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Comprehensive review of advancements, challenges, design, and environmental impact in floating photovoltaic systems

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ABSTRACT

Floating photovoltaic (FPV) systems have emerged as an innovative and sustainable solution for renewable energy generation, offering advantages such as enhanced efficiency, land conservation, and integration with aquatic environments. This review examines critical factors influencing the efficiency, cost-effectiveness, and long-term viability of FPV systems compared to conventional land-based photovoltaic installations. Key considerations include the natural cooling effect of water, structural stability under environmental forces, electrical system optimization for safety and performance, and site selection to balance ecological preservation with energy generation. The study also explores maintenance strategies to address challenges like biofouling and corrosion, along with the environmental impacts of FPV systems on aquatic ecosystems, water quality, and biodiversity. Advanced corrosion protection methods, including multilayer coatings and cathodic protection, are highlighted for their role in extending system durability, while innovations in design, such as compliant modular structures, address stability in variable-depth and high-stress environments. FPV systems benefiting from reduced maintenance and enhanced energy output due to water's cooling effect. Case studies, such as the Huainan Coal Mine FPV system in China and the Omkareshwar Reservoir FPV project in India, demonstrate the transformative potential of FPV technology in mitigating climate change, optimizing land use, and promoting energy security. The review provides a comprehensive framework for successful FPV system deployment, offering actionable insights for engineers, policymakers, and stakeholders to advance sustainable energy solutions.

Keywords: floating photovoltaic, efficiency, design, environmental factors.

INTRODUCTION

The transition to renewable energy sources has become imperative in addressing global challenges such as climate change and energy security [1, 2]. Among renewable technologies, photovoltaic (PV) solar power has gained significant traction due to its scalability, reduced environmental impact, significant cost reductions over the past decade [3,4]. While traditional ground-mounted PV systems have been widely deployed to effectively harness solar energy across various location [5, 6], they encounter significant limitations, including land-use conflicts, ecological concerns, and reduced efficiency caused by high operating temperatures [7, 8].

Floating photovoltaic (FPV) power plants present an innovative solution for utilizing solar energy in areas with limited land availability but abundant water bodies. By installing solar panels on reservoirs, lakes, or coastal regions, FPV systems eliminate land-use competition while benefiting from the natural cooling effects of water. This cooling not only enhances energy conversion efficiency but also slows the degradation of solar panels. The rising demand for FPV technology is driven by its application in utility-scale distributed solar solutions, particularly in water reservoirs and hydroelectric power plants. Large-scale FPV installations in countries such as China, India, the United States, Malaysia, and Japan, along with pioneering projects like the solar sea power (SSP), have further propelled its adoption [9]. In addition to their utility in hydropower reservoirs, FPV systems offer several advantages, including higher investment returns, improved aesthetics, reduced evaporation, lower surface reflectivity (albedo), and decreased water pollution [10].

While FPV technology offers significant advantages, its adoption remains limited, as the technology is still in the developmental stage and faces several challenges. Key obstacles include designing stable floating structures capable of withstanding fluctuations in water levels, wave forces, and other environmental stresses, as well as addressing the potential impacts of these structures on aquatic ecosystems and water quality [11]. Additionally, the durability and performance of FPV systems under varying climatic conditions have yet to be thoroughly investigated.

The development of FPV platforms requires addressing complex factors, including mooring systems, hydrodynamic performance, material selection, and environmental considerations. According to Lian et al. [12], offshore FPV platforms need robust mooring systems capable of enduring harsh oceanic conditions. Various mooring configurations have been studied, such as all-chain, chain-polyester ropes-chain, and chain-nylon ropes-chain systems. Among these, the nylon rope system experiences the lowest tension but allows for larger displacements, while all-chain systems provide the highest tension under similar conditions. The dynamic response of mooring systems, especially in shallow water environments, significantly impacts platform stability, with sensitivity analyses highlighting the influence of wave direction (particularly at 60°) on mooring chains' force, emphasizing the need for careful design [13].

Hydrodynamic performance is critical for FPV platform stability and efficiency. Studies using software like AQWA and Orcaflex show that hydrodynamic interactions can limit platform motion, which is beneficial for stability [14, 15]. However, managing these interactions is crucial to avoid negative effects during extreme sea conditions [16]. Nonlinear hydrodynamic properties, such as variations in restoring and Froude-Krylov forces, must be accurately modeled for shallow-draft FPV structures to optimize performance [17].

Material selection is another key factor in the durability and sustainability of FPV platforms. Bamboo-based composite materials offer a lightweight and low-carbon alternative, contributing to overall sustainability [18]. High-density polyethylene (HDPE) floaters, commonly used in FPV systems, provide flexibility and resilience in marine environments. The structural dynamics of these floaters, influenced by low-frequency excitations, play a crucial role in maintaining platform integrity [19].

The environmental impact of FPV systems, particularly their effects on aquatic ecosystems, such as shading and changes in hydrodynamics, must be carefully monitored. Stakeholder collaboration is essential to ensure sustainable deployment [20]. Economically, FPV systems present a viable alternative to traditional energy sources, with the potential for cost savings and reduced carbon emissions. For example, integrating FPV systems with offshore oil platforms can significantly lower carbon footprints while offering a competitive levelized cost of electricity [21].

Developed countries are increasingly interested in FPV systems due to their numerous advantages [22]. For example, Figure 1 depicts an FPV power plant located on Lake Maiwald, near Renchen/Baden, Germany, demonstrating a sustainable approach to energy production by utilizing water surfaces for solar panel installation [23]. The floating design maximizes space efficiency while also improving energy performance by leveraging the cooling effect of water on the panels.

In addition to developed countries, there is growing interest in FPV technology in developing nations as well. People in these countries are excited about floating solar panels, with projections indicating that they could become more affordable than land-based solar installations by 2030 [24]. One of the major challenges facing both the academic and industrial sectors is developing floating platforms that can withstand the harsh conditions of hydroelectric reservoirs for at least 25 years.Several developing countries are leading the way in exploring FPV technology. India is investigating FPV installations on its numerous reservoirs and lakes, particularly in

Figure 1. An FPV power plant with a net capacity of 749 kWp installed on Lake Maiwald near Renchen, Germany [23]

regions where land is limited [25]. Brazil, with its vast hydropower infrastructure, is actively pursuing research and development to overcome the challenges of deploying FPV systems in its reservoirs [26]. Kenya has launched pilot projects to assess the feasibility and benefits of FPV technology in rural areas with limited electricity access, as shown in Figure 2 [27]. In Indonesia, a 48-MW FPV system on Lake Singkarak highlights the effective use of FPV technology, optimized for local water conditions to enhance energy generation and support grid integration. With its vast archipelago, Indonesia is exploring FPV as a sustainable option to provide electricity to remote communities [28].

This study provides a comprehensive analysis of FPV systems, focusing on design considerations, performance metrics, and their broader impacts. It begins by examining the current state of FPV technology and its global evolution trends. The discussion then shifts to the composition of an FPV system, highlighting critical aspects such as material selection, anchoring methods, and essential electrical components that influence performance and durability. Additionally, the study presents findings from various corrosion tests, including static and dynamic corrosion tests, Tafel analysis, electrochemical impedance spectroscopy (EIS), and scanning electron microscopy (SEM) combined with

Figure 2. Pilot project of 69 kWp FPV in Naivasha, Kenya [27]

energy-dispersive X-ray spectroscopy (EDS). These analyses evaluate material degradation rates and estimate the corrosion lifespan of FPV components. The environmental context of FPV installations is also addressed, with a focus on interactions between FPV systems and aquatic ecosystems, water quality, and local biota. Finally, the study explores the economic implications of FPV systems, discussing costs, benefits, maintenance frequency, and the potential for integrating FPV with multi-use water infrastructure, such as hydropower and aquaculture.

The primary aim of this research is to identify key design and construction factors for FPV platforms and evaluate their costs relative to land-based photovoltaic systems. Additionally, the study examines the long-term benefits and efficiency improvements that FPV systems may offer over traditional solar power technologies. The scope of the study encompasses the following areas:

- Analyzing the efficiency of FPV systems, including the natural cooling effect of water.
- Evaluating the suitability of various water bodies for FPV installation, considering environmental sensitivity and existing infrastructure.
- Identifying design requirements for FPV systems to ensure stability and resilience in the face of environmental challenges, such as waves, wind, and water depth variations.
- Ensuring the safety, efficiency, and cost-effectiveness of electrical systems in FPV installations, focusing on lifecycle performance and cost analysis.
- Assessing the long-term maintenance needs for FPV systems.
- Examining the impact of FPV systems on marine life, water quality, and overall ecological balance.
- Investigating corrosion prevention methods to ensure the longevity and reliability of FPV platforms.

This study provides a detailed framework for understanding the critical aspects of designing and implementing FPV systems. By synthesizing the latest research and field data, it aims to highlight both the opportunities and challenges associated with FPV technology, contributing valuable insights to the broader conversation on renewable energy deployment. The findings are intended to guide policymakers, engineers, and stakeholders involved in the development and implementation of FPV systems, offering a pathway to more sustainable energy solutions.

KEY FACTORS IN DESIGNING A FLOATING PLATFORM

Technical key factors

These include optimizing efficiency while managing costs, selecting appropriate sites that balance environmental sensitivity with infrastructure availability, and ensuring that the structural design can withstand diverse environmental conditions. Additionally, the electrical system must be designed for safety and efficiency, while the maintenance and operational requirements need to be carefully planned to ensure long-term performance and cost-effectiveness. The following subsection provides a more detailed examination of these factors.

Efficiency

The land-based solar power systems have certain limitations, particularly in terms of efficiency [29]. One major issue is that the surface of the land can become increasingly hot, reducing the efficiency of solar panels [30, 31]. To maximize performance, PV systems require optimal placement [32, 33]. In contrast, solar generation on water tends to be more efficient because water naturally cools the panels, enhancing their performance compared to land-based systems [10].

Numerous experiments have compared solar systems on land and water. Saxena et al. [34] found that solar systems installed on a pond were 16% more efficient in terms of energy generation than those installed on land.

Another advantage of FPV systems is that they avoid the high cost of land for installation, as water is generally considered “free land”. With the increasing scarcity of suitable land for solar plants, developers are often forced to build solar plants on less ideal locations, such as hills. However, FPV systems offer an ideal solution to address these challenges faced by land-based solar installations [10].

Studies have further demonstrated the advantages of FPV systems. For instance, Mamatha & Kulkarni [35] shows that FPV systems can significantly increase energy output due to the cooling effect of water, which reduces the operating temperature of solar panels and improves their efficiency. Integrating FPV with hydroelectric plants can increase energy generation by 92% and improve the capacity factor by an average of 18.43%. In India, the cost of energy produced by FPV systems ranges from 2.65 to 3.05 INR/kWh, which is competitive.

Site selection and assessment

Site selection and assessment for FPV systems require careful consideration of a range of technical and environmental factors. As FPV is a relatively new technology, established methods for site selection are still developing. Most existing FPV installations have been located on inland water bodies, including hydroelectric dams, irrigation reservoirs, and drinking water treatment basins [36]. These man-made water bodies offer several advantages: the water surfaces are typically flat, simplifying platform design; existing energy and water infrastructure can reduce project costs; and utilizing these bodies for solar energy can offset the carbon footprint of the FPV system, potentially easing political resistance [37]. However, a challenge of installing FPV systems on water bodies is that some are located near ecologically sensitive areas, such as wetlands and flooded lands, which are rich in biodiversity and serve important environmental functions. Deploying FPV systems in such areas may lead to habitat loss and could face opposition from regulators and the public [38]. Japan, however, provides a unique example where the government has promoted solar installations on ponds and reservoirs at abandoned agricultural or industrial sites to mitigate farmland loss and avoid developing greenfield areas.

Offshore installations are considered a promising option for future growth. The most significant benefit of FPV is its ability to conserve land, an especially valuable resource in regions like Japan and the EU, where land prices are high and competition for land use is fierce. In these areas, FPV can help avoid sacrificing valuable agricultural or developable land. Coastal and offshore FPV installations are also cost-effective in island nations and countries with high electricity tariffs and limited land for solar projects [39].

When selecting a site, proximity to substations and grid infrastructure is critical, as connection costs can vary greatly and impact the overall economics of the project. Economic considerations, such as installation costs, maintenance, and potential energy yield, are essential factors influencing FPV site selection and the potential return on investment [40]. Social and regulatory factors, such as community acceptance and local regulations, must also be taken into account to ensure successful deployment [41].

In terms of technical criteria, global horizontal irradiance (GHI) is crucial for assessing the solar potential of a site. In Turkey, for instance, GHI was identified as the most important factor for FPV installation on lakes. Geographic Information Systems (GIS) and multi-criteria decision-making methods, like the Fuzzy Analytical Hierarchy Process, are valuable tools for evaluating potential FPV sites, combining both spatial and non-spatial data [42]. Additionally, while FPVs can reduce water evaporation and enhance the cooling efficiency of solar panels, the potential for ecological disruption must also be considered [43]. Hydrodynamic factors such as water surface velocity and reservoir depth are essential for ensuring the stability and efficiency of the FPV systems, as seen in studies like the analysis of the Sepaku Semoi Dam Reservoir, which identified optimal installation areas based on these factors.

Structural design considerations

Survivability is defined as a system’s ability to accomplish its mission while enduring intentional or unintentional hostile acts. This capability is influenced by the interplay between credible threats and the system’s vulnerability. Offshore platforms and ships are guided by specific codes and regulations to ensure an adequate level of survivability, which must also be considered during the design of FPV platforms [16].

For offshore platforms, survivability must correspond to the environmental conditions at the installation site, ensuring both structural integrity and system value. High winds and significant wave forces necessitate robust designs that account for gust factors and extreme wave heights. For instance, the API 2A (21st Edition), a standard by the American Petroleum Institute, mandates designing structures to withstand wave and wind conditions expected over a 100-year return period [44]. Similarly, the Japanese Class NK system, developed by Nippon Kaiji Kyokai, specifies a 100-year design life for marine structures based on local wind and wave data. For example, a warship’s low vulnerability is critical for its mission of force projection, whereas an oil tanker, with a relatively low structural value compared to its cargo, may tolerate higher vulnerability and lower susceptibility [45, 46].

In regions prone to cyclones, such as shallow reservoirs in tropical climates, platform designs must incorporate site-specific cyclone models to account for extreme wind conditions [47]. The platform’s value is another crucial factor, as higher-value systems require more extensive protection. A vulnerability, threat, and value (VTV) assessment helps define safety standards and acceptable risk levels for FPV systems, aiming to minimize costs and the potential loss of lifecycle value due to damage [48, 49].

Accurately assessing wave loads and wind forces is essential for maintaining FPV systems' structural integrity. These forces significantly affect the motion and stability of floating platforms, requiring thorough hydrodynamic analysis. The design and arrangement of mooring lines play a critical role in stability, with heavier chain sections effectively reducing undesirable motions [50]. Understanding the interaction between waves and FPV structures is vital for optimizing designs. Wave-induced motions such as surge, sway, and yaw can impact energy output and structural performance, highlighting the need for comprehensive analysis [51].

Materials such as glass-fiber-reinforced plastic (GFRP) significantly enhance the stability and durability of FPV systems. GFRP provides a lightweight yet robust solution for constructing floating bodies, making it particularly suitable for the challenging conditions of offshore environments [52]. Additionally, modular designs featuring interconnected FPV modules are increasingly favored for their inherent stability and cost-effectiveness. These configurations facilitate scalability and simplify maintenance, making them an attractive choice for large-scale implementations [53]. Furthermore, numerical simulations and semi-analytical approaches play a crucial role in optimizing mooring system designs, striking an effective balance between fabrication costs and hydrodynamic performance.

Electrical system design

Designing an electrical system for any solar power plant is crucial. However, the unique challenges posed by the marine environment and the evolving nature of floating solar panel technology make the design of electrical systems for FPV systems particularly demanding. Key considerations include system efficiency, platform safety, and the assessment of lifecycle costs and performance ratios [54].

Evaluating the lifecycle performance of the system is essential to ensure the designed electrical system meets expectations. This involves analyzing the performance ratio, which compares the potential solar energy production to the actual output. Factors such as shading from the surrounding environment, electrical losses, and array downtime can impact energy production. Lifecycle cost assessment encompasses initial manufacturing and installation costs, operations and maintenance (O&M) expenses, and decommissioning costs over a typical 25-year timescale [55]. Additionally, energy savings during operation must be converted into monetary terms to fully quantify cost-effectiveness. Thus, efforts should focus on designing electrical systems that achieve a higher performance ratio while minimizing lifecycle costs [56].

Ensuring the safety of the platform is a critical aspect of FPV electrical system design. The interaction between electric current and water introduces significant technical challenges, including the risk of electric shock for individuals engaging in water activities and potential harm to the surrounding ecosystem. Step potential, the voltage difference between two contact points on the ground, can be dangerous, particularly during maintenance activities. Limiting leakage current to no more than 300 mA from the array to the water is essential to prevent adverse effects. High voltage is another critical safety concern. Direct current (DC) transmission lines exceeding 60V are classified as high voltage, which can pose risks to human safety and contribute to electrical corrosion of the array. Systems operating below 30V are considered safer for both human interaction and array protection [14].

The development of waterproof cables with improved mechanical and environmental adaptability is vital for ensuring reliable electrical connections in FPV systems. These cables must withstand the harsh conditions of marine environments. Standardization efforts are underway to enhance their reliability and performance, ensuring their suitability for floating solar installations [57].

Maintenance and operations

PV systems require regular maintenance to achieve optimal energy production, as their output is directly dependent on the solar resource available to the array. Minimizing downtime and service interruptions is therefore essential. An effective maintenance program not only enhances system performance but also helps lower overall maintenance costs [58]. Traditional land-based PV systems often use a fixed tilt angle to maximize energy production. These systems are relatively simple, requiring minimal maintenance [59]. In contrast, FPV platforms involve multiple mechanical systems and interactions with floating structures, necessitating a detailed and proactive maintenance strategy [60]. A study conducted in Japan highlighted that FPV maintenance requirements vary based on construction methods and environmental conditions [61]. However, a general maintenance plan typically includes periodic inspections, surface cleaning, damage repairs, and component replacements. These activities can consume 5–15% of the initial system cost annually, significantly increasing O&M costs compared to fixed-tilt PV systems.

Challenges such as biofouling and corrosion in aquatic environments, further complicate maintenance. Regular inspections and cleaning are critical to mitigating these issues and maintaining system efficiency. Additionally, the setup and tilt angle of FPV panels, which are crucial for maximizing solar capture, must be carefully tailored to the specific water body conditions [62].

Due to the dual-system nature of FPV platforms-combining photovoltaic arrays with floating structures-maintenance is inherently more complex than for land-based PV systems. As technology advances and systems age, O&M costs for FPV platforms are expected to exceed those of land-based systems and rise proportionally with increased technological sophistication and system longevity [63].

Environmental factors

The estimated water depth at the installation site and its potential variations throughout the year are critical factors in FPV system design. Fixed FPV platforms are generally best suited for relatively shallow waters, less than 10 meters deep, as they can be anchored directly to the soil or seabed [64]. Additionally, locations with strong currents may be unsuitable for FPV systems due to the need for numerous mooring points to control lateral movement effectively.

Wind and wave conditions also play a crucial role in FPV design. Excessive platform movement caused by these forces can damage components and reduce energy generation [66]. The wind force acting on an object is determined using the drag equation, which incorporates the drag coefficient, object area, fluid density, and wind velocity squared. For square or rectangular frames, the drag coefficient is approximately 2.0, with the drag force acting perpendicular to the wind flow. Anchoring floaters at the platform's center can help balance wind forces and prevent lateral movement [67]. However, high wind and wave conditions necessitate stronger mooring systems and additional anchoring points, both of which increase costs. Assessing maximum wind and wave conditions at a given location may require professional engineering consultations.

FPV systems also impact aquatic ecosystems. By altering light penetration, they can affect photosynthesis, aquatic plant growth, and the behavior of fish and other organisms. Additionally, FPV installations can modify water flow and gas exchange processes, potentially affecting water quality and ecosystem health. The presence of these systems may disturb benthic communities and influence the movement and habitats of mobile species, necessitating comprehensive ecological assessments [20].

In tropical regions, humidity inversely affects FPV voltage output but can lower ambient temperatures, creating a cooler microclimate around the panels. This interaction of factors is vital for optimizing FPV performance in such environments [68]. Furthermore, FPV systems benefit from the cooling effect of water, which can enhance energy efficiency by up to 4.45% compared to land-based systems [11]. However, coastal and marine environments pose challenges, such as wave motion and saltwater corrosion. Innovative solutions, like compliant modular systems, are being developed to address these challenges [11, 69].

Water depth and currents

Designing for variable environmental conditions presents significant challenges due to the difficulty of predicting future changes. For floating structure design, issues such as fluctuating water depth and tide levels are particularly critical for FPV systems, whose power output is highly dependent on the angle of incident radiation on the solar panels. Fixed-tilt FPV systems demonstrate a nearly linear relationship between energy output and radiation changes, making them vulnerable to efficiency losses in shallow water conditions. To maintain high energy gains relative to costs, such systems may require adjustments to their mooring configurations or relocation strategies to mitigate long-term reductions in energy output [54].

For FPV systems incorporating tracking mechanisms, the design process becomes even more intricate as they attempt to counteract the adverse effects of changing water depths [70]. In cases where mechanical tracking is not feasible, a buoyancy system could be implemented to adjust the tilt angle. However, this adds complexity to the system. An alternative approach involves a double-float system with a heave plate, designed to keep the main platform above the waterline in shallow conditions. This configuration creates a shadowed region of water between the floats, warranting further research into its ecological impacts [71].

Extreme changes in water depth could necessitate platforms with low draft depths, though this may limit site selection and encounter legal constraints on maximum draft depths in certain areas [72]. Weighing the feasibility, costs, and potential damage of solutions against energy losses and future depth changes remains critical. For example, Ananda et al. [73] highlighted that a water depth of 70–90 meters, as observed in the Logung Dam study, provides adequate stability for FPV systems, even with fluctuating water levels. Similarly, Kwon et al. [74] reported that significant water-level changes are associated with reduced power generation efficiency, emphasizing the importance of stable depths for maintaining utilization rates.

Additionally, FPV platforms can impact local hydrodynamics. Studies by Karpouzoglou et al. [75] revealed that FPV systems in coastal areas may alter water mixing, stratification, and currents, influencing primary production and ecosystem dynamics. Du et al. [65] noted that shallow waters with substantial tidal variations could lead to slack or overly tense mooring systems, increasing the risk of damage. Taut mooring systems with integrated buoys or clumps are recommended to maintain stability under these conditions.

In deeper waters, wave loads become the dominant factor affecting FPV systems. Song et al. [76] found that the relationship between wavelength and FPV system length could lead to resonance effects, influencing dynamic responses. Moreover, currents can induce significant platform movement, impacting both stability and energy efficiency. Designing FPV systems to withstand dynamic responses from currents, wind, and wave loads is essential for ensuring performance and safety.

Wind loads and wave conditions

FPV systems are exposed to significant wind and wave loads, which pose challenges to their structural integrity. Traditional design methods often overestimate these loads, leading to higher costs for mooring and support structures. Numerical simulations offer a more accurate assessment by incorporating real-world environmental factors, improving both cost efficiency and system robustness [77]. Compared to land-based photovoltaic systems [78], FPVs experience significantly higher wind loads due to direct wind pressure and wind-induced wave action. These combined forces can result in wind loads more than three times greater than those on land-based systems, substantially increasing the cost of support structures.

The severity of wind and wave conditions influencing FPV design varies by location. In low-wind, calm-water environments, cost-effective buoyant structures tethered to a fixed point on the lakebed may suffice. Conversely, high-wind or rough-water areas require more stable platform designs to maintain array alignment and prevent structural damage caused by capsizing or wave action [50].

Wind and wave conditions also play a crucial role in determining the layout and inter-row spacing of PV arrays, which affect electricity generation [79]. Aligning arrays parallel to the prevailing wind direction can improve efficiency through cooling effects but may increase wind-induced loads on the support structure. Yan et al. [80] emphasized that the dynamic behavior of FPV systems, especially multi-connected modules, is strongly influenced by wave and wind conditions. Connector strength, particularly for hinged joints, is critical as these elements generate additional moments affecting platform stability. Avoiding wave headings such as 0° can help minimize motion responses and reduce structural stresses.

Wave loads dominate the hydrodynamic response of FPV systems, with resonance effects influenced by the relationship between wavelength and system length [76]. Increased wave heights amplify dynamic responses, necessitating careful design considerations to ensure stability. Huang [81] highlighted that wave-induced motions can cause energy fluctuations by altering the angle of sunlight intake, with a pitch amplitude of 6.7° resulting in an average power loss of 12.7%.

Although offshore FPV systems may experience slight decreases in power output due to wave effects, annual energy yield losses are minimal. For example, Alcañiz et al. [82] found that optimally-tilted FPV systems on water can outperform floating configurations in terms of DC power output, demonstrating the importance of optimized tilt angles in mitigating performance losses.

Impact on marine life

FPV systems, an emerging renewable energy technology, have the potential to significantly impact marine habitats and ecosystems. Nobre et al. [83] demonstrated that FPVs can affect socio-ecological activities such as fishing and recreation, which are vital for local communities. Similarly, Exley et al. [84] highlighted that FPVs may influence essential ecosystem services like water purification and carbon sequestration, with implications for achieving sustainable development goals.

The environmental impacts of FPVs on marine ecosystems are complex and multifaceted, involving changes in physical, chemical, and biological processes. Due to the ecological richness and biodiversity of rural climates, lakes, and inland waters, these locations often become contentious areas for PV development [20]. In many cases, controversies over marine life protection have prompted local governments to impose moratoriums, delaying FPV deployment until potential environmental effects are better understood. Comprehensive understanding of the impacts of FPVs on marine life is critical. Direct effects include water surface shading, which can lower oxygen levels and raise water temperatures, and risks of entrapment or physical damage to organisms and plant life from moorings and system components. Indirect effects, such as disruptions to nutrient cycles, are equally important but more challenging to predict, as illustrated in Figure 3 [38]. Both positive and negative changes to aquatic ecosystems may arise, but deviations from natural conditions are generally detrimental to ecosystems that have evolved under those conditions. Additionally, invasive species present a long-term concern, as they can cause irreversible ecological damage.

Shading caused by FPVs can significantly reduce sunlight penetration, impacting photosynthesis in aquatic plants and algae, which in turn affects primary production and energy transfer within food webs [20]. Reduced light availability also alters the thermal structure of water columns, influencing habitat conditions for aquatic species [85]. FPVs may create a cooling effect during the day and thermal insulation at night, affecting thermal stratification and potentially harming temperature-sensitive species. Furthermore, the shading effect can lower dissolved oxygen levels, potentially leading to anoxic conditions harmful to aquatic life.

FPVs also affect the chemical composition of water. Exley et al. [84] stated changes in nutrient levels, such as nitrate nitrogen and total phosphorus, which can influence phytoplankton growth and other aquatic organisms. These chemical alterations, coupled with the shading and thermal effects of FPVs, necessitate careful assessment to minimize ecological disruptions while enabling sustainable energy development.

CORROSION PROTECTION FOR FLOATING PHOTOVOLTAICS

Corrosion protection is a critical consideration in the deployment of FPV systems, as these systems are exposed to harsh environmental conditions that can accelerate material degradation [86]. A thorough understanding of corrosion mechanisms is essential for designing durable FPV platforms. Corrosion, characterized as the deterioration of material properties due to environmental reactions, presents a significant challenge in marine structures. Its effects can substantially shorten the lifespan of the platform and increase maintenance costs. Addressing corrosion during the design phase is therefore crucial,

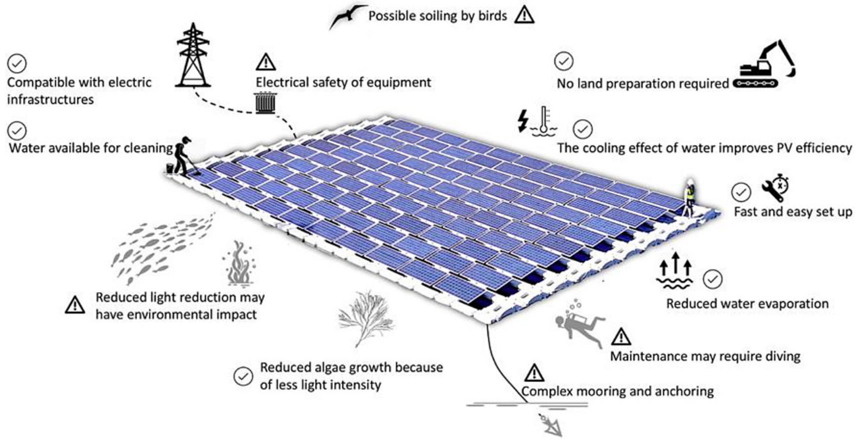

Figure 3. FPV environmental impact [38]

requiring detailed research into the types and rates of corrosion affecting the materials used in marine environments to develop effective and cost-efficient solutions.

To ensure the longevity and efficiency of FPV systems, various strategies have been developed to enhance the corrosion resistance of PV modules. Floating platforms for FPVs can be constructed from a range of materials, but all are susceptible to environmental stressors such as ultraviolet (UV) radiation, temperature fluctuations, and humidity [87]. These factors can degrade mechanical properties and reduce material lifespan. Additionally, aggressive agents like waterborne organisms, salt from seawater, and other chemicals further exacerbate material degradation. Over time, this degradation can compromise floatation and lead to the detachment of the solar PV system, emphasizing the necessity of effective material protection to ensure platform durability.

Cost is a significant consideration when selecting materials and protective measures, as these expenses should not exceed the cost of the solar PV system itself [88]. Addressing corrosion during the construction stage is crucial, yet this is often overlooked, resulting in additional costs for repairs and replacements. Implementing robust corrosion protection methods can preserve structural integrity throughout the design life of the system while minimizing maintenance costs. This is particularly advantageous for FPVs, as it supports a long operational lifespan with reduced upkeep expenses, aligning with the economic feasibility of renewable energy systems under current energy costs.

Corrosion protection methods

Corrosion is a natural electrochemical process that converts metals back to their stable mineral state, effectively returning refined materials to their original form. This degradation is comparable to other natural processes, such as the oxidation of iron to form rust or the tarnishing of silver to produce a patina [89]. In the context of renewable energy solutions, the cost of corrosion is significant and can considerably affect the financial viability and payback period of these systems. A study conducted in Korea revealed that corrosion-related expenses could account for up to 50% of a product's lifetime costs [90].

To mitigate corrosion in FPV structures, two primary protection methods are commonly employed: coating systems and cathodic protection [91]. Coating systems, such as Valspar Aquaguard E-coat, act as a barrier, shielding the metal from environmental exposure [92]. Conversely, cathodic protection employs electrochemical principles to inhibit corrosion by converting the FPV structure into the cathode of an electrochemical cell. These primary methods include various subcategories and adaptations, providing tailored solutions for different environmental conditions, as illustrated in Figure 4 [93].

Coating systems

Coating systems, commonly applied to floating structures, particularly those made of steel, provide an economical and effective means of corrosion protection and are well-established in the marine industry [94]. A traditional three-layer coating system designed to shield FPV structures

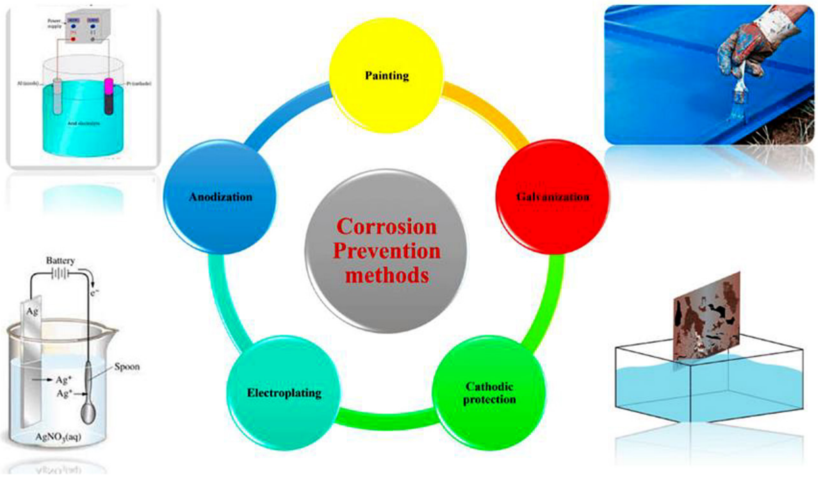

Figure 4. Corrosion prevention methods [93]

from environmental factors such as UV radiation, water, and salt exposure. This system typically consists of a polyurethane topcoat, an epoxy intermediate coat, and an epoxy zinc primer applied over a steel substrate. The composition of a standard two-component zinc-rich epoxy primer, detailing its essential components: zinc pigments, epoxy resin, hardener, solvents, and additives, all of which contribute to the corrosion protection of the steel substrate. A cross-sectional view of the coating layers on an FPV system is depicted in Figure 5, illustrating the multilayer structure. From top to bottom, it includes a pure zinc layer (blue), followed by layers with varying iron (Fe) content: 6% Fe (beige), 10% Fe (light blue), and finally the base steel layer (green). Each layer enhances the durability and corrosion resistance of FPV components by offering incremental protection.

The coating process for steel structures in FPV systems is comparable to automotive painting [96]. The steel part is submerged in a molten zinc bath during hot-dip galvanizing, ensuring a uniform and robust protective layer. Like other coating systems, the process involves surface preparation, primer application, and final finishing.

Additional protective measures include using metal foil layers, such as those made from nickel or nickel oxide, to shield PV cells from corrosive environments. These foils prevent direct contact between semiconductor materials and electrolytes, thereby enhancing the stability of PV cells under conditions such as water splitting [97]. The use of corrosion-resistant materials in PV module construction also bolsters durability. For example, aluminum alloys treated with anodic oxidation processes demonstrate improved strength and wear resistance, making them highly suitable for long-term use in corrosive settings [100].

Cathodic protection

Cathodic protection (CP) is a widely utilized method to mitigate steel corrosion in marine environments [98]. This electrochemical process transfers electrons to the protected structure from an external source using an anode, commonly a zinc-coated component applied to the metal surface. Zinc alloys, as well as aluminum (Al) and its alloys, are frequently used as galvanic anodes due to their effectiveness in protecting steel in seawater under varying conditions [99]. CP can be implemented through two primary systems:

- Galvanic system [100] – this approach employs sacrificial anodes, such as zinc or aluminum, to control the steel's potential. The sacrificial anodes corrode in place of the base metal, providing protection against degradation.
- Impressed current system (ICCP) [101] – this method uses an external power source and inert anodes to deliver a controlled current, thereby regulating the steel's potential and preventing corrosion.

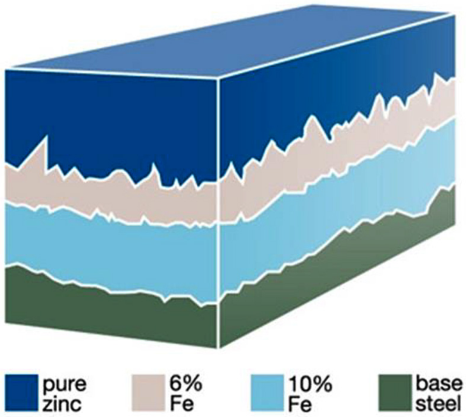

Figure 5. Cross-sectional diagram of a typical hot-dip galvanised coating [95]

Aluminum and its alloys have been extensively researched for their CP applications as alternatives to zinc, primarily due to their high current capacity, which enables the protection of a wide range of structures. When applying cathodic protection to an aluminum structure in seawater, the required protection potential is relatively negative, approximately -1.0 V (Ag/AgCl) [102]. This contrasts with conventional cathodic protection systems for steel structures, where the protection potential typically ranges from -0.85 V to -0.95 V (Ag/AgCl), depending on the type of coating and the degree of corrosion present [103]. High-purity aluminum anodes in compacted graphite have shown promise for protecting aluminum structures by acting as sacrificial anodes. However, the application of aluminum anodes for offshore platforms and Floating Production Storage and Offloading (FPSO) units remains underexplored [104].

ICCP systems offer additional benefits when integrated with PV systems, providing a sustainable and cost-effective power source. This approach is particularly advantageous in remote areas lacking grid electricity, as PV systems can deliver a continuous current to the protected structure, effectively converting it into a cathode and preventing corrosion [105, 106]. Figure 6 illustrates an ICCP system, depicting a protected structure connected to a DC power supply [107]. The system includes an insulated anode cable and an impressed current anode submerged in seawater. By applying a controlled current, the system counteracts corrosive electrochemical reactions, ensuring the longevity and integrity of the structure.

Sacrificial anodes

Sacrificial anodes are widely used to protect interconnector ribbons in PV modules. By attaching a sacrificial metal as an anode to the interconnector ribbon, corrosion of the connective parts between photovoltaic cells is effectively prevented. This approach helps maintain low series resistance and reduces efficiency degradation caused by environmental exposure [108, 109]. Another method involves photovoltaic-powered cathodic protection systems, where PV panels generate current to protect metallic structures from corrosion. These systems operate independently of the power grid, utilizing batteries for energy storage to ensure functionality at night, making them particularly useful in remote locations [110, 111].

Sacrificial anodes are especially effective in preventing corrosion across various metal structures, particularly in marine environments, as illustrated in Figure 7 [112]. For pontoons or floating structures, sacrificial anodes can be integrated into the design, offering a cost-effective solution. Common materials for these anodes include Al, zinc, or magnesium, with the choice depending on their reactivity and protective properties. The anode sacrifices itself by corroding preferentially to the structure it protects, ensuring the longevity of the primary structure [113]. This self-sacrificing process makes sacrificial anodes ideal for long-term, low-maintenance applications, such as FPV structures.

The protection level provided by sacrificial anodes can be monitored, and the anodes replaced once they are fully corroded, ensuring sustained protection over time [114]. This method also offers an even distribution of protection, often outperforming protective coatings, especially at edges and the underside of pontoons. Al and zinc alloys, for instance, have proven effective in controlling the corrosion of aluminum structures in seawater environments [115]. An example is the use of sacrificial anodes to safeguard aluminum solar shading devices on buildings, which has been successful due to the similar electrochemical potential between aluminum and zinc [116].

Selecting the appropriate sacrificial anode material is guided by the electrochemical potential series, ensuring compatibility with the protected structure [117]. This approach maximizes efficiency and effectiveness, particularly in systems requiring long-term corrosion protection. While not explicitly linked to PV-powered CP systems, sacrificial anodes offer a simpler form of protection that can be integrated with PV systems for enhanced performance [118].

Advanced system technologies

Innovations in PV module design now incorporate advanced techniques such as encapsulating materials and gas-phase corrosion inhibitors [119]. These inhibitors, which can adsorb onto metallic

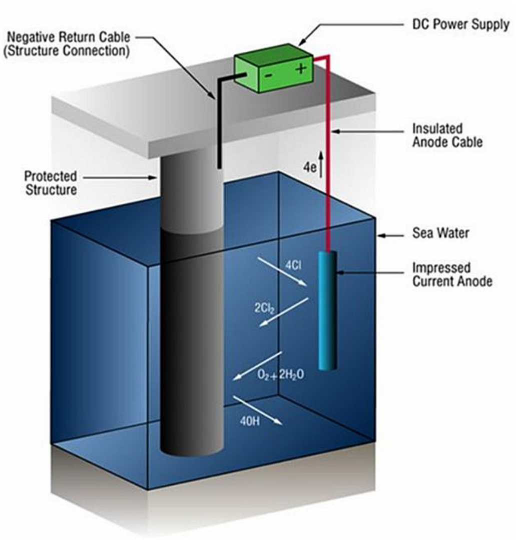

Figure 6. Impressed-current cathodic protection system in seawater [107]

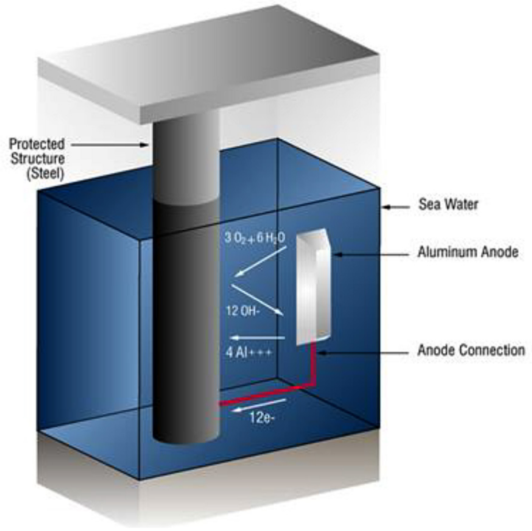

Figure 7. Scheme of sacrificial anode fixed to protect the metal [118]

components, enhance the corrosion resistance of PV modules, thereby improving their durability and performance [120]. Additionally, non-sacrificial photoanodes, such as those made from titanium dioxide (TiO_2) or zinc oxide (ZnO), present a sustainable approach to corrosion protection. These photoanodes operate under sunlight to deliver electrons directly to metal structures, effectively eliminating the need for external power sources. This approach not only reduces maintenance demands but also promotes long-term reliability in corrosion protection systems [121].

Field testing

Before implementing a FPV system in a new environment, it is essential to assess the environmental conditions and adapt the system accordingly. This adaptation process is critical to extending the FPV system's lifespan beyond that of current static land-based systems, which typically last 20–25 years. The primary objective is to simulate the potential environmental conditions where the FPV system will operate, ensuring its durability and functionality while building confidence in its performance.

A common strategy for evaluating the FPV system's durability and functionality in new environments is the "test-to-fail" approach. This involves testing the system in simulated environments until failure occurs, using the insights gained to redesign and improve the system to withstand similar conditions [122]. This iterative process is valuable, especially since the maintenance costs of FPV systems are expected to be minimal [123]. High durability is essential to minimize the risk of component damage, as failure of even a single element can be costly—particularly if the damage renders the component irreparable and compromises the entire system's functionality [124].

Field testing will be conducted in collaboration with various global research partners to evaluate the FPV system's performance in diverse environments. These efforts aim to ensure the system's reliability and functionality on an international scale.

Electrical safety considerations

Risk assessment and hazard identification are essential components of occupational safety and health for photovoltaic floating systems [125]. This process involves identifying stages within the system where electrical hazards may exist, particularly areas with electrical potential that can be dangerous to humans or animals. In this system, two primary electrical potential zones are identified: near the water surface and within the floating structure. The water surface, acting as a conductor, has electrical potential relative to the solar panels and cables, while the floating structure, mostly made of metal, also holds electrical potential in relation to the water [56]. The core objective of risk assessment is to prevent electrical shocks and safeguard valuable property from potential damage. A risk assessment matrix is utilized to assess risk levels, combining probability and severity. Hazards, or sources of harm, within the system are identified, and appropriate control measures are implemented to mitigate these risks.

Risk assessment and hazard identification

The risk evaluation and assessment process is designed to identify all potential hazards that could endanger workers in their work environment. The findings from this process should be documented and regularly reviewed, especially when there are changes in work conditions. The goal of hazard identification and risk assessment is to enhance job safety by implementing control measures aimed at eliminating or reducing work-related health and safety risks [126]. Additionally, risk assessment prioritizes hazards and control measures, emphasizing the need to address the most critical health and safety concerns first and ensuring effective implementation of control strategies. Failure to properly identify and assess risks can result in incidents and injuries. Inadequate risk assessments may lead to ineffective solutions since the true nature of the problem remains unclear, potentially introducing new hazards and exacerbating the original risks [127]. Risk assessment is a proactive, practical approach to ensuring worker safety and health. It involves systematically examining all aspects of the work environment to identify health and safety conditions. The process should be straightforward, step-by-step, and focused on the tasks at hand, with thorough documentation maintained to facilitate good communication between workers and contractors. Workers should be involved in the hazard identification and risk assessment process, with consultation from health and safety representatives being essential. Control measures should be developed in collaboration with workers, as those who perform the tasks are often best positioned to identify effective safety solutions that ensure both safety and practicality [128].

Electrical safety standards and regulations

This section is crucial in designing a reliable, safe, and efficient FPV system, as electrical safety standards and regulations significantly impact the system's design [129]. A standard provides a framework of principles, criteria, guidelines, and characteristics for specific activities or their outcomes. The task of this project has been facilitated by the recent draft standard for FPV systems from the IEC TC-82, which outlines guidelines for system security, reliability, economics, environmental concerns, manufacturability, and maintainability [130]. An assessment of these factors with quantified values will determine how well the system meets the standard, essentially providing design specifications for a safe and reliable system. Once these specifications are met, the system should be certifiable for use in electrical installations, such as solar farms, and deemed safe for operation.

The next step in determining the electrical safety regulations for a solar power system is identifying its installation type and the associated rules [131]. The regulations governing a specific installation depend on its classification as a particular type of electrical construction, which varies by country. Once the classification of the FPV system is established, it must comply with the regulations relevant to that classification. Typically, the FPV system is classified as a solar PV power system and must follow regulations specific to electric power generation, rather than those for other types of circuits. For instance, in Canada, the regulation guidelines for designing a power generation facility are outlined in standard CSA Z1000, which specifies requirements for managing the plant throughout its design, administration, and maintenance to control risks and ensure worker safety [130]. These regulations serve as design specifications to safeguard both workers and the general public.

Finally, as with any electrical installation, the FPV system must comply to fundamental safety rules that prevent hazards that could harm people or damage property. These basic safety requirements ensure that the installation and operation of the system do not pose risks. Examples of such safety measures include the use of rubber gloves, mats, barriers, or insulation to protect against live parts or prevent unauthorized operation.

Insulation and grounding systems

In terms of electrical safety, isolation is the most effective method to ensure safe operating voltage levels in the PV array. PV arrays typically operate within a voltage range of 30 V to 600 V for non-concentrated arrays, and up to 1500 V for concentrated arrays [131]. These voltage levels are classified as hazardous by IEEE standards, as they are capable of delivering a fatal electric shock.

Isolating the array from the earth with an insulation coating significantly reduces the risk of electric shock to personnel, as all conductive surfaces are maintained at the same electrical potential, essentially floating with respect to the earth [132]. In the case of a floating platform, where the array is isolated from the earth by insulators, a person could still receive an electric shock if they touch a live conductor and simultaneously come into contact with a conductive structure that is grounded. The risk of shock is further increased in wet conditions if metal components are not bonded to the same equipotential level. This contrasts with an earthed array, where all conductive surfaces are bonded to the earthed system, which can raise the risk of electric shock in wet conditions due to a conductor-to-earth fault. To mitigate this risk, bonding should be implemented with equipotential bonding conductors that connect all metallic conductive elements to the same electrical potential [133].

Protection devices and circuit breakers

Protection devices and circuit breakers play a crucial role in any electrical system, acting as safeguards to prevent damage caused by overcurrent, earth faults, lightning, and other potential electrical hazards [134]. Although the terms "protection device" and "circuit breaker" are often used interchangeably, there is a subtle distinction between the two. A protection device refers to any component used to interrupt or divert electrical current during over-voltage, over-current, or short-circuit conditions, thereby protecting the circuit from future damage. In contrast, a circuit breaker is a specific type of switch designed to protect an electrical circuit. When a protection device detects an overcurrent, short-circuit, or similar fault, the circuit breaker automatically disconnects the faulty circuit. It can be reset and re-engaged once the fault has been corrected, a key feature that ensures continuous operation and maintainability of the system. An electrical circuit that is stranded or disabled can significantly impact productivity [135].

CASE STUDIES AND APPLICATIONS

In recent years, FPVs have gained popularity for their ability to address land limitations and enhance energy efficiency by reducing water evaporation. The following subsections highlight several case studies and applications of FPV technology.

China – Huainan Coal Mine

The Huainan Coal Mine in China provides an example of FPV system application. Situated in Huainan City, Anhui Province, which is known for its vast coal reserves and extensive mining operations, the region faces serious environmental impacts such as air and water pollution, land degradation, and greenhouse gas emissions. To mitigate these effects, the Huainan Coal Mining Group has implemented a large-scale FPV system on an artificial lake created during the coal mining process [136].

The FPV system at the Huainan Coal Mine in China comprises over 166,000 solar panels spread across 400 hectares (approximately 1,000 acres). These floating solar panels are mounted on plastic floats and anchored to the lakebed with steel cables. In 2020, the system generated nearly 180 million kWh of electricity, reducing carbon dioxide emissions by approximately 184,000 tons and powering 115,000 urban and rural households. Completed in 2018, it is currently the world's largest floating solar power plant.

This FPV system offers several advantages over traditional land-based solar PV systems. First, the floating panels help reduce water evaporation from the lake, which is vital in a region facing water scarcity. Second, by utilizing the existing infrastructure – such as the artificial lake and the coal mine's electricity grid connection – the project minimizes both costs and environmental impact. Finally, the system's efficiency is enhanced by the cooling effect of the water, which lowers the operating temperature of the panels and improves their energy conversion efficiency. Furthermore, the Huainan FPV system has garnered recognition for its environmental and social benefits. It reduces carbon dioxide emissions by 18,000 tons annually and has contributed to the improvement of water quality in the lake. Additionally, the project has created job opportunities for local residents, and the electricity generated is sold at a lower price to nearby communities, providing affordable and clean energy.

This project serves as a prime example of how FPVs can be applied in the mining industry. It demonstrates the potential for floating solar panels to generate clean energy while mitigating the environmental impacts of mining operations. The success of this project has also set a precedent for similar initiatives in other coal mining regions around the world.

India – Omkareshwar Reservoir

The Omkareshwar Reservoir FPV project is another example of how FPVs can generate clean energy, conserve water resources, and foster sustainable development in India [137]. The success of this project has paved the way for additional FPV installations across the country, including a planned 100 MW project at the Rihand Reservoir in Uttar Pradesh. Additionally, as part of its National Solar Mission, the Indian government has set an ambitious target of installing 10 GW of FPV capacity by 2022, further advancing solar energy adoption.

The Omkareshwar FPV project has proven both efficient and cost-effective. Completed at an estimated cost of INR 31 crore ($4.1 million), the project is expected to generate 1.8 million units of electricity annually, offsetting around 1,400 tonnes of carbon dioxide emissions each year. The plant offers several key benefits: it helps conserve water resources by reducing evaporation from the reservoir, potentially saving up to 1.3 million litres of water per day; it produces clean energy that powers nearby villages and towns, reducing dependence on fossil fuels and enhancing energy security; and its floating platform minimizes land use, providing a flexible and scalable solution for future expansion.

In 2018, the Madhya Pradesh Urja Vikas Nigam (MPUVN) commissioned a 1.4 MW floating solar plant on the Omkareshwar Reservoir, featuring 4,000 solar panels installed on a floating platform, as illustrated. Developed by the Renewable Energy Service Company (RESCO), this installation is one of the largest FPV projects in India. The Omkareshwar Reservoir, located on the Narmada River in Madhya Pradesh, serves multiple purposes, including irrigation, power generation, and drinking water supply.

CONCLUSIONS

Floating photovoltaic systems present a promising, sustainable energy solution with the potential to significantly expand renewable energy capacity. This study has identified key factors that enhance FPV technology's efficiency and cost-effectiveness while acknowledging the challenges that must be addressed for successful implementation. The following key findings summarize the results of this study:

1. FPV systems benefit from the natural cooling effect of water, improving efficiency by up to 12% compared to traditional land-based photovoltaic systems.
2. FPV systems play a key role in reducing water evaporation, which is crucial in water-scarce areas. For instance, the Omkareshwar Reservoir FPV system conserves up to 1.3 million liters of water daily.
3. Case studies such as the Huainan Coal Mine FPV system show that FPVs can mitigate environmental impacts, reducing carbon dioxide emissions by approximately 184,000 tons annually and powering 115,000 households.
4. The challenges of designing FPV systems to withstand harsh marine and freshwater conditions are highlighted. Stability under wave and wind conditions requires advanced anchoring techniques and materials like glass-fiber-reinforced plastic and compliant modular designs.
5. Advanced materials and corrosion-resistant coatings are essential for the durability of FPV platforms, particularly in marine environments, where corrosion can be a major issue.
6. FPV installations can reduce ecological disruptions by improving water quality and reducing the thermal impact on aquatic ecosystems. Careful site selection and environmental assessments are essential to minimizing any adverse effects on local ecosystems.
7. FPV systems are expected to achieve grid parity by 2030, positioning them as competitive with land-based PV systems.

FPV systems offer a promising pathway to expanding renewable energy capacity while addressing key challenges like land scarcity and water conservation. Continued innovation and collaboration across sectors are essential to overcoming the remaining technical and environmental hurdles FPV systems are poised to play a crucial role in the global transition toward sustainable energy and climate change mitigation.

REFERENCES

1. A. Azzuni, A. Aghahosseini, M. Ram, D. Bogdanov, U. Caldera, C. Breyer, Energy Security Analysis for a 100% Renewable Energy Transition in Jordan by 2050, Sustainability 12 (2020) 4921. https://doi.org/10.3390/su12124921.
2. A. Alahmer, S. Ajib, Solar cooling technologies: State of art and perspectives, Energy Convers. Manag. 214 (2020) 112896. https://doi.org/10.1016/j.enconman.2020.112896.
3. M.M. Hasan, S. Hossain, M. Mofijur, Z. Kabir, I.A. Badruddin, T.M. Yunus Khan, E. Jassim, Harnessing Solar Power: A Review of Photovoltaic Innovations, Solar Thermal Systems, and the Dawn of Energy Storage Solutions, Energies 16 (2023). https://doi.org/10.3390/en16186456.
4. A. Alahmer, S. Alsaqoor, Energy efficient of Using Chilled Water System for Sustainable Health Care Facility Operating by Solar Photovoltaic Technology, Energy Procedia 156 (2019) 65–71.
5. M. Alanazi, H. Attar, A. Amer, A. Amjad, M. Mohamed, M.S. Majid, K. Yahya, M. Salem, A Comprehensive Study on the Performance of Various Tracker Systems in Hybrid Renewable Energy Systems, Saudi Arabia, Sustainability 15 (2023) 10626.
6. S. Alsaqoor, A. Alqatamin, A. Alahmer, Z. Nan, Y. Al-Husban, H. Jouhara, The impact of phase change material on photovoltaic thermal (PVT) systems: A numerical study, Int. J. Thermofluids 18 (2023) 100365.
7. S. Mallak, M. Kanan, S. Alsadi, G. Sabbah, S. Zahran, H. Attar, A. Hamdan, Predicting the behavior of solar energy in tulkarm city using Markov chains and fuzzy Markov chains, Appl. Math. Inf. Sci. 17 (2023) 285–292.
8. I.B. Turner, C.M. Pansino, M.J.S. de Lemos, Land–Energy–Food Nexus: Competition and societal impact of land use for sustainable energy and food production – A review, J. Energy Resour. Technol. 145 (2023) 110802. https://doi.org/10.1115/1.4062507.
9. Y. Jin, S. Hu, A.D. Ziegler, L. Gibson, J.E. Campbell, R. Xu, D. Chen, K. Zhu, Y. Zheng, B. Ye, F. Ye, Z. Zeng, Energy production and water savings from floating solar photovoltaics on global reservoirs, Nat. Sustain. 6 (2023) 865–874. https://doi.org/10.1038/s41893-023-01089-6.
10. A. Amer, H. Attar, S. As'ad, S. Alsaqoor, I. Colak, A. Alahmer, M. Alali, G. Borowski, M. Hmada, A. Solyman, Floating photovoltaics: assessing the potential, advantages, and challenges of harnessing solar energy on water bodies, J. Ecol. Eng. 24 (2023) 324–339. https://doi.org/10.12911/22998993/170917.
11. R. C.J., K.H. Lim, J.C. Kurnia, S. Roy, B.J. Bora, B.J. Medhi, Towards sustainable power generation: Recent advancements in floating photovoltaic technologies, Renew. Sustain. Energy Rev. 194 (2024)

114322. https://doi.org/https://doi.org/10.1016/j.rser.2024.114322.

12. Y. Lian, Q. Chen, S. Shen, J. Zheng, W. Chen, S.C. Yim, Numerical Study on the Dynamic Response of Mooring Systems for an Offshore Floating Photovoltaic Platform, (2024). https://doi.org/10.1115/OMAE2024-120796.
13. F. Wu, K. Zhang, X. Cheng, J. Wang, C. Xie, J. Yu, Y. Gu, Analysis of Hydrodynamic Performance and Mooring Dynamic Response of Offshore Dual-Module Floating Photovoltaic Platform, (2024). https://doi.org/10.1115/OMAE2024-125502.
14. Y. Tang, X. Chen, G. Huang, M. Chen, K. Zhang, Y. Jiang, T. Li, T. Tao, Y. Yang, Dynamic analysis of multi-module floating photovoltaic platforms with composite mooring system by considering tidal variation and platform configuration, Ocean Eng. 312 (2024) 119243. https://doi.org/https://doi.org/10.1016/j.oceaneng.2024.119243.
15. Y. Tang, M. Chen, Y. Jiang, T. Li, K. Zhang, H. Zhou, Hydrodynamic and Dynamic Analysis of a Multi-Module Semi-Submersible Photovoltaic Platform Considering Tidal Variation, (2024). https://doi.org/10.1115/OMAE2024-124385.
16. A. Djalab, Z. Djalab, A. El Hammoumi, G. Marco TINA, S. Motahhir, A.A. Laouid, A comprehensive Review of Floating Photovoltaic Systems: Tech Advances, Marine Environmental Influences on Offshore PV Systems, and Economic Feasibility Analysis, Sol. Energy 277 (2024) 112711. https://doi.org/https://doi.org/10.1016/j.solener.2024.112711.
17. H. Cao, J. Du, S. Zhao, D. Zhang, A. Chang, Analysis of nonlinear hydrodynamic properties of shallow-draft floating photovoltaic structure, (2024). https://doi.org/10.1115/OMAE2024-127917.
18. T. Trzepieciński, T. Batu, F. Kibrete, H.G. Lemu, Application of composite materials for energy generation devices, J. Compos. Sci. 7 (2023) 55. https://doi.org/10.3390/jcs7020055.
19. F. Gavin Surjadi, F.P. Bakti, C. Jin, P.K.P. Simamora, Global Response Performance of HDPE Based Offshore Floating Solar Farm by Using Beam-Floater Model, (2024). https://doi.org/10.1115/OMAE2024-126115.
20. S. Benjamins, B. Williamson, S.-L. Billing, Z. Yuan, M. Collu, C. Fox, L. Hobbs, E.A. Masden, E.J. Cottier-Cook, B. Wilson, Potential environmental impacts of floating solar photovoltaic systems, Renew. Sustain. Energy Rev. 199 (2024) 114463. https://doi.org/https://doi.org/10.1016/j.rser.2024.114463.
21. C. Veliathur Chinnasamy Srinivasan, P.K. Soori, F.A. Ghaith, Techno-Economic Feasibility of the Use of Floating Solar PV Systems in Oil Platforms, Sustainability 16 (2024) 1039. https://doi.org/10.3390/su16031039.
22. M.A. Koondhar, L. Albasha, I. Mahariq, B.B. Graba, E. Touti, Reviewing floating photovoltaic (FPV) technology for solar energy generation, Energy Strateg. Rev. 54 (2024) 101449. https://doi.org/https://doi.org/10.1016/j.esr.2024.101449.
23. K. Ilgen, D. Schindler, S. Wieland, J. Lange, The impact of floating photovoltaic power plants on lake water temperature and stratification, Sci. Rep. 13 (2023) 7932. https://doi.org/10.1038/s41598-023-34751-2.
24. S.A. Chowdhury, National Solar Energy Roadmap, 2021–2041, Sustain. Renew. Energy Dev. Auth. (SREDA). Retrieved July 11 (2020) 2021.
25. K.K. Agrawal, S.K. Jha, R.K. Mittal, S. Vashishtha, Assessment of floating solar PV (FSPV) potential and water conservation: Case study on Rajghat Dam in Uttar Pradesh, India, Energy Sustain. Dev. 66 (2022) 287–295. https://doi.org/https://doi.org/10.1016/j.esd.2021.12.007.
26. S. Sulaeman, E. Brown, R. Quispe-Abad, N. Müller, Floating PV system as an alternative pathway to the amazon dam underproduction, Renew. Sustain. Energy Rev. 135 (2021) 110082. https://doi.org/https://doi.org/10.1016/j.rser.2020.110082.
27. M. Elshafei, A. Ibrahim, A. Helmy, M. Abdallah, A. Eldeib, M. Badawy, S. AbdelRazek, Study of Massive Floating Solar Panels over Lake Nasser, J. Energy 2021 (2021) 6674091. https://doi.org/https://doi.org/10.1155/2021/6674091.
28. T.K. Adrianti, M. Nasir, P. Anugrah, A 48-MW floating photovoltaic design and integration to a grid, Indones. J. Electr. Eng. Comput. Sci. 30 (2023) 1331–1338. https://doi.org/10.11591/ijeecs.v30.i3.pp1331-1338.
29. N. Beithou, M.A. Mansour, N. Abdellatif, S. Alsaqoor, S. Tarawneh, A.H. Jaber, A. Andruszkiewicz, M. Alsqour, G. Borowski, A. Alahmer, J. Siderska, Effect of the Residential Photovoltaic Systems Evolution on Electricity and Thermal Energy Usage in Jordan, Adv. Sci. Technol. Res. J. 17 (2023) 79–87. https://doi.org/10.12913/22998624/163257.
30. G. Lorenzini, M. Kamarposhti, A. Solyman, Maximum power point tracking in the photovoltaic module using incremental conductance algorithm with variable step length, J. Eur. Des Systèmes Autom. 54 (2021) 395–402. https://doi.org/10.18280/jesa.540302.
31. S. Al-Dahidi, B. Rinchi, M. Alrbai, A. Alahmer, Enhancing daily energy prediction in solar photovoltaic systems: weighted k-nearest neighbors with Pearson correlation integration. In: 12th Int. Conf. Intell. Syst., IEEE (2024) 1–6.
32. I.T. Ali, K. Yahya, M. Aldababsa, A. Amer, M. Hafez, R.D. Sarreb, Optimum-location of PV in distribution system using NR method with Matlab-ETap program. In: 2nd Int. Eng. Conf. Electr. Energy, Artif. Intell., (2023) 1–5. https://doi.org/10.1109/EICEEAI60672.2023.10590581.

33. I.T. Ali, A.E.M. Yahya, A. Amer, R.D. Sarreb, K. Yahya, M. Aldababsa, M. Hafez, Optimizing PV system placement in Kirkuk City power system using PSO algorithm. In: 2nd Int. Eng. Conf. Electr. Energy, Artif. Intell. (2023) 1–5. https://doi.org/10.1109/EICEEAI60672.2023.10590146.
34. A. Saxena, E. Cuce, D. Bandhu Singh, P. Mert Cuce, P. Gupta, A. Suryavanshi, M. Farrokhi, A.A. El-Sebaii, A thermodynamic review on solar ponds, Sol. Energy 242 (2022) 335–363. https://doi.org/https://doi.org/10.1016/j.solener.2022.07.016.
35. M. Kumar, H. Mohammed Niyaz, R. Gupta, Challenges and opportunities towards the development of floating photovoltaic systems, Sol. Energy Mater. Sol. Cells 233 (2021) 111408. https://doi.org/https://doi.org/10.1016/j.solmat.2021.111408.
36. F. Ali, A. Etemad-Shahidi, R.A. Stewart, M.J. Sanjari, J.A. Hayward, R.C. Nicholson, Co-located offshore wind and floating solar farms: A systematic quantitative literature review of site selection criteria, Renew. Energy Focus 50 (2024) 100611. https://doi.org/https://doi.org/10.1016/j.ref.2024.100611.
37. T.I. Ingo, L. Gyoh, Y. Sheng, M.K. Kaymak, A.D. Şahin, H.M. Pouran, Accelerating the Low-Carbon Energy Transition in Sub-Saharan Africa through Floating Photovoltaic Solar Farms, Atmosphere (Basel). 15 (2024) 653. https://doi.org/10.3390/atmos15060653.
38. H.M. Pouran, M. Padilha Campos Lopes, T. Nogueira, D. Alves Castelo Branco, Y. Sheng, Environmental and technical impacts of floating photovoltaic plants as an emerging clean energy technology, IScience 25 (2022) 105253. https://doi.org/10.1016/j.isci.2022.105253.
39. H. Meschede, P. Bertheau, S. Khalili, C. Breyer, A review of 100% renewable energy scenarios on islands, WIREs Energy Environ. 11 (2022) e450. https://doi.org/https://doi.org/10.1002/wene.450.
40. A.B. Melek, S. Gökmener, E. Haspolat, D.D. Çiçek, M. Deveci, E. Oğuz, M. Khorasanchi, Fuzzy Einstein-based decision-making model for the evaluation of site selection criteria of floating photovoltaic system, Ocean Eng. 301 (2024) 117521. https://doi.org/https://doi.org/10.1016/j.oceaneng.2024.117521.
41. F. Karipoğlu, K. Koca, E. İlbahar, Convenient Site Selection of a Floating PV Power Plant in Türkiye by using GIS-Fuzzy Analytical Hierarchy Process, Environ. Sci. Pollut. Res. 31 (2024) 23193–23210. https://doi.org/10.1007/s11356-024-32470-3.
42. A. Garrod, S. Neda Hussain, A. Ghosh, S. Nahata, C. Wynne, S. Paver, An assessment of floating photovoltaic systems and energy storage methods: A comprehensive review, Results Eng. 21 (2024) 101940. https://doi.org/https://doi.org/10.1016/j.rineng.2024.101940.
43. I.F. Herlambang, S. Lestari, T. Yuniarti, Optimizing Solar Potential: Site Potential Selection for Floating Photovoltaics in the Sepaku Semoi Dam Reservoir, IOP Conf. Ser. Earth Environ. Sci. 1343 (2024) 12022. https://doi.org/10.1088/1755-1315/1343/1/012022.
44. J. Chen, R.B. Gilbert, Calibration of Load and Resistance Factors of API RP 2A-LRFD, for Fixed Offshore Platforms, J. Struct. Eng. 147 (2021) 4020339. https://doi.org/10.1061/(ASCE)ST.1943-541X.000291.
45. C. Ng, R. Jiang, Classification principles for very large floating structures. In WCFS2019: Proceedings of the World Conference on Floating Solutions, in: C.M. Wang, S.H. Lim, Z.Y. Tay (Eds.), Springer Singapore, Singapore, 2020: pp. 235–251.
46. P. Tulet, B. Aunay, G. Barruol, C. Barthe, R. Belon, S. Bielli, F. Bonnardot, O. Bousquet, J.-P. Cammas, J. Cattiaux, F. Chauvin, I. Fontaine, F.R. Fontaine, F. Gabarrot, S. Garabedian, A. Gonzalez, J.-L. Join, F. Jouvenot, D. Nortes-Martinez, D. Mékiès, P. Mouquet, G. Payen, G. Pennober, J. Pianezze, C. Rault, C. Revillion, E.J. Rindraharisaona, K. Samyn, C. Thompson, H. Vérèmes, ReNovRisk: a multidisciplinary programme to study the cyclonic risks in the South-West Indian Ocean, Nat. Hazards 107 (2021) 1191–1223. https://doi.org/10.1007/s11069-021-04624-w.
47. O.S. Martin, Wind Resource Estimation and Conceptual Design of a Near Future Wind Turbine for Tropical Cyclone Winds, The Florida State University, 2022.
48. A. Sen, S. Karmakar, OSH risk perception of safety managers and scope for ergonomics design interventions in floating solar photovoltaic projects BT - ergonomics for design and innovation. In: D. Chakrabarti, S. Karmakar, U.R. Salve (Eds.), Springer International Publishing, Cham, 2022: pp. 871–880.
49. J. Charles Rajesh Kumar, M.A. Majid, Floating solar photovoltaic plants in India – A rapid transition to a green energy market and sustainable future, Energy Environ. 34 (2021) 304–358. https://doi.org/10.1177/0958305X211057185.
50. R. Claus, M. López, A methodology to assess the dynamic response and the structural performance of floating photovoltaic systems, Sol. Energy 262 (2023) 111826. https://doi.org/https://doi.org/10.1016/j.solener.2023.111826.
51. W. Shi, C. Yan, Z. Ren, Z. Yuan, Y. Liu, S. Zheng, X. Li, X. Han, Review on the development of marine floating photovoltaic systems, Ocean Eng. 286 (2023) 115560. https://doi.org/https://doi.org/10.1016/j.oceaneng.2023.115560.
52. K. Lee, B. Park, B.W. Kim, A Study on the Floating Body Performance and Mooring System Design of an Offshore Floating Solar System with Glass Fiber Reinforced Polymer Frame Members, J. Korean Sol. Energy Soc. 44 (2024) 73–90. https://doi.

org/10.7836/kses.2024.44.2.073.

53. J. Jin, L. Zhang, Z. Lin, J. Kong, Z. Gao, Optimization of Offshore FPV Modules in Early Design Phase, ASME 2024 43rd Int. Conf. Ocean. Offshore Arct. Eng. June 9–14, 2024 Singapore. 7 (2024) V007T09A090. https://doi.org/10.1115/OMAE2024-121546.
54. R. Claus, M. López, Key issues in the design of floating photovoltaic structures for the marine environment, Renew. Sustain. Energy Rev. 164 (2022) 112502. https://doi.org/https://doi.org/10.1016/j.rser.2022.112502.
55. R.M. Ghoniem, A. Alahmer, H. Rezk, S. As'ad, Optimal design and sizing of hybrid photovoltaic/fuel cell electrical power system, Sustainability 15 (2023) 12026. https://doi.org/10.3390/su151512026.
56. M. Fereshtehpour, R. Javidi Sabbaghian, A. Farrokhi, E.B. Jovein, E. Ebrahimi Sarindizaj, Evaluation of factors governing the use of floating solar system: A study on Iran's important water infrastructures, Renew. Energy 171 (2021) 1171–1187. https://doi.org/https://doi.org/10.1016/j.renene.2020.12.005.
57. J. Zhou, B. Liang, G. Wang, J. Jing, D. Li, W. Huang, Standardization proposal and product design of offshore floating photovoltaic system cables, J. Phys. Conf. Ser. 2592 (2023) 12041. https://doi.org/10.1088/1742-6596/2592/1/012041.
58. L. Alhmoud, Why Does the PV Solar Power Plant Operate Ineffectively?, Energies 16 (2023) 4074. https://doi.org/10.3390/en16104074.
59. Z.M. Mahdi, A.N. Al-Shamani, A. Al-Manea, H.A. Al-zurfi, R. Al-Rbaihat, K. Sopian, A. Alahmer, Enhancing photovoltaic thermal (PVT) performance with hybrid solar collector using phase change material, porous media, and nanofluid, Sol. Energy 283 (2024) 112983. https://doi.org/https://doi.org/10.1016/j.solener.2024.112983.
60. R.O. Yakubu, D.A. Quansah, L.D. Mensah, W. Ahiataku-Togobo, P. Acheampong, M.S. Adaramola, Comparison of ground-based and floating solar photovoltaic systems performance based on monofacial and bifacial modules in Ghana, Energy Nexus 12 (2023) 100245. https://doi.org/https://doi.org/10.1016/j.nexus.2023.100245.
61. E.C. Edwards, A. Holcombe, S. Brown, E. Ransley, M. Hann, D. Greaves, Evolution of floating offshore wind platforms: A review of at-sea devices, Renew. Sustain. Energy Rev. 183 (2023) 113416. https://doi.org/https://doi.org/10.1016/j.rser.2023.113416.
62. A. Badhoutiya, Advancements in PV technology floating photovoltaics. In: 5th Int. Conf. Smart Syst. Inven. Technol. (2023) 382–385. https://doi.org/10.1109/ICSSIT55814.2023.10060971.
63. U.A. Ünlükuş, Economic feasiblity of floating solar pv and land-based solar pv in Northern Cyprus, (2023).
64. P. Rosa-Clot, Chapter 9 - FPV and Environmental Compatibility, in: M. Rosa-Clot, G.B.T.-F.P.V.P. Marco Tina (Eds.), Academic Press, 2020: pp. 101–118. https://doi.org/https://doi.org/10.1016/B978-0-12-817061-8.00009-9.
65. J. Du, D. Zhang, Y. Zhang, K. Xu, A. Chang, S. Zhao, Design and comparative analysis of alternative mooring systems for offshore floating photovoltaics arrays in ultra-shallow water with significant tidal range, Ocean Eng. 302 (2024) 117649. https://doi.org/https://doi.org/10.1016/j.oceaneng.2024.117649.
66. M.R.A. Refaai, L. Dhanesh, B.P. Ganthia, M. Mohanty, R. Subbiah, E.M. Anbese, design and implementation of a floating PV model to analyse the power generation, Int. J. Photoenergy 2022 (2022) 3891881. https://doi.org/https://doi.org/10.1155/2022/3891881.
67. G. Huang, Y. Tang, X. Chen, M. Chen, Y. Jiang, A comprehensive review of floating solar plants and potentials for offshore applications, J. Mar. Sci. Eng. 11 (2023) 2064. https://doi.org/10.3390/jmse11112064.
68. R. Hendarti, J. Linggarjati, J.C. Kurnia, R. Arkan Hanan H, Influence of humidity on the performance of floating photovoltaic systems over ponds in a tropical urban environment. In: IOP Conf. Ser. Earth Environ. Sci. 1375 (2024) 12015. https://doi.org/10.1088/1755-1315/1375/1/012015.
69. C. Zhang, J. Dai, K.K. Ang, H.V. Lim, Development of compliant modular floating photovoltaic farm for coastal conditions, Renew. Sustain. Energy Rev. 190 (2024) 114084. https://doi.org/https://doi.org/10.1016/j.rser.2023.114084.
70. S. Bossi, L. Blasi, G. Cupertino, R. Dell'Erba, A. Cipollini, S. De Vito, M. Santoro, G. Di Francia, G.M. Tina, Floating Photovoltaic Plant Monitoring: A Review of Requirements and Feasible Technologies, Sustainability 16 (2024) 8367. https://doi.org/10.3390/su16198367.
71. D. Friel, M. Karimirad, T. Whittaker, W.J. Doran, E. Howlin, A review of floating photovoltaic design concepts and installed variations. In: 4th Int. Conf. Offshore Renew. Energy. CORE2019 Proceedings, Glas. ASRANet Ltd, UK, 30 Aug 2019, ASRANet Ltd, 2019.
72. A.E. Cagle, A. Armstrong, G. Exley, S.M. Grodsky, J. Macknick, J. Sherwin, R.R. Hernandez, The Land Sparing, Water Surface Use Efficiency, and Water Surface Transformation of Floating Photovoltaic Solar Energy Installations, Sustainability 12 (2020) 8154. https://doi.org/10.3390/su12198154.
73. R.F. Ananda, R. Budiarto, I.E. Prabowo, Preliminary design of floating photovoltaic at the logung dam. In: Int. Conf. Technol. Policy Energy Electr. Power (2022) 289–294. https://doi.org/10.1109/ICT-PEP57242.2022.9988940.

74. T.H. Kwon, J. Kim, E. Kim, S.-K. Hong, Effect on power generation of floating photovoltaic power system power by water level change, J. Korean Sol. Energy Soc. 42 (2022) 13–21. https://doi.org/10.7836/kses.2022.42.2.013.
75. T. Karpouzoglou, B. Vlaswinkel, J. van der Molen, Effects of large-scale floating (solar photovoltaic) platforms on hydrodynamics and primary production in a coastal sea from a water column model, Ocean Sci. 16 (2020) 195–208. https://doi.org/10.5194/os-16-195-2020.
76. J. Song, H. Imani, J. Yue, S. Yang, Hydrodynamic Characteristics of Floating Photovoltaic Systems under Ocean Loads, J. Mar. Sci. Eng. 11 (2023) 1813. https://doi.org/10.3390/jmse11091813.
77. G.-H. Lee, J.-W. Choi, J.-H. Seo, H. Ha, Comparative study of effect of wind and wave load on floating PV: Computational simulation and design method, J. Korean Soc. Manuf. Process Eng. 18 (2019) 9–17. https://doi.org/10.14775/ksmpe.2019.18.11.009.
78. M.R. Gomaa, M. Al-Dhaifallah, A. Alahmer, H. Rezk, Design, modeling, and experimental investigation of active water cooling concentrating photovoltaic system, Sustainability 12 (2020) 5392.
79. J. Manuel Longares, A. García-Jiménez, N. García-Polanco, Multiphysics simulation of bifacial photovoltaic modules and software comparison, Sol. Energy 257 (2023) 155–163. https://doi.org/https://doi.org/10.1016/j.solener.2023.04.005.
80. C. Yan, W. Shi, X. Han, X. Li, A.S. Verma, Assessing the dynamic behavior of multiconnected offshore floating photovoltaic systems under combined wave-wind loads: A comprehensive numerical analysis, Sustain. Horizons 8 (2023) 100072. https://doi.org/https://doi.org/10.1016/j.horiz.2023.100072.
81. L. Huang, Energy Fluctuation of Floating Photovoltaic Solar Panel due to Wave-Induced Motions, (2024). https://doi.org/10.1115/OMAE2024-123989.
82. A. Alcañiz, N. Monaco, O. Isabella, H. Ziar, Offshore floating PV–DC and AC yield analysis considering wave effects, Energy Convers. Manag. 300 (2024) 117897. https://doi.org/https://doi.org/10.1016/j.enconman.2023.117897.
83. R. Nobre, S. Boulêtreau, F. Colas, F. Azemar, L. Tudesque, N. Parthuisot, P. Favriou, J. Cucherousset, Potential ecological impacts of floating photovoltaics on lake biodiversity and ecosystem functioning, Renew. Sustain. Energy Rev. 188 (2023) 113852. https://doi.org/https://doi.org/10.1016/j.rser.2023.113852.
84. G. Exley, R.R. Hernandez, T. Page, M. Chipps, S. Gambro, M. Hersey, R. Lake, K.-S. Zoannou, A. Armstrong, Scientific and stakeholder evidence-based assessment: Ecosystem response to floating solar photovoltaics and implications for sustainability, Renew. Sustain. Energy Rev. 152 (2021) 111639. https://doi.org/https://doi.org/10.1016/j.rser.2021.111639.
85. Z. Liu, C. Ma, X. Li, Z. Deng, Z. Tian, Aquatic environment impacts of floating photovoltaic and implications for climate change challenges, J. Environ. Manage. 346 (2023) 118851. https://doi.org/https://doi.org/10.1016/j.jenvman.2023.118851.
86. A.S. Makhija, S.S. Bohra, Performance and degradation analysis for different solar photovoltaic technologies under hot and humid environment: a review, Prog. Energy 5 (2023) 42002. https://doi.org/10.1088/2516-1083/acfc92.
87. L. Xiong, C. Le, P. Zhang, H. Ding, J. Li, Harnessing the power of floating photovoltaic: A global review, J. Renew. Sustain. Energy 15 (2023) 052701. https://doi.org/10.1063/5.0159394.
88. S. Wu, N. Jiang, S. Zhang, P. Zhang, P. Zhao, Y. Liu, Y. Wang, Discussion on the development of offshore floating photovoltaic plants, emphasizing marine environmental protection, Front. Mar. Sci. 11 (2024) 1336783. https://doi.org/10.3389/fmars.2024.1336783.
89. C. Deyá, P.S. Carrizo, Corrosion on Ancient Metals BT - Reverse Engineering of Ancient Metals, in: P.S. Carrizo (Ed.), Springer International Publishing, Cham, 2021: pp. 123–146. https://doi.org/10.1007/978-3-030-72842-7_7.
90. T.W. Quadri, E.D. Akpan, L.O. Olasunkanmi, O.E. Fayemi, E.E. Ebenso, 2 - Fundamentals of corrosion chemistry. In: C.M. Hussain, C. Verma, J.B.T.-E.S.C.I. Aslam (Eds.), Elsevier, 2022: pp. 25–45. https://doi.org/https://doi.org/10.1016/B978-0-323-85405-4.00019-7.
91. C.-K. Liu, Z.-R. Kong, M.-J. Kao, T.-C. Wu, A Novel Accelerated Corrosion Test for Supporting Devices in a Floating Photovoltaic System, Appl. Sci. 11 (2021) 3308. https://doi.org/10.3390/app11083308.
92. T. Kim, B.T. Nguyen, V. Minassian, C.-T. Lin, Paints and coatings monitored by laser-induced breakdown spectroscopy, J. Coatings Technol. Res. 4 (2007) 241–253. https://doi.org/10.1007/s11998-007-9029-9.
93. K. Bijapur, V. Molahalli, A. Shetty, A. Toghan, P. De Padova, G. Hegde, Recent Trends and Progress in Corrosion Inhibitors and Electrochemical Evaluation, Appl. Sci. 13 (2023) 10107. https://doi.org/10.3390/app131810107.
94. A.K. Hussain, N. Seetharamaiah, M. Pichumani, C.S. Chakra, Research progress in organic zinc rich primer coatings for cathodic protection of metals – A comprehensive review, Prog. Org. Coatings 153 (2021) 106040. https://doi.org/https://doi.org/10.1016/j.porgcoat.2020.106040.
95. Galvanizers Association. Galvanised coating, (n.d.) 2024. https://galvanizing.org.uk/hot-dip-galvanizing/galvanised-coating/ (accessed November 25, 2024).

96. EonCoat. "What Is Metal Galvanization and What Are the Dangers?" EonCoat, (2024). https://eoncoat.com/what-is-metal-galvanization-and-what-are-the-dangers/ (accessed November 25, 2024).
97. P. Subudhi, D. Punetha, Progress, challenges, and perspectives on polymer substrates for emerging flexible solar cells: A holistic panoramic review, Prog. Photovoltaics Res. Appl. 31 (2023) 753–789. https://doi.org/https://doi.org/10.1002/pip.3703.
98. H. Zhu, J. Li, Advancements in corrosion protection for aerospace aluminum alloys through surface treatment, Int. J. Electrochem. Sci. 19 (2024) 100487. https://doi.org/https://doi.org/10.1016/j.ijoes.2024.100487.
99. L. Xu, Y. Xin, L. Ma, H. Zhang, Z. Lin, X. Li, Challenges and solutions of cathodic protection for marine ships, Corros. Commun. 2 (2021) 33–40. https://doi.org/https://doi.org/10.1016/j.corcom.2021.08.003.
100. S. Szabo, I. Bakos, Cathodic protection with sacrificial anodes, Corros. Rev. 24 (2006) 231–280. https://doi.org/10.1515/CORRREV.2006.24.3-4.231.
101. S.J. Price, R.B. Figueira, Corrosion protection systems and fatigue corrosion in offshore wind structures: current status and future perspectives. Coatings 7 (2017) 25. https://doi.org/10.3390/coatings7020025.
102. Z. Fang, J. Cao, Y. Guan, Electrochemical protection and design BT – corrosion control technologies for aluminum alloy vessel. In: Z. Fang, J. Cao, Y. Guan (Eds.), Springer Singapore, Singapore, 2020: pp. 231–289. https://doi.org/10.1007/978-981-15-1932-1_6.
103. D. Clematis, A. Marroccu, M. Panizza, A. Barbucci, A critical analysis on the current design criteria for cathodic protection of ships and superyachts, Materials (Basel). 15 (2022) 2645. https://doi.org/10.3390/ma15072645.
104. R. Baxter, J. Britton, Deep-water, Offshore cathodic protection 101, (2007). https://stoprust.com/technical-library-items/cp-101/ (accessed November 25, 2024).
105. F. Merahi, T. Brihmouche, Modeling, Sizing and Simulation of an Impressed Current Cathodic Protection System Powered by Photovoltaic Source. In: 2nd Int. Conf. Electr. Eng. Autom. Control, IEEE (2024) 1–6.
106. G.S. Adly, W.R. Anis, I.M. Hafez, Design of photovoltaic powered cathodic protection system, Int. J. Sci. Technol. 6 (2017) 246–253.
107. W. Oh, S.-I. Chan, Corrosion mitigation of photovoltaic ribbon using a sacrificial anode, J. Korea Acad. Coop. Soc. 18 (2017) 681–686. https://doi.org/10.5762/KAIS.2017.18.3.681.
108. J.-H. Kim, J. Park, D. Kim, N. Park, Study on Mitigation Method of Solder Corrosion for Crystalline Silicon Photovoltaic Modules, Int. J. Photoenergy 2014 (2014) 809075. https://doi.org/https://doi.org/10.1155/2014/809075.
109. A.O.M. Maka, T.N. Chaudhary, G. Alaswad, O. Elsayah, Applications of solar photovoltaics in powering cathodic protection systems: a review, Clean Technol. Environ. Policy 26 (2024) 2755–2776. https://doi.org/10.1007/s10098-024-02750-0.
110. K.D. Khudoyorov, Automatic control of photovoltaic cathodic protection system used for various metals, Appl. Sol. Energy 58 (2022) 244–249. https://doi.org/10.3103/S0003701X22020098.
111. Himoya Corrosion Technology. Galvanic/Sacrificial Anode Cathodic Protection System, (2024). https://www.himoyacorrosion.com/sacrificial-anode-cathodic-protection-system/ (accessed November 25, 2024).
112. J.E. Gray, B. Luan, Protective coatings on magnesium and its alloys – a critical review, J. Alloys Compd. 336 (2002) 88–113. https://doi.org/https://doi.org/10.1016/S0925-8388(01)01899-0.
113. N. Martin, A. Mohamed, Sacrificial Anodes and Environmental Effects. In: Evol. Manuf. Des. Oper. Pract. Resour. Environ. Sustain. (2024) 81–106. https://doi.org/https://doi.org/10.1002/9781394198221.ch7.
114. K.K. Maniam, S. Paul, Corrosion Performance of Electrodeposited Zinc and Zinc-Alloy Coatings in Marine Environment, Corros. Mater. Degrad. 2 (2021) 163–189. https://doi.org/10.3390/cmd2020010.
115. Y. Li, L. Wen, W. Guo, A guide to organic electroreduction using sacrificial anodes, Chem. Soc. Rev. 52 (2023) 1168–1188.
116. S. Al-Dahidi, M. Madhiarasan, L. Al-Ghussain, A.M. Abubaker, A.D. Ahmad, M. Alrbai, M. Aghaei, H. Alahmer, A. Alahmer, P. Baraldi, E. Zio, Forecasting Solar Photovoltaic Power Production: A Comprehensive Review and Innovative Data-Driven Modeling Framework, Energies 17 (2024). https://doi.org/10.3390/en17164145.
117. P.B. Raja, M.A. Assad, M. Ismail, Chapter 6 – Inhibitor-encapsulated smart nanocontainers for the controlled release of corrosion inhibitors, in: S. Rajendran, T.A.N.H. Nguyen, S. Kakooei, M. Yeganeh, Y.B.T.-C.P. at the N. Li (Eds.), Micro Nano Technol., Elsevier, 2020: pp. 91–105. https://doi.org/https://doi.org/10.1016/B978-0-12-819359-4.00006-4.
118. P. Wipataphan, J. Laohawattanajinda, T.N. Wichean, W. Sripianem, R. Techapiesancharoenkij, Photocathodic protection of amorphous and nanorod zinc oxide thin-film coatings on stainless steel AISI 304 fabricated by spray pyrolysis and hydrothermal technique, Mater. Chem. Phys. 291 (2022) 126714. https://doi.org/https://doi.org/10.1016/j.matchemphys.2022.126714.

119. N. Manoj Kumar, S. Chakraborty, S. Kumar Yadav, J. Singh, S.S. Chopra, Advancing simulation tools specific to floating solar photovoltaic systems – Comparative analysis of field-measured and simulated energy performance, Sustain. Energy Technol. Assessments 52 (2022) 102168. https://doi.org/https://doi.org/10.1016/j.seta.2022.102168.
120. M.K. Kaymak, A.D. Şahin, Problems encountered with floating photovoltaic systems under real conditions: A new FPV concept and novel solutions, Sustain. Energy Technol. Assessments 47 (2021) 101504. https://doi.org/https://doi.org/10.1016/j.seta.2021.101504.
121. R.B. Patil, A. Khalkar, S. Al-Dahidi, R.S. Pimpalkar, S. Bhandari, M. Pecht, A Reliability and Risk Assessment of Solar Photovoltaic Panels Using a Failure Mode and Effects Analysis Approach: A Case Study, Sustainability 16 (2024) 4183. https://doi.org/10.3390/su16104183.
122. A. Sen, A.S. Mohankar, A. Khamaj, S. Karmakar, Emerging OSH Issues in Installation and Maintenance of Floating Solar Photovoltaic Projects and Their Link with Sustainable Development Goals, Risk Manag. Healthc. Policy 14 (2021) 1939–1957. https://doi.org/10.2147/RMHP.S304732.
123. B. Erten, B. Oral, M.Z. Yakut, The role of virtual and augmented reality in occupational health and safety training of employees in PV power systems and evaluation with a sustainability perspective, J. Clean. Prod. 379 (2022) 134499. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.134499.
124. H. Wang, K. Wang, X. Liu, Y. Liu, Z. Qian, S. Ding, Evaluation of damage performance in offshore floating photovoltaics-based hydrogen production system due to potential hydrogen release, Front. Mar. Sci. 11 (2024) 1413678. https://doi.org/10.3389/fmars.2024.1413678.
125. J.T. Dellosa, E. V Palconit, N.H. Enano, Risk Assessment and Policy Recommendations for a Floating Solar Photovoltaic (FSPV) System, IEEE Access 12 (2024) 30452–30471. https://doi.org/10.1109/ACCESS.2024.3368620.
126. M. Aram, X. Zhang, D. Qi, Y. Ko, A state-of-the-art review of fire safety of photovoltaic systems in buildings, J. Clean. Prod. 308 (2021) 127239. https://doi.org/https://doi.org/10.1016/j.jclepro.2021.127239.
127. V. Piana, A. Kahl, C. Saviozzi, R. Schumann, Floating PV in mountain artificial lakes: a checklist for site assessment, Renew. Energy Environ. Sustain. 6 (2021) 4.
128. Y.-K. Wu, J.-H. Lin, H.-J. Lin, Standards and Guidelines for Grid-Connected Photovoltaic Generation Systems: A Review and Comparison, IEEE Trans. Ind. Appl. 53 (2017) 3205–3216. https://doi.org/10.1109/TIA.2017.2680409.
129. H.L. Floyd, M. Valdes, Leveraging prevention through design principles (PtD) in electrical installations. In: IEEE IAS Electr. Saf. Work. (2020) 1–10. https://doi.org/10.1109/ESW42757.2020.9188318.
130. R. Rebelo, L. Fialho, M.H. Novais, Floating photovoltaic systems: photovoltaic cable submersion testing and potential impacts, Open Res. Eur. 3 (2024) 61. https://doi.org/10.12688/openreseurope.15122.2.
131. Y. Chu, P. Meisen, Review and comparison of different solar energy technologies, Glob. Energy Netw. Inst. (GENI), San Diego, CA 1 (2011) 1–52.
132. P.M. Mircea, Electrical Safety in LV Energy Installations BT - Energy Transition Holistic Impact Challenge (ETHIC): A New Environmental and Climatic Era, in: G.C. Lazaroiu, M. Roscia, V.S. Dancu (Eds.), Springer Nature Switzerland, Cham, 2024: pp. 401–440. https://doi.org/10.1007/978-3-031-55448-3_16.
133. S. Zhao, Y.M. Low, C.D. Rodríguez-Gallegos, T. Reindl, Potential root causes for failures in floating PV systems. In: Int. Conf. Offshore Mech. Arct. Eng., American Society of Mechanical Engineers (2023) V008T09A012.
134. L. Hewitson, M. Brown, R. Balakrishnan, Practical power system protection, Elsevier, 2004.
135. N.-H. Nguyen, B.-C. Le, L.-N. Nguyen, T.-T. Bui, Technical analysis of the large capacity grid-connected floating photovoltaic system on the hydropower reservoir, Energies 16 (2023) 3780. https://doi.org/10.3390/en16093780.
136. Y. Bei, B. Yuan, Z. Wang, J. Tang, Floating photovoltaic for the coal mining subsidence water area – an effective way to reduce evaporation. In: 5th Int. Conf. Energy, Electr. Power Eng. (2022) 1126–1130. https://doi.org/10.1109/CEEPE55110.2022.9783259.
137. D. Misra, Floating photovoltaic plant in india: current status and future prospect BT – advances in thermal engineering, manufacturing, and production management. In: S.K. Ghosh, K. Ghosh, S. Das, P.K. Dan, A. Kundu (Eds.), Springer Singapore, Singapore, 2021: pp. 219–232.