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Floating solar on Colombia's reservoirs: opportunities, challenges, and regulatory pathways

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Abstract

Hydroelectric reservoirs in Colombia are vast, underutilized surfaces with enormous potential in complementary renewable generation via floating photovoltaic (FPV) systems. The study assesses the technical potential and feasibility of FPV deployment in the country's largest hydroelectric power plants, such as Guavio, San Carlos, Ituango, Chivor, Sogamoso, Porce III, Pagua, Guatapé, and Betania, each exceeding 500 megawatts (MW) of effective net capacity. In order to avail the available information from existing reservoir surface and solar irradiance maps and in terms of typical FPV performance variables, potential annual energy production is estimated over several (5%, 15%, and 30%) coverage scenarios. Our research demonstrates that even a conservative deployment (≤5% for instance) could generate several terawatt-hours (TWh) per year, providing considerable contributions to Colombia's renewable energy mix with lower evaporation losses and better grid stability with hydro-solar hybridization. It also includes environmental, technical, and operational challenges such as aquatic ecosystem impacts, anchoring and maintenance, as well as the variability of water levels. Moreover, the paper reviews Colombia's new regulatory regime, including the National Environmental Licensing Authority (ANLA) processes and the Energy and Gas Regulatory Commission (CREG) grid-connection regulations, to identify possible avenues for more efficient project authorization and integration. In general, the research presents floating solar technology as a practical and logical add-on to the hydroelectric infrastructure, in the context of Colombia's energy transition and decarbonization ambitions.

Key words. Floating photovoltaic systems, Hydroelectric reservoirs, Renewable energy integration, Colombia energy transition, Environmental and regulatory assessment.

1. Introduction

Floating photovoltaic (FPV) has become a good and timely alternative to increase the capacity of renewable generation without conflicting with agricultural or urban land. The structure of this system is the placement of photovoltaic modules on floating platforms on water bodies (reservoirs, lakes, or dams). Hydroelectric reservoirs present a well-suited environment for this application as they have huge surface water, infrastructure for access, operation, and grid connectivity, which diminishes both costs and complexity of implementation [1]. On the worldwide scale, there has been an exponential rise in the uptake of FPV systems. Total installed capacity rose above 7 gigawatts peak (GWp) at the end of 2023 (International Renewable Energy Agency, IRENA, 2023) [2], especially in Asia focusing more on countries like China, South Korea, India, and Singapore which are spearheading large project size projects. The Tengeh floating plant in Singapore (60 MWp capacity, an annual output estimate of ~80 GWh), and the Huainan installation in China, above 150 MWp capacity, on a flooded former mining site, are two such examples [3]. These experiences have shown not only the technical maturity of the technology, but also its efficiency and sustainability benefits.

Floating solar power holds substantial technical potential globally. Modeling studies conducted by the National Renewable Energy Laboratory [4] indicate that only about one percent of the global surface of reservoirs could be covered with floating solar modules and this system could be used to produce about 400 GWp, equivalent to a significant portion of global electricity generation. Within the Colombian context, where hydroelectric reservoirs span thousands of hectares, the opportunity to integrate FPV systems as a complement to hydropower is large based on the high average solar radiation levels of approximately 4.5 $kWh/m^2/day$ [5].

Essak and Ghosh (2022) state that FPV systems mainly gain energy yield improvement because of the cooling effect of the water, which decreases module temperature and improves efficiency by five to ten percent compared to land-based installations [6]. Partial coverage of the water surface also reduces evaporation, which is beneficial in climatic variability and water scarcity [1]. There is also less dust accumulation on panels and existing transmission lines and substations of hydroelectric facilities can be used [3].

Nevertheless, the technology still faces important challenges. From an environmental perspective, floating structures may alter the thermal balance of reservoirs, affect light penetration, and modify oxygen levels, potentially impacting aquatic ecosystems [7]. From a technical standpoint, the mechanical stability and anchoring systems require specialized design to withstand water level fluctuations, currents, and strong winds [6]. Economically and regulatorily, the initial cost per installed megawatt remains slightly higher than ground-mounted systems, and many national regulatory frameworks still lack specific procedures for FPV deployment [1].

Floating solar power is under development in Colombia but exhibits promising models. Empresas Públicas de Medellín (EPM) implemented in 2018 the country's first pilot FPV in the El Peñol–Guatapé reservoir with an approximate capacity of 100 kilowatts (kW) and an annual generation of around 145 megawatt-hours (MWh), to perform the technical and environmental testing of the technology under local conditions [8]. Due to Colombia's more than 10 large-capacity hydroelectric plants that could benefit from hydro-solar hybridization, this project gave a basis for scaling up the technology at other hydroelectric reservoirs.

This study concentrates on the main hydroelectric plant reservoirs, from Guavio, San Carlos, Ituango, Chivor, Sogamoso, Porce III, Pagua, Guatapé, and Betania, with an effective net capacity greater than 500 megawatts (MW). It aims to assess the technical feasibility, environmental and economic as well as regulatory aspects of installing floating photovoltaic in the above reservoirs, and assess annual potential for energy generation at different surface-level coverage. Moreover, it will analyze hydro-solar integration's hydrological and energetic benefits, the most critical environmental and operational risks, investigate the Colombian regulatory framework in general, particularly following the ANLA and the CREG regulations including the recommendations for the proposal of implementation pathways and a strategy for further pilot projects in support of the country's energy transition.

2. Material and method

This study focuses on Colombia's principal hydroelectric reservoirs with an effective net capacity greater than 500 megawatts (MW). The selected facilities include Guavio (1250 MW, located in Ubalá, Cundinamarca; reservoir area ≈ 6500 (15000) ha), San Carlos (1240 MW, in San Carlos, Antioquia; ≈ 340 ha), Ituango (1200 MW, in Ituango, Antioquia; ≈ 3800 ha), Chivor (1000 MW, in Santa María, Boyacá; ≈ 1300 ha), Sogamoso (819 MW, in Girón, Santander; ≈ 7000 ha), Porce III (700 MW, in Anorí, Antioquia; ≈ 461 ha), Pagua (600 MW, in La Mesa, Cundinamarca; ≈ 950 ha), Guatapé (560 MW, in Guatapé, Antioquia; ≈ 6240 ha), and Betania (540 MW, in Yaguará, Huila; ≈ 7400 ha). These reservoirs were chosen due to their large surface areas, high solar irradiance, and existing grid connection infrastructure, which together make them suitable for floating photovoltaic (FPV) deployment.

They use a systematic method based on geospatial analysis, solar resource analysis, and technical modeling to forecast the potential energy production of Floating Photovoltaics (FPV) under different deployments. Data of reservoir surface area were obtained from IDEAM (Colombian Institute of Hydrology, Meteorology and Environmental Studies), the Ministry of Mines and Energy, and reports from the energy companies (ENEL Colombia, EPM, ISAGEN and AES Colombia). Solar irradiance data (Global Horizontal Irradiance and average annual solar insolation) was sourced from the Solar Radiation Atlas of Colombia (IDEAM, 2022) and confirmed via NASA's Surface Meteorology and Solar Energy (SSE) database.

The technical potential of FPV was estimated for each reservoir using water surface area (A, hectares) and standard power density (Pd) of 1 MW per 1.3 hectares that is typical for average FPV performance and compared to international FPV criteria [4,6]. The surface coverage scenarios were evaluated: 5%, 15%, and 30% of the reservoir area and conservative, moderate and extensive installation level respectively.

The expected annual electricity generation (E) for each case was estimated using Eq. (1).

$$E = P_{FPV} x CF x 8760 \tag{1}$$

Where PFPV is the installed FPV capacity (MW), CF is the solar capacity factor, and 8760 represents the total hours per year. The solar capacity factor for each site was selected based on regional irradiance, altitude, and climatology, ranging from 12 % to 21 %, consistent with performance data of existing Colombian solar plants [2, 9].

Energy potentials generated were expressed as gigawatt-hours per year (GWh yr^{-1}). Other qualitative elements like reservoir hydrology, variation in water levels, environmental sensitivity, and accessibility were also considered. Regulatory aspects regarding the environmental licensing processes led by the National Environmental Licensing Authority (ANLA) and the interconnection procedures regulated by the Energy and Gas Regulatory Commission (CREG) were also addressed in the analysis.

A reservoir-wide PFPV estimation is conducted by accounting for both average irradiance of the area of influence and the area suitable for panel installation. To keep an estimate as conservative as possible that represents the minimum generation, the average irradiance of the worst month of the year, G (typically expressed in kWh/m²·day), indicates the amount of solar energy incident on each square meter of the reservoir per day. The available area, A_{disp}, corresponds to the portion of the reservoir surface where photovoltaic panels can physically be installed.

In practice, the system does not convert all the incident energy into electricity due to losses from temperature effects, cabling, inverters, soiling, and partial shading; these are represented by a loss factor (f_{loss}), typically ranging from 0.8 to 0.9, with an average value of 0.85 used for calculations. Considering these elements, the net photovoltaic power is calculated using the following Eq. (2).

$$P_{FPV} = G x A_{disp} x f_{loss} \tag{2}$$

The average irradiance G used in the estimation of floating photovoltaic power is obtained from historical solar radiation data measured or simulated over the reservoir area of influence. These data are typically collected from meteorological stations, satellite observations or solar resource databases and provide the daily or monthly solar energy incident on each m². To ensure a conservative and reliable assessment, the worst month of the year, that is the month with the lowest average solar irradiance, is selected so that the resulting power estimate reflects a minimum expected generation scenario.

Once G is determined, the CF of the floating photovoltaic system can be estimated as a function of the available solar resource. The capacity factor represents the ratio of the actual energy generated over a period to the theoretical maximum energy that would be produced if the system operated at its nominal power continuously. In terms of irradiance, the capacity factor can be approximated by dividing the effective daily or monthly energy yield, considering losses through the factor $f_{loss,}$ by the maximum possible energy based on the installed area and peak irradiance. Mathematically, this can be expressed as Eq. (3).

$$CF = \frac{P_{FPV}}{P_{installed} x 24\ h} \tag{2}$$

where $P_{installed}$ represents the installed peak power of the system. This approach links the CF directly to the local solar resource, allowing planners to evaluate system performance under realistic operating conditions and providing a quantitative basis for energy yield projections and economic assessments.

3. Results and Discussion

FPV holds significant potential for hydroelectric facilities. Evaluating the presence of solar resource, water surface availability, and typical performance for the FPV system can give not only a capacity factor but also the potential annual energy production under different coverage scenarios. This shows that conservative installations covering a small fraction of the reservoir can generate significant amounts of electricity. This is a meaningful contribution to the national renewable energy mix.

Figure 1 shows the estimated CF for each reservoir, calculated using the average solar irradiance of the worst month of the year and incorporating typical system losses (floss=0.85). The CF varies across sites due to differences in solar irradiance, geographic location, and local climatic conditions.

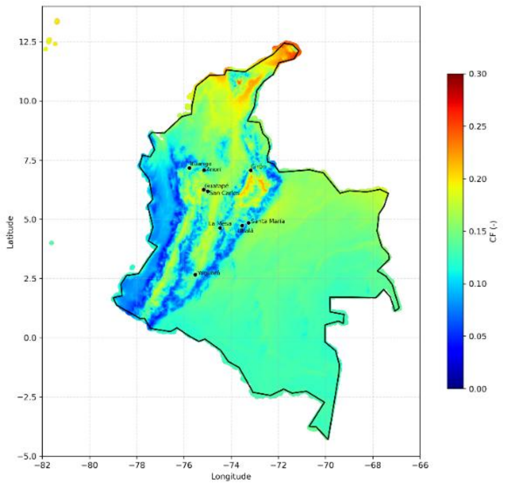

Fig. 1. Capacity factor.

Figure 2 presents the average irradiance over the reservoir influence areas, highlighting sites such as Guatapé, Guavio, Sogamoso, and Betania as particularly favorable for FPV deployment.

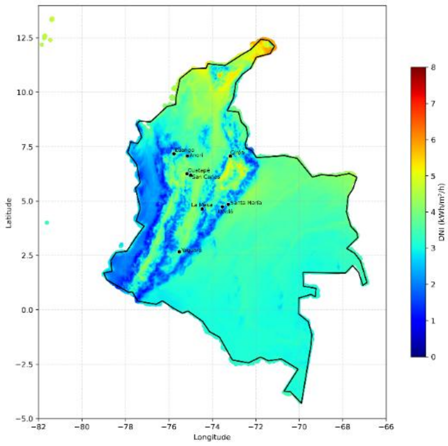

Fig. 2. Direct normal irradiance.

From available reservoir surface data, the technical potential for the installation of FPV was estimated using three coverage scenarios: 5%, 15%, and 30% of the water surface. Table 1 presents the estimated installed capacity and annual energy generation for each scenario based on the effective area available and loss factor. Even under this conservative 5% coverage scenario, most of the reservoirs could be home to FPV systems with hundreds of megawatts of installed capacity, generating several terawatt-hours (TWh) a year. For instance, Betania, with a reservoir area of around 7400 ha, can provide an FPV capacity of 285 MW at 5% coverage, producing 0.386 TWh each year, whilst Guatapé and Sogamoso could achieve similar capacities due to the combination of area and irradiance. However, the reservoir with the highest potential generation would be the Guavio hydropower plant, which could host up to 577 MW of installed FPV capacity while covering only 5% of its reservoir area, making it the largest contributor among the analyzed sites.

The results of the analysis indicate that the installation of floating photovoltaic (FPV) systems on Colombia's main hydroelectric reservoirs could provide a significant contribution to the national power system. Under a conservative scenario in which 5% of the reservoir surface area is covered, the estimated total electricity generation amounts to approximately 2.218 terawatt-hours (TWh) per year, while coverage levels of 15% and 30% could increase generation to about 6.655 TWh/year and 13.31 TWh/year, respectively. In comparison to these values, the total electricity generation in Colombia in recent years has been at the level of between 80 and 90 TWh annually, of which nearly 70% represents hydropower. That is, on the most conservative scenario, the implementation of FPV solutions in the surveyed reservoirs can account for around 3–4% of the country's annual electricity generation, while on a much larger scale the adoption could reach an additional 15% of the national generation of hydropower. This potential is especially significant as such projects can avail a wider capacity of operating the existing electricity infrastructure, lower grid-connection costs and secure the country's energy security with better diversification of the electricity mix. Also, the coexistence of daytime solar generation and hydroelectric regulation would promote the best hybrid operation for reducing seasonal fluctuations and stabilizing the grid.

Table 1. Capacity and annual energy by scenario

Reservoir	Area (ha)	G (kW/m^2)	CF	Installed capacity 5% (MW)	Electricity generation (E) 5% (TWh-yr)	Installed capacity 15% (MW)	Electricity generation (E) 15% (TWh-yr)	Installed capacity 30% (MW)	Electricity generation (E) 30% (TWh-yr)
Guavio	15000	3.653	0.152	576.92	0.769	1730.76	2.307	3461.53	4.615
San Carlos	340	3.530	0.147	13.07	0.016	39.23	0.050	78.46	0.101
Ituango	3800	3.591	0.149	146.15	0.191	438.46	0.574	876.92	1.149
Chivor	1300	2.618	0.109	50.00	0.047	150.00	0.143	300.00	0.286
Sogamoso	7000	3.846	0.160	269.23	0.377	807.69	1.133	1615.38	2.266
Porce III	461	3.085	0.128	17.73	0.019	53.19	0.059	106.38	0.119
Pagua	950	3.163	0.131	36.53	0.042	109.61	0.126	219.23	0.253
Guatapé	6240	4.183	0.174	240.00	0.366	720.00	1.099	1440.00	2.198
Betania	7400	3.723	0.155	284.61	0.386	853.84	1.160	1707.69	2.302
Total	42491			1634.26	2.218	4902.80	6.655	9805.61	13.310

The results indicate that the implementation of FPV in the greatest hydroelectric reservoirs of Colombia is likely to realize the utilization of hydroelectric electricity, since the utilization of the existing generation of hydroelectric is integrated. Figure 1 and the irradiance patterns in Figure 2 suggest capacity factors could be expected to lead to predictable year-round solar renewable electricity generation, particularly upon considering hybrid hydro–solar operation to reduce seasonal variability. High coverage, e.g. 15% or 30% of the full reservoir surface, may strongly increase the contribution of renewable resources, but requires considering the environmental effects, reservoir management, and anchoring logistics. In general, the results show that FPV deployment at Colombia's predominant hydroelectric reservoirs is technically feasible. More conservative installations, nonetheless, can add substantially to the country's renewable energy mix.

Such results form a quantitative basis that policy-makers, project developers, grid operators, and others can use to assess hydro-solar hybrid strategies, optimize the utilization of water surfaces, and formulate deployment plans that balance energy yield along with environmental and operational risks.

Implementation of FPV as a tool in the hydropower storage system of Colombian hydroelectric facilities faces some technical challenges and requires intensive multidisciplinary work. The main challenge is to implement anchoring and mooring systems that must be able to accommodate seasonal changes in water level along with surface waves, currents, and flood risks, that can guarantee high structural strength of the panels and a high level of safety during the installation. Floating platforms must be resistant to corrosion, ultraviolet radiation, humidity, and mechanical phenomena, and they should have low maintenance costs and long stability.

An additional thing that should be considered is the placement, as well as orientation, of the solar modules on the surface of the reservoir. The spacing of rows and the angle of rotation in a solar panel has also to be optimized for optimal irradiance capture, without creating mutual shading, and the ability to shift water and aquatic fauna around the room. Sedimentation, debris accumulation, and the increase in the number of floating plants are also things to consider to prevent it from disrupting the floatation system and the efficiency of energy output. To detect anomalies, ensure correct module operation, prevent system integrity damage, etc, the system must have remote monitoring tools and preventive maintenance systems installed.

From an electrical perspective, FPV application within the context of existing hydro installations need to be appropriately integrated, meaning that grids, transformers, substations, and transmission lines have to be interconnected. When solar and hydroelectric generation are operating together, it must be ensured that protection, control, and synchronization systems are present in order to monitor peak generation, avoid grid overloads, and maintain stable operation. Problems such as variations in voltage, harmonics, and interaction with hydroelectric control systems need to be rectified in order to provide a continuous and safe supply.

At last, technical design will need to embed considerations on security and resilience to extreme weather like storms, high winds, or flooding, as well as be compatible with many reservoirs uses, including navigation, recreation, and water regulation. Such an integrated planning approach, addressing the technical needs of FPV projects facilitates its realization of high energy efficiency, minimization of operational risk, and long-run operational life of the project. Environmentally, the floating photovoltaic (FPV) systems in the case of Colombia are regulated by a distinct legal framework, describing when environmental impact studies, licenses, and other permits should be processed. Pursuant to Article 49 of Law 99 of 1993, "Projects, works or activities that may cause the serious deterioration of the environment, renewable natural resources or the landscape shall require an environmental license for their execution." One of these activities in the law is "construction of electric power generation plants exceeding 100,000 kW of installed capacity" and the installation of transmission lines connected to the national interconnection system, which is to be covered by the provision of the licensing of the projects in Article 52. Additionally, Law 1715 of 2014, which regulates the integration of non-conventional renewable energy sources into the National Energy System, declares the promotion of such renewable sources as a matter of public utility and social interest. Building on these foundations, Decree 1076 of 2015 compiles the regulations of the environmental and sustainable development sector and defines the competencies for issuing environmental licenses through the National Authority of Environmental Licenses (ANLA) and the Regional Autonomous Corporations (CAR), depending on the installed capacity of the project.

Recently, Decree 852 of 2024 modified this framework by redefining ANLA's competence for renewable energy projects with installed capacity equal to or greater than 50 MW, instead of 100 MW, and assigning CARs the responsibility for projects between 10 MW and 50 MW. This change is particularly relevant for FPV projects on reservoirs, as many installations fall within this range, thus affecting the competent authority, procedural requirements, and approval timelines.

In line with Decree 852 of 2024, the environmental license must be obtained from ANLA for an FPV project on a reservoir, with > 50 MW installed capacity. Some key considerations are (i) a comprehensive environmental impact study of water body hydrodynamics, aquatic ecosystems, and changes in water temperature or light penetration, (ii) cumulative implications and synergies with existing hydroelectric projects, (iii) mitigation measures dealing with sedimentation, shoreline erosion, or fauna displacement, (iv) compliance with energy sector standards for grid connection, and (v) local community engagement and public consultation. On projects with capacity in the range of 10 MW – 50 MW, CAR assumes competence, yet strong environmental assessment is nevertheless necessary.

Strict adherence to this legal framework is not only a legal requirement but also a strategic consideration to maintain the social, environmental, and technical feasibility of FPV projects. A focus on these early concerns limits regulatory risk, time losses, and the subsequent expenses, and ensures sustainable operation and the integrated use with Colombia's hydro-solar infrastructure in the long term.

The Energy and Gas Regulatory Commission (CREG) defines the technical and operating standards for integrating power generation systems and the national grid which ensures safety, reliability, and efficiency for the interconnection. In the case of FPV systems, there are unique technical complexities with their interconnection with existing hydroelectric stations due to both technologies possessing similar electrical foundations and shared grid connection sites. This will entail more detailed grid connection capacity studies, power flow analyses, and transient and frequency stability assessments of the technology to assess the technical feasibility of incorporating additional solar generation without interfering with hydroelectric plant operations and violating established power quality standards (i.e., CREG Resolution 060 of 2019 for plants under 100 MW and CREG Resolution 025 of 1995 for larger systems).

The FPV integration also requires an integrated electrical design in which the hydroelectric plant's transformation, protection, and control systems are planned simultaneously. Protection design schemes should be adjusted, if appropriate, to cope with additional short-circuit currents, voltage fluctuations, and bidirectional power supplies that would change the selectivity and response of protection devices in use. Furthermore, a coordinated production of photovoltaic and hydroelectric generation has to be provided; solar power must be synchronized in order to supply the grid during high-irradiance hours while hydropower operates in a support or regulation mode. Water uses are optimized in an operational manner, and mechanical requirements of turbine systems are minimized via this hybrid operational option.

Another critical factor is the seasonal variability of solar irradiance and its interaction with reservoir water levels. During the dry season, FPV systems typically achieve higher generation levels, coinciding with reduced hydrological inflows an operational advantage for energy management. However, this variability necessitates dynamic control strategies and intelligent energy management systems capable of adjusting combined generation in real time to maintain grid frequency and voltage stability. Coordination with Distribution System Operators (DSOs) and the National Dispatch Center (CND) under the Mining and Energy Planning Unit (UPME) is crucial for scheduling generation dispatch and ensuring the secure integration of hybrid hydro-solar production into the national electricity market.

Lastly, during the design phase, FPV project developers have to assess existing transmission infrastructure availability and capacity and the evacuation potential of the linked electrical node. In some instances, growth of transmission lines or substations needs to be undertaken in compliance with environmental and technical regulations, and approval from CREG and the National Environmental Licensing Authority (ANLA), particularly when capacity thresholds established under Decree 1076 of 2015 and its subsequent amendments are exceeded. The overall strategic planning of grid interconnection and the congruence with local sector regulations to ensure the technical feasibility of the project are important for reducing connection costs, promoting the interconnection system reliability, and providing Colombia with a solid base for renewable power supply as it grows in the case of variable renewable energy penetration.

The integration of Floating Solar Photovoltaic (FPV) systems within Colombia's existing hydroelectric infrastructure offers a compelling economic proposition. FPV installation costs vary extensively across different regions, primarily influenced by site-specific conditions. Key factors include water depth and geography, project capacity, and the technical complexity of the selected mooring and anchoring solutions [10].

While the initial investment for FPV is typically 25% higher than land-based solar due to floating structures and mooring systems [11, 12], these costs are partially offset by the elimination of land acquisition and site preparation expenses. According to Okoye and Solyali (2017), land acquisition typically accounts for approximately 20% of the total system installation cost [13]. In the Colombian context, where land rights and environmental licensing for new areas can be prolonged, leveraging existing submerged areas under utility control significantly streamlines the deployment phase, potentially reducing the overall project timeline.

Assuming a 25-year operational lifespan and utilizing economic parameters from Brazil, that is a regional benchmark with a hydro-dominant matrix similar to Colombia’s, with an average electricity price of €0.12/kWh and a conservative 15% capacity factor, the estimated payback period ranges between 6 and 8 years [14]. This timeframe is further optimized in the Colombian context by the fiscal incentives of Law 1715, such as VAT exemptions and accelerated depreciation. Moreover, the 5–10% efficiency gain resulting from the water’s cooling effect [15] significantly lowers the Levelized Cost of Energy (LCOE), positioning FPV as a competitive alternative to traditional thermal firming for grid stability.

A critical strategic advantage lies in the use of hydroelectricity as a battery for solar generation. During daylight hours, FPV can supply the grid or auxiliary services, allowing the hydroelectric plant to curtail its water discharge and conserve potential energy in the reservoir [16]. By synchronizing these two sources, operators can optimize the matching between energy supply and demand, providing a more stable and predictable power profile to the National Interconnected System (SIN).

Installation of FPV on hydropower reservoirs is particularly relevant during extreme hydrological droughts and prolonged dry seasons, which frequently compromise Colombia’s energy security by reducing reservoir levels. FPV systems mitigate these risks through two mechanisms: first, by providing an alternative generation source when water heads are low, and second, by reducing water loss due to evaporation [17]. Dry seasons typically correspond to the high solar irradiation months [18]. Furthermore, the technical synergy extends to shared infrastructure. FPV installations utilize the existing grid connection, substations, and transmission lines of the hydropower plant [19], which represent a massive saving in "balance of system" costs. This shared footprint not only minimizes the environmental impact on surrounding territories but also simplifies the regulatory pathways under current CREG resolutions, which are increasingly favoring co-located renewable resources. This dual-asset approach transforms traditional dams into modern energy hubs, aligning with Colombia's decarbonization goals while ensuring that the transition remains economically viable for private and public stakeholders alike.

The operational integrity of FPV systems in tropical reservoirs is subject to specific environmental factors that must be mitigated to ensure a 25-year lifespan. Corrosion is a primary concern in high-humidity environments; therefore, the use of corrosion-resistant, such as plastic or stainless steel, alloys for mooring components is essential [20]. Furthermore, Colombia’s reservoirs experience significant seasonal water level fluctuations, requiring advanced elastic mooring systems that can adapt to vertical displacement without compromising structural stability. Table 2 summarizes the potential negative environmental impacts during the installation and operation of FPV systems, along with their corresponding technical and management mitigation strategies.

Table 2. Impact of Environmental Factors on FPV Structural Integrity

Factor	Technical impact	Mitigation strategy
Corrosion and material degradation	Degradation of metallic joints and mooring cables due to high humidity.	Use of UV-stabilized HDPE (High-Density Polyethylene), SS316 stainless steel, and fiber-reinforced polymers (FRP).
Water levels fluctuations	Mechanical stress on mooring lines; risk of grounding in shallow areas.	Implementation of elastic mooring lines and bathymetric mapping to maintain optimal distance from shorelines
Waves & Wind loading	Fatigue on floating platforms and potential misalignment of PV arrays.	Reinforced anchoring points, and the use of breakwaters or wave-damping floating structures.

4. Conclusion

This study shows that Colombia’s key hydroelectric reservoirs possess a considerable technological potential to use floating photovoltaic (FPV) systems, which is a strategic alternative to diversify and complement the national energy matrix. Existing hydroelectric facilities (substations, transmission pathways, access routes) can be integrated with low land footprint and less environmental impact through FPV installations, including hydropower.
According to nine representative reservoirs analysis, the technical FPV generation capacity in total is expected to be in the range of 1.6–9.9 gigawatts (GW) of installed capacity, depending on how much of the reservoir areas covered by the FPV. In a conservative scenario for a 5% surface coverage, the annual generation was estimated at approximately 2.21 terawatt-hours (TWh), or 2.45% of Colombia’s current electricity demands. If the coverage increases to 15%, or 30%, the annual generation would be approximately 6.65 TWh and 13.31 TWh each. These results illustrate that even partial utilization of the reservoir surfaces could serve as a great contribution to the country's renewable power generation expansion. From a technical point of view, whether FPV systems can actually be built depends on the proper design of anchoring solutions, electrical interconnection and hybrid control of running. Due to the variability due to water level variations, currents variations and seasonal solar irradiance variables, strong floating systems, strong materials, and energy management facilities capable of maximizing hydro-solar complementarity are needed. The link with hydro production will lead to more efficient filling for the reservoir such as lower evaporation loss, flexible operation in low availability of hydrologic solution, and stability of the whole national power system.

From a regulatory and environmental perspective, Colombia has developed a comprehensive legal landscape of laws that, although sound in nature, should be tailored to the unique features of hybrid renewable projects. The requirements for the environmental licensing and the jurisdictional thresholds between the National Environmental Licensing Authority (ANLA) and the Regional Autonomous Corporations (CARs) are defined in Law 99 of 1993, Law 1715 of 2014, Decree 1076 of 2015 and its amendment through Decree 852 of 2024. The ANLA (the country's National Environmental Licensing Authority) must grant an environmental license to FPV projects with installed capacities equal to or greater than 50 MW, whereas the CARs regulate projects of 10 MW to 50 MW. It is equally important to advance pre-planning and adhere to these standards in order to minimize legal, environmental and social risks and enhance social acceptance of projects.

Altogether, floating photovoltaic technology has the potential to provide a technologically feasible, environmentally friendly and strategically valuable addition to the hydroelectric base in Colombia. This would allow for increased generation potential, reduced exposure to hydrological variability and would advance the national decarbonization objectives through integrating hydro-solar with a combination of hydro-solar systems. Further studies can focus on hydrodynamic and energy modeling, optimizing operating control strategies and cost–benefit analysis under actual operation conditions as well to consolidate large-scale installations of FPV systems in tropical hydroelectric settings in Colombia.

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