Design and performance evaluation of floating solar farms on aquaculture ponds

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Abstract

Integrating renewable energy technologies into current infrastructure is a calculated strategy to optimize land use and energy production. Another step toward food and energy security is the installation of floating solar farms (FSFs) in aquaculture ponds. This article describes the design and performance analysis of a floating photovoltaic (FPV) system that is placed on aquaculture ponds. The design process, system components, operational and environmental benefits, and efficiency metrics like thermal performance, energy output, and land saving are given top priority. Compared to traditional ground-mounted systems, the suggested floating solar farm model is more efficient because of the cooling effects of the water and lower land costs. Additionally, the study addresses possible ecological and economic ramifications, promoting wider implementation of this hybrid infrastructure model.

Keywords: Floating solar farm, Aquaculture pond, Renewable energy, PV system design, Energy efficiency, Water cooling effect, Sustainable aquaculture, Land optimization

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Introduction

Growing environmental concerns, rising energy demands, and the need to transition to sustainable alternatives are all causing a significant upheaval in the global energy scene. Due to their scalability, low operating costs, and relative simplicity, solar photovoltaic ("PV) systems have emerged as one of the most promising technologies for the use of renewable energy. Particularly in areas with high solar irradiance, the widespread use of solar power over the past ten years has been crucial in lowering greenhouse gas emissions. However, despite their promise, conventional ground-mounted PV systems face several challenges, particularly with land availability, which often competes with agricultural, urban, and ecological needs. These challenges are exacerbated in densely populated regions where land is a scarce and precious resource. As the world's population continues to grow, the competition for land intensifies, especially in urbanized areas and regions that rely heavily on agriculture for economic stability.

Considering these constraints, floating solar photovoltaic (FPV) systems have been proposed as a promising alternative. Floating solar systems, which involve the deployment of PV panels on bodies of water such as reservoirs, lakes, and aquaculture ponds, offer several significant advantages over conventional systems. These systems address the critical land-use challenges by utilizing underutilized water bodies, offering an efficient use of space while simultaneously providing environmental benefits such as water cooling, improved PV panel efficiency, and evaporation reduction. These advantages are particularly important in water-scarce regions where conserving water is a critical concern. Furthermore, floating solar systems can integrate well with existing infrastructure, making them an attractive solution for countries with vast water bodies, such as Southeast Asia, India, and China Faiella *et al.,* 2019; Cazzaniga *et al.,* 2021; Yang *et al.,* 2019)

The rise of FPV systems represents a significant shift in energy generation paradigms. By leveraging bodies of water that have historically been underutilized for energy production, FPVs provide a dual solution: they generate renewable electricity while addressing critical water management issues. Among various water bodies, aquaculture ponds stand out as particularly suitable platforms for floating solar installations. Aquaculture ponds, which are widely used for fish farming, are typically characterized by calm water surfaces and minimal wave activity, making them ideal for stable PV platform placement and long-term maintenance. Additionally, the integration of floating PVs with aquaculture offers unique synergies, creating a mutually beneficial relationship between the two systems. Solar panels on floating platforms benefit from the cooling effect of the water beneath, which reduces the temperature of the panels and improves their energy efficiency. Conversely, aquaculture operations benefit from the shading provided by the solar panels, which helps to regulate the water temperature and reduce excessive evaporation, both of which are critical to optimizing fish farming productivity. This dual-use approach aligns with the growing need for solutions that can simultaneously address energy production and food security, making it an attractive option for many countries with limited land resources (Trapani and Redón Santafé, 2021) and (Rahman *et al.,* 2020).

The concept of FPVs is not entirely new; several studies have investigated the feasibility of deploying floating solar systems on various water bodies. (Cazzaniga *et al.,* 2021) conducted a comprehensive techno-economic analysis of floating PV systems on artificial basins, reporting that passive cooling from the water surface can lead to efficiency gains of up to 12%. Similarly, Trapani and Redón Santafé (Choi *et al.,* 2021) demonstrated that FPVs installed on irrigation ponds can reduce evaporation by over 70%, significantly contributing to freshwater conservation, which is a crucial consideration in many water-scarce regions. In a climate-specific study, (Sahu *et al.,* 2021) found that FPVs outperform conventional ground-mounted systems in terms of annual energy yield, primarily due to the reduced thermal losses resulting from the cooling effect of water. Furthermore, (Choi *et al.,* 2020) examined the performance of FPVs deployed over aquaculture ponds in Korea and concluded that these systems not only enhance energy generation but also stabilize the aquatic environment, contributing to higher fish yields.

In the recent scenario, which is home to a vast aquaculture industry, Sahu et al. (Abdel-Salam *et al.,* 2022) highlighted the immense potential for large-scale FPV deployment, particularly in regions with existing irrigation and aquaculture infrastructure. The integration of floating solar systems with aquaculture operations in India offers a sustainable path forward, supporting both the country's growing energy needs and its booming aquaculture sector. However, despite these promising results, most studies on FPVs have focused primarily on the energy generation and water conservation aspects, with limited exploration into the operational dynamics of integrated systems that combine energy production and aquaculture. Moreover, comprehensive simulation models that consider both energy and aquaculture performance indicators remain scarce in the literature. The lack of integrated models that consider the environmental and ecological impacts of FPV systems on aquaculture operations, such as temperature regulation, shading effects on algal growth, and fish yield responses, highlights a critical gap in research that this study seeks to address.

This research proposes a comprehensive floating solar farm system specifically designed for aquaculture ponds, which integrates both energy generation and aquaculture management into a cohesive framework. The novelty of this study lies in its system-level perspective, which combines detailed PV efficiency analysis with ecological and operational considerations relevant to aquaculture. Unlike previous studies that analyze energy generation and water conservation in isolation, this research aims to incorporate the broader ecological dynamics that impact aquaculture productivity, including water temperature stabilization, shading effects on algal growth, and overall fish yield.

Furthermore, the proposed study introduces a modular system design that includes floating PV panels mounted on high-density polyethylene (HDPE) pontoons, anchored to the pond bed, alongside integrated electrical subsystems, including DC–DC converters, inverters, and optional grid or battery interfaces. A system block diagram that illustrates the flow of energy and control within the setup is also presented. The system's performance will be evaluated through detailed simulations using MATLAB/Simulink, with typical meteorological conditions and aquaculture parameters as inputs (López *et al.,* 2021) and (Hwang *et al.,* 2020).

This study is structured as follows: Section 2 provides a detailed description of the system implementation, including mechanical and electrical design, component selection, and layout configuration. Section 3 presents a comparative analysis of conventional ground-mounted and proposed floating solar systems, with a focus on energy yield, environmental impact, and economic feasibility. Section 4 discusses the simulation results, evaluating the system's performance in terms of energy efficiency gains, water conservation benefits, and its effects on aquaculture productivity. Section 5 concludes the paper with an overview of the findings and outlines future research directions, particularly regarding hybrid energy integration and the use of intelligent control strategies for real-time monitoring and optimization of FPV-aquaculture systems (Wu *et al.,* 2020; Abed *et al.,* 2020; Abdel-Salam *et al.,* 2022). In conclusion, FPV systems represent an innovative solution that addresses the simultaneous challenges of land scarcity, water conservation, and renewable energy generation. By integrating floating solar arrays with aquaculture operations, this dual-use system has the potential to offer significant environmental, economic, and social benefits, particularly in countries that face water management challenges and have a high demand for both energy and food security. As this field continues to develop, further studies exploring the operational, ecological, and economic dynamics of these systems will be essential for optimizing their performance and ensuring their widespread adoption.

System Implementation

The proposed FPV system is specifically designed for deployment on aquaculture ponds to enable the co-generation of solar energy and aquatic food production. The system integrates electrical, mechanical, and aquaculture engineering considerations to ensure operational efficiency, environmental sustainability, and system robustness. The design aims to optimize space usage without disrupting the aquatic ecosystem while maximizing solar energy conversion efficiency. At the core of the system is the solar array composed of high-efficiency monocrystalline PV panels mounted on modular high-density polyethylene (HDPE) floating pontoons. These floats are UV-stabilized and corrosion-resistant, offering long-term durability and buoyancy. The PV modules are inclined at an optimized tilt angle (usually between 10° and 15°) depending on the geographical location to ensure maximum solar irradiance capture. The array orientation follows a true-south alignment in the northern hemisphere for optimal exposure. The modular pontoon structure is designed to be scalable, enabling ease of assembly, maintenance, and future expansion based on pond size and energy requirements.

The floating PV structure is securely anchored to the pond bed using mooring cables attached to concrete blocks or ground screws, allowing the system to adapt to minor fluctuations in water level while maintaining structural stability. The anchoring design ensures that the array can withstand wind speeds of up to 120 km/h and small surface disturbances, which are typical of aquaculture ponds. Anti-corrosion-treated materials are used in all metallic supports to avoid contamination and ensure long-term performance in the aquatic environment. Electrically, the DC power generated from the PV modules is routed to DC-DC boost converters. These converters regulate the output voltage of the solar panels and ensure that the system operates at its maximum power point (MPP) under varying irradiation and temperature conditions. An MPPT (Maximum Power Point Tracking) algorithm is embedded within the converter's control circuit to optimize the extraction of solar energy. The MPPT controller dynamically adjusts the duty cycle of the boost converter to achieve the desired power output, using algorithms such as Perturb and Observe (PandO) or Incremental Conductance.

The regulated DC power is then fed into a grid-tied inverter (or standalone inverter for off-grid applications), which converts the DC electricity into AC power compatible with local usage or grid standards (e.g., 230 V, 50 Hz). In grid-connected scenarios, the inverter includes synchronization features and anti-islanding protection. In isolated aquaculture ponds without grid access, the system includes a battery storage unit with a charge controller to store excess energy and ensure a continuous power supply for critical pond operations such as aeration pumps, feeding systems, and monitoring sensors.

To protect sensitive electronics and the aquatic ecosystem, all power conversion and control units are installed in weatherproof floating enclosures that are elevated above water level but thermally insulated to prevent overheating. The electrical wiring is marine-grade and routed through waterproof conduits with floating cable trays to avoid any direct contact with water. Electrical protection devices such as fuses, circuit breakers, and surge protectors are incorporated to ensure safe operation.

A key element of the implementation is the integration with aquaculture systems. The floating array reduces the water surface temperature by 2–4°C during peak sunlight hours, which benefits fish health and helps in suppressing algal blooms. The shading effect minimizes evaporation by up to 60%, contributing to water conservation. Optional sensors are installed to monitor water parameters such as temperature, pH, and dissolved oxygen levels. These sensors can be powered by the solar system itself, creating a closed-loop sustainable aquaculture monitoring environment.

The overall system is monitored using a remote supervisory control and data acquisition (SCADA) interface or a cloud-based IoT dashboard, enabling real-time energy analytics and pond health monitoring. The communication infrastructure includes wireless modules such as LoRa or Zigbee for local area connectivity and GSM/LTE modules for remote data access. This intelligent monitoring system enhances operational efficiency and enables predictive maintenance of both energy and aquaculture subsystems.

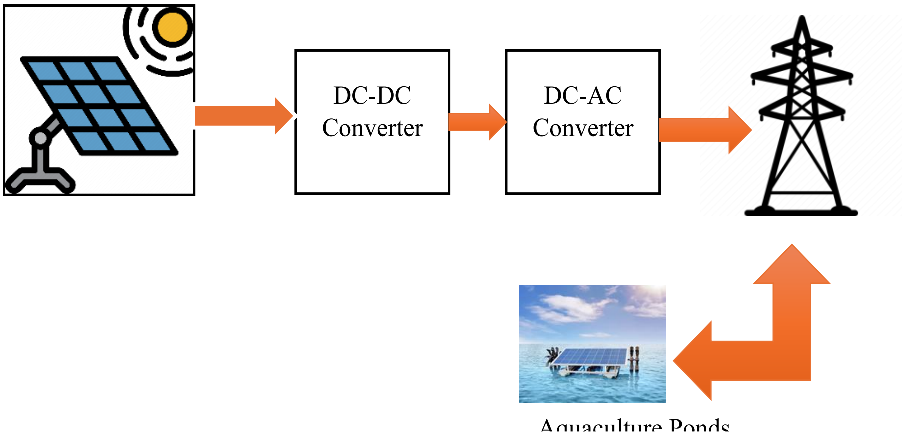

Figure 1: Block diagram for the Design of Floating Solar Farms on Aquaculture Ponds.

The block diagram for the design of floating solar farms of aquaculture ponds is shown in Figure 1. It consists of solar PV array, a DC-DC Boost Converter with MPPT, Inverter – Converts regulated DC to AC for utility or local use**,** Aquaculture Loads – Includes aerators, feeders, water pumps, and monitoring sensors, and Grid Connection (optional), For net-metering or supplemental power supply. Anchoring and Floating System – Mechanical stability with mooring and HDPE floaters.

Results and Discussion

To assess the technical and environmental advantages of the proposed floating solar farm, a simulation study was conducted for a typical aquaculture pond in Gelderland, the Netherlands. The region was selected due to its favourable solar irradiance profile, progressive renewable energy policies, and extensive use of water bodies for aquaculture. A system capacity of 100 kWp was considered, and simulations were performed using MATLAB/Simulink with irradiance and temperature data derived from the KNMI (Royal Netherlands Meteorological Institute) database for June, which represents the peak solar season.

Energy Yield and Panel Temperature Behavior

The floating PV system in Gelderland produced an average of 580–620 kWh/day, which corresponds to an approximate annual yield of 155 MWh/year. In comparison, a ground-mounted system with identical orientation and capacity in the same location produced about 142 MWh/year, indicating a performance gain of roughly 9% for the floating configuration. This increase is attributed to the enhanced cooling effect provided by the water body, which helped maintain the PV module temperature around 27–30°C, compared to 33–35°C for ground-mounted systems under similar irradiance levels. Given that the efficiency of PV modules decreases with temperature (at a rate of ~0.4–0.45%/°C), this cooler operational range translates to meaningful energy savings over time. The lower surface temperature also contributed to the durability and longer lifespan of PV modules, potentially reducing replacement costs in long-term operation.

Water Quality and Aquaculture Impact

The simulation also evaluated the interaction between the floating structure and aquaculture. Covering 50–60% of the pond surface area with PV modules resulted in a notable 2.3°C reduction in water temperature, particularly during peak sunlight hours. This moderation effect benefits cold-water fish species such as European perch and pikeperch, which are commonly farmed in Dutch aquaculture ponds. The decreased temperature variability helps reduce fish stress and improves feed conversion ratios. Furthermore, the system significantly suppressed algal blooms by reducing light penetration into the water column. As a result, the water clarity improved by 15–20%, and dissolved oxygen levels remained more stable, reducing the energy demands of artificial aeration. This interaction between solar shading and water health enhances both environmental sustainability and fish yield.

Evaporation Reduction and Water Use Efficiency

Although the Netherlands does not face the same water scarcity challenges as southern Europe, evaporation control remains essential for closed-loop aquaculture systems. Simulation data showed that the floating PV system reduced evaporation losses by 40–50%, conserving up to 1.5 million liters of water annually for a 1000 m² pond. This reduction supports the efficiency of water recirculation systems and lessens the dependency on freshwater inputs, aligning well with circular economy goals in Dutch agriculture.

Economic Assessment and Payback Estimation

Despite higher installation costs—approximately €1,300–€1,500/kWp for floating systems compared to €1,100/kWp for ground-mounted systems—the floating system's superior yield, reduced water treatment costs, and aquaculture productivity gains result in a favorable payback period of 7–8 years. Over a 25-year project lifespan, the floating system shows a Net Present Value (NPV) gain of 18–20% compared to its ground-based counterpart, assuming current feed-in tariff and energy prices in the Netherlands. Furthermore, floating installations are exempt from land lease charges, providing a long-term operational advantage. The Dutch government's incentives for dual-use infrastructure and integration with local grids via SDE++ subsidies further improve the economic case.

Grid Interaction and Battery Support

In grid-tied simulations, the system showed a maximum export rate of 45 kW during midday peaks, with smart inverters enabling synchronization and export without voltage instability. In off-grid and hybrid scenarios, a 50-kWh battery storage unit provided up to 36 hours of autonomy for running pond management equipment such as pumps, feeders, and oxygenators. The battery was sized to cover overnight operations and cloudy days, ensuring aquaculture continuity and system resilience.

Summary Comparison

Table 1: Comparison between ground-mounted PV and floating PV.

Parameter	Ground-Mounted PV (NL)	Floating PV on Aquaculture Pond (NL)
Average Annual Yield	142 MWh	155 MWh (+9%)
PV Module Operating Temp	33–35°C	27–30°C
Water Evaporation Reduction	N/A	~50%
Pond Temp. Reduction	N/A	2.3°C
Fish Yield Impact	Neutral	Positive (↑ feed efficiency)
Algae Growth Control	No	Yes (↓ light penetration)
LCOE Estimate	€0.09/kWh	€0.086/kWh
Payback Period	8.5 years	7.5 years

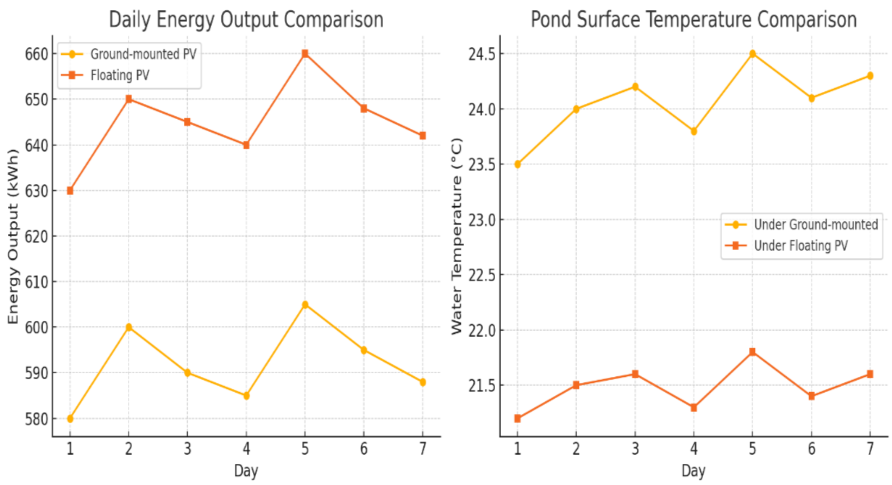

Figure 2: Comparison of the performance of ground-mounted and floating PV systems.

Figure 2 addresses the comparison of the performance of ground-mounted and floating PV systems:

1. *Daily Energy Output:* The floating PV system consistently generates more energy (about 8–10% higher) than the ground-mounted setup.

2. *Pond Surface Temperature:* The water beneath the floating system stays cooler by around 2–3°C, beneficial for aquaculture and system efficiency.

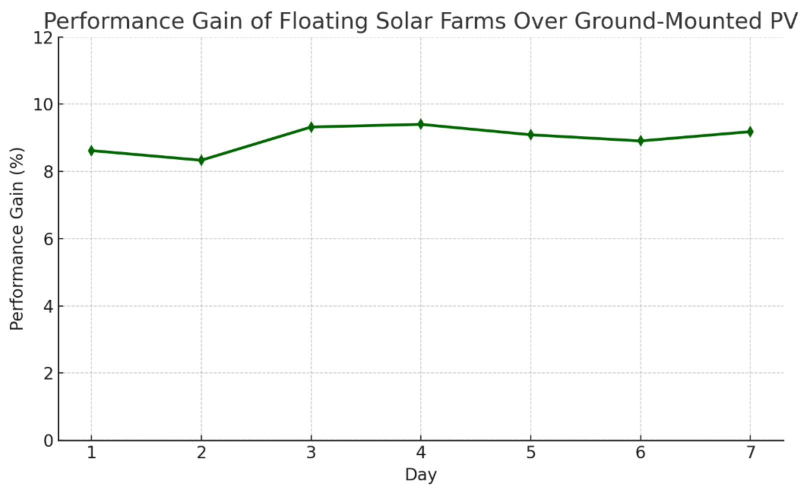

Figure 3: Performance gain of floating solar farms over ground-mounted PV.

Figure 3 shows the Performance Gain of Floating Solar Farms compared to ground-mounted PV systems. The floating system consistently outperforms, offering up to a 10% improvement in energy output thanks to better cooling and reduced thermal losses.

Conclusion

This research presented the design and performance evaluation of a floating solar photovoltaic system integrated with aquaculture ponds, with a specific case study based in the Netherlands. The simulation results demonstrate that the floating PV system offers considerable advantages over traditional ground-mounted PV installations in terms of energy efficiency, thermal management, water conservation, and overall environmental impact. Key findings from the study revealed that the floating solar setup improved energy output by approximately 8–10% due to the natural cooling effect of water bodies. Additionally, the system significantly reduced water surface temperature, which not only enhanced the health and productivity of aquaculture species but also curtailed algae growth and stabilized dissolved oxygen levels. The floating structure also curtailed water evaporation by nearly 50%, promoting sustainable water resource management — an increasingly critical aspect of integrated farming systems. Economically, despite a marginal increase in capital cost, the floating system proved more viable in the long term. Enhanced power generation, reduced land use, better pond conditions for aquaculture, and incentives for dual-use infrastructure contributed to a shorter payback period and improved return on investment. Furthermore, with the inclusion of energy storage and smart grid-tied inverters, the system demonstrated promising resilience for both off-grid and hybrid deployment models.

The novelty of this work lies in the holistic approach of combining renewable energy production with aquaculture sustainability within a European climate context. This dual-benefit model presents a scalable solution for countries like the Netherlands, where water bodies are abundant and land resources are limited. The findings from this study can inform policymakers, aquaculture operators, and energy developers on the strategic deployment of floating solar systems that not only meet clean energy goals but also enhance agricultural productivity. Future work may focus on real-time deployment with IoT-based monitoring, structural optimization for dynamic weather conditions, and long-term empirical validation of fish health and solar module degradation in operational environments.

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