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Review article

Towards sustainable power generation: Recent advancements in floating photovoltaic technologies

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ABSTRACT

Floating solar photovoltaic systems are rapidly gaining traction due to their potential for higher energy yield and efficiency compared to conventional land-based solar photovoltaic systems. Recent studies indicate that this technology generates 0.6% to 4.4% more energy and exhibits efficiency improvements ranging from 0.1% to 4.45% over its land-based counterpart. Numerous studies conducted on evaluating this innovative technology have been reported, providing various insights required for further development. Unfortunately, these important pieces of information have been scattered: a comprehensive compilation of these findings is currently unavailable, resulting in a significant gap in knowledge and information. Thus, the main objective of this work is to provide a comprehensive insight into this new technology, various research and developments that have been reported and potential future development. The critical review indicates that advancements in this technology shall focus on improved floating structure design, robust instrumentation, wireless monitoring, and sensing capabilities. Moreover, novel technological solutions such as tracking systems, bi-facial solar panels, satellite-based array optimization, programming algorithms for grid integration, and artificial intelligence shall be further explored. Additionally, it was found that the integration of floating photovoltaic in marine environments and hydropower reservoirs holds significant promise for transforming global energy production. Despite these advancements, several hurdles remain, including safety concerns, risks associated with electricity–water interactions, standardization issues, national policy considerations, and potential increases in surrounding ground temperatures. It is vital to address the remaining challenges and leverage technological innovations to realize the full potential of floating photovoltaics in the transition towards sustainable energy production.

1. Introduction

The demand for global energy has been rising significantly over the years. A recent report by the Energy Information Administration predicted that global energy consumption will grow by 50% between 2020 to 2050 if the current trend in policy and technology development remains [1]. In 2021, the primary energy demand for heat, electricity, and transportation has risen by 5.8%, higher than the pre-pandemic rise recorded in 2019 by 1.3%, [2]. To meet this growing demand, the global community is not only relying on fossil-based fuels. In fact, the global market indicated 3% drops in fossil fuel usage. Instead, some of this energy demand is covered by the adoption of renewable energy sources, such as hydroelectric power, solar power, biomass and wind energy [2]. The statistical data reported by the United Nations (UN) [3] highlights the constant growing trend of renewable sources usage in the energy sector. Particularly, the production of electricity using renewable sources has increased from 19.7% in the year 2010 to 26.2% in the year 2019 [3]. This is indeed an encouraging progression in our collective effort to achieve Sustainable Development Goals. Among all renewable energy resources, hydropower energy has seen the highest increase in installed capacity in the past years. At present, however, the title has been taken by solar energy which achieved the highest growth of 58% share recorded between 2017 and 2021 [4]. This is partly attributed to the recent recognition of solar power as a mature and clean energy source. Furthermore, the recent G20 Energy

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Nomenclature

η	Efficiency
AC	Alternating current
C	Celsius
DC	Direct current
EU	European Union
FPV	Floating solar photovoltaics
GW	Gigawatt
HDPE	High density polyethylene
K	Kelvin
km	Kilometer
kW	Kilowatt
LCOE	Levelized cost of energy
LPV	Land solar photovoltaics
mg/L	Milligrams per litre
mm	millimeter
MW	Megawatt
NASA	National Aeronautics and Space Administration
PV	Photovoltaic
PW	Petawatt
Ref.	Reference
SDG	Sustainable Development Goals
TW	Terawatt
UN	United Nations
USA	United States of America
V	Volt
W	Watt

Transitions Working Group (ETWG) meeting concluded that members of G20 will continue the deployment of solar PV as well as offshore wind turbines [5]. This has elevated solar PV to the next level of growth in the renewable energy sector.

Solar power can be utilized for the production of both heat or electricity through various technologies such as concentrated solar power, solar collectors, solar heaters, solar photovoltaics, solar desalination and solar-based appliances [6]. The most widespread solar technology is solar photovoltaics (PV) for electricity production, which accounts for 3.6% of global electricity production. In 2021, its growth was 22% higher compared to the previous year [7]. Typical solar PVs, currently available in the market have an efficiency of around 10% to 20%. This relatively low efficiency and energy yield of solar PV is influenced by several factors, including cell temperature, which is considered the dominant one. In general, these PV panels can operate efficiently at a standard temperature of 25 °C [8]. A study for poly-crystalline panels indicated that for each 1 °C increase in the temperature, there is a voltage drop of 0.12 V [9]. This temperature-dependent phenomenon affects all types of solar PV panels. This temperature-driven performance degradation phenomenon is more pronounced for a large-scale solar farm where heat accumulation is significant leading to considerable cell temperature increase. Hence, numerous cooling strategies have been implemented to manage the temperature at the optimum level. One of these strategies is installing solar PV above the body of water which is called floating solar PV.

Floating solar photovoltaics (FPV) [10], also known as floatovoltaics or floating photovoltaics, made its first appearance in 2007 [11,12]. This innovative PV installation offers several benefits compared to traditional land-based systems. These include natural cooling phenomena that lead to better cell temperature management, resulting in improved energy yield. Additionally, the installation reduces land usage and minimizes evaporation from the body of water where the PV is installed. However, it is important to note that this innovative PV installation may also present challenges such as increased complexity in design and installation, as well as potential maintenance considerations associated with water-based systems. The complexity of designing and developing an FPV system requires interdisciplinary involvement from mechanical, electrical, and civil to instrumentation engineering. This design and development encompasses various tasks including fabrication, construction, installation, and stability reinforcement. Given the multifaceted nature of these tasks, a comprehensive overview of the system and insights from previous studies are essential. Unfortunately, a compilation of these crucial pieces of information is currently absent in the existing body of knowledge. As a result, researchers and technology developers need to invest considerable effort in gathering and synthesizing this information. To assist this effort, this review paper is prepared to effectively address the challenges and optimize the performance of FPV systems.

The objective of this review paper is to address the current gap in knowledge regarding innovative floating solar photovoltaic systems. Through a comparative analysis between FPV and LPV systems, based on data available in the published literature, this paper aims to provide insights into the unique benefits and challenges associated with FPV technology. Additionally, the setup of FPV systems used for analysis will be compiled and discussed to offer guidance for future research in the field. Furthermore, recent advancements in FPV technology will be elaborated upon to indicate the state-of-the-art of this sustainable energy system, followed by the identification of potential challenges and barriers, especially pertaining to economic, environmental, technological, and other relevant aspects. Deliberation on the global presence of FPV will be provided to facilitate the growth of FPV adoption. Finally, the paper will be concluded with a suggestion on the future directions for efficient FPV system development, providing a general guideline for research consideration.

2. Floating solar photovoltaics: A conceptual overview

Floating solar photovoltaics refers to the installation of PV panels on a floating structure, which is anchored to the bottom and/or the sides of a water body for stability. Compared to land-based systems, installing solar panels on a floating structure requires additional components and structural modifications. This section discusses the components, structure, and arrangements of FPV systems, along with their evolution and benefits.

2.1. Origin of floating solar photovoltaics

The history of floating solar PV can be traced back a century ago when a US warship participated in the first world war known as "Jacona" [13] was converted into a power-generating plant by England in the 1930s, marking the first power generation technology in a water body. The concept of FPV was however officially coined when two Japanese companies Mitsui Engineering & Shipbuilding Co. Ltd. and Mitsui Zosen KK, filed a patent on FPV, making Japan the pioneer in this technology [14]. Japan was also the first country to install the FPV in 2007, followed by the USA, Europe, South Korea, China, India, and Brazil [12,15]. The concept of FPV gained further attention and momentum following a report on the improved performance of solar PV in water presented at a European conference in 2008 [16]. This marked a significant milestone in the development of FPV technology. Subsequently, the worldwide installed capacity of FPV power plants experienced remarkable growth, reaching over 3 GW in 2021 from 100 MW in 2016 [12,17]. Moreover, projections indicate a promising future for FPV, with an expected growth rate of 22.5% by the year 2030 [18]. Several leading institutes are actively working on the research and development of FPV technology [19,20]. Some of these are Ciel et Terre, Sungrow, Solar Energy Research Institute of Singapore [21], Florida Solar Energy Center (FSEC) [22], and Cranfield University [23].

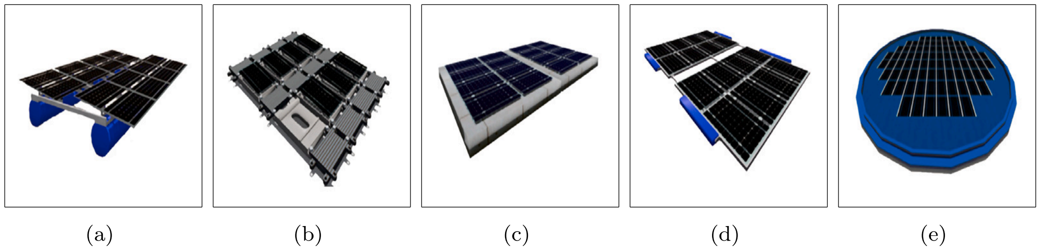

Fig. 1. Category of FPV (a) Type 1: Class 1 pontoon structure, (b) Type 2: Class 2 pontoon structure, (c) Type 3: Class 3 pontoon structure (d) Type 4: Superficial rigid structure and (e) Type 5: Superficial flexible structure [29]. From "Key issues in the design of floating photovoltaic structures for the marine environment" by R. Claus and M. Lopez, 2022, Renewable and Sustainable Energy Reviews, Vol.164. Reprinted with permission from Elsevier.

2.2. Structure and installation of floating solar photovoltaics

The basic floating structure of FPV consists of two main components [24,25]: (a) PV panels with their auxiliary electrical components, and (b) the body structure comprising floats, mooring systems, waterproof materials, and buoyant force. PV panels are attached to an array of interconnected floats that are moored and anchored. These floats are typically constructed from lightweight materials such as polyethylene (mostly HDPE), hydro-elastic membranes, polystyrene foam, ferrocements, or fibre-reinforced plastics with aluminium or steel rafts [26–28]. Meanwhile, the electrical cables used in FPV are typically those claded with polyurethane or thermoset rubber as they are water resistant. Finally, rubber mats are used to cover the structure [28].

Fig. 1 illustrates five typical structural types of FPV systems [10,29]:

- Type 1 contains rafts built with parallel HDPE cylinders as floats with supporting structures.
- Type 2 consists of many individual panels fixed in individual floats accompanied by built-in rails without a supporting structure.
- Type 3 involves a widespread floating platform like an island, to hold the PV modules along with a space to walk in between them.
- Type 4 refers to the PV modules in the floating structure over a water body that is partially submersible and can float back to the surface.
- Type 5 has a flexible structure developed for thin-film modules made of neoprene sheets, enclosed by floats.

During installation, it is crucial to consider the meteorological and geological conditions of the site, as some locations may require additional facilities. Not all geographical conditions are suitable for FPV installation. For example, remote areas, highly frigid regions, heavily soiled or humid urban areas, recreational water bodies, soft ground or mud, reserved water bodies for protected species, water bodies dedicated to birds, and risky disaster regions like volcanoes, storms, or hurricanes are not suitable for FPV installation [30,31]. These conditions may result in the collapse of the floating structure, degradation of the solar irradiance or endanger the ecosystem.

Once the location is determined, the next factors to be considered are the tilt angle, size of the array, and type of solar panel. The tilt angle of FPV systems is typically set to maximize solar radiation capture, similar to conventional LPV systems. The size of the array depends on the surface area and depth of the water body, impacting both production capacity and the anchoring and mooring of the floating structure [28]. Subsequently, the selection of the solar panel type should be carefully considered, as it significantly impacts the economic feasibility of the FPV system. For instance, Ravichandran et al. [32] found that polycrystalline solar panels are more suitable for FPV installations in certain locations like Egypt. As a reference, Chiang and Young [33] provide comprehensive installation guidelines based on their experience with a 3.2 MW FPV system installed in Taiwan.

2.3. Benefits of floating solar photovoltaics

As previously stated, floating solar panels offer several advantages, including a natural cooling effect that enhances energy yield and efficiency. Additionally, they can help reduce water evaporation by providing shading to the water beneath them. As reported by Nisar et al. [34] and Hafeez et al. [31], up to 28% reduction in water evaporation can be achieved by installing solar PV atop the water surface. In addition to performance improvement and evaporation reduction, installing FPV systems on water bodies can significantly expand solar energy capacity without significantly burdening land usage. With 70% of the world covered with water, research and development of FPV on ocean platforms opens a new era of solar energy with the advancement of robust floating structures. However, it should be noted that oceans are not necessarily calm, and harsh ocean currents may pose serious challenges to FPV structures. Therefore, research and development efforts addressing this issue are crucial. Currently, China and the United Kingdom are leading the structural analysis of FPV systems to endure extreme ocean conditions. [23,35,36]. Another promising location to install FPV is hydropower dams. Almeida et al. [37] reported that the installation of FPV in 10% area of the world's hydropower reservoirs is equivalent to the installed electricity generation capacity of the fossil fuel power plants. Currently, there are no reports on the aquatic environment disruption with the FPV system installation over a water body [38]. The integration of FPV on hydropower dams not only maximizes renewable energy generation but also capitalizes on existing infrastructure, potentially revolutionizing the energy landscape. Furthermore, it can provide a green energy supply to the nearest residential areas, contributing to local sustainability and reducing reliance on non-renewable energy sources [39].

3. Performance analysis of floating solar photovoltaics

The performance comparison between floating solar PV and conventional land-based PV systems is typically assessed based on energy yield and efficiency. In a three-day comparative study conducted by Nisar et al. [34] at the National University of Science and Technology in Pakistan, it was found that the overall energy generated by both mono-crystalline and poly-crystalline FPV panels are 35.9% and 27.5% more, respectively, compared to their corresponding LPV panels at a tilt angle of 0° [34]. The temperature of the FPV panel was found to lower by 2% to 11% as compared to LPV. At an optimal PV tilt angle of 30° at this location, the performance enhancement offered by FPV as compared to FPV is less pronounced at 8% for both mono/poly-crystalline PV modules. This is mostly attributed to the weaker cooling effect on the PV panel distant from the water surface despite optimum solar radiation capture. Nisar et al. [34] claimed that further performance enhancement of 10% to 17% is possible through careful design considerations and by taking into account meteorological conditions. A similar study was reported by Shatil et al. [40] using a 400 W FPV system with an angle of tilt 0°. The system was analysed for thirteen hours and found that FPV has an average higher power output of 3.25% as compared to the ground-mounted counterpart.

A pilot-scale study comparing FPV and ground-mounted systems was conducted in Kilinochchi, Sri Lanka [41]. The study revealed that FPV achieved an average of 0.6% higher yield than LPV. Additionally, Hammoumi et al. [42] investigated an 87.5 W FPV system in the city of Fez in Morocco with the optimal tilt angle of 30°. The total energy gain of FPV is observed to be 2.33% higher than the LPV system. Furthermore, the study suggested that even higher energy gain up to 43.5% is possible with the FPV module angle set at 0°, making the panel closer to the water surface. Junianto et al. [43] conducted a one-week experiment in Palembang, South Sumatra, using a 100 W poly-crystalline panel tilted at 10°. The study concluded with an observed efficiency of 5.8% for the LPV system, while the FPV system demonstrated superior efficiency of 7% due to a temperature drop of 2 °C. Additionally, the average power generation by the FPV system was reported to be 20.66% higher than that of the LPV system. Sasmanto et al. [44] conducted a one-month investigation on a 100 W poly-crystalline based FPV system over the brackish water of Sungsang in Sumatra. The study reported a lower temperature by up to 4.7 °C along with an increase in the average power production of 11.89 W as compared to the LPV counterpart. Liu et al. [19] installed eight FPV systems with tilt angles varied from 5° to 12° for structural analysis and its thermoelectric performance at the Solar Energy Research Institute of Singapore. The FPV was found to have a temperature drop within a range of 5 °C to 10 °C and the mean performance ratio is observed to be 5% to 10% higher than a rooftop system [19]. Yadav et al. [45] performed a one-month experiment at Jodhpur (India) using a 250 W poly-crystalline PV module tilted at an angle of 23°. They found that the maximum power generated by the FPV is 1.13% higher than that of the LPV system. A similar study was conducted at the Laboratory of Universiti Kebangsaan Malaysia [46]. The performance of FPV and LPV were examined under the irradiance level of 417 W/m^2, 667 W/m^2 and 834 W/m^2. The study concluded that the temperature of FPV reduces within a range of 3.34 °C to 3.73 °C with corresponding power generation of 3.61% to 14.55% higher than the LPV system on average.

In tandem with experimental investigation, mathematical simulation plays a crucial role in analysing FPV systems, especially in understanding the correlation between PV cells and environmental factors. For instance, Hafeez et al. [31] modelled a 100 kW poly-crystalline FPV system using System Advisor Model (SAM) software [47] for a lake in the National University of Science and Technology of Islamabad, Pakistan. This research work [31] considered the temperature of FPV to be 5 °C to 10 °C lower than the ground-mounted system, referring to the previous study [19]. The resulting annual energy yield is found to be 1559 kWh/kW for the standard PV system. For FPV systems, it was 1591 kWh/kW and 1623 kWh/kW for the corresponding temperature drop of 5 °C and 10 °C. This represents a production increase of approximately 2% to 4% higher than the ground-mounted solar PV system. By using MATLAB/Simulink, Meena et al. [48] modelled a 100 kW FPV system and found that FPV cell temperature is 5.4 °C lower than that of the ground-mounted system. Accordingly, the estimated average power output of the FPV system is 96.63 kW, which is 4.06 kW higher than that of the conventional ground PV system. Similar performance enhancement was reported in thin-film solar PV module by Ravichandran et al. [49]. Using Helioscope software, the solar PV was evaluated at an optimal tilt angle of 7° for the Maldives, with data support from NASA TMY. The numerical analysis resulted in a notable annual energy yield increase of 1.6% compared to ground-mounted systems. Semeskandeh et al. [50] conducted an investigation on a 5 kW FPV plant for the Caspian Sea in Iran using MATLAB/Simulink and RET Screen. The FPV panel tilted at 30°, yielded 19.47% more energy per annum compared to a ground PV system, attributed to an 11 °C lower temperature.

Dörenkämper et al. [51] examined the performance of FPV under different conditions in the Netherlands and Singapore using PVSyst software. The tilt angle was set at 12° for both locations but the orientation was different depending on the location. Real data from installed FPV sites in these regions were collected for comparative analysis. The simulation results revealed that FPV generated an average energy yield increase of 3% in the Netherlands and 6% in Singapore. Additionally, FPV demonstrated a cooling effect, with temperatures measured 3.2 °C and 14.5 °C lower than the benchmark system in the respective locations. Sukarso et al. [52] analysed a 1 MW FPV system in West Java, Indonesia, using QGIS and SAM software. The study considered a tilt angle of 10° for an LPV and 12° for the FPV system in two different locations. The efficiency of the LPV system was found to be 17.469%, while it was 17.564% and 17.581% for the two FPV systems. The estimated potential yields of the LPV system are 1.408 GWh/year, and for the two FPV systems, they are 1.432 GWh/year and 1.439 GWh/year. Meanwhile, a techno-economic analysis of FPV for Nepal was conducted by Rai et al. [53] using PVSyst and NASA data. The study reported that the annual energy yield of FPV was 18.25% higher than that of the conventional system. Similarly, Bist et al. [54] used PVWatts and NASA data to analyse an 8.3 kW system in Nainital, India. They reported that the annual energy production of FPV is 2.25% higher for a temperature drop of 5 °C in comparison to the conventional PV system. In another study, Charles et al. [55] performed an analysis using Matlab Simulink and Minitab for two FPV systems of 100 kW and 500 kW size in the Hapcheon dam of Korea. The yearly normalized energy output increased by 9% to 16% with a yearly average temperature decrease of 4 °C. Additionally, a 1 MW FPV system was analysed using MS Excel and NIWE - India meteorological data in Jodhpur, India [56]. The study identified that the FPV temperature decreases by up to 5 °C, and the annual energy yield extends by 2.48% for the FPV system.

3.1. Energy yield of floating solar photovoltaics

Based on the comprehensive review spanning from 2013 to 2022, it has been consistently demonstrated that floating photovoltaic systems outperform conventional land solar PV systems under homogeneous conditions. The range of increased electricity yield and temperature reduction achieved by FPV systems compared to standard solar PV systems is summarized in Table 1. In cases where specific values were not directly reported in the literature, data extraction was performed using OriginPro statistical software and calculated using Eq. (1),

$$E(\%) = \left(\frac{Y_{FPV} - Y_{LPV}}{Y_{LPV}} \right) \times 100, \tag{1}$$

where E is the gain percentage in the energy yield of FPV, Y_{FPV} and Y_{LPV} are the energy yield of FPV and LPV respectively in Watt-hour (Wh).

The high heat loss coefficient value of the water-cooled solar PV panel contributes to the higher energy yield of FPV systems compared to conventional solar PV systems [57]. For FPV, wind plays a crucial role in cooling the solar panels, complementing the cooling effect of the surrounding water body [41,57,58]. The effectiveness of wind in cooling the solar panels of FPV systems can be influenced by various obstacles, such as rocks, grass, and panels positioned at the edges of the array, as well as by the varying elevation of the land in its pathway. Consequently, the performance of FPV may be impacted by disturbances in the flow of wind [41]. For instance, Peters et al. [58] noted a case where, during their analysis, the temperature of FPV was observed to be 9.1 ± 2 K higher than that of a rooftop PV system during peak sun hours. This observation underscores the fact that the performance of FPV systems is highly dependent on the specific location where they are installed.

The difference in performance favouring FPV systems is most pronounced when the PV panels are positioned flat on the water's surface, typically at a tilt angle of 0°. This configuration allows efficient heat dissipation across the entire panel due to its proximity to the water. However, for optimal energy generation, solar PV systems are typically tilted to absorb maximum solar radiation. The performance characteristics of FPV is not directly reported in terms of energy in some literature.

Table 1
Energy gain in FPV relative to LPV.

Author	Ref.	Location	Size	Tilt angle	Temp.↓	E ↑	Method
Hafeez et al. (2022)	[31]	NUST, Pakistan	100 kW	20°	5–10	2%–4%	SAM
Nisar et al. (2022)	[34]	NSUT, Pakistan	80 W	0°, 15°, 30°	2%–11%	8%–35.9%	Experiment
Meena et al. (2022)	[48]	Odisha, India	100 kW	30°	5.4	4.4%	MATLAB-Simulink
Shatil et al. (2022)	[40]	Chalan Beel, Bangladesh	400 W	0°	–	3.25%	Experiment
Ravichandran et al. (2022)	[49]	Maldives	5 MW	7°	–	1.6%	Helioscope, NASA TMY
Kjeldstad et al. (2022)	[41]	Kilinochchi, Sri Lanka	44 kW	15°	Yes	0.6%	Experiment
Semeskandeh et al. (2022)	[50]	Caspian Sea, Iran	5 kW	30°	11	19.47%	MATLAB Simulink, RET Screen
Dörenkämper et al. (2021)	[51]	Netherland & Singapore	46 kW	12°	3.2–14.5	3%–6%	PVSyst, Meteonorm
Hammoumi et al. (2021)	[42]	Fez, Morocco	87.5 W	30°	2.74	2.33%	Experiment
Sukarso et al. (2020)	[52]	West Java, Indonesia	1 MW	10°–12°	8	1.7%–2.2%	QGIS, SAM
Junianto et al. (2020)	[43]	Palembang, Indonesia	100 W	10°	2	20.27%	Experiment
Sasmanto et al. (2020)	[44]	Sungsang, South Sumatra	100 W	0°	4.7	11.89 W	Experiment
Rai et al. (2020)	[53]	Nepal	1 MW	10°	–	18.25%	PVSyst, NASA SSE
Bist et al. (2019)	[54]	Nainital, India	8.3 kW	–	5	2.25%	PV Watts, NASA data
Liu et al. (2018)	[19]	SERI, Singapore	1 MW	5°–15°	5–10	Yes	Experiment
Charles et al. (2018)	[55]	Hapcheon Dam, Korea	100 kW, 500 kW	33°	4	9% & 16%	Matlab, Minitab
Mittal et al. (2017)	[56]	Jodhpur, India	1 MW	–	5	2.48%	MS Excel, NIWE-India
Yadav et al. (2016)	[45]	Bhopal, India	250 W	23°	–	1.13%	Experiment
Azmi et al. (2013)	[46]	Universiti Kebangsaan, Malaysia	16 W	0°	3.35–3.73	3.61%–14.55%	Experiment

E↑ - Increased electrical energy in FPV compared to the LPV system (%).
Temp.↓ - Temperature drop in FPV compared to LPV (°C).

For the energy improvement estimation, the output power is considered to be directly proportional to the energy with consistency in the increment, regardless of any affecting parameters. Research indicates that FPV systems yield between 0.6% and 35.9% more electricity compared to conventional systems. The persisting additional yield observed in the literature ranges from 0.6% to 4.4%. Experimental investigations also show that FPV systems can achieve an energy yield increase ranging from 6% to 35.9%. However, achieving the maximum yield within this range depends on various factors, including irradiance level, tilt angle, temperature, cooling effect, humidity, wind speed, PV panel type, and associated losses.

Table 2
Efficiency (η) gain in FPV relative to LPV.

Authors	Ref.	G
Nisar et al. (2022)	[34]	1–4
Semeskandeh et al. (2022)	[50]	4.45
Hammoumi et al. (2021)	[42]	1.87–2.57
Junianto et al. (2020)	[43]	1.20
Sasmanto et al. (2020)	[44]	4
Sukarso et al. (2020)	[52]	0.10–0.11
Kamuyu et al. (2018)	[55]	1–2
Yadav et al. (2016)	[45]	0.79
Do Sacramento et al. (2015)	[59]	1
Azmi et al. (2013)	[46]	0.70

3.2. Efficiency of floating solar photovoltaics

As discussed, FPVs consistently offer higher efficiency than their land-based counterparts. The reported efficiency increase offered by FPV from several studies is summarized in Table 2. The efficiency gain (G) by the FPV over LPV is calculated using the following Eq. (2).

$$G = \eta_{FPV} - \eta_{LPV} \tag{2}$$

Several studies [59–62] have investigated submerged solar PV, partially submerged solar PV, and solar PV in contact with water for cooling. These technologies are associated with solar PV systems near water bodies and involve cooling methods, but they do not exactly represent FPV systems. In this review, we exclude these analyses and focus solely on valid FPV systems for discussion. Additionally, the integrated efficiency assessment in this work reports the efficiency of FPV without considering the influencing parameters. From the data compiled in Table 2, it can be observed that the efficiency gain of the FPV ranges between 0.1% to 4.45%.

3.3. Limitations on the FPV and LPV comparative analysis

Despite providing crucial insight towards the performance of FPV, the comparative analysis reviewed in this study possesses certain limitations. For instance, some investigations have relied on assumptions regarding increased performance or lower temperature values for FPV, based on earlier research findings [31,48]. These assumptions may introduce biases or inaccuracies into the analyses, affecting the reliability of the conclusions drawn. In addition, these studies varied in duration, ranging from single-day to multi-week studies [34,40,42,43], with a few lasting a month [44,45]. This variability in study duration may have influenced the depth and scope of their findings, potentially impacting the comprehensiveness of the conclusions drawn. Furthermore, several analyses were conducted using numerical simulations without real-world comparisons [31,48–56]. While numerical simulations provide valuable insights and predictions, they may not always accurately reflect real-world conditions or account for all variables and uncertainties present in practical FPV installations. Therefore, the findings from such simulations should be interpreted with caution and validated with experimental studies whenever possible.

The study conducted at the Solar Energy Research Institute of Singapore with a pilot-scale FPV plant [19] focused mainly on structural analysis, missing detailed information on energy yield and instrumentation used in the set-up. While structural analysis is essential for assessing the integrity and stability of FPV systems, comprehensive information on energy yield and instrumentation is crucial for understanding their overall performance and efficiency in real-world conditions. Therefore, the lack of detailed data in this study limits its usefulness for comprehensive comparative analysis and practical application of FPV technology. Kjelstad et al. [41] reported configurations for both FPV and LPV systems, but variations in panel size, tilt angle, and orientation rendered direct comparison difficult. Their study also omitted analysis of wind effects, water evaporation, and FPV panel temperature. Additionally, using default LPV parameters in PV software may not accurately simulate FPV performance in real-world conditions [41]. Kumar et al. [63] encountered discrepancies between experimental outcomes and results from a leading solar PV software when comparing a 2 MW FPV system. Similar inconsistencies were noted by Choi et al. [64]. Despite these discouraging reports, PVsyst [65] remains one of the reliable software for FPV simulation at present [66].

4. Floating solar PV system set-up for research analysis

The research on floating solar PV systems requires multidisciplinary skills for fabrication, installation, continuous monitoring and data collection. Studies used different materials and incorporated various methodologies to perform the FPV analysis. The framework includes the solar PV size, analysed parameters, the FPV structure, duration of the study, data monitoring system, sensors, the output load and the instruments. This section provides an overview of the system setup employed in the analysis of FPV, offering valuable insights into the research methodology.

Nisar et al. [34] developed a floating structure using aluminium and polyethylene cans to bear the load of the solar panel. The structure was designed to stay afloat over an artificial pond that is located on top of a building. The data was continuously monitored at an interval of 30 s and stored on an SD card with the help of an Arduino Uno board and a data logger. As this analysis is based on water, the author enclosed the electronic devices with a waterproof casing as a safety measure. Thermal imaging was manually employed to inspect PV panel hot spots and degradation. Furthermore, an anemometer was installed to measure the speed of the wind. Meanwhile, Hammoummi et al. [42] developed a less sophisticated small-scale PV system comprised of an array of four panels that accounted for 87.5 W. An Arduino Uno board was used to measure the ambient temperature while other parameters were monitored and recorded manually. Another rather simple approach was taken by Sasmanto et al. [44] by incorporating a 100 Ohm shunt resistor and a 100 W DC lamp as a load. The use of a shunt resistor measures the flow of current along with the protection of the circuit from high-voltage damage. Similarly, Junianto et al. [43] conducted an FPV analysis with a 100 W solar panel linked to a 100 W DC lamp. Data monitoring was performed manually using digital meters connected to the terminals.

Shatil et al. [40] employed a straightforward design for their FPV system, constructing the floating structure using plastic tanks supported by iron frames. The electricity generated by the solar panels was charge-controlled and fed into a battery, which in turn powered a 400 W DC motor. This power system was positioned on the shore near the water body for operation. Meanwhile, Yadav et al. [45] analysed a 250 W FPV system manually for a day, utilizing a conventional solar module analyser, an infra-red thermometer, and a thermal hygrometer to measure electric and thermal properties. Liu et al. [19] reported data measurement of humidity and temperature for an interval of 1 min. For the analysis, three to four PT100 temperature sensors were fixed behind the panels of the floating platform. An albedometer was installed to measure the reflection of solar rays on the water's surface. Kjeldstad et al. [41] connected the power output of the solar panel to the inverter and used an MPPT charge controller to maintain maximum power tracking during the analysis. The used Kipp & Zonen RT1 device is capable of measuring both the irradiance and temperature of the solar panel. The Campbell scientific instruments model 109, CS215 and CR310 were used to measure the water temperature, ambient temperature, and relative humidity. The summary of the measured parameters and various instruments used in the reviewed studies are listed in Table 3.

The common parameters monitored in FPV studies are solar irradiance, generated voltage and ampere, panel temperature, ambient temperature, water temperature and relative humidity. These parameters provide crucial insights into the performance of the FPV system. Additionally, a DC load is often connected to the system, matching the power capacity of the solar panel. In instances where an AC load is required, inverters are employed to convert the DC output to AC, ensuring compatibility with the load requirements. Hammoumi et al. [42] and Yadav et al. [45] measured the open circuit voltage and the short circuit current without any load, a cost-effective approach commonly used in research. However, this method is not suitable for large-scale FPV analysis due to potential electricity wastage. Data recording in FPV studies can be done manually or through automated data logging systems. While manual recording is sufficient for short durations, continuous monitoring or long-term studies benefit from automated systems. Manual monitoring avoids data collection during nighttime, saving time and effort. Nisar et al. [34], Sasmanto et al. [44], and Hammoummi et al. [42] employed miniature research-scale FPV setups with essential components for continuous monitoring and data storage. Conversely, Liu et al. [19] and Kjeldstad et al. [41] conducted large-scale FPV system analyses.

5. Global presence of floating solar photovoltaics

Increasingly, floating solar PV installations are emerging as a promising renewable energy solution worldwide. In the global market, utilizing just 30% of the surface area of the 114,555 available reservoirs could potentially generate a staggering 9434 TWh/year of electricity [67]. Similarly, in Europe, FPV has the potential to double power generation by harnessing only 1% of the surface area of the 146 hydropower reservoirs [68]. Another study estimated that covering just 2.3% of hydropower reservoirs' surface area could yield 42.31 TWh of energy [69]. In addition, water evaporation can be reduced by approximately 557,000 litres with the installation of FPV in the EU [39]. Portugal is anticipated to host the largest FPV in the EU

Table 3
Summary of floating PV's materials and methodology.

Ref.	[19]	[34]	[40]	[41]	[42]	[43]	[44]	[45]
Year PV size Duration	2018 1 MW 1 year	2022 80 W 3 days	2022 400 W 9 h	2022 50 kW 1 year	2021 21.9 W 5 days	2020 100 W 7 days	2020 100 W 1 month	2016 250 W 1 day
FPV structure	–	Aluminium, polyethylene cans	Iron frame, plastic tank	SMA inverter, MPPT charge controller	Polyethylene cans, metallic structure	Cans and metallic structure	–	HDPE blocks, aluminium plates
Solar irradiance	–	Pyranometer	–	Kipp & Zonen RT1 sensor, POA irradiance sensors	LP PYRA 03 AV, TES 132 solar power meter	–	–	Solar power meter (Model No-TM-207, Taiwan)
Voltage	–	Voltage sensor	Power meter	–	Chauvin Arnoux multimeters	Voltmeter	Voltmeter	Solar module analyser (Model no-MECO-9009, India)
Ampere	–	ACS712	Power meter	–	Chauvin Arnoux multimeters	Ampere meter	Multimeter	Solar module analyser (Model no-MECO-9009, India)
Panel temperature	PT100 sensor	DS18B20	–	Kipp & Zonen RT1	FLIR ThermaCAM E4 (front side), DS18B20 sensors (back side)	–	Sensor	Infra-red thermometer (Ray Tek, China)
Ambient temperature	–	DHT 11 sensor	–	Campbell scientific CS215	DS18B20 sensors	–	–	Thermo hygrometer (HT-3006A, China)
Water temperature	Campbell scientific 109	–	DS18B20	DS18B20	Sensors	–	–	–
Humidity	–	DHT 11 sensor	–	Campbell scientific	–	–	–	–
Data monitoring and storage	–	Arduino Uno, real time current module (RTC)	Manual	Campbell scientific CR310 datalogger	Manual, Arduino Uno for S18B20	Manual	Sensors, Meters and camera	Manual
Load	On grid	Charge controller, battery, Load	DC motor 400 Watts	50 kW SMA inverter with 6 MPPTs	Voc, Isc	100 W load (DC lamp)	Shunt resistor 100 Ω and 100-W 24VDC lamp	Voc, Isc

(also the largest PV installation) with a targeted installed capacity of 500 MW [17,70]. Furthermore, recent analyses have shed light on the potential of FPV for cleaner energy production in Romania, with projections indicating that specific regions could produce over 700 kWh from a 540 W FPV system [71,72]. Similarly, in Spain, harnessing FPV in 10% of its inland water bodies could generate a remarkable 80 TWh of energy annually [73].

While renewable energy consumption is high in European countries, China has taken the lead in FPV energy production with the world's largest 320 MW FPV plant operational since 2021 [17,74]. Joining the ranks of FPV pioneers, Singapore has installed a 60 MW FPV plant alongside Japan and Korea [17]. Moving eastward from Singapore, FPV has emerged as a valuable energy source for diverse communities, exemplified by its successful implementation in the fisherman community residing on Mainit Lake in the Philippines [75]. This community-specific application highlights FPV's adaptability and effectiveness in addressing unique energy needs. Recent policies favouring renewable energy installations in Southeast Asia, coupled with growing environmental awareness, have significantly boosted the installation of FPV systems in recent years, with continued growth expected in the coming years [76].

Moving west, India has set an ambitious target of achieving 1.7 GW of energy production through FPV systems by leveraging favourable renewable energy policies [12]. The installation of FPV in the 18,000 km^2 water reservoirs available in the country can benefit with 280 GW of power generation [77,78]. The complete installation of the 600 MW FPV plant in the Madhya Pradesh state of India will become the largest in the world [79]. Meanwhile, in neighbouring Bangladesh, FPV technology is emerging as a significant player in the nation's energy landscape, with demonstrated potential to contribute towards achieving the country's ambitious target of generating 6000 MW of electricity through solar PV by 2041 [80]. A similar feasibility study conducted for the Hatirjheel Lake in Dhaka underscores the potential of FPV systems to support Bangladesh in meeting its solar PV target by 2041 [81].

Meanwhile, the Middle East region has seen its first FPV installation in Abu Dhabi [82]. Studies on the feasibility of FPV installations in Yemen, Iraq, Turkey, Israel, and Jordan have shown promising results both technically and economically [38,83–86]. Similarly, positive findings regarding the viability of FPV in Iran have prompted suggestions for the implementation of governmental policies to promote FPV adoption [50,87]. Furthermore, the recent installation of a 145 MW floating PV plant in Indonesia by Masdar of UAE marks the largest FPV installation in Southeast Asia to date [88,89]. It is noteworthy that Gulf countries, despite their rich fossil fuel resources, are increasingly focusing on FPV installations to align with the UN's Sustainable Development Goals and enhance their energy security [90].

The growth of FPV installation is not exclusive to Asia and Europe. It has become a global collective effort. For instance, the USA has set a target for a 10 MW FPV plant by the year 2023 [69,91]. It should be noted, however, that FPV growth in the USA has been slower compared to other regions due to abundant land availability and policy-related challenges. Additionally, Brazil has embraced FPV as part of its renewable energy strategy, aiming for self-reliance and sustainability [37]. An

Table 4
Recent findings on the FPV integration with hydropower reservoirs.

Location	No. of HPR	Tilt angle	Power capacity	Annual production	Method	Ref.
European Union	337	–	1609 GW	138.7 TWh	–	[39]
Mettur dam, India	1	20°	3.6 MW	5.9 MWh	Helioscope & NASA	[95]
Zambia	6	5°	25.408 GW	43,448 GWh	SAM	[96]
India	117	10°	109.93 GW	174.59 TWh	Satellite image & data	[97]
Greece	24	–	3861 MW	5212 GWh	Data	[98]
Island of Crete, Greece	5	–	55.76 MW	78,301 MWh	Data	[99]
Rajghat dam, India	1	10°	6.5 GW	10,624 GWh	PVSyst & data	[100]

Ref. Reference, No. of HPR - Number of Hydropower Reservoirs.

analysis using the SunData tool indicated an encouraging potential of FPV installation in the Tocantins-Araguaia basin and Passaúna River to achieve higher energy production [92,93]. By installing FPV in just 1% of its artificial water bodies, Brazil could generate 12% of its electricity, benefiting over 16.6% of its population [94].

In Africa, high solar irradiance, wind velocity and atmospheric temperature render FPV systems highly suitable for harnessing renewable energy from Ethiopian dams [101]. Using SAM software, Chirwa et al. [96], projected that covering just 10% of Zambia's hydropower reservoirs with FPV could increase the present installed capacity of power generators by eightfold. By analysing historical data, it is predicted that a hybrid system of FPV and wind power in the Kainji hydropower station of Nigeria could have produced a maximum combined power output of 608 MW to 1447 MW between 2016 and 2019 [102]. FPV technology also offers a solution to land acquisition challenges in Nigeria, making it a viable option for expanding renewable energy infrastructure [103]. Moreover, studies indicate that FPV systems have the potential to mitigate water evaporation, with an estimated 80% reduction in evaporation observed at South Africa's Nqweba dam [104]. This dual benefit of electricity generation and water conservation positions FPV as a promising solution for African countries, addressing both energy needs and water scarcity concerns, a critical issue highlighted by the United Nations [105,106]. As such, FPV technology has been proposed as an effective solution for addressing water crises in Egypt [107].

The integration of FPV installations with hydropower reservoirs can highly underscore the global potential in enhancing green energy production. In addition, the strategic deployment of FPV can serve as a financial resource for the maintenance and refurbishment of the hydro dams [108]. Several investigations have been conducted on this topic, and recent reports on the integration of FPV with hydropower reservoirs are summarized in Table 4. The production capacity is influenced by the coverage ratio of FPV over the hydropower reservoir. While a coverage ratio of 10% is commonly considered, studies by Agarwal et al. [100] and Ravichandran et al. [95] have reported ratios of 25% and 30%, respectively.

6. Challenging aspects of floating solar photovoltaics

The emergence of floating photovoltaic technology in the present decade, particularly with large-scale installations starting after 2013 [12], has brought forth various challenges that need to be carefully addressed. In the following, these identified challenges will be presented and discussed.

6.1. Technological aspect

The energy yield of FPV can be significantly enhanced through the integration of advanced technologies such as PV trackers, alterations to the PV array, and the implementation of embedded algorithms in the controller. Research indicates that solar PV systems equipped with tracking systems yield higher energy outputs compared to systems with fixed angles [109]. For example, comparisons between FPVs with tracking system and idle angle system by using PVsyst and PVWatts calculator reveal improvement in energy yields by 2.4% to 3.3% when tracking was incorporated [110]. In addition to tracking systems, the use of bi-facial PV panels is gaining popularity in FPV applications. These panels feature silicon wafers on both the top and bottom sides, allowing them to harness the reflection of solar rays (albedo) by the water body, thereby contributing to higher energy yields [19,111]. Studies estimated that the electricity production of a bi-facial panel is approximately 13% higher than that of a conventional PV panel [66,103,112]. Khan et al. [113] estimated that bi-facial PV panels and bi-facial PV panels with a single-axis tracking system could achieve energy gains of 20% to 30% and 20% to 40%, respectively. Additionally, research suggests that the dynamic albedo resulting from the wave nature of water surfaces enhances performance compared to a constant albedo [114]. Numerical estimations using PVsyst software indicate that FPV systems with bi-facial panels, dual-axis tracking, and cooling effects could achieve energy gains ranging from 42.5% to 47.5% [112].

Aside tracking technology, some other advanced technologies have also been incorporated into FPV. For instance, Dellosa and Palconit [75] introduced the application of Artificial Intelligence in Data Receiving, Monitoring, and Supervision (DRMS) for PV plant systems, showcasing the incorporation of cutting-edge technology into the management of FPV systems. Additionally, advanced methods such as the "FAO Penman–Monteith method" and the "Assouline, Narkis, and Or method" have been employed by Santos et al. [93] to estimate water evaporation and quantify the amount of water evaporation prevented by FPV, respectively [93]. Moreover, utilizing tools like the High Altitude Solar Power Research (HASPR) python suite, Eyring and Kittner [115] have identified high-altitude alpine regions with immense potential for FPV installations, underscoring the global applicability of FPV technology. Furthermore, GIS software has been instrumental in providing a hierarchical method for evaluating the technical, environmental, and logistical aspects of FPV installations, as demonstrated by Koca et al. [84]. In addition to these advancements, Hong and Alano [116] have developed an energy management system tailored for the integration of FPV with microgrid networks, offering a solution that can particularly benefit rural areas requiring small-scale FPV integration.

Temiz and Dincer [117] introduced an advanced integration system of FPV with concentrating solar power, particularly beneficial for meeting energy demands on islands where conventional energy sources may be limited. Similarly, Aweid et al. [118] explored the novel integration of FPV with solar ponds, resulting in increased system efficiency. Furthermore, FPV systems have been identified as efficient solutions for various applications beyond electricity generation. Del et al. [119] proposed the use of FPV systems to power desalination plants, showcasing their potential to address water scarcity issues. Additionally, FPV systems have been suggested for pump irrigation systems [120,121], offering sustainable solutions for agricultural water management. In a case study conducted in Spain, Osorio et al. [122] demonstrated that floatovoltaics, when combined with agrivoltaics, can generate high income and benefit farmers. In this application, it should be noted that the size of a PV array in a water body is directly related to the electricity generation capacity. Reges et al. [123] proposed a simple method for determining the size of the PV array by analysing historical data on water reservoirs. Yilmaz et al. [85] successfully demonstrated the use of satellite images of the water body to optimize the location and size of FPV setups. By tuning the Hue-Saturation value, they could identify optimal locations while also identifying areas with shading or sand deposits, thereby optimizing the extension of the PV array.

6.2. Marine based floating solar photovoltaics

The potential of ocean-based FPV systems is undeniable, offering a vast and untapped resource for renewable energy generation. Although offshore-based FPV technology is still in the developmental stage, its deployment holds the promise of significant milestones in the energy sector. For instance, the utilization of ocean-based FPV could enable countries like the Maldives to fulfil their entire electricity demand [124]. While the adverse effects of FPV in inland water bodies require thorough examination, the exploration of FPV feasibility in marine environments has already commenced [35,36]. China's installation of a pilot-scale marine FPV system marks a significant step in this direction [35,36].

However, deploying FPV systems in marine environments presents unique challenges, including harsh waves, strong winds, corrosion, and the corrosive nature of seawater, among others [125]. To address these challenges, Claus et al. [29] propose innovative solutions such as pontoon-type floats made of HDPE material, Fiber Reinforced Plastic, over-coatings, and encapsulation for FPV in the marine environment. They also suggested for adapting mooring and anchoring techniques similar to those used in ships for FPV systems in marine environments. Other strategies such as column-stabilized systems have also been suggested as viable alternatives in some studies [126]. Meanwhile, several researchers argued that pontoon structures may not be suitable for the marine environment, instead, they proposed the use of thin film solar PV [49,126]. Abbasnia et al. [127] proposed a novel twin hull double circular cylinder FPV platform design to withstand marine loads. Nevertheless, numerical and experimental investigation of the structure raised concern about its stability [127]. To address this stability issue, several strategies have been proposed. Floating structures protected with porous polypropylene sheets have been demonstrated encouraging results by diminishing the impact of the wave over the stability of the FPV system [128]. Moreover, research on low-weight, soft, and circular partially submerged floats for FPV systems has demonstrated good performance against harsh waves exceeding 10 meters in height [129]. Further research is underway to develop stable structures tailored specifically for FPV deployment in marine environments [130,131]. These studies aim to address the unique challenges posed by marine conditions and optimize the design and performance of FPV systems in such environments.

6.3. Economical aspects

The economic viability of any advanced technology is crucial for its competitiveness in the global market. Typically, this is assessed using the Levelized Cost of Energy (LCOE) in the energy sector, representing the average price of a unit energy [132]. However, the LCOE is not static and varies depending on various factors, including location [133]. The LCOE range of a grid-tied solar PV is predicted to be $0.19 to $0.21/kWh in 2019 [134]. Meanwhile, the projected average LCOE of conventional solar PV is $70/MWh in 2022 [135]. In the case of FPV systems, economic analyses have indicated a potential reduction in LCOE compared to conventional solar PV systems, with a projected decrease of 22.23% [136]. Specific studies have reported even lower LCOE values for FPV, such as $0.056/kWh in Bangladesh [137] and $46/MWh for a 50 MW plant in India [138]. Comparative LCOE analysis using Homer Pro software for the Bhilai steel plant of Chhattisgarh, India, estimated the corresponding value of $0.10 and $0.03 for conventional grid-connected PV and grid-connected FPV system with a price difference of $0.07 in favour of FPV [139]. Makhija et al. [140] performed FPV analysis using SAM software and found a reduction of cost from $0.0598 to $0.0538 per kWh. They also stated that the additional energy production by FPV is equivalent to 454 houses' electricity supply. In Iran, significant differences in LCOE between FPV and LPV systems have been observed, with FPV showing lower price of 5722 IRR/kWh compared to 7631 IRR/kWh for LPV [50]. Similarly, economic assessments in other regions, such as Vietnam, have suggested that FPV systems offer greater feasibility and effectiveness in terms of recovering capital investments based on available resources [141].

In contrast, a study in Europe predicts that the LCOE of FPV can only match that of LPV by the year 2050 [39]. This projection emphasizes the significant cost savings associated with land use, thereby affirming the long-term economic stability of FPV systems. This finding is echoed by Cazzaniga and Rosa-clot [76] in their analysis. However, the economic viability of FPV compared to LPV is heavily influenced by meteorological parameters, which directly impact FPV performance [31]. Despite the initial capital investment for FPV being reported to be 25% to 30% higher than that of LPV due to additional components like the floating structure [38,142], studies suggest that the inherent increase in energy production from FPV can potentially decrease the LCOE by up to 85% [142]. Moreover, the indirect benefits of FPV, such as emissions control and reduced water evaporation, contribute to its economic feasibility. Conservation of water through evaporation reduction can serve multiple purposes, including drinking, irrigation, and industrial use [143]. This can lead to cost savings related to water procurement, treatment, and distribution, as well as reduced operational expenses for industries reliant on water resources. Additionally, the shading provided by FPV systems helps prevent the overgrowth of algae [142], reducing costs associated with algae removal in water treatment, and maintaining the ecological balance of aquatic ecosystems. Furthermore, the conserved water can be utilized in hydroelectric plants for clean electricity generation, reducing reliance on coal-based power generation and minimizing greenhouse gas emissions [57]. Lastly, it is estimated that the installation of FPV systems could lead to an annual reduction of 3.30 million tons of CO_2 emissions [144]. With the current trend of carbon taxing and increasing emphasis on carbon footprint reduction, such emissions reductions can translate into significant cost savings and environmental benefits for both governments and businesses alike, as they may avoid or reduce carbon taxes and penalties while enhancing their environmental reputation and potentially accessing carbon credit markets for additional revenue streams.

6.4. Environmental aspects

The potential impacts of FPV systems on the ecological balance, particularly their effects on aquatic ecosystems, remain subject to further exploration and study. A study examining the environmental impact of FPV in Büyükçekmece Lake in Turkey found no adverse effects [38]. In other studies, however, FPV systems have been observed to alter various water parameters such as temperature, pH, and dissolved oxygen, which can affect aquatic plants and organisms [145,146]. For instance, in a case study at the Xiangjiaba hydropower reservoir in China, FPV-induced temperature changes in the water body led to increased fish spawning rates during seasonal changes [145]. Additionally, the use of aerators powered by FPV systems supplied sufficient dissolved oxygen, resulting in increased growth rates of cultured species compared to normal production rates [145]. In another case study, the dissolved oxygen content increased from 3.2 mg/L to 4.4 mg/L through the use of an aerator powered by the same FPV system [147]. Furthermore, FPV installations covering water bodies have been associated with higher oxidation–reduction potential, resulting in the increased production of the cultured species with more nitrification [145].

The above findings underscore the importance of considering ecological factors in renewable energy planning. Despite the potential benefits of FPV installations, careful site selection is crucial to minimize negative impacts on ecosystems. For instance, it is estimated that Turkey can generate 125 TWh energy per year from its 25 hydrological river basins with FPV in just 10% of its water surfaces despite only 2755 was selected of 4003 river branches [148]. The study filtered small water bodies, national nature parks, environmental reserve areas and locally important wetlands that are necessary for the ecosystem [148]. This approach effectively balances the diversity of nature while meeting the growing energy demands sustainably. Similarly, in Spain, deploying 490 MWp of FPV over 25% of the surface area of agricultural ponds can meet a significant portion of energy demand, including agricultural electricity needs, with minimal impact on water quality [149]. Likewise, an analysis of FPV in irrigation reservoirs in Albania emphasizes the importance of considering geophysical and hydro-meteorological parameters to avoid disrupting primary usage [108]. This conscientious approach not only maximizes the potential benefits of renewable energy but also minimizes the negative impacts on ecosystems.

As previously discussed, FPV systems have been observed to reduce the intensity of sunlight, consequently impacting the photosynthesis reaction [150,151]. This reduction in sunlight intensity plays a crucial role in preventing the growth of weed plants in water bodies. Water hyacinth, a widespread weed plant, has become a serious concern for many countries due to its adverse effects on aquatic ecosystems [152]. The detrimental effects of water hyacinth are well-documented, including decreased dissolved oxygen levels, alterations in pH levels, changes in water quality, disruption of natural bio, physical, and chemical processes, and obstruction of water flow [153,154]. One example of addressing this issue is seen in the Cirata river of Indonesia, where the area of water hyacinth spread was assessed using the Earth Observatory System. Subsequently, FPV installation was proposed as a means to mitigate the growth of these invasive aquatic plants [155]. Besides preventing the growth of weed plants in water bodies, FPV systems offer other environmental benefits by reducing CO_2 emissions. This benefit can be maximized by introducing a tracking system where Ravichandran et al. [95] suggested that FPV equipped with a single axis tracking system performs 12% higher in CO_2 emission control than the fixed system. A similar study by Mirzaei Omrani [87] on the environmental impact of FPV did not observe any CO_2 or NOx emission.

6.5. Public acceptance

In addition to technical evaluations, public perception of FPV systems is also being studied. An investigation into the acceptance rate for establishing an FPV system in Oostvoornse Lake, Netherlands, revealed mixed responses [156]. While amateur re-creationists showed positive feedback on the FPV projects, local stakeholders expressed opposition to the construction. Such surveys provide valuable insights into societal values, perceptions, and potential impacts on various aspects including socioeconomic factors, ecology, culture, and landscape. Furthermore, an analysis conducted by Yingjie et al. in the Huainan city of China found that FPV systems can raise the ground temperature within a radius of 200 m from their location, contributing to global warming [157]. This finding suggests that FPV installations may face disapproval from nearby communities, underscoring the importance of raising public awareness about the environmental implications to ensure the preservation of ecosystems.

6.6. Other challenges

The advancement of FPV technology faces several challenges from an industrial perspective [158–162]. One significant barrier is the lack of established policies, incentives, and subsidies to support FPV development. Additionally, there is a need for standardization in the installation procedures, requirements, and guidelines for FPV technology. The combination of electricity and water in FPV installations presents safety risks that must be carefully addressed. Moreover, the installation and maintenance of transmission infrastructure near water bodies require heightened vigilance. Furthermore, the potential for FPV expansion is constrained by the limited availability of suitable water bodies for deployment.

In addition, structural challenges, particularly regarding the durability of FPV systems in diverse water bodies, have not been thoroughly investigated. Concerns include degradation, corrosion, friction, and stress on moving parts, which may lead to catastrophic failures, especially during climate change and floods. The safety of large floating structures is another major consideration, as high wind forces can potentially collapse the floating structure [163]. Additionally, the effectiveness of mooring and anchoring systems varies with water levels, necessitating a comprehensive understanding of water body topography and the suitability of anchorage for floats. Boduch et al. [164] highlighted the challenge of inappropriate tilt angles of solar panels available in the market, making FPV installation difficult in certain regions like Poland. It highlights the need for the availability of well-designed PV panels in the market. Moreover, the higher energy yield by the cooling effect of FPV can only be achieved at high ambient temperatures. For example, in a study by Qianfeng Ji et al. [165], the higher energy yield due to the cooling effect was observed at temperatures of 24 °C and 37 °C, while no performance change was observed at 6 °C or 16 °C. This limitation undermines the potential benefit of FPV installation in cold regions.

7. Future direction

The rapid growth of floating solar PV indicates a promising trajectory for the technology in the coming decade. Looking ahead, it becomes increasingly clear that FPV offers substantial advantages over traditional PV systems, with consistently higher energy yield and efficiency. This promising trend not only emphasize the potential of FPV but also provides valuable insights for stakeholders and promoters seeking to capitalize on its market expansion. However, amidst this growth, the evolving landscape of FPV and the emerging challenges it faces must be recognized. In this section, the future direction of FPV is presented and discussed, examining both its opportunities and the obstacles that lie ahead.

- Considering the cost efficiency of research, manual data monitoring and recording can be performed for short durations using digital meters or Solar Analyzer devices [40,42,43,45]. However, this approach presents challenges such as long frequency gaps in data collection, manual errors, health issues due to prolonged exposure to sunlight, and limitations in analysing data under harsh weather conditions. For more convenient and continuous monitoring, micro-controller boards or single-board computers like Arduino Uno can be utilized, albeit requiring computer programming skills [34,42]. Alternatively, for long-term analysis, the use of a data logger is recommended, although the cost of these devices can be high [41]. Thus, it would be beneficial to explore and develop automated data monitoring and recording systems for FPV installations. This could involve the integration of sensors and data logging devices that are specifically designed for outdoor environments and capable of withstanding harsh weather conditions. Additionally, research focusing on the development of cost-effective and user-friendly monitoring solutions, such as low-cost data loggers or wireless sensor networks, could greatly improve the efficiency and accessibility of data collection in FPV systems. Moreover, investigating novel approaches for data analysis and interpretation, including machine learning algorithms or artificial intelligence techniques, could provide valuable insights into the performance and optimization of FPV installations over time.

- The concern of environmental impact contributed by FPV is highlighted positively in most studies [145–147,165]. However, some studies highlighted that FPV systems can raise the ground temperature within a radius of 200 m from their location. Therefore, further exploration and analysis of the environmental impact are highly encouraged to provide robust evidence for the stable establishment of FPV in different water bodies.
- As discussed in the previous section, several studies explore FPV system hybridization and advanced technology incorporation, to improve the reduction of greenhouse effects. While these advancements are commendable, their feasibility, both from a technical and economic standpoint, remains crucial for their practical implementation. Thus, future studies should be directed towards assessing the technical viability and economic sustainability of these integrated FPV systems, ensuring their effectiveness in mitigating greenhouse gas emissions.
- The development of offshore-based FPV represents a significant milestone in the energy sector. Recent studies indicate rapid progress in developing stable structures for marine or ocean-based FPV systems. This progress is fuelled by strong interest groups and ongoing technological advancements. However, the development of these robust floating structures faces challenges in navigating rough sea environments and implementing rigorous maintenance protocols, leading to relatively slow progress in this area. Thus, further research and development are required to address this issue by focusing on enhancing structural integrity, improving maintenance efficiency, and optimizing performance in harsh marine conditions.
- The existing techno-economic analyses and predictions on FPV performance often rely on software tools, which offer advantages in terms of cost, time, and resource efficiency compared to traditional research methods. However, these software tools often require significant modifications to their user interfaces to adequately accommodate the unique characteristics and requirements of FPV systems. Additionally, some studies have found that even reputable solar PV software may not be fully capable of accurately predicting the performance of FPV systems. Therefore, there is a pressing need for further development of software dedicated to numerical modelling and prediction specifically tailored for FPV applications. This development would enable more accurate and reliable assessments of FPV performance, contributing to the advancement and widespread adoption of the technology in the renewable energy sector.
- The Levelized Cost of Energy associated with FPV systems is generally lower compared to other energy sources. However, in some countries, the initial investment may still pose affordability challenges. To achieve stable economic feasibility and ensure widespread adoption, FPV technology requires further enhancements aimed at increasing its energy yield. This could involve the implementation of more efficient energy management systems or additional advancements in the technology itself. By improving energy yield and reducing overall costs, FPV systems can become more economically viable and accessible, contributing to global efforts towards sustainable energy transition.

8. Concluding remarks

The development of floating solar photovoltaics (FPV) represents a significant advancement in renewable energy technology, offering high energy output with minimal environmental impact. However, to fully realize its potential, further improvements in FPV technology are needed, particularly in floating structure design, instrumentation, and monitoring systems. Addressing challenges such as safety concerns, standardization issues, and policy considerations will be crucial for the widespread adoption of FPV systems. Nonetheless, with continued innovation and technological advancements, FPV has the potential to play a significant role in global energy production, providing a sustainable alternative to fossil fuels and contributing to the transition to a cleaner and more environmentally friendly energy landscape.

Looking ahead, future studies should explore and develop automated data monitoring and recording systems for FPV installations to improve the efficiency and accessibility of data collection. Additionally, further research is needed to assess the environmental impact of FPV systems, particularly in terms of ground temperature effects and their implications for different water bodies. Evaluation of the technical viability and economic sustainability of integrated FPV systems is essential for their practical implementation and effectiveness in mitigating greenhouse gas emissions.

Moreover, further development of software dedicated to numerical modelling and prediction tailored for FPV applications is necessary to enable accurate assessments of FPV performance. Enhancements in energy management systems and technology advancements aimed at increasing energy yield will be crucial for achieving stable economic feasibility and widespread adoption of FPV technology. With these efforts, FPV holds great promise as a key player in shaping a more sustainable energy future.

CRediT authorship contribution statement

Ramanan C.J.: Writing – original draft, Conceptualization, Data curation, Methodology. **King Hann Lim:** Conceptualization, Funding acquisition, Supervision, Review & editing. **Jundika Candra Kurnia:** Conceptualization, Review & editing, Supervision. **Sukanta Roy:** Funding acquisition, Review & suggestion, Supervision. **Bhaskor Jyoti Bora:** Review & suggestion, Supervision. **Bhaskar Jyoti Medhi:** Review & suggestion, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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