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POWERING THE TRANSITION TO CLEAN ENERGY WITH FLOATING PHOTOVOLTAIC SYSTEMS

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Abstract - Floating photovoltaic (FPV) systems have gained significant attention and popularity in recent years. It possesses several distinct advantages over its traditional land-based counterparts, and it is poised for exponential growth soon. Hence, to contribute to the rapid developments in FPV systems, this article critically reviews and presents the latest state of knowledge in FPV's technologies, applications, and outlook. This article also discusses the present standards for FPV project designs, learnings from past installations, and its sustainability aspects, including its end-of-life management and carbon footprint. Overall, while scholars and the industry are cognizant of the need for more research and development to accelerate FPV deployment, they should also channel their efforts and resources to developing industry standards and focus on enabling FPV systems to participate in the circular economy.

Keywords: Clean energy; Floating photovoltaics; installations; waste management.

1. INTRODUCTION

With the advancements in technology, the dependence on energy sources has also been increasing at a rapid pace. The BP Statistical Review of 2021 shows that consumption of primary energy sources has increased worldwide at the rate of 1.6% per annum from 2008 to 2018, although it had shown a decline of 4.5% in 2020 due to COVID-19 [1]. Non-renewable energy sources such as coal and petroleum are depleting at an alarming rate and are proving unsuitable for future sustainability. It is due to their long regeneration time and adverse effects of environmental pollution, such as carbon emissions and release of Chlorofluorocarbons (CFCs) during production and usage [2], which raised concerns at national and global levels. Thus, renewable energy sources like Solar, Wind, Thermal, Biomass, and Hydro are gaining a lot of attention due to their advantages over non-renewable sources in paving a sustainable way for harnessing energy. According to the same review, renewables' contribution to electricity generation grew from 10.3 % to 11.7 %, the largest growth rate for any source in 2020[1]. A research article[3] published in 2021, taking into account reports till 2019, predicted that the contribution of fossil fuels to electric energy production would go down from 64.8% to 41.1%, while the Renewable energy source contribution might rise from 25.1 to 51.0% and the FPV contribution would reach around 1.9% in 2030. PV+FPV installations are projected to increase their energy generation capacity to 6980 TWh by 2030, which is the highest compared to Hydro and wind at 4950 TWh and 4730 TWh, respectively.

Along with being environmentally friendly, solar energy also possess noise-free characteristics. PV systems are devices that use solar energy to produce electricity via the photoelectric effect, where electrons are emitted from the material's surface when photons from light hit the surface, transmitting their energy [4]. With many developments in the deployment of solar PV modules that have been aided by government incentives and financing schemes worldwide, solar energy harnessed with PV modules has shown considerable socio-economic benefits, including the security of energy supply, possibilities for significant creation of jobs, support for restructuring in energy markets worldwide due to reduced reliance on fossil fuel imports as well as acceleration for rural electrification in remote/isolated places[5]. Evidently, at the end of 2018, global PV installation capacity exceeded 500 GW[6], and by 2020, solar energy capacity rose to 127GW, occupying a 27% share within the renewable energy sector [1].

Good efficiency, modularity, and simplicity are considered desirable characteristics in a PV system[4]. The major drawback concerning land-based PV solar is the drifting effect, i.e., efficiency reduction caused when solar panel temperatures rise, requiring the constant need to reduce the panel temperature. As a result, solar cells with a temperature coefficient of 2.1%~5.0% showed a photoelectric efficiency drop of 2.9~9.0% [7]. The other disadvantage involves large stretches of land to harness electricity due to low PV panel efficiency (typically 15%), which equals 1 MWp power station requiring at least 10,000 m2 of land[3]. This is significantly large compared to coal which requires 2023 m2 for 1MW installation [8] (1MWp equals 4000 ~ 5000 KWh to power up to 164 homes as per US standards, and 2023 m2 equals the land requirement of 833 car parking spaces). Lower efficiency corresponds to longer time or larger land area requirements to harness the same amount of energy, leading to extra operating costs.

FPV requires less time and resources for implementation and integration within communities: The well-developed PV and hydro-power technology reduces time and resources in developing FPV. They require very little land compared to land-based PV; thus, it does not compete with agricultural, industrial, or residential land. As water bodies like lakes and ponds are present close to most human habitats thus cost for installation and transportation is reduced. The installation of a typical FPV plant is simpler than land-mounted solar PV plants. Floating platforms are made in the form of modular interconnected floats. Once completed, the entire platform is towed to the exact location with the help of boats [9]. No ground leveling or civil work is required to prepare the site; the grid infrastructure is readily available due to its proximity to living areas and existing reservoirs/dams.

According to a study in 2018 by Farfan, J., and Breyer, C [10], the worldwide reservoirs span about 265.7 thousand km2 and have the capacity to host 4400 GW of floating photovoltaic, while FPV power plants at 25% reservoir surface coverage can generate around 6270 TWh of energy. Another study by Tina et al. in 2014 also approximated that 25% of the electrical energy demand throughout the world can be supplied by covering just 1% of natural basin surfaces with FPV panels [11]. Several projects have been presented that couple the FPV to activities related to fish or shrimp farms [12], mainly in China and in Southeast Asia, thus supporting people and businesses that depend on fisheries and sericulture. A 320 MW facility in China's Zhejiang province is estimated to produce 352 million kWh per year, providing yearly revenue of $45 million from generated power, while annual fisheries income reaches almost $5 million.[13] Such deployments are seen especially where large-scale FPV projects are deployed, like in Singapore, China and Taiwan.

FPV also facilitates increasing efficiency output: A typical PV module turns 4–18% of incoming solar energy into electricity, depending on the kind of solar cells, its working condition, and the climatic parameters. The remaining solar energy is converted into heat, considerably raising the temperature of the PV. This produced heat is lowered by the flowing water or passing wind beneath the panels. A report by Fesharaki et al.[14] studied the effect of temperature on the efficiency of photovoltaic modules in cloudy climates. They showed that when the temperature rises, the efficiency of the PV module decreases. Thus, the efficiency of a PV module can be improved by lowering the temperature with the cooling effect provided by water, which is possible in FPV Installations with water beneath the panels.

In a study published in 2014, [15] water was sprayed over the solar cells to accomplish this effect. A solenoid valve and a microcontroller unit are used to detect the temperature of the PV cell. If the temperature reaches a specific threshold, water is sprayed over the cells automatically. The study found the power of the solar cells is boosted when water is sprayed on them. Taking this argument further, by considering the case of FPV, Azmi and group [16] showed that FPV's average PV temperature is lower than that of a standard PV module, allowing it to produce more electricity, therefore FPV has better efficiency and overall power gain than that of a traditional PV module.

In conclusion, even if the costs of FPV installations are much like for the land-based solar PV plant, the electricity generation is greater in FPV owing to good tracking and cooling effects, which can increase the annual electricity production significantly. In the FPV plants in Pisa and Suvereto, these two effects have been measured, and experimental findings confirmed the possibility of gaining up to 30% in energy[17]. Also, in a study by Rosa-Clot and team [18], three sites in South Australia which were investigated showed quantitative energy improvements could increase annual energy production by up to 10%. In the Bifacial PV modules (Solar radiation captured from both above and below the solar panel), this is not the case as studies show that efficiency is reduced in FPV compared to land-based because of the albedo effect (measures the amount of solar irradiance reflected from the ground and received by the PV module). In water albedo effect is low, this effect is not seen in Monofacial PV modules where FPV installations surpass rooftop installation significantly [18]

Water conservation and quality of water improvement are also possible with FPV: FPV reduces the water evaporation in the reservoir, where water is better managed in arid and semi-arid regions [19]. The same study by the Rosa-Clot team also demonstrated each MWp installed saved a considerable amount of water that would otherwise be wasted due to evaporation, demonstrating quantifiable improvements in energy yield and water saving. [17]. Projects in India demonstrated similar results - A 1 MW floating plant in Kota barrage, 37 million liters of water were saved, generating 18,38,519 kWh of electricity per year and approximately reducing 1,714 tonnes of CO2 emissions per year. Another 1 MW floating plant in Kishore Sagar Lake generated 18,58,959 kWh of electrical energy annually, saving 37 million liters of water and preventing 1,733 tons of CO2 emissions yearly [20]. A different case study in Jodhpur, India, in 2014 estimates that 1MW FPV could save 191.174 million liters of water from being evaporated annually. [21].

In African hydropower reservoirs, the overall FPV potential is estimated to be 2922 GWp. A 1% FPV cover saves up to 743 mcm of water annually and generates an additional 171 GWh. In Kenya, a 1% cover doubles existing capacity and boosts power production by 58% [22]. It was stated that the possibility of using the existing transmission infrastructure is arguably the most significant benefit for the floating PV plants that will be installed in hydropower plant reservoirs in Brazil[23]. Along with water saving, algae production in the water bodies is reduced with FPV, thus reducing the degradation of water bodies[18], [24], although studies on these effects are limited.

In reservoir-based hydropower facilities [HEEP], FPV power plants improve hydropower output by increasing water availability. A reservoir-based hydropower facilities PV power plant in India showed that the FPV system had a positive impact on the environment by saving 42,731.56 m3 of water annually [25]. Along with reduced water loss from evaporation, FPV systems integrated with Hydro-power reservoirs facilitate electricity generation for the communities. According to a study in 2018 [10], about 74 billion m3 of water was saved from evaporation, by an estimated 6.3 percent and contributed an estimated 142.5 TWh of power production. A full-scale prototype of the FPV was constructed in Agost in 2009 above an irrigation water reservoir (Alicante, Spain). The electricity-generating plant has a nominal capacity of 300 KWh, resulting in the yearly renewable energy output of 425,000 kWh per year. In 2012, 1458 PV panels supported by 750 pontoons filled the reservoir, covering 4490 m2 of water surface. Water was conserved. The water saved by covering the reservoir exceeds 5000 m3 per year, or 25% of its storage capacity[19].

An interesting forward notion to these drawbacks would be shifting these PV panels to the waterbed, tackling the major issues simultaneously. Solar panels on water bodies are becoming a feasible solution in localities with limited land resources. FPV is a technology where solar PV modules are floated on a water body resulting in the conservation of land resources and maximized utilization of the earth's water surface. This review provides a comprehensive understanding of the different aspects involved in FPV technology. Apart from answering how digital technologies are integrated within the framework to enhance productivity, end-of-life (EOL) analysis has also been studied. This provides a complete understanding of how the FPV technology can be addressed, especially in its assessment as a clean, renewable source of energy for sustainability in the long run.

2. ENGINEERING DESIGN FOR FPV

Components of FPV include solar PV modules, Inverters, and Floating platforms, apart from power conversion and grid infrastructure, as shown in Fig 1. In many ways, the technical design of "above water" FPV plants is like that of ground mounted FPV plants. However, the difference lies in the floating structures, anchoring, and mooring mechanisms. FPV systems can be classified on their generation capacity as Small Scale (a few kW outputs), Medium Scale (kW to MW output), and High Scale (MW to GW output). Based on the structure design, they can be further divided into a Fixed floating structure, where the structure is fixed in its place with anchoring and mooring, and a Floating-Tracking structure, where sensors tilt the structure throughout the day based on the position of the sun. The described divisions are shown in table 1.

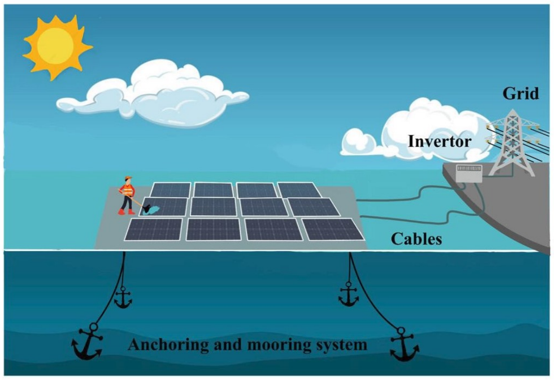
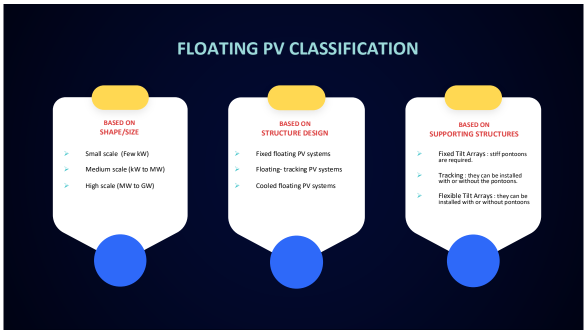


Fig. 1. Structural components in Floating solar PV

Table. 1. Classifications of FPV are shown in the diagram below



FLOATING PV CLASSIFICATION

BASED ON
SHAPE/SIZE

- Small scale (Few kW)
- Medium scale (kW to MW)
- High scale (MW to GW)

BASED ON
STRUCTURE DESIGN

- Fixed floating PV systems
- Floating- tracking PV systems
- Cooled floating PV systems

BASED ON
SUPPORTING STRUCTURES

- Fixed Tilt Arrays : stiff pontoons are required.
- Tracking : they can be installed with or without the pontoons.
- Flexible Tilt Arrays : they can be installed with or without pontoons

For FPV Installation to sustain, they should withstand nature (a combination of elements such as sun, wind, waves, animals, snow, saline water, algae, and fungus). The technology must work for the designed lifetime of the project (up to 30 years). Being relatively new, with no FPV installation having completed its 25-year tenure, the operating conditions and risk cannot be fully assessed due to the lack of studies done throughout the lifetime of FPV. However, simulation studies have been carried out.

2.1. Solar PV modules

The primary component of the FPV plant is solar PV modules. Like typical PV projects, for the FPV project's installation, general poly / monocrystalline or thin-film solar panels and, more recently, Bifacial/glass on glass modules are used. Monocrystalline PV is the most commonly preferred since it has the best efficiency in the PV modules used on land due to its low-temperature coefficient, as stated in several studies[25]–[27]. Bifacial modules are utilized for higher power density and less humidity effect, but they hold the risk of developing micro-cracks. For FPV Thin film technology, the most efficient energy extraction method available has been proven to be in FPV systems[7]. The choice of FPV module technology is also influenced by factors such as space available, cost, relative humidity, waterbody type, etc.

2.2. Inverters

As in a traditional solar plant, DC electricity generated by solar PV modules is routed to the inverter via a series of combiner boxes before being converted to AC power. It is similar to FPV. Here, inverters are placed on a floating platform or on land to generate power from solar panels depending on their size and distance from the coast. The Project developer responsible for the smooth interworking of engineering, procurement, and construction teams can authorize several string inverters or a single/central inverter depending on the project goals and requirements. Both types have merits and limitations depending on locality and end goal and should be chosen carefully.

2.3. Floating Structure

It is the most essential part of FPV, as it supports all the components for the plant like solar PV, cabling, etc. for the project's lifetime. This makes it essential to have proper materials for the floating structure/platform. The main elements for judging the merits of different FPV Floating structure materials are their robustness, simplicity in assembling and launching, the possibility for mooring to adapt to local conditions, minimum environmental impact, and resistance to water contamination [28]. The most common material utilized in most FPV power plants is HDPE (High-Density Polyethene). Other materials used for the floating platform include FRP (Fibre reinforced polymers), medium-density polyethylene (MDPE), and Ferro-cement. There are different designs for floating structures, some of which are discussed below.

2.3.1. Pure Floats Design

It employs a specifically constructed float that can directly hold PV panels. The entire system is built in a modular way and may be joined together with pins or bolts to form a huge structural platform. Typically, each unit of such a system includes primary and secondary floats; the goal of the secondary float is to create a pathway for maintenance and increased buoyancy of the system, whereas the primary float carries the main structure of the PV panel. Pure Floats Design has the most installations overall with several hundreds of MWp (Megawatt Peak) generated between 2016 to 2018. This system has been implemented worldwide, mostly in China and Southeast Asia. The main advantage of this design is its low cost, but there exist some safety concerns regarding its functioning, like short-circuiting and fire outbreaks when there are fluctuations in the water level [29].

2.3.2. Pontoon + metal structures design

Another common design employed by some project developers combines a metal framework like a land-based system with pontoons to give buoyancy to the system, thus obviating the need for specially designed floats. The major benefit of this design is that it is easier to build floats and thus can be locally manufactured. This technology offers other advantages like increased cooling effect due to elevated structure, which allows free flow of wind and water waves to cool the panels. Like in a ground-mounted system, shared anchoring systems with a smaller number of connections directly with the floater and large block sizes are possible as each floater can accommodate 8 to 10 PV panels and can be customized as per the size of the panel (by increasing the length of the pipes). However, such a design is difficult to access for operation and maintenance. Apart from this, it is slightly expensive and difficult to produce near project sites due to the involvement of extrusion technology in fabrication. [30]

2.3.3. Membrane Module Design

The solar panels are mounted on a circular hydro elastic membrane that floats like those used in the fish farming industry. Direct contact between PV modules and the membrane surface enables heat transmission of PV to the lower temperature of water through the membrane surface [31]. This is because water as a medium has higher thermal conductivity than air (λwater = 0.6 W/mK, λair = 0.026 W/mK) this helps to cool the PV modules faster when the water temperature is lower. Since one surface is in closer contact with the water in this design, the water temperature and flow play a crucial role in temperature reduction. However, on the whole, even when the water temperatures are higher than the air, the panel showed higher efficiency in contact with water as the temperatures of the panels are better reduced when in contact with water than air [31], [32].

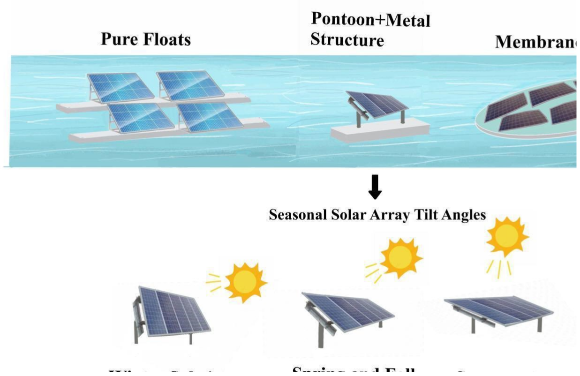


Fig. 2. Classification of FPV modules based on supporting structure and tilt angles of the panels.

2.4. Anchoring and mooring system

The floating platform is held in place by the anchoring and mooring system. It provides the necessary mechanical stability during the operation of the FPV plant. The floating platform's design is site-specific and will be determined by the water body's intended use, soil characteristics of the reservoir bed, wind forces, and other environmental factors [29]. A suitable design requires achieving the correct balance between mooring lines, i.e., it should not be held too tight nor too loose while limiting the lateral movement and rotation of the floating systems and guaranteeing that the system can tolerate variations in water level [33]. The construction can range from basic shore anchoring, which is common in smaller water bodies, to very sophisticated anchors that are used for reservoirs with huge variations in water level.

Floating systems are commonly attached to the site's bottom and/or the basin edge [34]. To place the anchors firmly to the shore, civil work is required for bank anchoring. Wire rope, galvanized steel wires, chains, synthetic fiber rope, elastic rubber hawsers, and other materials are commonly used for these mooring lines. Soil tests need to be done to choose between gravity and cement anchors. For base anchoring, dead weights, like concrete blocks, helical anchors are screwed and piled to the earth. To obtain the desired mooring performance, various line types, sizes, and configurations are used.

Anchoring and mooring systems are critical in the plants' success or failure. This is seen in the Japanese Yamakura incident, where a 13.7 MW Floating solar project caught fire in a typhoon carrying winds of 120mph in September 2019 due to bad anchoring and mooring systems [35]. In some cases, wind and tide may cause anchoring or mooring points to be damaged, this causes the platform to drift and clash with one another. When mooring points fail, the wind might flip the platform and remove the peripheral rows. These incidents can have disastrous consequences such as damage to the entire facility, in rare circumstances, causing a fire. Thus, the anchoring system should have high redundancy so that the loss of a single mooring line does not result in the failure of the remaining lines. The float supplier usually evaluates and specifies the wind-load endurance of the anchoring by working with project designers and engineers to determine the drag forces generated by the floating structures.

Wind force being the most common source of failure, it is often impacted by the mooring solution hence having enough data on the tensile strength of the lugs and a mooring attachment design that transmits the loads in the correct way is highly important for long-term serviceability [36], [37].

Because the energy gain relies on the type and accuracy of the alignment of the PV cells to the direction of highest irradiance, a tracking system seeks to maximize the yearly PV energy. The tracking system for a floating platform must account for not only the lack of a stable foundation but also the disruptions caused by the floating condition.
Alternatively, PV modules can be deployed as semi-submerged and underwater PV, offshore FPV in the sea, or can be integrated with other power plants called Hybrid plants.

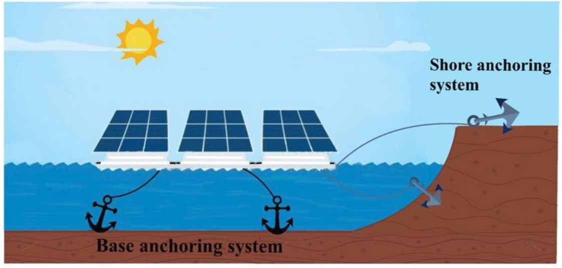


Fig. 3. Base and Shore anchoring systems in FPV

Some of the parameter consideration and their impacts while designing the FPV projects has been detailed in the

Table 2.

Key specifications	Findings and its Impact
Installation should be able to withstand Mother Nature. The combination of sun, wind, waves, animals especially birds, snow, saline water, algae, and fungus are elements, the technology must sustain up to the designed life of 25-30 years.	Biodiversity
Study of the bathymetry survey report, Hydrodynamic study for waves and currents in the locality of installation.	Selection criteria of mooring and anchoring, recommendation for the right location, caring for reservoir beds and embankments
Feasibility study based on 100 years' weather history of the location in addition to the above-mentioned studies .	History of any century storms and seasonal variations of water levels
Quality of floating structure used (Higher strength and minimum thickness, UV and anti-corrosive additives, and highest resistance of float anchoring points), Flexibility of structure (fatigue tolerance)	Life of floaters, minimum links to reduce the anchoring points
Percentage of the surface/water body covered to minimize environmental impact	Biodiversity
Type of anchoring possible (onshore VS bottom)	Maximum depth, highest wind speed and wave height
Minimum distance between blocks / islands (3 times of the maximum depth as a thumb rule)	Crisscross effect and cable lengths / cable bridges between each block and to the bank
Buoyancy calculations (workers, invertors, cables, String Boxes)	safety and O&M (operation & maintenance)
Electrical equipment (insulation, corrosion)	IP 67 protection for String Inverters & SCBs, canopy / shade & cable sleeves
Safety for working in installation and O&M (safe and easy access to all components)	Maintenance walkways with sufficient buoyancy to carry the tools and equipment for O&M activity
cost of the cables, distance to the shore and cable routing design and safety of cable terminations, and design of cable bridges to avoid submerging in the water	Marine grade cables for DC connections / protection of cables with non-corrosive metal sleeves, cable bridges for large size AC cables
Good grounding and lightning arrestors system design from an electrical safety point of view	Perfect sizing and selection of grounding and Lightning Arrestors as the FPV deals with water
Tilt angle calculations to design the system handle the wind loads vs cooling of the panels vs cost of anchoring and mooring system.	right balance of tilt angle in consideration of shading effect and wind forces to decide Mooring / anchoring system cost for the optimum LCOE
Orientation of the PV panels (Landscape / Portrait) depending on the project location	EAST to WEST or NORTH to SOUTH for higher yield and to check the possibility of minimum DC cable lengths with portrait mode
Maximum and minimum water levels (seasonal variation like summer and monsoon season)	anchoring and mooring cost
Maximum depth, highest wind speed, under current water flow rate, wave heights to design the suitable anchoring and mooring systems	Safety and anchoring cost
Shading effect analysis to decide the optimum gap (pitch) between each row of the panels	Yield / Generation of the plant
FPV structure suppliers should have experience in handling hurricane Category 2 storms with no known failures, any failure in high wind speed conditions should be explained and countermeasures must be made to ensure higher factor of safety and lessons learned	Now a days, century storms are occurring once in a decade or even less than a decade.

Apart from these, there are a few technical considerations for bankable FPV installations, which include:

- Raw materials must be approved for use in drinking water conditions per local government regulations. The raw material must be virgin (no reprocessed or recycled material may be used) and compounded (A homogeneous mixture of the base polymer and additives i.e., antioxidants, pigments, carbon black, UV- Stabilizers). The materials should be subjected to life testing following ISO12162:2009 (for pipe-type floaters extruded) [14], and the HDPE samples should be subjected to UV testing following ISO 4892-3:2016(E) Method A cycle no.1 for 3,000 hours, for tensile strength according to ISO 527-2:2012 plastics for determination of tensile properties. To ensure life expectancy (as per expectations and adding buoyancy support if the water line is more than 50%), the float material should also meet fire safety criteria and fire hazard tests according to IEC 60692-2 -11 - Glow-wire flammability test technique for end-products (GWEPT).

- Buoyancy loads should be considered for the overall stability and the complete installation of the floating structure. It must be able to float on a water body with a draught of 30-50 percent of the flotation body itself, which means providing weight when the water line is less than 30 percent (too high buoyancy to avoid system tip over) and increasing buoyancy support when the water line is greater than 50 percent. The external impact can often cause floater body damage, structural loss, buoyancy loss, and the system sinking. To avoid these, it should be made essential to fill floater bodies with Styrofoam (polystyrene) or expanded polyethylene. Within the entire system, a proper fire-safe compartment should also be made accessible.
- A wind tunnel test, as well as a CFD simulation, should be performed to assess overall system stability [37], [38]. To assure the structural stability of the design, the simulation must incorporate a variety of parameters such as wind speeds, current flows, and wave analyses. The provider of the FPV structure must demonstrate a proven correlation between CFD modelling and real wind tunnel testing. Wind speed studies and CFD should be performed from 0-180 degrees since winds and gusts can change direction extremely fast in a storm, affecting anchoring and mooring loads and causing early failures. Ciel & Terre, for example, work with CFD study experts/wind tunnels like ONERA – The French Aerospace Lab to define the wind effects and test full-scale experiments, similarly for anti-bird systems working with AGRILASER to provide protection to FPV plants from birds.

The most crucial part of floating solar design is the connection points; at all anchoring places, the minimum needed break strength must be ensured. Furthermore, if the system includes extra connection points, all connections must fulfill the same standards. In mass manufacturing, the break strength must be confirmed using extensive SPC (Statistical Process Control) research using random samples. These standards must be met for the designs to function properly. There have been several reports of micro-cracks on the panel caused by the difference in coefficient of expansion between the panel and the floater worldwide. This problem can be effectively controlled using an intermediary metallic framework. To prevent micro-cracking, the module can be supported by metal racking; nevertheless, such a module does not enable direct contact/fastening with the plastic.

3. FPV INSTALLATIONS WORLDWIDE

The FPV technology, which was initially developed to reduce land use and reliance on non-renewable resources in agricultural areas, witnessed significant expansion in terms of installations in the last decade. The FPV industry progressed from a small-scale niche market business, developed in 2007 by a group of researchers from the National Institute of Advanced Science and Technology in Japan (with only a capacity of 20 kWh) [39] to worldwide installations for electricity today involving Japan, UK, USA, Italy, Spain, France, South Korea, Singapore, etc totaling 60 countries[13]. Between 2007 and 2013, Trapani, K. and Redón Santafé, M, identified 19 floating photovoltaic systems with a total installed capacity of 3581.5 kWp [39]. At the same time, Kim et al.[34] drew attention to Korea's advancements in FPV, as they documented five research installations and eight commercial installations in Korea between 2009 and 2010. Later in 2016 Sahu, A., Yadav, N., and Sudhakar, K.[40] documented a total of 10 additional installations, which raised the total capacity of FPV to 26.45 MWp. Mittal et al.[20] documented 5 small FPV structures in India in 2017 and a feasibility study for a 1 MW FPV project in India- Kota in 2017. Two of Brazil's first floating solar pilot projects were reported by Galdino et al.[23] in 2017.

Due to phenomenal growth in the sector, it is hard to document all the small FPV projects in recent times. China currently has the largest FPV plant of 320 MW in China's Shandong province, which was completed in 2022 in 2 phases. The 1st phase, which was completed in 2021, was of 200 MW installation, and an additional 120 MW installation was completed in 2022. This broke the record of the largest FPV installation of a 150 MW capacity plant in Anhui province in China, which, when completed in 2017, was the largest plant until the 320 MW FPV plant opened in 2022.

India aimed to construct a 600 MW FPV plant in Khandwa district on the omkareshwar dam near Narmada River, and the project is said to be completed in 2022-2023. When completed, it would be the largest FPV installation. Currently, India's largest FPV installation is in Andhra Pradesh, with a capacity of 25 MW in Simhadri.

Laos plans to build a 240 MW FPV project on its Nam Theun 2 hydropower station, which, when completed in 2022-23, could be the second largest FPV installation with an area covering 3.2 km2, which would have 11 times more energy production compared to the countries combined solar power production capacity.

The world's biggest inland solar farm has a capacity of 60 MWp whose development started in 2016 and was opened in Singapore on 14th July 2021 on Tengeh Reservoir. This FPV will produce enough electricity to run its five-water treatment plants and covers an area of around 45 football fields on the reservoir. This project would provide carbon savings equivalent to removing 7,000 cars [41]. A 145 MW FPV power project is installed on the reservoir of the current hydropower station in Carita, Indonesia. The site provides electricity to 50,000 houses and cuts annual carbon emissions by up to 200,000 tonnes [42]. The project will be completed in Q4 of 2022.

South Korea had its 41 MW FPV plant operating from late 2021- Hapcheon Dam floating PV power plant. In 2022 a pilot project of a 2.1 GW FPV complex was announced in South Korea near the Saemangeum region called the Saemangeum floating solar energy project. Still, as of now, the project is delayed due to Covid restrictions.

Outside of Asia Netherlands is said to have the largest FPV project in Europe, with FPV installation on Andijk Reservoir in North Holland encompassing its 15 islands. Before this Netherlands had the largest European FPV installation country in Europe, with a 14.5 MWp capacity plant in 2019 in Zwolle.

Another FPV project began commercial operations at Statkraft's Banja reservoir in Albania, Norway, on the 2nd of June 2021, where Statkraft's 72-megawatt Banja hydropower project is located. The first unit, which consists of 1536 solar panels, has a 0.5 MWp installed capacity and covers over 4,000 square meters. The project is anticipated to enter its second phase by installing three floating units totaling 1.5 MWp extra capacity. Furthermore, 160 identical panels have been installed on land for comparison and recording of the cooling process [43]–[45].

Japan presently has the most completed FPV projects of any country in the world (in 2017, Japan had 45 or a total of 70 FPV projects worldwide), although projects are typically smaller and, therefore, cumulative capacity is less. Indonesia, which is aiming for a 23 percent renewable energy share by 2025, will have a significant impact on FPV growth over the next five years. In 2020, Vietnam's FPV market grew by 150 percent yearly, indicating that the country's FPV business is booming [46].

4. OTHER RESEARCH-SCALE DEVELOPMENTs in FPV

4.1 Semi-submerged and Underwater PV

PV panels submerged in water have a few advantages. The possibility of this system was discussed in a 2017 paper by Clot, M. R., Rosa-Clot, P., & Tina, G. M.[47]. According to the paper, PV panels that are submerged underwater aid reduction in cleaning costs, reflection losses, and improved efficiency of the system.

A study of the cooling impact on temperature decline was done by Sheeba et al. in 2015 [43]. The greatest performance is seen at different depths and for varied water flow rates in an underwater environment. It showed a maximum efficiency of 21.6 % at a depth of 4 cm and 17.4% for a flow rate of 30 ml/sec at an optimum depth.

An article by Rosa-Clot et al. [48] shows non-submerged panels have an efficiency loss of more than 10% during their cleaning intervals. Still, no such efficiency loss was recorded between cleaning intervals (done monthly) in submerged PV modules. The reason being the temperature of submerged panels is spatially uniform and fluctuates very little during the day. This improves the efficiency because there is no discrepancy between various cell activities owing to non-uniform cell temperatures.

Both cooling and refractive properties of water greatly improve the energy harvesting of a PV panel submerged in water. Still, they are offset by the absorption of solar radiation by water. Because of the novelty of the concept, submerged plant systems have not been deployed yet, and most potential uses are in the development phase.

4.2 Offshore PV

The theory behind offshore PV power generation is to capture solar energy in oceans and seas utilizing the FPV system. Due to strong winds which cause harsher waves, FPV designs in offshore environments differ from those in ordinary lakes; thus, freshwater FPV insights cannot be easily transferred offshore. Insights from other marine energy infrastructures must be explored to explain how the marine ecosystem may influence photovoltaics [49], [50].

Additionally, wind-driven water wave heights are assessed to evaluate the offshore system's design and material selection compared to the usual FPV designs. The key technical obstacles with the offshore PV system include saltwater corrosion, wave heights, the necessity for an appropriate anchoring mechanism, and wave breakers.

Offshore PV is an attractive proposition for load centers since it lowers the requirement for long-distance power transfer from other areas [51]. This can shorten the time it takes from energy generation to consumption. The temperature at sea is substantially lower at the floating installation due to increased relative humidity and wind velocity.

In a 2020 publication [52], Golroodbari, and Sark, devised a method that takes into consideration the impacts of sea waves, wind speed, and relative humidity to model, simulate, and assess the results of a PV system on land and at sea. The results reveal that the relative yearly average production energy in the water is roughly 12% greater than on land. Only a few offshore FPV projects are under trial operation/construction/preparation. Studies for the plant performance and potential risks are yet to come up from installations deployed worldwide.

5.END OF LIFE CYCLE MANAGEMENT OF SOLAR PV

As a result of technological improvements and reduced manufacturing costs for the PV parallels, solar projects are being deployed worldwide at a faster rate. Solar power deployment will be paramount in countries aiming for net zero carbon emissions. Henbest et al. predict that to achieve net zero targets by the mid-century, the solar projects need to be deployed worldwide at more than half their present cumulative capacity every year until 2030 [53]. As the solar project's deployment cost is also showing a steep trend of cost reduction from their initial development, the PV’s cost of production reduced by up to 90% in the preceding decade [54]. The enormous growth in solar energy is predicted in the next decade thus also lies the enormous amount of waste that will be generated and could cause environmental impacts. The wastage is produced especially during the manufacture and disposal of PV panels. If not handled properly, the waste produced could have disastrous effects on the ecology. On the flip side, good management of resources during manufacture and better ways to dispose of waste by either reducing, reusing, or recycling the waste produced has positive effects on future availability and thus add to the continued production of Solar PV.

The International Renewable Energy Agency (IRENA) projected approximately 250,000 metric tons of solar panel trash globally at the end of 2016[55]. By 2034, yearly trash will be 70–80 times more than before 2020[59], and close to 75 million tons of PV-related waste by 2050[55]. One of the biggest concerns in the high influx of PV waste is the butterfly effect: technology improves yearly, ensuring improved efficiency, and the price drops for installing newer versions of PV panels encouraging companies to opt for the latest models of panels, eventually resulting in discarding solar panels before their life span of 30 years is completed. This would lead to more waste accumulation which is not accounted for in the IRENA report [56].

Developments in Land-based PV panels show that with an approximate lifetime of 30 years, they accumulate a huge stock of embodied raw materials which will not be recoverable for some time. Recovered raw materials can be reintroduced into the economy and utilized to manufacture new PV panels or other goods. It is expected that the total quantity of PV panels EOL will reach 9.57 million tonnes by 2050 [44]. An effective framework, as well as institutions, should be established to enable sustainable end-of-life (EOL) management plans for PV panels. The argument of keeping the life span and materials used for PV panels minimum since existing PV modules will eventually be replaced by newer technologies could aid in managing the EOL of PV panels. However, in the lack of enforceable standards, specific business models addressing the increase of PV waste and related value generation is difficult to assess. European Commission [57] has shown initiative to do research on the same.

EOL of PV panel systems has the capability to open new avenues for industry growth and provide job opportunities for a wide range of stakeholders that could potentially develop technologies in tapping the value of raw materials used. These developments help introduce new jobs and companies in the PV industry.

Most of the waste is generally produced throughout the four key life cycle periods of any PV panel. These are as follows: 1) panel manufacture, 2) panel transportation, 3) panel installation and usage, and 4) panel end-of-life disposal [58]. Previous studies have found that tiny fractures and failures account for 40% of PV panel failures [59]. This is the most prevalent cause for newer panels made after 2008 when thin cell panel production began.

5.1 Ways to tackle the PV waste management include

Reducing:

The most efficient method to enhance panel sustainability is by lowering the quantity of material needed. To save money, research should be conducted to reduce the number of hazardous chemicals as well as to reduce the amount of material used per panel. An example of this is seen when with increasing efficiency, thinner wafers, and diamond wire cutting, as well as bigger ingots, silicon cell material use has decreased considerably over the previous 16 years, from about 16 g/Wp to less than 3 g/Wp. If the trend continues, it could help the industry in the long run. Reducing materials and resources needed for the market is needed however, this cannot solve the immediate need for FPV's sustainable growth. A lot of research needs to be done to accomplish good efficiency with fewer materials, thus only following this process may not help tackle the immediate need of the hour.

Reusing:

Buyers can claim warranties for repair or replacement if faults and deficiencies are detected during the early stages of a PV panel's life. Insurance companies may also be called in to cover any or all the expenses of repair/replacement. Whenever a panel is replaced, quality tests to ensure electrical safety and power output – such as flash test characterization and a wet leakage test – can be performed to extract the use from these. Repaired PV panels may also be sold as spares or as secondhand modules at a selling price of roughly 70% of the initial selling price, thus catering to the circular economy within the FPV.

Recycling:

Most of the industry is looking forward to this approach to address the EOL of PV because it can be implemented quicker than the previous two approaches. Japan, Europe, and the US focus on research and development related to solar module recycling [58].

End-of-life PV panels are often recycled at existing recycling facilities which are less efficient and limited due to the system's capacity. Currently, recovery methods are mostly focused on improving systems processes, either in physical processes or chemical processes. The potential release of harmful substances and environmental effects of the extraction optimization process [60] are not being accounted for, as seen in the FRELP (Full Recovery End Life Photovoltaic) framework. Understanding the environmental consequences of collecting and processing these materials is also critical in facilitating the implementation of recycling infrastructure. There is still great scope for improvement, mainly in containing harmful chemicals recoveries like silicon which are responsible for high contamination of land and water.

Currently, PV waste is relatively low, reducing the incentive to build specialized PV panel recycling operations. Higher pricing to buy new panels will encourage the economics toward recycling activities and stimulate investment in more efficient mining techniques, like the extraction of metals used in electronics. In the long term, establishing a specialized PV plant may boost capacity while increasing income due to higher output quality.

The creation of PV-specific collection and recycling laws will become critical in the future. To support the establishment, more data and analysis are required. Regular reporting and monitoring of PV panel waste systems, including volumes produced by nation and technology; waste stream composition; and other features of PV waste management, should be included in the data. More data on the whole spectrum of value creation, including socioeconomic advantages, will also aid in promoting end-of-life care. In a study published in Jan 2020[61], PV electronic waste rules, including PV-specific collection, recovery, and recycling objectives, are pioneered by the EU. The EU's Waste of Electrical and Electronic Equipment (WEEE) Directive requires all PV panel manufacturers serving the EU market to cover the expenses of collecting and recycling EOL PV panels in Europe.

Apart from just PV panel disposal, major concerns in PV panel waste categorization adhere to waste classification's core principles - Material properties, solubility, flammability, and toxicity are all factors to consider. The goal is to determine if a product damages the environment or human health during its life cycle management. Materials leaking into water, harmful matter entering the soil, and human exposure to toxicity are all considered major risks. Although solar panels are disposed of on regular sites, it is not advisable because the modules can degrade, and harmful chemicals can leach into the ground, causing drinking water contamination [62].

Despite extensive study into photovoltaic technology, nothing is known about how EOL PV modules can be managed on a large scale, and even so little research is done concerning FPV. There have been no assessments of the present state of worldwide performance in managing PV modules after the end of their useful life. A review published in 2019[63] quantitatively measured where the research on EOL management for PV systems is in terms of geographical location, scale, and kind of treatments, the trend of studies on a worldwide scale, the developing research direction, and the gaps. The study drew conclusions from 70 articles examining the impacts of EOL on PV modules and the then existing 5 review articles on EOL of PV systems between 1981 to 2018. The findings from this study highlight the global landscape of research on dismantled PV panels, including treatment, policy, and management, PV waste generation projections, life cycle analysis, and reverse logistics. The review highlights that most of the existing studies are focused on the collection and recycling of PV panels. At the same time, still, many countries have yet to attempt to predict their solar-panel waste and establish recycling facilities. The study further states significant challenges in developing and scaling up current PV recycling technologies, such as lowering gas emissions and temperature during delamination, selecting an appropriate mixing ratio for the etching process, reducing chemicals and chemical waste production, and achieving a high level of purification.

Developing a universal monitoring system that systematically monitors the amount of PV waste and treatments on different scales could potentially aid decision-makers, investors, and businesses develop more reliable solutions and management strategies.

Additional challenges concerning FPV EOL include the potential ecological problem caused in the water body and disturbances caused to birds. FPV has a major issue of extensive use of plastic on the surface and the danger of electric shocks caused by the cabling systems or release of toxic chemicals from the PV module or its components when not properly disposed of after its usage. No detailed study has been done on these effects up until now, and many companies handle these issues with the site and project in mind. Since many FPV plants have been set up in the past few years, there is still time for them to reach their EOL, but down the lane in 5 to 10 years, the EOL of FPV might become a bigger problem.

5.2 Carbon Footprint in Solar PV electricity generation vs other sources of energy

It was thought that solar energy had a hidden carbon footprint during its manufacturing and processing. A metric to assess this is the energy returned on invested or EROI. In a study [58], the EROI for common power facilities such as wind, photovoltaics, solar thermal, hydro, natural gas, biogas, coal, and nuclear power has been assessed. According to the study findings, nuclear, hydro, coal, and natural gas power plants are more efficient than photovoltaics and wind power. However, more recently, an article published in 2017 [64] analysed the integration of life-cycle assessment and integrated energy modelling after accounting for emissions from manufacturing, building, and fuel supply to understand future emissions for low-carbon power systems. It reveals that solar, wind and nuclear power have a much smaller carbon footprint than coal or natural gas with carbon capture and storage (CCS).

According to a study conducted in India, an FPV plant with a capacity of 1.14 MW can generate 1.9 GWh of energy, saving 44,734.62 tons of CO_2 [25]. Another Indian study predicts FPV systems might save around 1.7 tonnes of CO2 per year [20]. An FPV power plant in Korea generates 2932 GWh of power while reducing approximately 1,294,450 tonnes of greenhouse gas emissions annually [65] thus, reduction of CO2 emission is feasible with the growth of FPV technology.

6. CONCLUSION

Globally the FPV installations have increased phenomenally in the past decade. In 60 countries worldwide, FPV is growing to be one of the major sources of energy generation. Japan presently has the most completed FPV projects of any country in the world, while China has the largest one. Top10 installations worldwide, along with major FPV installations in the coming years worldwide, are mentioned in the article.

In general, the main advantages of FPV over conventional ground-based PV systems are observed to be - less time and resources for FPV implementation and integration within communities, an increase in efficiency, and water conservation and improvement in water quality. These advantages are observed due to the less drifting effect and land resources needed in FPV systems. Further on, when considering large-scale studies done to examine the technology like that of the "Singapore test bed," major improvements in the efficiency are observed with freestanding, mono facial module due to lower ambient temperatures and albedo effect in FPV.

All components of FPV - Solar PV Modules, Inverters, and Floating structures (materials used, design considerations, Anchoring, and mooring) have been mentioned, along with bankable technical considerations. Digital solutions for Solar PV under implementation currently focus on - The Internet of things (IoT) As it has an interoperability environment where all devices in the field are connected to each other. It represents a valid solution for FPV systems to address the issues of frequent failures of communication between devices and cloud/data centers. IoT implementation spontaneously shows all the connected devices as available and thus can be easily connected to the system (Solar Power Europe O&M Task Force, 2018).

EOL of FPV systems needs focus as the plants are near their end of life. A huge problem of disposal of the plant will cause ecological problems in the water bodies and land. The 3R EOL management currently implemented in PV are Reducing, Reusing, and Recycling - these ideas can be extended to FPV systems as well.

Overall, FPV is shown to create less carbon footprint and possesses huge potential for a clean, sustainable, and good socio-economic way of harnessing energy in the coming decade. An effective framework, as well as institutions, should be established for setting sustainable, bankable parameters and end-of-life management plans for FPV plants. The present EOL analysis shows the urgent need to set up global, legally enforceable standards for FPV systems as these could potentially increase FPV installations along with creating new avenues for value creation, industry growth, and jobs for communities.

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