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Review article

An assessment of floating photovoltaic systems and energy storage methods: A comprehensive review

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ABSTRACT

In recent years, floating photovoltaic (FPV) systems have emerged as a promising technology for generating renewable energy using the surface of water bodies such as reservoirs, lakes, and oceans. FPV systems offer several advantages over traditional land-based solar arrays, including increased land-use efficiency, reduced water evaporation, and improved cooling and maintenance. However, like all solar power systems, FPVs are subject to variability and intermittency due to changes in weather, seasons, and time of day. The environmental impact is discussed along with the deployment consideration and the feasibility for a better understanding of the system. Challenges associated with this are addressed by progressed research suggesting the integration of FPVs with various energy storage and hybrid systems. The most promising areas researched in this paper look at hybrid FPV hydropower plants (HPP), in parts of the world experiencing droughts HPP is not working to its optimum capacity. A review of available literature has been conducted on the topic of offshore and onshore floating solar electricity generation using floating solar photovoltaics to identify the challenges and opportunities presented. This work looks at a variety of other hybrid FPV energy sources with varying technology readiness levels. This paper concludes with the possibility of integrating different renewable technologies with existing FPVs and highlights the boons of doing so with some examples. Ultimately, current as well as future perspectives have been provided which consolidate the current research being done and give recommendations for future research work.

1. Introduction

One of the biggest challenges that is faced by the world is global warming due to which both humans and the planet are suffering as a whole, this is directly linked to the burning of the fossil fuels that we rely on to facilitate our daily life. The Intergovernmental Panel on Climate Change (IPCC) set out the impacts of global warming 1.5 °C above preindustrial levels [1]. We are not currently on course to limit 21st-century global warming to under 1.5 °C or even 2 °C [2]. Another key issue is the lack of clean electrification for a vast population which is hampering the development of the planet in tackling the climate change issue as many rely on the burning of fossil fuel for various daily requirements from generating electricity to cooking. It has been estimated that about 675 million people are still forced to live in the dark most of them belong to sub-Saharan Africa according to 2021 data. Though there has been an increase in the rate of access to electricity from 87% in 2015 to 91% in 2019, this has provided electricity to nearly 800 million people [3]. This is where solar PV can play a substantial role, solar PV has the benefit of being a renewable energy source, producing electricity from solar irradiance without any greenhouse emission [4].

However, there are challenges that must be addressed in order to fully realize the potential of solar energy and traditional photovoltaics [5]. These challenges include land usage, intermittency, storage, and integration into existing energy grids. One promising and upcoming alternative to traditional land-based photovoltaics is Floating Photovoltaics (FPV) or flotavoltaics [6]. The majority of renewable energy sources, such as biomass, solar, and others, take considerable footprint areas to generate electricity on a larger scale, which restricts the use of land for agriculture [7–9]. This sparked the discussion over whether land should be used for food production or energy production [10,11], encouraging research into offshore renewable technologies [12], and led to the creation of the floating photovoltaic (PV) array concept for the production of commercial electricity [13]. FPV technology is a concept

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Nomenclature

CAES	Compressed air energy storage
CAPEX	Capital expenditure
DIRφ	Direct diffuse irradiance (*W/m2*)
DIFφ	Diffuse irradiance (*W/m2*)
ESOI	Energy storage on investment
EST	Energy storage technology
FPV	Floating photovoltaic
GTI	Irradiance on the surface of a tilted plane (*W/m2*)
HPP	Hydro power plant
IPCC	Intergovernmental panel on climate change
IRR	Internal rate of return
MEPCM	Micro-enhanced phase change material
PHS	Pumped hydro storage
TES	Thermal energy storage
Rφ	Reflected irradiance (*W/m2*)
β	Surface tile angle (°)
γ	Azimuth angle (°)

in which solar panels are placed on platforms that float on water bodies such as natural lakes, man-made reservoirs, and the seas and oceans [14]. Fig. 1 shows a typical standalone floating photovoltaic system with all the components including an inverter, pontoons, solar panels, and cables connected to the grid.

There is a huge potential for electricity generation by utilizing the water surface for the production of power. The oceans receive 70% of the global primary energy resource, radiation from the sun [16]. Harnessing just a fraction of this would boost global renewable generation. Offshore electricity generation will also prove to be a good way of supplying electricity to coastal regions, where 50% of the world's population lives within 100 km of the coast [17], with minimal transmission losses. There is also potential for supplying electricity for ships and offshore platforms [18] considerably reducing CO_2 emissions. The offshore environment presents many challenges but equally poses opportunities for increased yield and high-efficiency solar farms. This report will detail the technical and economic challenges and opportunities presented by offshore solar generation by assessing and reviewing relevant available literature. Table 1 shows the comparison between the floating photovoltaic and ground-mounted photovoltaic.

Despite the various advantages of FPV over on-ground photovoltaics, neither of these technologies solves the problem of energy storage.

Table 1
Comparison of floating photovoltaic systems and ground-based photovoltaic systems [19].

	Floating PV	Ground-based PV
Maturity	Over 350 projects operational so far	Over 1000 projects were built
Energy Yield	• Change in performance due to temperature is significantly low. •Bifacial module can be used due to reflection from water. •Lower soiling impact, though bird dropping might be an issue. •Movement due to wave and wind must be considered during theoretical analysis. •Shading impact is negligible	•Significant reduction in power generation due to rise in temperature. •Ground type influences the albedo impact. •Prominent soiling impact depending on the location. •Rigid structure •Shading loss due to surrounding
Regulation	Licensing and permission an issue due to a lack of clear ownership	Clear guidance regarding permission
Investment	•Site cost is low. •Structural costs are related to floats, anchoring, mooring and plant design	•Land acquisition increases the capital cost. •Structural cost is lower
Environmental impact	Reduction in water evaporation	Loss of agricultural land
Installation and deployment	Easy assemble and deposition	Installation depends on the quality of soil
Testing and grounding	International standards not yet available	Testing and grounding facility available

When it comes to utilizing renewable energy sources, energy storage is essential for reducing uncertainty and fluctuations and boosting their dependability and sustainability [20,21]. Storage systems are suggested to store the generated energy so that it can be used again during times of high demand in order to address energy generation and consumption imbalances [22]. There can be many energy storage technologies (EST) ranging from mechanical to electrical and electrochemical systems [23]. Fig. 2 represents the development of the FPV system over time. Over the years, FPV technology has developed starting from a prototype developed in Aichi province in Japan [24] while the first commercial one was installed in California, United States [25]. The first hybrid FPV came into existence in Portugal with a pumped storage hydropower reservoir.

This paper reviews the available literature on offshore FPV and the existing technologies and investigates the potential hybrid systems with energy storage along with a comparison with the conventional land-based photovoltaic system. Thorough research has been done on

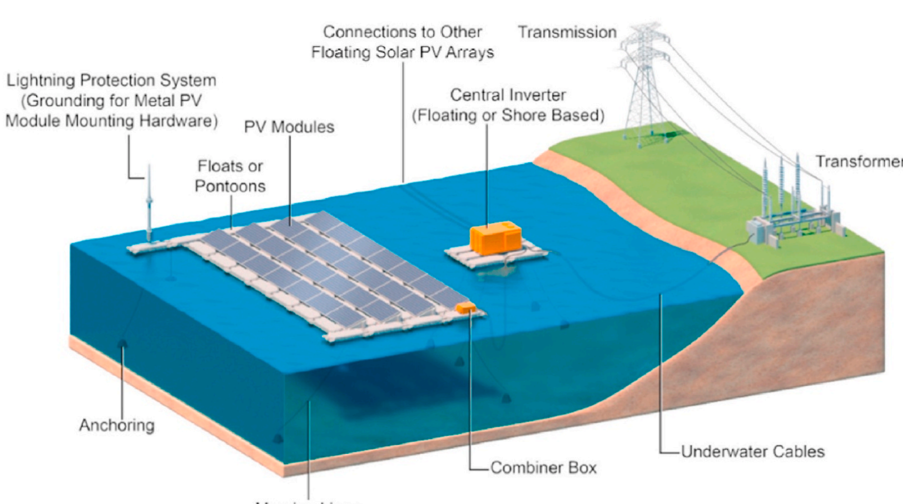

Fig. 1. Example of a standalone floating photovoltaic system, adapted from [15].

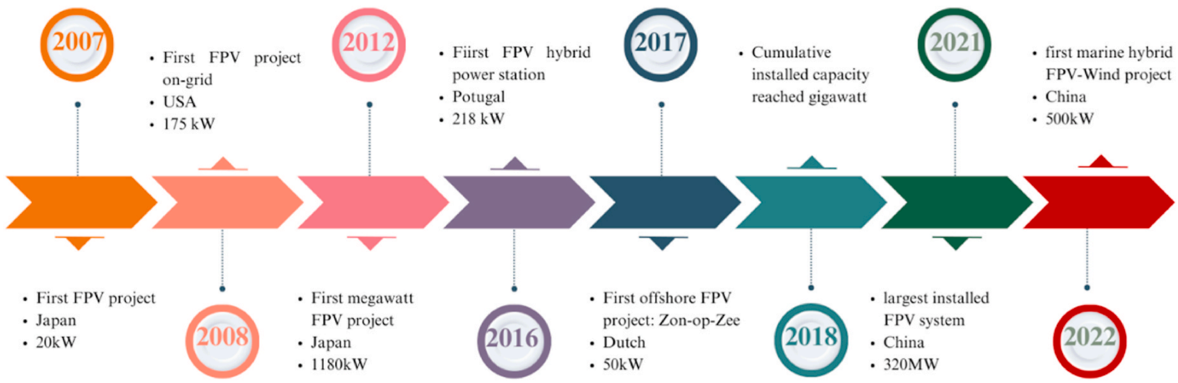

Fig. 2. Advancement in the floating photovoltaic over the period.

different topics related to this technology which has been showcased through the explanation of the principle of each energy storage technology and previous work done on the integration of floating photovoltaic and storage as well as elucidation of research gaps.

2. Floating photovoltaic (Flotavoltaics/FPV)

A FPV system is a recent technology that amends the existing issues associated with ground-based photovoltaic to some extent by installing a photovoltaic array on the water bodies instead of rooftops or ground [19]. The first FPV system was installed by the Institute of Advanced Industrial Science and Technology (AIST), Japan as a prototype in 2007 with a capacity of 20 kW [26]. However, the first commercial FPV system came into existence in 2008, when a 175 kW system was installed over an irrigation pond at the Far Niente Winery in California due to the high cost of land acquisition which discouraged large-scale system installation [27]. In the last decade, many countries have installed flotavoltaic systems generating a total power of about 134,308 kW till 2017 [28]. In 2023, a 192 MWp FPV system was deployed in West Java, Indonesia at Cirata Hydropower reservoir that is estimated to power 50, 000 homes. This is also the largest FPV to be installed on a reservoir with a depth of 100 m and with a water fluctuation difference of 18 m–50 m in water bottom elevation [29]. Countries like Singapore and South Korea which have a scarcity of land are implying this technology to fulfil their electricity demand. This can also help in achieving affordable and clean energy and climate action targets for the United Nations.

2.1. Advantages of floating photovoltaic

Water is a cooling agent and since these photovoltaic systems are on water bodies, they experience a cooling effect which assists in lowering the temperature of the system and enhancing the overall performance [30]. Loss of water due to evaporation is a huge concern in many parts of the world especially places experiencing water shortage, as the water is covered by the floating photovoltaic array the area of the surface in direct contact with the sunlight hence reducing the evaporation rate [25]. It has been estimated that about 42 million litres of water were saved from evaporation in Visakhapatnam, India after the installation of 1 MW of floating photovoltaic system [31]. The floating photovoltaics have a better performance rate compared to conventional ones by 10% reducing water evaporation by up to 70% from water bodies [32]. This has also led to a decline in algae bloom resulting in the chlorophyll and nitrate level of the water body, improving the water quality along with decreasing evaporation by 60% [33,34]. The elimination of land acquisition has encouraged many countries to consider this technology especially those with high populations and limited land available for the installation of ground photovoltaic [13]. Soiling and shading have always impacted the performance of photovoltaic systems by reducing the output, floating photovoltaic modules experience less accumulation of dust due to the water bodies [34–37].

2.2. Disadvantages of floating photovoltaic

Floating photovoltaic systems have been observed to experience higher humidity as compared to ground photovoltaic which has increased the temperature of the system thus altering the performance of the array [38]. There is a risk of aquatic life getting entangled in the cables and mooring lines, however, this can be overcome by using cables of increased diameter and taut mooring [39]. There is a risk of corrosion and degradation of the photovoltaic panels in the water due to moisture [40]. The cables attached to the floating photovoltaic system tend to radiate electromagnetic fields which can hinder the aquatic animals [41].

2.3. FPV design

A typical floating photovoltaic system consists of different components including photovoltaic panels, mounting structure, mooring lines and anchoring, inverter, transformer, and transmission cables [42]. An addition of a battery system can enhance the performance of the system drastically by eliminating fluctuation and providing a storage system for the surplus energy produced during the day.

2.3.1. Module types

PV modules type for the FPV application can be categorised into four groups [43]; Thin film, submerged, tilted arrays, and micro-encapsulated phase change material (MEPCM). However, the common type of PV modules used for this application is first-generation silicon-based modules. Thin film FPV does not require a strong pontoon support structure as the panels are relatively light compared to conventional silicon panels. Submerged panels can be installed with or without a pontoon and the generation capacity varies with submersion depth. Tilted arrays require a rigid pontoon to support the weight of the panels and MEPCM is still a new concept, however, would require a pontoon for support [43].

For thin-film PV, amorphous silicon is the popular choice. The flexible thin film panel has the advantage of being able to adapt to the dynamic surface of the sea and yield to the oncoming waves [9]. Trapani et al. (2013) propose a flexible thin film PV, encapsulated in a buoyant, marinised laminate, floating directly on the water surface. Placing the panels in direct contact with the water's surface aids in cooling the panels and maintaining high-efficiency electricity production. The water then acts as a heat sink and the more constant temperature of the sea allows for more consistent production year-round. It is estimated that when the panel is in direct equilibrium with the water, the panel will be around 20 °C less than an equivalent ground-mounted panel. This could result in a 4% improvement in efficiency over an array of FPV panels [9]. A disadvantage of this technology however is its inability to orientate to the optimal tilt angle thereby not optimizing output yield. The efficiency of thin film PV compared to poly or mono-crystalline PV also is considered to be a drawback to this floating design. There may also be a reduction in electrical reliability due to saturation of the thin film PV [9]. A thin layer of water on top of the panel (<2 mm) does not affect the impacted solar radiation and will instead enhance the temperature control of the panel. To ensure the stability of the module on the water surface, mooring is required to secure the assigned place, limiting free movement, and preventing possible damage to the module. Different types of mooring systems are employed depending on the nature of the water and location. Fig. 3 (a) shows the rigid mooring system which consists of an anchored rigid pile that limits horizontal movement and allows vertical movements making it economically viable for shallow water. Fig. 3(b) depicts a taut mooring that utilizes surplus buoyancy to maintain tension in the mooring lines limiting the vertical motion posing a challenge for significant water level fluctuations. Another important type of mooring system is the catenary mooring system as presented in Fig. 3(c) which generally consists of chains that use their weight to impart spring-like characteristics to moored float and respond adequately to water level fluctuation. Compliant moorings are similar to catenary moorings that use more than one weight as anchors to adjust the layout of mooring lines limiting vertical motion as shown in Fig. 3(d) [44].

2.4. Bifacial PV for FPV

Bifacial PV systems offer greater opportunities for power production due to their ability to exploit irradiance on the rear side of the panel as well as the front side [45]. However, in order to get a substantial benefit from Bifacial systems, it is necessary to maximize the surface albedo [46]. This is generally low for water so may limit the bifacial gain possible for the system [47]. A study was conducted to evaluate the comparative performance of monofacial and bifacial floating PV systems, it was found that the bifacial gain of the system was higher for locations that had a higher proportion of diffuse light [48]. The results of this study however do not seem to be true for just floating PV systems, as it is well documented that bifacial gain is higher under conditions in which there is a higher fraction of diffuse irradiance [49]. A study was conducted to investigate the effect of orientation on bifacial gain on systems with a tilt angle of 30° [50].

It found that for a north/south orientation, bifacial modules were able to receive 55% more irradiance than the monofacial modules, it also found that for panels oriented in an east/west orientation, there was still an advantage, however, it was decreased to 31% [51]. In order to gain a benefit from bifacial modules, they must be mounted at an angle large enough for the rear side to receive sufficient irradiance [52]. With this in mind, there is a compromise that must be made when using bifacial panels for a floating PV system, to make use of the cooling effect of water and increase the electrical efficiency of the system, the panels must be mounted close to the surface, though doing this could nullify the benefit received from the bifacial panel [53]. When the water body is static then albedo impact is experienced leading to a change in the net radiation received which impacts the latent heat of the water bodies. The surface albedo of static water is of great importance due because it the water-air interaction improves the parameterization of the hydrological surface process. In an experiment where albedo was calculated for different water bodies, it was concluded that the albedo values were between 0.04 and 0.28 while most lakes had more than 0.10. At the same time, it was observed that albedo is affected by multiple factors water quality, wind speed, and solar altitude angle [54]. Fig. 4 shows the albedo of onshore and offshore in Singapore.

2.4.1. Module tilt

Power output from offshore PV is dependent on the solar resource and the panel's location. The type of panel and the orientation of the panels also influence the power output. Many papers list the varying tilt angle as a potential barrier to developing competitive FPV farms. The issue is addressed by Golroodbari and van Sark in which it was found that the varying tilt angle due to the motion of the waves away from optimum does not significantly decrease output [43]. Therefore, it is concluded that the light incident of the panel is irrespective of irradiance type, making it possible to calculate the front and the rear irradiance. The surface irradiance on the panel can be expressed as the sum of direct irradiance, irradiance due to ground reflection, and diffused irradiance.

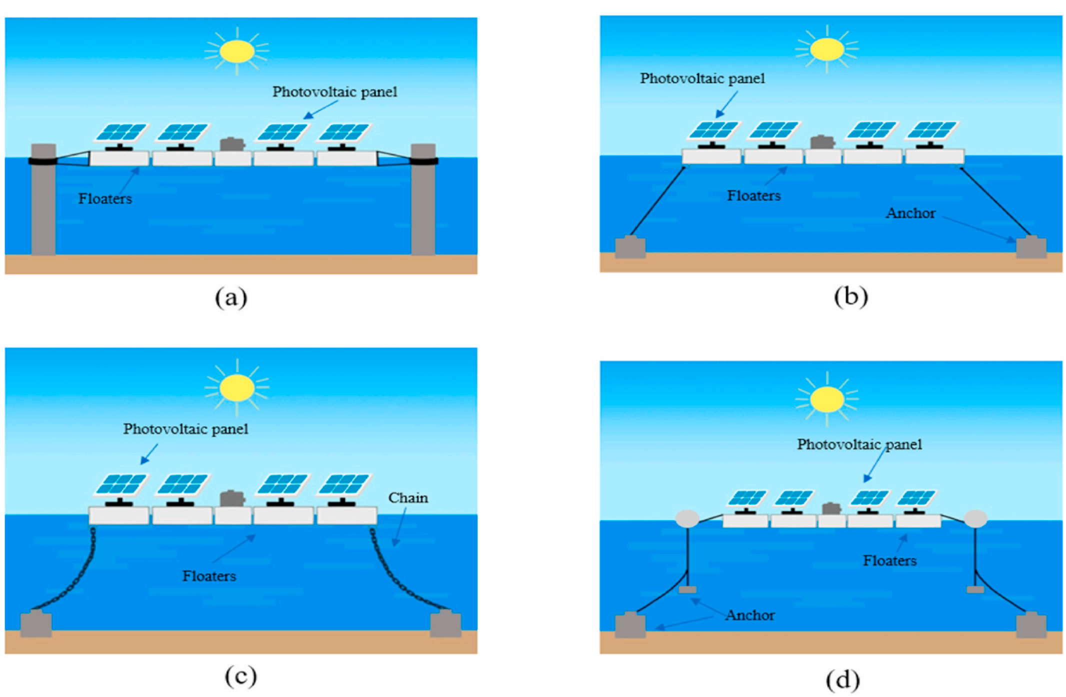

Fig. 3. Schematics showing the different possible mooring systems for floating photovoltaic systems. (a) Rigid mooring system, (b) Taut mooring system, (c) Catenary mooring system and (d) Compliant mooring system.

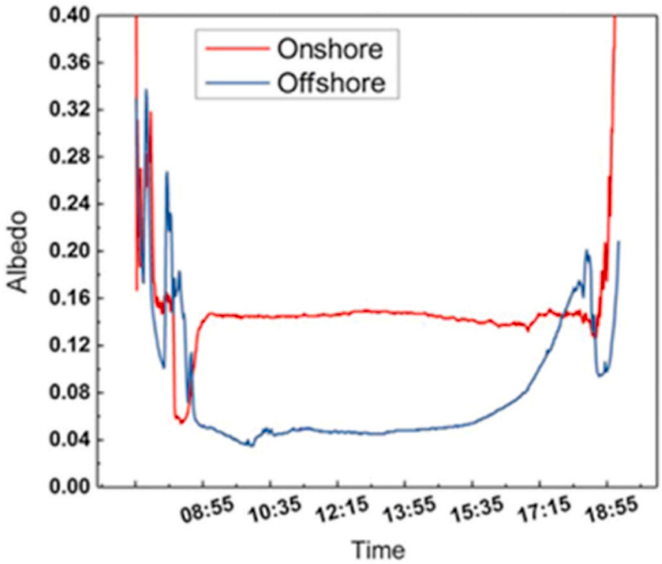

Fig. 4. Comparison of onshore and offshore albedo in Singapore [55].

The irradiation over the surface of a tilted panel can be calculated from Equation (1) and used when calculating the power output considering the surface tilt angle and azimuth angle.

$$GTI = DIR_{\varphi} + DIF_{\varphi} + R_{\varphi} \tag{1}$$

where DIR_{φ} is the direct diffuse irradiance, DIF_{φ} is the diffuse irradiance and R_{φ} is the reflected irradiance. $\varphi = \{\beta, \gamma\}$ where β is the surface tilt angle and γ is the azimuth angle. Direct diffused irradiance due to tilt can be expressed as

$$DIR\ \varphi = B_h * r_b \tag{2}$$

Where B_h is direct normal irradiance and r_b is direct irradiance conversion factor which can be expressed as

$$r\_(b) = \max\left(0, \frac{\cos\theta}{\cos\theta z}\right) \tag{3}$$

where,

$$\cos\theta = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(\gamma_s\text{-}\gamma) \tag{4}$$

where θ_z is the solar zenith angle and γ_s is the azimuth angle [43].

The tilt angle is adjusted to account for the motion of the waves using the Joint North Sea Wave Project wave spectrum. It was found that for most of the day, the tilt angle varies only slightly, between 0° and 3°. Rarely did the tilt angle exceed 10° and only once in the measured time frame did it get to 20° [43]. The tilt angle varies more over the winter months which coincides with when the irradiation is lower.

2.4.2. Mounting structure

The floating structure is to give buoyancy and stability to the platform, it needs to be able to withstand large amounts of weight and have some flexibility to move with the surface of the water. They are normally constructed from a HDPE (High Density PolyEthylene) which avoids UV and weather corrosion [56]. A modular design allows flexibility in design, size, and shape for the user. This is not the only type of pontoon structure, there are 5 types of structures in the industry, and depending on environmental factors, one is chosen accordingly. The role of the mooring system is to keep the Floating PV structure in one place. The type used mainly depends on the geometry of the structure, wind load, float type, water depth, and variability of water level [57]. Mooring can be either with lines that run directly back to shore or anchored to the floor with a combination of chains and synthetic rope [58]. As Depth and other factors, increase anchoring/mooring systems get more complicated and more expensive [59].

2.5. FPV performance under cooler ambience

Solar PV systems, which are made with first or second-generation PV cells, possess temperature degradation [60,61]. Third-generation types such as perovskite [62], DSSC, and organics are less impacted by this temperature enhanced efficiency degradation [63]. FPV which mainly depends on the first generation can have a positive impact from the integration. The presence of water and wind produces less temperature, which creates, a lower ambient [64,65]. In addition, water transmits solar energy thus the temperature of the water body remains low compared to land, roof, or agri-based systems. Due to free circulation solar radiation mixes well with cooler water at the deep level. A high wind speed of 15 km/h had the potential to reduce 17% levelized cost of energy and 69.51 kg CO_2 emission [66]. In Singapore, FPV showed 5–10 C reduction in temperature compared to land-based [67]. In another work, passively cooled FPV showed 3-degree temperature reduction and over 17% electrical efficiency improvement [68].

2.6. Cost

The CAPEX for an FPV system is typically 25% higher than for ground-mounted solar farms due to the extra requirement for floats, moorings, and anchors [69]. Trapani et al. (2013) noted that any novel offshore technology has to compete with offshore wind to be commercially viable. As such, deploying an offshore solar farm that will be commercially competitive with offshore wind is challenging. The study however finds that thin film PV can be competitive with offshore wind in latitudes 45° N to 45° S [9]. Electricity generating potential for thin film PV per unit area is more than double that for wind, this implies that less than half the area would be required to produce the same amount of energy. Crystalline PV, in which additional costs for pontoons and protection from the dynamic environment [70], as well as being more expensive to produce in itself, brings the cost of such panels into a region not competitive with traditional offshore technologies.

Operation and Maintenance (O&M) costs are high for all offshore technologies and floating solar is the same. The marine environment poses challenges for the structures placed in them, requiring them to withstand extreme environmental forces and a corrosive environment. Hence, material choice is vital to minimise maintenance costs. When considering the most common failure for offshore technologies is from mechanical motion for power take off, which is not required for solar PV, in which solid-state technology generates electricity, Trapani et al. (2013) suggest that large-scale floating thin film PV could prove a more reliable technology than conventional offshore generation. This relates to the loading experienced by the mooring system. In a comparison done between floating photovoltaic and ground-mounted photovoltaic in the United States in 2021, it was observed that the levelized operation and maintenance cost was lower for floating photovoltaic as compared to ground-mounted. The levelized O&M for ground-mounted was found to be $18 while for floating photovoltaic was estimated to be $15.5 per kW annually for a 10 MW system [71]. Due to the unavailability of data for the rest of the world, the operation and maintenance cost could not be estimated for other places, however, from the example of the United States, similar outcomes can be assumed. Fig. 5 illustrates the cost of installing floating photovoltaic systems in different parts of the world depending on the latitude in US dollars per MWh.

3. Hybrid systems

3.1. FPV with hydropower plants (HPP)

The integration of FPV has the greatest potential; the generation in 2021 was 4327 TWh, which was 0.4% lower than in 2020, because of

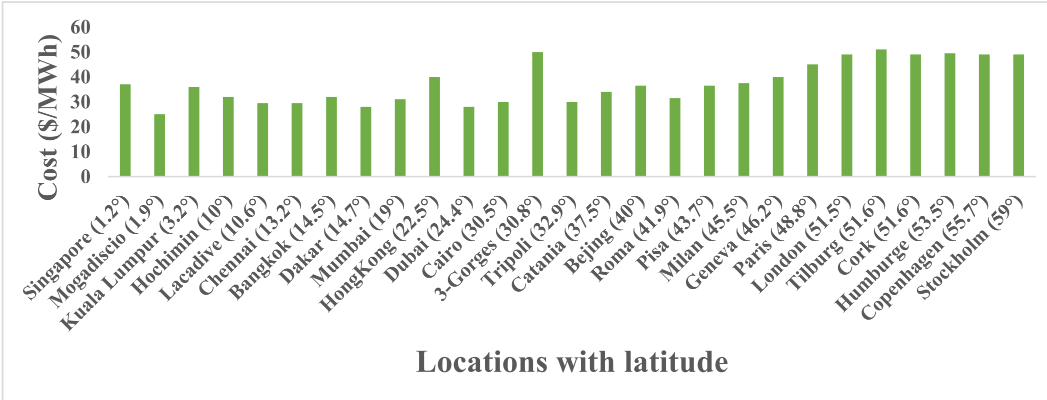

Fig. 5. Cost of solar energy production from 1 MWh FPV system according to the latitude and longitude.

several droughts around the world [72]. There are in excess of 60,000 large dams worldwide, with over 9000 of them being HPP [73]. These 9000 reservoirs cove an area of 265,700 km^2, if 25% of these reservoirs were covered with FPV they would be able to host 4400 GW of FPV [74]. Covering the water will reduce evaporation annually from somewhere between 7000–10,000 m^3 per MWp of installed capacity, this is based on studies from European countries [75]. Using these numbers, a rough estimation of water saved annually across the globe can be calculated as 30.1 billion m^3 of water every year; this was using the estimate from Quaranta et al. which is based on European reservoirs' evaporation rate.

Hydropower is expected to grow in the future due to new projects as well as the upgradation of existing HPPs [72]. A simple schematic of an FPV-HPP system is depicted in Fig. 6. FPV installed on HPP reservoirs would work on the principle of a complete injection of power generated by FPP during daytime into the grid while the HPP would adjust its supply accordingly. Such reservoirs can also be used for pumped hydro storage, since there is abundant water available for storage in an HPP reservoir. Pianco et al. carried out an in-depth analysis of the integration of FPV with HPPs in Brazil with data taken from an actual HPP [76]. The reservoir was estimated to have 19 GWh of energy storage capacity. They found that the inclusion of the FPV would not only result in an increase in generation but would also improve both the substation's and the transmission system's efficiency, allowing for an increase in energy supply without requiring increased capital for the transmission network. Hence, with the inclusion of FPV over only 2.8% of the available reservoir surface area, the capacity factor of the grid connection was increased by 50% from 0.4 to 0.6. The total energy output was increased by about 20 TWh, assuming a 20-year lifetime operational period without having any significant impact on water storage capacity and the level of the reservoir.

Similar results have been found in other research studies, with one study claiming that if 1% of reservoir surface area were to be covered by FPV, it would translate into a 5% increase in power production as opposed to just hydropower production [77]. Moreover, it was calculated that the water savings alone would lead to increased hydroelectric generation in the range of 16.17–892.90 GWh/year in Brazil alone [78]. El Hammoumi et al. found that the working temperature of FPV modules on a reservoir was always lower than land-based PV modules, with differences going up to 2.74 °C, resulting in an increase in generation of up to 2.33% [79]. Another study conducted in Iran calculated that using floating solar panels to cover just one square kilometre of some dams in Iran could provide enough electricity for roughly 90,000 people on average [80]. Such FPV systems would have a payback period of 5–6 years in terms of capital costs and 0.2 years in terms of carbon emissions. A research investigating the feasibility and potential of FPV on 146 largest African HPP water catchment areas found that 46 TWh of additional energy can be generated per year with FPV installed over an area covering less than 1% of such catchment areas [81]. Having FPV combined with HPP addresses issues with variability, they are complementary to each other. Fig. 7 illustrates the complementary nature across a

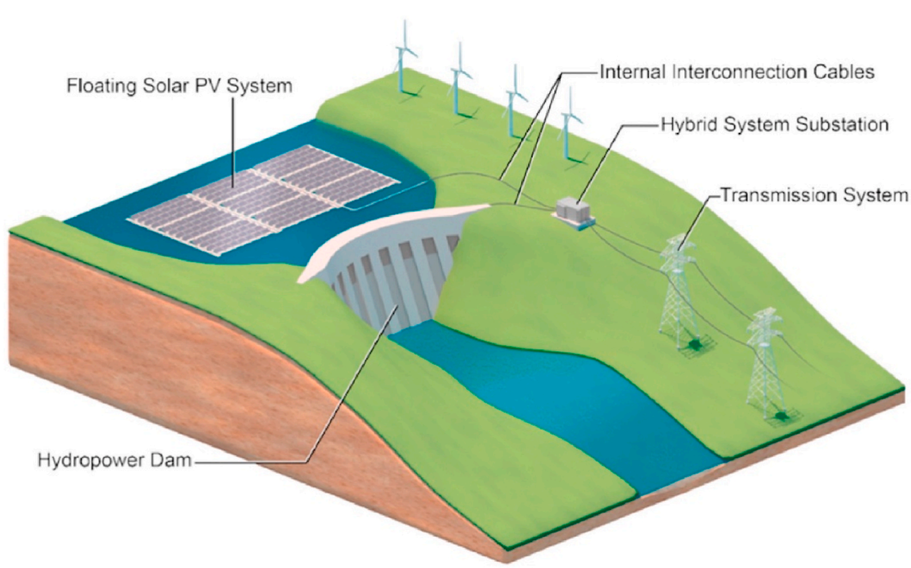

Fig. 6. Schematic of floating photovoltaic-integrated hydropower plant, adapted from [15].

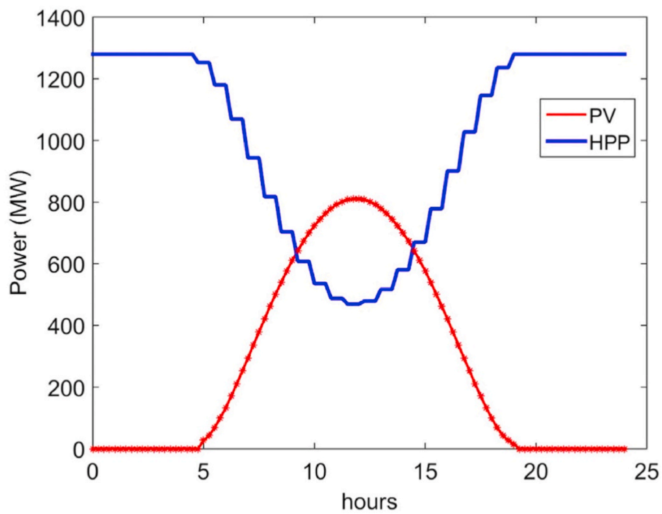

Fig. 7. Hydropower plant and floating photovoltaic power in MW across a summer day for the Longyanxia plant [75].

sunny summer day. The difference in peaks smooths out the power generation curve and makes it far more stable. Table 2 gives an estimation of the total power generation due to the integration of the hydropower plant with floating photovoltaic plant until 2018.

It can be observed from Table 2 that FPV-HPP integrated systems have gained a lot of industry as well as research interest in different countries around the world. However, the future application of FPV-integrated-HPP systems would require additional research before FPV plants could be installed on water surfaces. Research should focus on licencing and regulatory issues [83], environmental factors, including estimating the project's effect on the surrounding ecosystem, and all potential economic factors.

3.2. FPV with offshore wind

The combination of FPV and offshore wind is in its infancy, there is only one confirmed hybrid off-shore wind-solar power plant, and this was completed by China SPIC. Two floating arrays are moored up to an off-shore turbine with a shared submarine cable it has a peak capacity of 0.5 MW, with plans to upgrade the pilot project to 20 MW next year [84]. RWE and a company called SolarDuck have a joint venture for an offshore pilot of 0.5 MWp in the North Belgian Sea in 2023 [85]. As these are the first two pilot schemes and this technology has been relatively untested case studies of a hybrid FPV and wind have been looked at.

Placing solar arrays in the large distances between the turbines will mean a higher production of energy per area of the sea used. Placing the two together will result in lower environmental conditions due to park effects; placing objects in the water can significantly reduce the local sea level climate [16]. Turbines also require a large distance between them so the wake effects of the turbine do not interfere with each other, this is the proposed locations for the panels, which can be seen in Fig. 8.

Table 2
Total added capacity of floating photovoltaic-integrated-hydropower plant (FPV-HPP) as of 2018 from Ref. [82].

Country	Total added capacity
China	376.50 MW
Japan	22.66 MW
United Kingdom	9.33 MW
South Korea	6.00 MW
France	4.00 MW
Italy	0.77 MW
Spain	0.67 MW
United States	0.12 MW

As discussed in section 4.3 the cost of cabling is £170,000 per MW, as well as reduced costs from shared O&M and grid infrastructure [86,87]. A simulation of a 1.5 MW turbine and solar capacity of 750 kWp hybrid system shows less variability of the system, ultimately resulting in better compatibility with the grid [87]. Fig. 9 shows the result of this simulation.

Offshore FPV is still in its infancy, with the harsh environments of the sea, designing the structures capable to withstand these elements will begin with pilot plants. This gives the time needed to increase pilot plants and testing, as FPV is forecasted to mature in 2030, reaching 100 MW in 2030 and 500 MW in 2035 in the North Sea [88].

3.3. FPV with aquaculture

Aquaculture provided 82.1 million tonnes of farmed seafood in 2018 [89]. Aquaculture is an essential part of the water-energy-food nexus, it increases food production which is essential, it's an efficient way of using water and currently uses energy for its production [90], by using FPV these aquacultures ponds can become self-sufficient thus making them grid independent. Currently, most aquaculture ponds rely on diesel generators to carry out day-to-day operations FPV will remove this carbon-intense process making it green and reducing the costs of fuel [91]. As well as the benefit of being self-sufficient FPV covered ponds showed lower values of bio-chemical demand and plankton biomass, lower pH, and water temperature [92]. FPV-covered ponds exhibited greater yields of 1.1, 1.2, and 1.4 times greater yield of different fish [92]. Economic uncertainty may prolong the private sector investment into FPV, but through government incentives and further research [90], a better understanding can be installed into companies allowing them to be more informed about installing FPV.

4. FPV with energy storage

4.1. FPV with compressed air energy storage

Among the many forms of energy storage systems utilised for both standalone and grid-connected PV systems, Compressed Air Energy Storage (CAES) is another viable storage option [93,94]. An example of this is demonstrated in the schematic in Fig. 10 which gives an example of a hybrid compressed air storage system.

A CAES system uses grid off-peak power or electricity produced from renewable sources when there is less demand to compress and pump air at high pressure into a storage tank [95,96]. This process has been illustrated in Fig. 10. The linked generator generates power whenever there is a need for it due to the high-pressure air that is pulled out of the tank and utilised to power the turbine. According to a life cycle assessment used to compare Energy Storage Systems (ESSs) of various types reported by Ref. [97], traditional CAES (Compressed Air Energy Storage) and PHS (Pumped Hydro Storage) have the highest Energy Storage On Investment (ESOI) indicators. ESOI refers to the sum of all energy that is stored across the ESS lifespan, divided by the energy utilised to create that unit. Additionally, CAES can be of three different types [98]:

- Isothermal CAES (ICAES), which is limited to being a slow process and requires a wide surface for heat transfer with an efficient external heat sink [99].
- Adiabatic CAES (ACAES), which denotes a sizable, insulated high-pressure reservoir. ACAES can operate independently of thermal energy storage (TES) [100].
- Mixed system, where an adiabatic expansion occurs and a transfer of heat with a sink or even the use of fossil fuels is assisted to partially offset the temperature drop that occurs during the expansion process [101].

In one study, Cazzaniga et al. investigated the integration of FPV with CAES and found that although the Li-ion technology has the highest

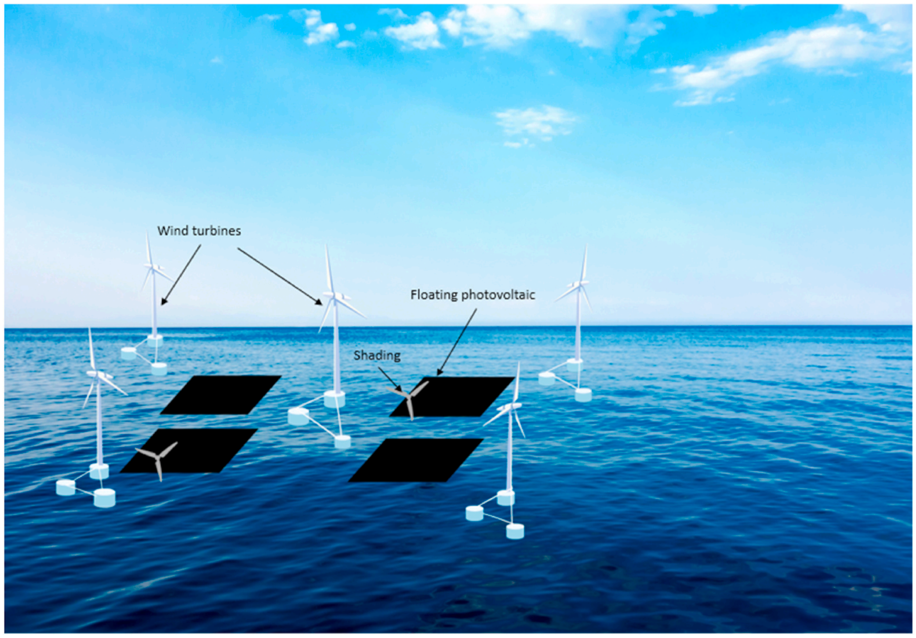

Fig. 8. An example of the possible layout for an offshore wind farm integrated with floating photovoltaics.

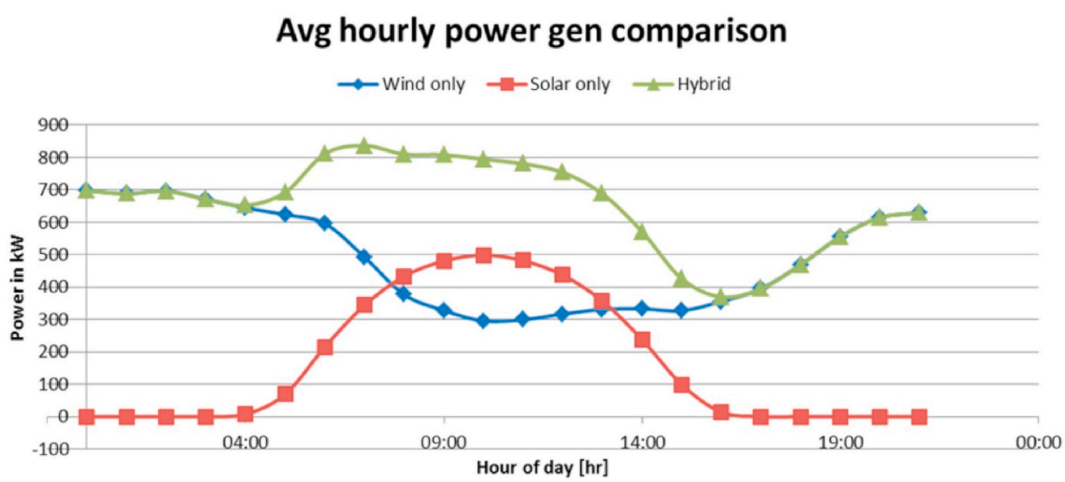

Fig. 9. Power generation of a 1.5 MW wind turbine, 750 kWp, and the hybrid system [87].

ESOI of 10 among BES systems, it is still low when compared with CAES and PHS [102]. Normal pontoon buoyancy pipes are made of polyethylene or another lightweight, inexpensive material. However, as seen in Fig. 11, this study is novel in its approach to advising using steel pipes for the pontoon instead of cheaper materials such as air cylinders for energy storage. The material replacement leads to a small increase in costs without much increase in structural complexity. The study is mainly focused on two variations of the ICAES system:

- The first variation involves the compression of external air inside the steel pipes. In this case, 84 kWh of energy could be stored per pontoon. Furthermore, assuming an infinite heat sink (a large water body) facilitating efficient heat transfer, the process is assumed to be reversible with around 60% of restorable energy.
- The second variation involves the compression of air from a pressure of 10 MPa–20 MPa through air exchange from an external equal-volume tank. Although the energy stored is lesser than the first variation, this solution does not assume an infinite heat sink, which means that even in the case of an irreversible process, the efficiency would still be above 80%.

Overall, it was concluded that FPV integrated with CAES is a favourable system and that experimental verification can be carried out.

4.2. FPV with battery energy storage (FPV-BES)

Battery Energy Storage (BES) systems are one of the most promising storage technologies, being widely used throughout the renewable energy sector and especially with solar technologies [103]. Jamroen conducted a techno-economic analysis of a micro-scale standalone FPV system integrated with BES system to supply energy for an aquaculture aeration system in Thailand [104]. They analyzed and sized the system after taking into consideration the weight of an FPV-BES system and subsequently optimizing the capacities of FPV and BES systems independently. Dawoud et al. found that BES systems can account for up to 54% of the infrastructure capital costs [105] which is why Jamroen focused on optimal sizing for maximum cost-benefit ratio. The floating

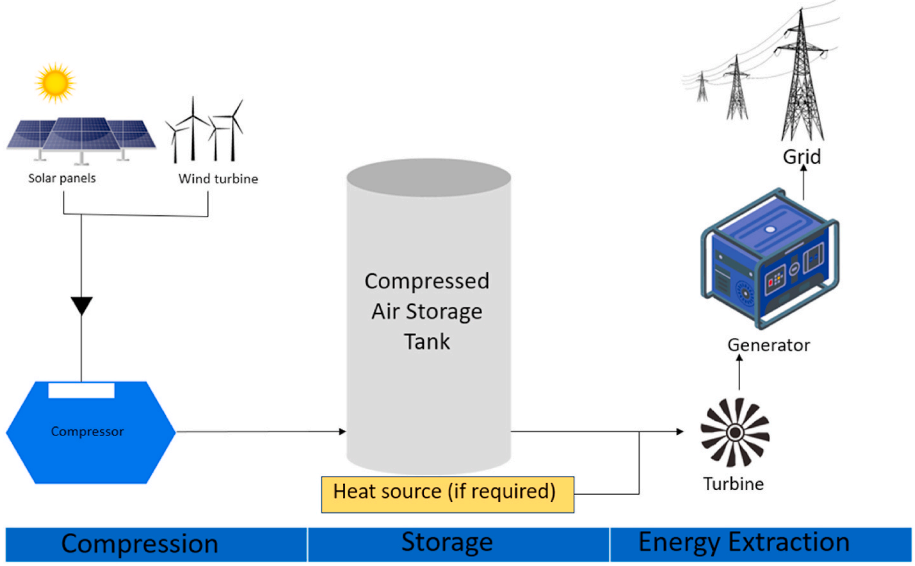

Fig. 10. Schematic of the compressed air energy storage system process.

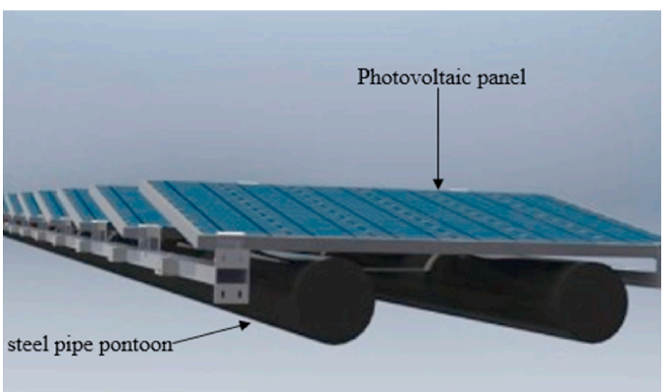

Fig. 11. Example of a steel pipe pontoon system for floating photovoltaics [102].

platform was suggested to be placed on high-density polyethylene (HDPE) floats which, in order to support both the aerator and PV/BES system, are connected into a single piece by a galvanised steel frame. An essential feature of this floating platform is its 100 kg weight capability limitation. They found that a standalone FPV/BES system was feasible from a technical as well as economic standpoint in the Gulf of Thailand. Two scenarios were investigated – day-aeration and night-aeration. For the former, a 450 Wp PV module was chosen with a 60 Ah capacity of BES whereas a 535 Wp PV module with 150 Ah capacity was chosen for the latter. In terms of economic feasibility, the LCOE values for the combined FPV-BES systems were reduced by more than 90% when compared with diesel generator systems. Jamroen also found that the LCOE values were significantly influenced by variations in BES costs.

Overall, it was unexpected to see that there is not much research completed on the integration of FPV with BESs, since both of these technologies are established. Future work could focus on such an implementation since BESs have already been put in place with numerous large land-based solar farms [106]. Recently a change of trend has been observed where floating photovoltaic systems are being integrated with storage systems. In July 2022, a new floating photovoltaic plant with hybridisation of a storage system of capacity 2 MWh using lithium-ion technology was inaugurated in Alqueva that is estimated to meet the electricity demand of approximately 1500 families [107]. In December 2023, Sri Lanka announced a 700 MW floating solar project with a 1500 MWh battery storage system in Killinochi district which will be one of the biggest projects of its kind [108].

4.3. FPV with hydrogen storage

Hydrogen storage is considered an environmentally friendly and sustainable storage solution for solar PV generation [109]. Potential benefits of hydrogen storage with FPV include the widespread integration of renewable energy with smart grids [110], reduction in pollution effects due to lower greenhouse gas emissions [111], high energy density for storage purposes [112,113] and relatively easy transportability due to the advent of Fuel Cell Electric Vehicle (FCEVs). In terms of energy density, Hydrogen contains 2.8 times the energy for the same mass of gasoline [114,115] since it is compressed to high pressures ranging from 5000 to 10,000 psi [116].

A study on FPV integrated with hydrogen storage in Turkey found that a unit designed to use FPV-generated electricity for hydrogen production and accumulation was able to decrease unsatisfied electrical demand from 49.34% to almost zero [109]. However, it is also important to note that although hydrogen could provide a continuous power supply, the same study also found that the LCOE of such a system was much higher than conventional energy systems. Another study investigated hydrogen production from FPV for a marine urban transit system, with 270 kg of hydrogen storage tanks fuelling hydrogen-powered ferries at a rate of 3.05 kg/h [117]. A thermodynamic analysis calculated the energy and exergy efficiencies at 20.7% and 21.8% respectively and a payback period of 7.25 years at an Internal Rate of Return (IRR) of 11.25%. Another theoretical study which was verified experimentally as well focused on exploring different catalysts for hydrogen production from alkaline electrolysis cells. It was verified that out of Graphite, Nickel and Cobalt, the maximum augmentation in hydrogen production was observed when Cobalt was used as a catalyst for the electrolysis of water [118].

In general, more research needs to be done to estimate the feasibility and performance characteristics of hydrogen production from FPV systems. However, some other research projects have explored hydrogen production from other renewable energy sources as well, which could clarify and optimize the performance of FPV-integrated hydrogen storage systems. One such study aimed at generating hydrogen from solar and wind energy for residential applications calculated the overall efficiency for their system to be 43% [119]. In another study focusing on wind power integration with hydrogen and methane production, average energy and exergy efficiencies of 44% and 45% respectively were calculated [120]. Although the proposed system was not fine-tuned to provide an optimal output, some parameters could be changed to obtain the best-case solutions. Research conducted by He et al. explored the design and thermodynamic performance of a photovoltaics-powered steam electrolyzer system. They found that the designed system could produce 98% of hydrogen from the inlet water at an overall energy and exergy efficiency of 21.5% and 22.5% respectively [121]. The authors also noted that the heat absorption by PV panels was primarily influenced by irradiance and incident angle while remaining almost unchanged by relative humidity.

4.4. FPV with mixed storage

The previous subsections have discussed about FPV integration with a singular energy storage technology. However, there can be multiple energy storage options which can be considered for specific use cases. One such novel study was done by Temiz and Dincer, where they integrated FPV with hydrogen and ammonia energy storage, pumped hydro storage and underground energy storage to power remote communities [117]. The whole system was analyzed from a thermodynamic perspective after taking energy and exergy flows into consideration. The system layout has been illustrated in Fig. 6. Solar irradiation is captured by the FPV system, which then turns it into power. This electricity is then used to store energy or to produce fuel. In underground electricity storage, the altitude differential between the lower reservoir (a mine) and higher reservoir (a lake) is used to store the extra electricity as potential energy. If the pump's capacity is reached or the higher reservoir is full, the extra energy is then used in an Anion Exchange Membrane (AEM) electrolyser to generate hydrogen. Hence, Proton Exchange Membrane (PEM) fuel cells can generate power during peak hours using hydrogen. Next, an ammonia and pressure swing adsorption reactor make up the ammonia generating unit, from which ammonia can then be used to store excess energy and eventually, transported.

The results from this study stated that a mixed energy storage system was able to use the excess energy generated from FPV systems more efficiently by directing it towards storage systems specific to the use case and time of year. The overall efficiencies were highest in December, at about 20%. Another advantage of such a system is that abandoned mines and underutilized natural bodies can be used for underground energy storage. It was also observed that pumped hydro storage had a higher round-trip efficiency compared to hydrogen-based storage, where the former had an efficiency of 67.24% as opposed to 46.50% for the latter.

5. Discussion and perspectives

FPV is showing a rapid increase with an expected growth rate of 22% year on year [122], it is the third pillar of solar alongside ground-mounted and rooftop systems [123]. The hybridization of floating PV with other renewable energy sources is still relatively new, the most promising area seems to be with hydropower plants. With a huge number of existing HPPs across the globe an existing grid infrastructure has already been built for these, ensuring no massive changes would have to be made and that FPV can just be installed. The complementary nature of the two energy sources is shown in Fig. 8, making it a very suitable technology to pair to reduce the fluctuation that is associated with renewable energy. The water savings from placing a structure on the body of water have been shown as a direct result of reduced evaporation HPP produces more energy, depending on the coverage. The African continent is where FPV-HPP could see the best results; large parts of the continent are heavily reliant on HPP [81], while experiencing the worst droughts in the world [124]. Implementing FPV in the 146 largest reservoirs would save 743 million m^3/year, increasing the hydroelectricity generation by 170.64 GWh [81]. In relation to the water-energy-food nexus set out by the UN, energy and water have been directly improved, and food will be in-directly affected but will also see an improvement.

The sections of hybrid FPV explored in this article are more recent developments, as the technology FPV will be paired with develops it will create a bigger market that FPV can expand into. Combining PV with off-shore wind will be an exciting market over the next few years, with the offshore wind capacity set to reach 630 GW by 2050 [125]. With this rapid increase, FPV can be combined to increase the power generated by offshore wind farms. The current pilot schemes being tested will be of paramount importance to this sector; essentially a robust design that can withstand the off-shore environment is required to reach industry levels.

Aquaculture is essential for food production; FPV has been shown to make this a carbon neutral process while improving water quality and providing a greater yield. Relating back to the water-energy-food nexus, using FPV for aquaculture reduces energy and increases production. Parts of the world that are big exporters of farmed fish receive high levels of radiation making them suitable to change from diesel generators to PV [126]. Hydrogen and methanol production shows a lot of promise and will be necessary for the decarbonization of the shipping industry. To complete a green transition a lot more must be done in the production of green Hydrogen and Methanol.

Among all the types of FPV-storage options reviewed in this article, the mechanical forms of storage, i.e. compressed air energy storage and pumped hydro storage are easier to integrate with FPV systems due to a lower requirement of additional supporting structures and storage units. Compressed air energy storage can be implemented within the 'pontoon' supporting structures of the FPV panels and pumped hydro storage can directly be used if FPV panels are placed on water reservoirs of pre-existing dams and other hydropower projects. Hydrogen storage is also seen as a strong competitor to other forms of energy storage because of its transportability and potential to replace fossil fuels. However, more experimental research needs to be done in this regard to optimize hydrogen production and storage solutions and to bring down associated costs. Despite battery energy storage systems being an already established means of storing energy, not much research has been done looking at its conjunction with the FPV technology. Lastly, mixed energy storage systems can be employed based on specific energy storage requirements and geographic conditions. Such systems can also utilize abandoned mineshafts and peculiar geographic features for energy storage, reducing their environmental impact and bringing down capital costs.

One important takeaway of this study was that FPV with BESs needs to be investigated more thoroughly. There are gaps in the research on the integration of FPV with battery energy storage systems (BESs), even though both technologies have been accepted by researchers as well as the industry. BESs, especially, have been one of the most widely accepted forms of energy storage. One possible reason for the less amount of research being done on an FPV-BES system is that BESs require a large amount of space. Consequently, placing them on land would lead to higher transmission costs as well as losses. Moreover, placing them on the water's surface could prove to be unfeasible due to the high density and weight of such systems, resulting in more floating platforms. Table 3 represents the top 20 potential countries for floating solar arrays.

6. Conclusion

This review article has examined the current state of research on the integration of floating photovoltaics with different storage and hybrid systems, including batteries, pumped hydro storage, compressed air energy storage, hydrogen storage and mixed energy storage options as well as the hybrid systems of FPV wind, FPV aquaculture, and FPV hydrogen production. The findings suggest that such systems have the potential to significantly increase the efficiency and reliability of renewable energy generation, as well as provide additional flexibility in managing electricity supply and demand.

FPV has many benefits over ground-mounted such as reduced land

Table 3
Potential for floating photovoltaics in the world as of 2023 from [127].

S. No.	Country	Power (TWh/year)
1	United States	1911
2	China	1107
3	Brazil	865
4	India	766
5	Canada	506
6	Russia	236
7	Mexico	228
8	Australia	210
9	Turkey	171
10	South Africa	144
11	Thailand	134
12	Spain	132
13	Argentina	117
14	Vietnam	108
15	Nigeria	93
16	Iran	85
17	Zimbabwe	84
18	Sri Lanka	80
19	Sweden	80
20	Venezuela	80

costs, increased efficiency, reduced soiling, reduced shading, reduced evaporation, and lower visual impact. Hybrid FPV has all of these benefits while being able to reduce its lifetime costs when paired with another technology a reduction in O&M costs, grid infrastructure and cable pooling. Overall, hybrid FPV has all the benefits of FPV plus reduced costs, while enhancing another technology. While FPV is set to rise this will initially be in land first with offshore following, the priority should be covering HPP first due to its complementary nature and benefits for both technologies. Countries, which have HPP reservoirs, should be looking into all the benefits of combining FPV with it. As FPV becomes more common it will be seen moving offshore, as the offshore wind increases it creates the opportunity for FPV to become a hybrid system.

Two gaps in the available literature have been identified which are considered to have the most impact on the performance of FPV and the widespread use of FPV. Further work to establish a way to minimise the impact of salt spray on the PV panels to maximize energy production is needed. A proposal for how combining solar PV with offshore wind to implement offshore charging for vessels will likely assist in ensuring the widespread use of FPV in the future.

CRediT authorship contribution statement

Aydan Garrod: Writing – review & editing, Writing – original draft, Methodology, Data curation. **Shanza Neda Hussain:** Writing – review & editing, Resources, Investigation, Data curation. **Aritra Ghosh:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Saiyam Nahata:** Writing – original draft, Resources, Investigation, Data curation. **Caitlin Wynne:** Writing – review & editing, Resources, Funding acquisition, Data curation. **Sebastian Paver:** Writing – review & editing, Investigation, Formal analysis, Data curation.

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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