convert sunlight into electricity in the same way that a ground-mounted solar PV installation does, but they offer other environmental and operational advantages as well [2], [4], [8].

Solar modules on floats produce direct current (DC) power, and that power flows through waterproof cables to inverters to be converted into alternating current (AC). The electricity is routed to the grid for consumption or used locally. When implemented in floating solar over hydro reservoirs, the FPV would integrate with the hydropower: solar energy production would supply energy during the day, while the water that is saved is used to generate energy during the night or on cloudy days—all while improving grid stability and dispatch flexibility [4], [6], [7].

FPV modules, for the most part, see a cooling effect from the water, allowing them to operate at lower temperatures than ground-mounted solar panels for 5–10% efficiency improvements [8], [9]. Furthermore, with partial surface coverage, FPV projects have shown to reduce evaporation of water in reservoirs due to weather, for up to 70%, which can help conserve valuable water resources and provide a more reliable power source in drought or water scarcity situations [8]. Brazil's Furnas Hydropower Plant and Ghana's Bui Station have implemented this hybrid approach and improved their total output by nearly 50%, without the need for additional land for installation [1, 4].

Ultimately, Floating Photovoltaics (FPV) systems provide effective solar generation, conservation of water, and improved integration with the hydropower program—creating a more secure and pliable hybrid energy system [6], [8].

3.2 Components of FPV Systems

The floating photovoltaic system is composed of interdependent subsystems which are designed to provide stability, dependability, and durability over time in aquatic environments [2], [4], [6]. The subsystems consist of photovoltaic modules, floating platforms, anchoring and mooring equipment, and cabling and inverter systems. Each subsystem will individually require attention to withstand worsened outdoor conditions, such as ultraviolet exposure, temperature differential, and hydrodynamic forces

3.2.1. Photovoltaic Modules

The photovoltaic panels used within FPV systems are similar, in structure and composition, to land-based photovoltaic systems with the addition of anti-corrosion coatings and UV encapsulants to withstand humidity and salt content [3], [4]. Monocrystalline silicon modules are most advantageous due to their efficiency and mechanical resistance, as shown in the Furnas case study using mono crystalline with 10° tilt angles to ensure liability in high winds while enhancing power productions [4].

Since FPV modules are in water, the average operating temperature of FPV systems are 5– 8 °C lower than ground-mounted PV systems, increasing energy yield in areas where temperatures normally cause lost productivity [8]. Furthermore, when considering solar yield, ambient dust loads are reduced due to reduced dust while reflected sunlight increases total solar yield, especially in tropical climates [9], [10].

3.2.2. Floating Platforms

Floating structures, typically constructed from high-density polyethylene (HDPE) or fiber-reinforced composites, both account for the weight of the PV modules and associated systems, while maintaining buoyancy. Their modular interlocking arrangement provides easy scalability and adaptability to multiple shapes and sizes of reservoirs [2], [6].

These floating platforms are designed to remain in a tilt angle range of 5°–15°, reducing shading losses while maintaining hydrodynamic stability. Some permit more advanced systems to utilize semi-submersible pontoons or varying raft type systems to reduce oscillations from wind or wave activity. Comparison studies of floating platforms indicate a typical 5 to 10% increase in the total project costs but reduce maintenance by minimizing ground erosion, vegetation control, and available solar generation [4], [8].

3.2.3. Anchoring and Mooring Systems

Anchoring and mooring systems play an essential role in stabilizing the floating array in dynamic water conditions such as varying water levels, waves, and strong winds [2], [6]. One of the typical configurations for an anchoring system includes bank anchoring, bottom anchoring, or hybrid anchoring that incorporates both configurations into one design that can be more flexible, while distributing the total load.

Improper anchoring could impose mechanical loads and an array misalignment that has the potential to cause system efficiency decreases and shortened life span of the floating system [2]. For that reason, advanced modeling techniques will be used to simulate mooring tension and variations to water level. The Brazilian Promissão and Furnas along with studies have both included adjustable mooring systems that allow for seasonal variations of ±5 m, that would not affect the structural integrity [4], [6].

3.2.4. Cabling and Inverters

FPV systems require water-resistant cabling, corrosion-resistant connectors, and floating conduits for the electrical connections to prevent mechanical strain and moisture ingress [1], [5]. The inverter units are often located onshore or on small floating platforms, converting DC power into AC power compatible with the grid.

Implementation of a hybrid system with hydropower allows sharing the substations and transmission lines already built in place, reducing the investment of additional infrastructure [6], [7]. In Bui hybrid plant in Ghana, inverter control synchronized using the DIgSILENT Power Factory model regulated voltage variations while minimizing active power losses when the solar generation occurred [1]. Following the example of the intolerance to oscillations, coordinated inverter control in wastewater hybrid systems in China showed an increase in reliability of at least 15% with solar, wind, and hydro units working together [5]

3.3 Summary

Floating PV (FPV) technology is an exciting advancement to traditional solar technology that provides increased energy yield, reduces water evaporation, and maximizes our use of existing hydropower infrastructure. The pairing of FPV technology with hydropower reservoirs can change a water body into an integrated, multi-purpose renewable platform for energy production and water conservation.

Future research must continue to investigate durable materials, real-time control, and scalable designs to keep the long-term viability and economic viability of FPV systems under variable conditions. [2], [4], [6], [8].

4. HYDROPOWER RESERVIOR SYSTEM

4.1 . Hydropower Generation

Hydropower plants take advantage of the potential and kinetic energies of the stored water to generate electricity. The hydraulic head between the water level stored in a reservoir and the turbine intake allows water to be driven through the turbine, creating mechanical rotation that is directly converted to electrical power with synchronous generators [1], [6]. The generated AC voltage and current is transformed to a higher voltage in transformers and returned to the grid.

In hybrid FPV-hydropower plants, the hydropower plant serves as a source of dispatchable energy to offset the variability and uncertainty in solar generation and the demand [4], [7]. This complementary behavior supports frequency and voltage stability and therefore hydropower naturally complements integration of these intermittent renewable resources, such as solar [1], [6].

According to recent studies, when the FPV produces day time power it is possible to conserve and release reservoir water during peak hours - thus facilitating hydropower to serve its energy storage function or "virtual battery..." [4] [7]. For longer increments, operational flexibility, as provided by FPV, will reduce renewable curtailment, while maximizing transmission system efficiency and utilization [6].

Hydropower continues to serve a host of strategic advantages in global decarbonization strategies due to: low lifecycle emissions, fast response times and a large fleet of assets already deployed - especially in global regions with high hydro potential like Africa, India and Brazil [8], [10]. Solar PV and hydropower can work exceptionally well together to provide increased operational resilience while also accelerating the pace of clean energy employment [3] [6].

4.2 Reservoir Operation and Seasonal Storage

Reservoir hydropower systems incorporate water-retention facilities that enables energy shifting both seasonally and daily. This allows for stable supply amid changing rainfall regimes as well as changing demands [8]. In terms of stored water, hydropower stations can produce electricity even in dry windows of time, allowing for energy security [6].

However, ongoing and extended drought events in certain regions, regional climate variability, and increased demand for electricity have made reservoir reliability weaker in some regions [8]. An advantage of adding FPV capacity is that it expands supply in sunny periods, decreasing reliance on hydro generation and consequently increasing water storage [4], [9].

Research conducted in Ghana and Brazil found that hybrid systems can result in substantial decreases in spillage losses, and lower operational stress on turbines by regulating sudden loading changes [1], [4]. Moreover, FPV installations reduce reservoir evaporation losses by almost 70%, thus preserving valued water resources needed for energy production, agriculture, and drinking water [8], [9].

The two systems combined therefore improve the electrical output of the system and enhance hydrological sustainability, making hybrid reservoirs especially useful in changing climates in tropical landscapes [8], [10].

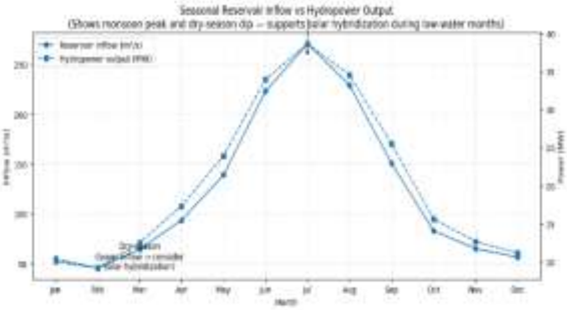

Fig 4.2.1 Graph of seasonal reservoir inflow vs Hydropower output

5. HYBRID FPV–HYDROPOWER INTEGRATION

Hybrid Floating Photovoltaic–Hydropower (FPV–Hydro) systems integrate dispatchable flexibility of hydropower together with low-cost daytime generation from solar PV. When used in tandem, both energy sources can offset each other seasonally and daily, provide energy reliability, and improve the economic use of existing water infrastructure [1], [4], [6].

5.1 Energy Dispatch Strategy

The primary advantage of FPV–hydro coordination comes from power scheduling. During the daytime, FPV provides a bulk of the load, thereby allowing for hydropower to reduce water discharge and store that potential energy in the reservoir. In the evening or during cloudy conditions, hydropower replaces the loss of solar generation [4], [7].

This load-sharing strategy reduces renewable curtailment and provides greater frequency and voltage support to the grid, which is particularly important during peak loads [1], [6]. For example,

- At Bui Generating Station, hybrid coordination mitigated grid losses [1].
- In the Furnas system in Brazil, shared use of transmission improved the overall capacity factor by ~50% [4].

Dispatch flexibility also serves to reduce mechanical cycling of the hydro turbine, which improves generator health and reduces long-term maintenance costs [6].

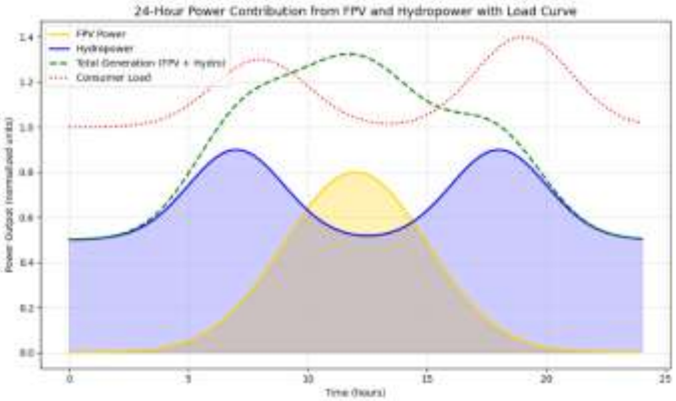

Fig 5.2.1. Daily Load Sharing: FPV vs Hydropower

5.2 Pumped Storage and Seasonal Synergy

Hydropower facilities with pumped storage capabilities, can capture additional solar power surpluses by utilizing additional floating PV energy to pump water back to the reservoir during low-demand periods [2], [4]. This provides a closed-loop storage network, enhancing overall efficiency:

$$E_{stored} = P_{pump} \times t \times \eta_{pump/turbine}$$

Where,

- E_{stored} = net stored recoverable energy
- P_{pump} = input to pumping energy
- t = duration of pumping
- $\eta_{pump/turbine}$ = round-trip efficiency

This integration becomes highly beneficial during:

- **Dry Season** → Conserves water and pumped for later
- **Monsoon/Wet Season** → excess water + solar → improves annual outputs

As such, hybridization builds climate resilience especially in regions that have variable rainfall such as India and Africa [8], [10].

5.3 Hybrid Power Output Estimation

The yearly hybrid system output is generally modeled as:

$$P_{Hybrid}(t) = P_{FPV}(t) + P_{Hydro(t)}$$

With an operational constraint:

$$W_{Reservoir}(t+1) = W_{Reservoir}(t) + Inflow(t) - Discharge(t)$$

This ensures the dynamic optimization of water storage while meeting grid demand [3], [6].

Simulation studies indicate the FPV–Hydro hybrid projects provide:

Performance	Gain Value
Increase of annual energy yield	30–58% [4], [8], [10]
Decrease of evaporation loss	30–70% [8], [9]
Increase stability on grid and power quality	Significantly [1], [6]

This highlights its dual advantage of boosting renewable penetration and protecting critical water resources.

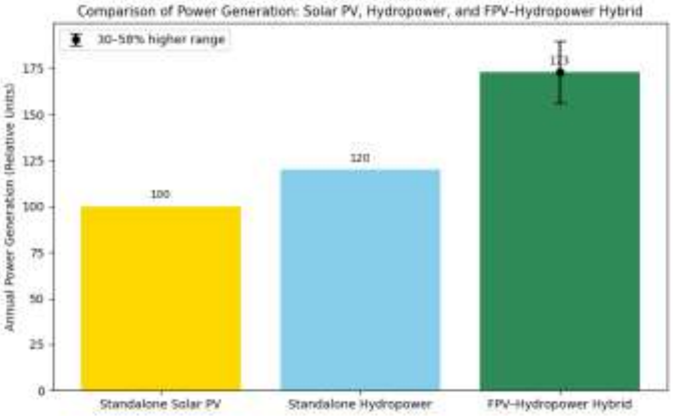

Fig 5.3.1. Annual Energy Output Comparison for PV, Hydro, and Hybrid FPV–Hydro

5.4 Summary

Hybrid FPV-Hydro systems effectively provide:

Key Benefit	**Reason**
Stable renewable energy	Hydropower creates variability in solar energy
Greater economic returns	Substation, roads, and grid connection can be shared.
Decreased environmental stress.	Water is conserved + reduced GHG emission reduction
Flexible and resilient operations	Better peak-shifting and seasonal storage.

Overall, this hybrid configuration is a smart-grid-ready solution for countries interested in efficient decarbonizing while delivering value for reliable power supply [4], [7], [10].

6. METHODOLOGY

The design procedures for a hybrid Floating Solar - Hydropower Renewable Energy (FSHyRE) system encompass modeling, engineering (including but not limited to design) consideration, environmental analysis and economic viability for the purposes of system performance optimization [2], [4], [8].

6.1 Model-level Analysis

FPV performance can be modeled empirically with single or double-diode models with the capability to establish FPV power production under floating conditions [2, 3]. The cooling effects of the water allows for FPV modules to achieve 10-12% increased efficiency performance compared to typical ground-mounted PV systems [8], [9].

Hydropower generation is modeled around the standard hydraulic power equation [4], [6]:

$$P_{hydro}=\rho . g . H . Q . \eta$$

In the hydropower generation model, the model used consumption and inflow/discharge data from the reservoir in order to establish seasonal flexibility and capacity to shift energy from the reservoir [6, 8].

In cases where pumped hydro option is being analyzed, configurations will also be modeled to assess storage and round-trip efficiency [2, 4].

6.2 Hybrid design topologies

Different possible integration schemes, overall the reviewed studies showed:

- **FPV + Battery + A large Hydro:** This can improve dry-season support, and better optimize the use of existing transmission infrastructure [4], [7].
- **FPV + Pumped Hydro Storage (PHS) + Battery:** During the day, excess solar energy can be used to pump water into the upper reservoir, adding capacity during the night [2], [4].
- **FPV + Battery + Small Hydro:** Operation of a run-of-river or other small hydro can be supported without significant ecological impacts [10].

Energy management Systems (EMS) historic and actual real-time demand dispatch-based systems ensures optimal dispatch options [1], [5].

6.3 Site evaluation and environmental assessment

- **Bathymetric and GIS studies:** To assess depth, elevation and position FPV project infrastructure and arrays [8], [10].
- **Soils & mooring system design**: The anchoring systems ensures component mechanical stability due to changing water levels, such as drought conditions, within the ranges of service life [2], [6].
- **Meteorological data review:** To assess solar irradiation, wind loads and wave dynamics tools such as PVsyst and SAM were used to model actual yield [3], [5].
- **Water quality data review:** Both biological and chemical parameters of water quality was used to assess the appropriateness of floating material (HDPE, GRP, etc.) [9].

6.4 Structural load and stability analysis

Wind loads impact on FPV are calculated as [2], [3]:

$$F = C_d . A_s . K_s . V^2$$

Wave loads are considered based on marine structure design capacities using standard calculations to avoid fatigue and disconnection of the platform [6], [8].

Coverage of reservoirs was limited to 5–40% of the total area to preserve ecosystems and local livelihoods [8], [9].

6.5 Techno-Economic and Environmental Feasibility

Performance is evaluated using:

Technical indicators: Capacity factor, utilization factor, performance ratio [1], [5]

Economic indicators: Net Present Cost (NPC), Payback Period (PBP), Levelized Cost of Energy (LCOE) [4], [10]

Environment indicators: CO_2 emission reduction, the benefits of water conversion [8], [9]

Water conservation is calculated by the following formula [8]:

$$W_r = W_n . C_e$$

7. ADVANTAGES OF FPV–HYDRO HYBRID SYSTEM

Hybrid Floating Photovoltaic–Hydropower systems provide additional performance, environmental and economic benefits not obtainable by a standalone renewable energy generation project. Their combined operation adds value in terms of continuous reliable power supply, improved resource efficiencies, and ecological sustainability [1], [4] [8].

Key Advantages

- **Greater Total Energy Output** - Solar generation during daylight hours preserves hydropower releases, resulting in additional total annual electricity generation of 30-58% [4], [8] [10].
- **Improved Grid Stability** - Hydropower can mitigate solar variability in output, leading to improved frequency response and voltage swings in grid operation [1], [6].
- **Improved Use of Existing Infrastructure** - Floating photovoltaic (FPV) will use the same transmission, access

roads and substation networks as hydropower, therefore reducing costs of expanding existing projects [4], [7].

- **Evaporation Reduction and Water Conservation** - FPV shading reduces evaporative surface area and is conservatively estimated to result in 30–70% less water lost to evaporation, which would be an important factor for locations where water availability is limited due to drought [8], [9].
- **Increased efficiency of Solar Production** - The water will help cool the modules, keeping the panels performing at even 5-10% higher efficiency [8].
- **No Land Requirements** - There is no need for land acquisition that could interfere with agricultural or habitat preservation considerations [2], [8].
- **Lower Operation and Maintenance Costs** - Annual operation and maintenance (O&M) costs will be lower due to less dirt accumulation on the panels and less cleaning [9].
- **Environmental Sustainability** - due to hybrid system operation, reductions in CO_2 emissions, reduction in algae growth, and stabilized reservoir ecosystems [4], [10].
- **Scalable and Flexible** - Modular floating platforms make capacity expansion easy and flexible with seasonal changing water levels [2], [6].

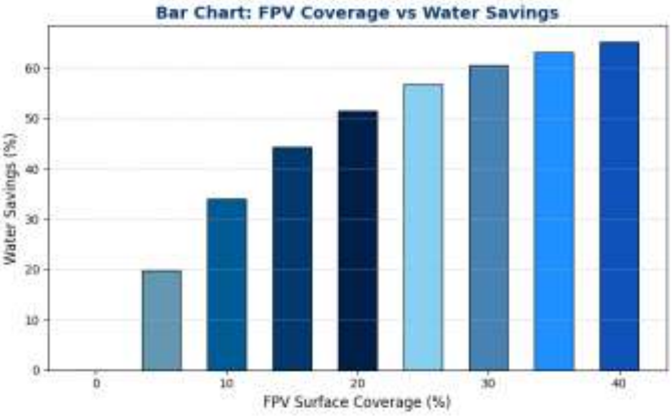

Fig 7.1. Evaporation Reduction at Different FPV Coverage Levels

8. CHALLENGES AND LIMITATIONS

Although Floating PV–Hydropower hybrid systems can have advantages, there are multiple engineering, environmental, and operational challenges when they are deployed. These challenges need to be addressed to provide consistency for long-term system reliability and sustainability [2], [6], [8].

Key Challenges:

- **Complexity in Anchoring/Mooring:** Reservoirs undergo variations in water level, period wind and wave action requires durable anchoring and mooring systems for floating structures [2], [6].
- **Higher Initial Capital Cost**: The cost of floating structures and corrosion resistant components add to the upfront cost of installing the plant, despite lower O&M costs over the long term [4], [9].
- **Grid Integration Issues:** A sudden displacement of irradiance on the solar surface may cause power generation to fluctuate requiring complex control systems to control voltage and frequency [1], [6].
- **Biofouling/Sediment Buildup:** Peeling off algae and debris from the floating system may affect movement and longevity of structures [8].
- **Possible Environmental Effects on Aquatic Ecosystems:** Shading of the water surface may have consequences for lowered oxygen levels and other aspects of aquatic life if not properly considered [8], [9].
- **More Severe Environmental Exposure:** FPV structural materials are subjected to frequent high humidity conditions, UV rays, and corrosion [3], [4].
- **Limited Technical Standards and Regulations:** The FPV industry is still relatively new, and therefore no technical or regulatory standards for design, plant operation, or grid compliance have been established [7].
- **Operational Safety:** Electrical equipment situated close to open water greatly increases the risk of hazards; waterproofing and protocols of safety must be in place [1], [5].
- **Skilled Workforce Requirement**: Hybrid operation demands expertise in both solar and hydropower domains, not widely available in developing regions [10].

These challenges highlight the need for innovative engineering**,** strong policy frameworks**,** and continuous environmental monitoring to ensure

9. FUTURE POTENTIAL AND GROWTH

Floating PV-hydropower hybrid systems are at an early stage of maturation, yet show considerable promise and will likely grow as technology, associated policies, and climate conditions continue to facilitate the expansion of renewable energy. In an urgent need to satisfy rising demand for global electricity while minimizing the impacts on water resources, future developments will improve system performance, reduce environmental burden, and facilitate additional deployment throughout the developing world [4], [6], [8].

Future Prospects:

- **Advanced Control and Integration with Smart Grids:** Forecasting systems utilizing AI and IoT technologies can balance hydro and solar generation in real-time, optimizing flexibility and stability within the grid [1], [5].
- **Integration with Pumped Hydro Storage:** FPV electricity can be used to pump water from low-demand levels → this creates an opportunity for large-scale renewable energy storage [2], [4].
- **Expansion in Tropical and Water Stressed Regions:** Many countries invested in FPV–Hydro systems include India, China, and numerous nations in Africa for the abundant solar resources and hydropower infrastructure [8], [10].
- **Reduced Carbon Footprint and Global Decarbonization:** Hybridization can reduce reliance on fossil-fuel powered peaking plants, thus contributing to national climate commitments in conjunction with SDG 7 and SDG 3 [6], [7].
- **Floating Wind and Multi-Hybrid Systems:** Research is investigating the integration of floating wind + FPV + hydropower in order to maximize the energy density of the reservoir [3].

- **Better Materials and Longer Lifespan:** The availability of UV resistant, corrosion proof floating structure materials, paired with marine-grade cabling will reduce cost and improve durability [3], [4]
- **Hydrogen Production from Surplus FPV Energy**: Excess daily generation can be directed to electrolysis systems to create green hydrogen, adding another avenue for revenue [5].
- **Enhanced Environmental Planning**: As science evolves, optimized partial cover FPV designs will promote aquatic health and biodiversity protection [8], [9].
- **Growth of Government Policy and Standardization Broad:** , standardized guidelines and supportive tariffs will allow for a rapid, the safe and large-scale deployment across the globe [7].

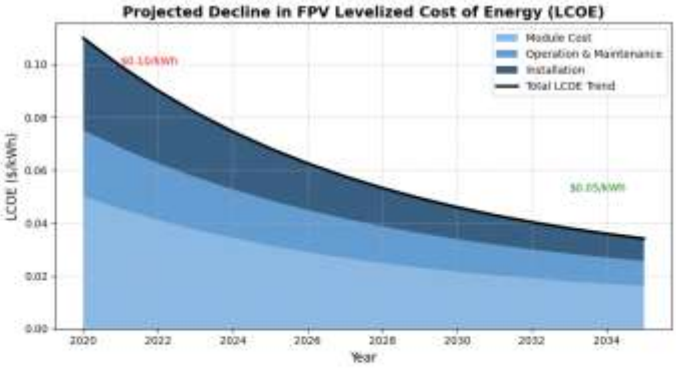

Fig 9.1. Projected Decline in FPV Levelized Cost of Electricity (LCOE)

10. RESULTS AND DISCUSSION

The hybrid FPV–Hydropower system evaluation provides significant improvements in operational functionality and renewable energy production. In the simulated daily dispatch strategy, FPV generates the bulk of the daytime energy demand while generating less hydropower to conserve the stored water for night time and periods with low irradiance [1], [4]. This coordinated operation both enhances the flexibility of hydropower and increases grid frequency and voltage stability, as seen at the Ghana Bui Station [1], [6]. The yearly energy data analysis finds that the hybrid configuration increases total electricity production by approximately 30–58%, given the same input data and available resources to standalone configurations, particularly in dry seasons where solar production assists reduced inflows into the reservoir [4], [8], [10]. The use of FPV also results in a greater seasonal reduction in evaporation rates, projected to reach as high as 70% of the water lost for greater water surface coverage, while promoting sustainable water resource management [8], [9].

The economic projections show that the levelized cost of electricity (LCOE) for FPV will continue to be on a decline as technology matures and scale up increases its economic competitiveness to hybrid systems [10]. Nevertheless, there are a variety of technical issues that still persist. These technical issues include the longevity of mooring systems, environmental impacts of shading in hydropower reservoirs, and the demand for a sealed optimized control mechanism for managing fast and climatic shifts in energy generation [2], [6], [9]. In summary, the evidence presented clearly aligns with our conclusion that FPV–Hydropower hybrid systems deliver a dependable, affordable and climate-resilient opportunity for scaling clean energy production and water savings [4], [7], [10].

11. CONCLUSION.

Combining Floating Photovoltaic (FPV) technologies with hydropower reservoirs creates a very appropriate hybrid solution for clean energy generation. The complementary generation profiles of solar and hydropower will improve grid resilience as daytime and nighttime electricity generation store. Additionally, this combined system provides increased overall energy generation and increases efficiency by utilizing existing hydropower infrastructure and leads to a reduced total cost to deliver the energy.

FPV deployments on reservoirs improve performance, reduce conflicts with land use, and offer a lower evaporative loss of a valuable water resource. While issues of anchorage of the systems, environmental compatibility, and durability remain, this hybrid approach provides a pathway to continued energy generation to meet demand while enhancing climate resiliency and meeting domestic clean energy goals.

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