

Review

Floating PVs in Terms of Power Generation, Environmental Aspects, Market Potential, and Challenges

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Abstract: Limited reserves of fossil fuels, rising environmental concerns, and a remarkable increase in electricity demand have led to the necessity of harnessing solar energy on a large scale. For this purpose, there has been a noticeable stimulation into photovoltaic power plants (PVPPs) over the last three decades, but the land requirement for PVPPs is still a handicap in many countries since valuable lands are considered for other purposes such as agriculture and livestock. For effective conservation of valuable lands and water resources, PVPPs are preferred to be installed on various water bodies such as oceans, seas, lagoons, lakes, rivers, dams, canals, wastewater treatment plants, irrigation ponds, fish farms, wineries, reservoirs, etc. PV systems on water bodies are called floating PVPPs, and they have outstanding advantages compared with land-based PVPPs including better energy generation owing to passive cooling effects, higher system efficiency and reliability, and lower dirt and dust accumulation on PV modules thus lower operating costs. There are also some significant environmental features provided by floating PVs. Shading effects due to PV coverage reduce water losses arising from evaporation. Moreover, algae growth is limited because of mitigated solar radiation, which yields better water quality. This review presents more insight on floating PVPPs in terms of several aspects such as electricity generation, system efficiency, reliability and sustainability, experimental applications and facilities in operation, water and carbon saving as well as challenges.

Keywords: solar PV; floating PV power plants; electricity generation; system efficiency; water saving

1. Introduction

In the 21st century, one of the most crucial issues is eco-friendly energy supply. There is no doubt that renewable energy sources (RES) play a notable role in cost-effective, sustainable, and environmentally desirable energy production on a global scale. As declared by the International Energy Agency (IEA) [1], nearly 14% of the total primary energy supply (TPES) is fulfilled by RES composed of hydro, biofuels and waste, solar, wind, geothermal, and tidal, according to the data of 2017. The annual increase in renewable energy supply is 2% between 1990–2017. However, the growth rate of TPES is at the level of 1.7% annually.

It is demonstrated in Figure 1 that solar PVs account for 37% of the annual growth rate of the energy supply. Wind power has the second-highest growth rate at 24%, followed by biogases, solar thermal, and liquid biofuels, etc.

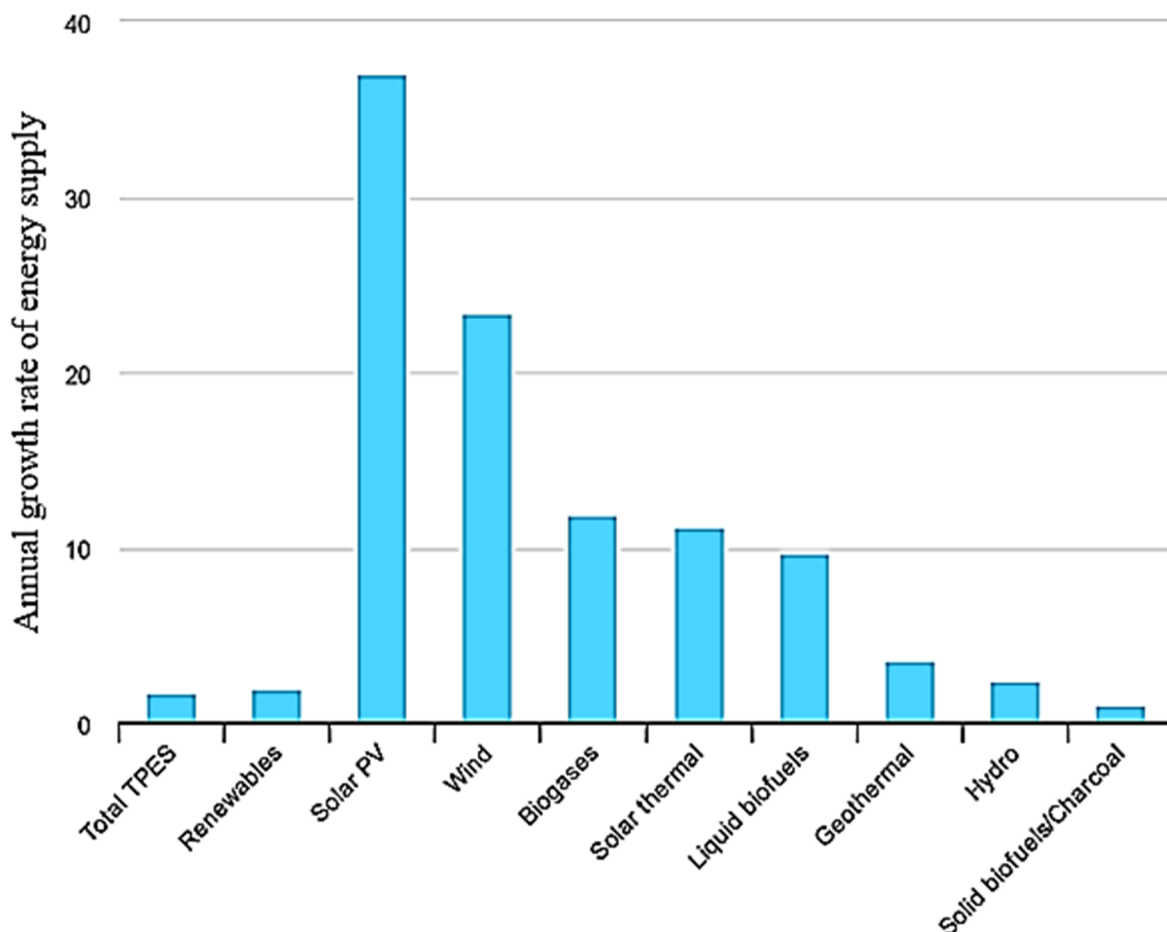


Figure 1. Average annual growth rates of RES supply between 1990 and 2017 [1].

Among the RES, the advancements in solar PVs are exceptional especially over the last two decades as shown in Figure 2. An exponential increase is observed in solar-PV-based electricity generation. When the electricity generated in 2016 and 2017 is evaluated, an outstanding rise of about 115TWh is noticed in solar PV electricity [2]. The ongoing interest in solar PV technology can be ascribed to a couple of reasons as follows:

- Simplicity and reliability
- Scalability
- Low costs
- Availability worldwide
- Limited environmental impacts

Despite the aforesaid superiorities, there are two main challenges for solar PV technology which considerably limit these systems to become widespread. The first handicap is “land use” as about 15,000 m² of land is necessary to install a 1 MW solar PV plant. The second challenge is “low incentives” since the PV market suffers from not being able to compete with the other RES because of the low incentive rates [3]. In this respect, alternative solutions are considered for solar PVs to be able to overcome the said drawback in practice. Floating PVs (FPVs) is such a solution that can be considered as a new concept of harnessing solar energy. FPVs have more competitive advantages in countries with scarce or expensive land for installing land-based photovoltaics (LBPVs). To be able to consider

FPV systems as an alternative to land-based PVs, abundant and convenient water resources are required to be available in the region for the installation of FPVs. It is emphasized in the literature that water losses in any resource due to evaporation occurring from water surfaces can be considerably decreased through using FPV. Not only that, but the energy performance of FPV is reported to be quite higher compared with LBPVs. Therefore, this research aims at pointing out the pros and cons of deploying FPV systems to water bodies in terms of energy generation potential and environmental aspects. From this point of view, comprehensive comparisons between FPV and LBPV are done within the scope of several performance parameters such as energy production, carbon and water saving, and the quality of water basins when covered with FPVs.

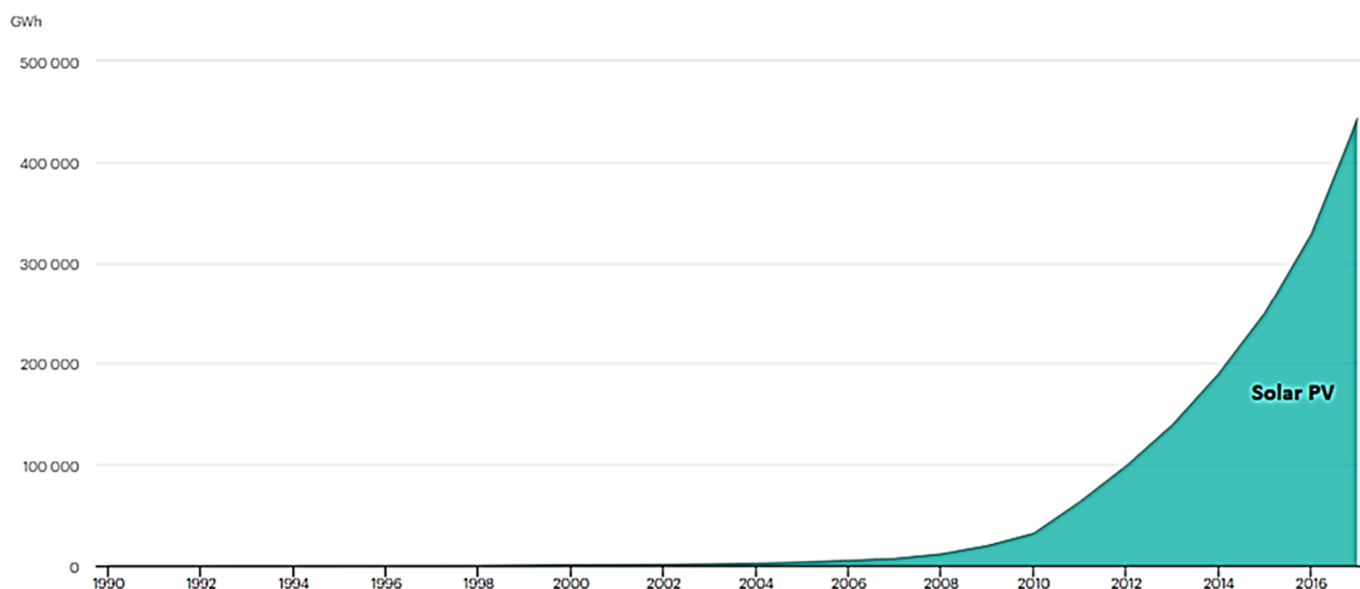


Figure 2. Total world renewable electricity generation by solar PV systems between 1990 and 2017 [2].

2. Solar PV Systems

Solar electricity based on PVs has an expanding range of applications especially over the last two decades. In this regard, it is useful to classify the installations of PV systems as the goal of this section. Solar PV applications can be split into five commonly known groups as depicted in Figure 3 [4].

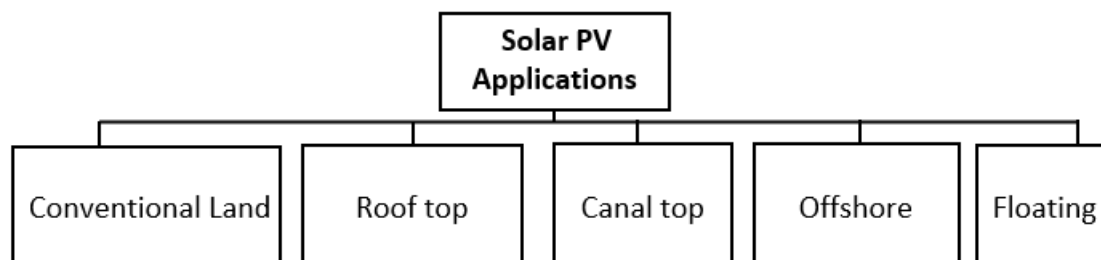


Figure 3. Types of solar PV installations [4].

2.1. Conventional Land-Based Solar PV Applications

Installation of PV systems on lands for small, middle, and large scale electricity generation purposes is the most common understanding of solar PV applications. LBPVs can be basically described as mounting PV arrays on land at a certain DC power capacity to be able to achieve a target AC power. The solar modules of PV arrays are fixed in the ground by land-based mounting equipment such as pole mounts, foundation mounts, and ballasted footing elements.

2.2. Roof Top PV Applications

PV systems can be integrated into residential or commercial buildings as a roof [5] or facade application [6,7] to generate electricity. The electricity generated can be consumed both on-grid and off-grid. Roof-type PV systems are usually preferred in rural areas where access to the power grid is difficult or expensive [8]. The area covered by rooftop PV systems is quite small compared with ground-mounted PV applications. In addition, LBPVs show higher electricity generations in contrast to the rooftop, depending on the installed power capacity.

2.3. Canal Top PV Applications

Canal top PV systems are installed above the water canal not to occupy the large scale of land area as shown in Figure 4. These systems operate more efficiently than LBPVs due to the continuous cooling effects through the back surface of PV modules [9]. The air medium beneath the PV modules acts as a thermal insulator and prevents them from warming up by mitigating the thermal effects from the ground [10]. Canal top PV systems also contribute substantially to the use of the land areas efficiently [11].

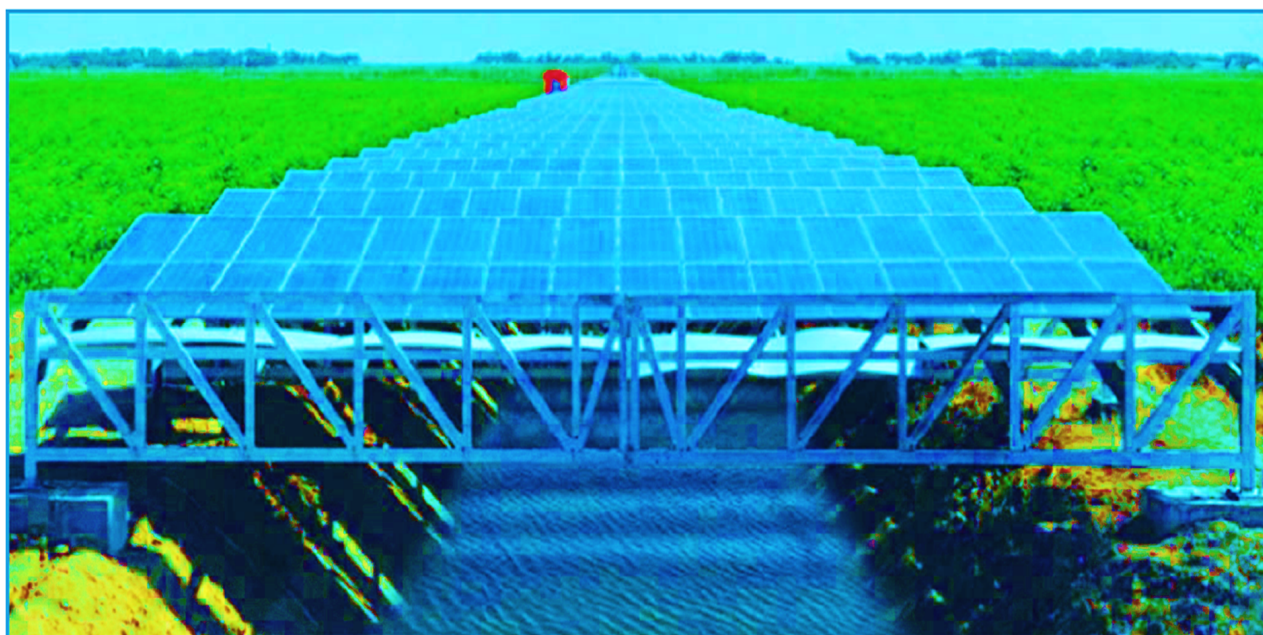


Figure 4. Canal-type solar PV installations [11].

2.4. Offshore Solar PV Applications

Oceans account for more than two-thirds of the world. Oceans and seas can be considered as potential energy sources owing to receiving huge amounts of solar radiation. For this reason, these water resources are used to generate electricity by utilizing offshore solar PV technologies [12]. By the means of these applications, agricultural land is not required to be destroyed unless compulsory.

2.5. Floating PV Applications

Among the solar PV applications, floating systems draw attention year after year as a consequence of remarkably better energy generation performance and outstanding environmental effects. A typical FPV system can be defined as the solar PV arrays installed on the water basin surfaces such as hydropower plants, freshwater, and human-made reservoirs, mining ponds, water treatment facilities, near the coast of seas or oceans as illustrated in Figure 5 [13]. FPV systems can be designed in different ways for different purposes. However, the main system components are almost the same as follows: PV

modules, inverter, floats or pontoons, mooring systems, and cables [14,15]. The components of FPV are clearly demonstrated in Figure 6.

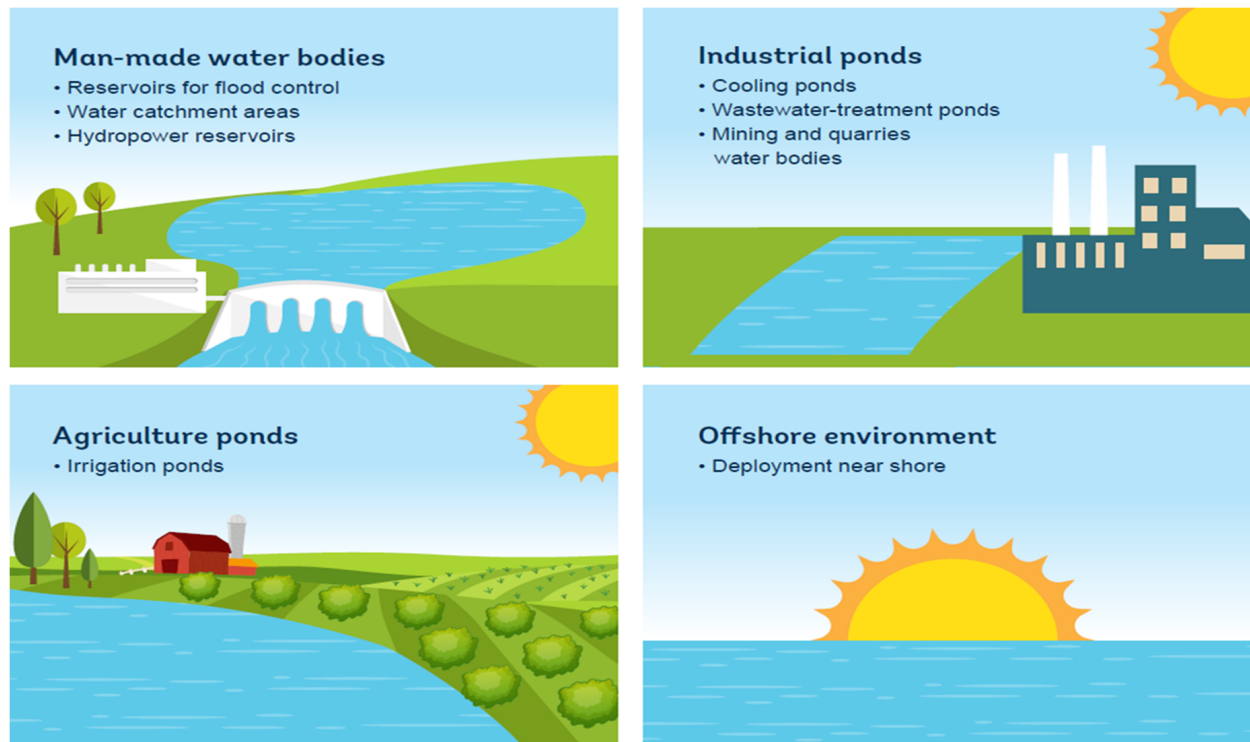


Figure 5. Schematic illustrations of FPV applications [13].

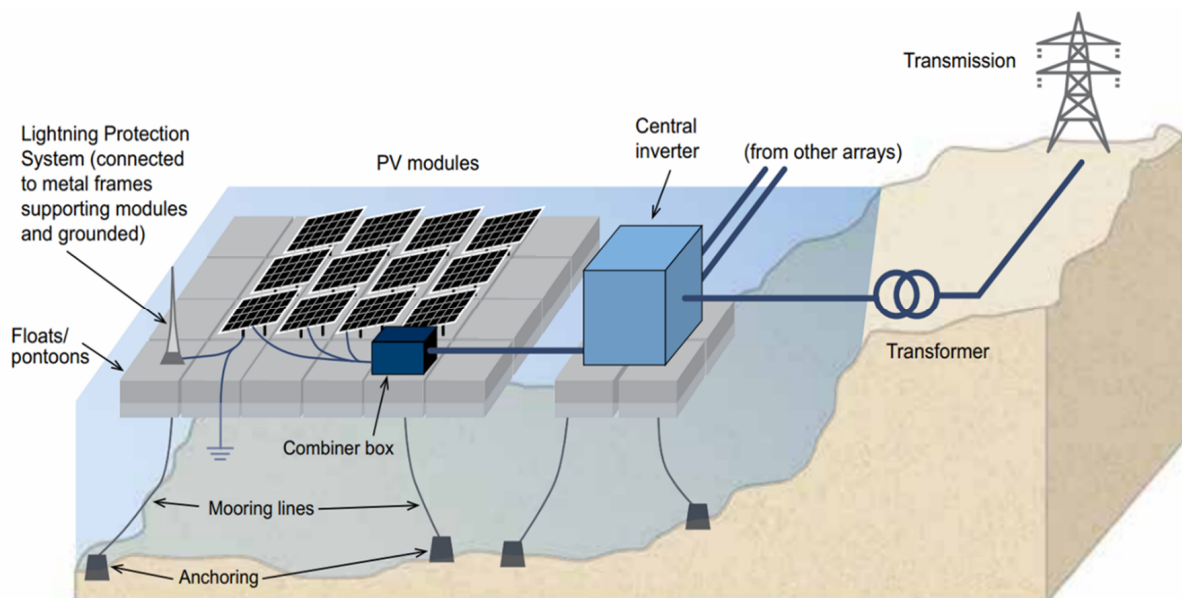


Figure 6. Main system components of FPV applications [13].

The first FPV system was installed in Japan in 2007 for scientific purposes. Afterward, FPV systems were considered to be built for commercial purposes, and the first applications were observed in the USA by utilizing the water reservoir [16]. The installed capacity of the first FPV system in the USA was reported to be 175 kW. The recent reports of the World Bank indicate that there is a clear stimulation of the installation of FPV systems around the globe, notably, by Far East countries (Japan, Republic of Korea, and China), the USA, the U.K., Netherlands, Norway, Portugal, Spain, Singapore, Turkey, and Vietnam. The growth in FPV installation is illustrated in Figure 7 by using two different parameters such as cumulative and annual installed capacity (reached up to 1.3 GW and 786 MW, respectively) [17].

When the installed capacities of FPV systems are investigated at the country level as shown in Figure 8, it is understood that China accounts for about 73% of the total installed FPV systems worldwide [17]. China is followed by the Republic of Korea, Taiwan, and the U.K. It is explained in different works that the increase in the installed FPV systems depends on several advantages of the FPVs compared with other PV systems. The aforesaid superiorities of FPVs compared with LBPVs are useful to discuss as follows for easier understanding of the scope and findings [18,19]:

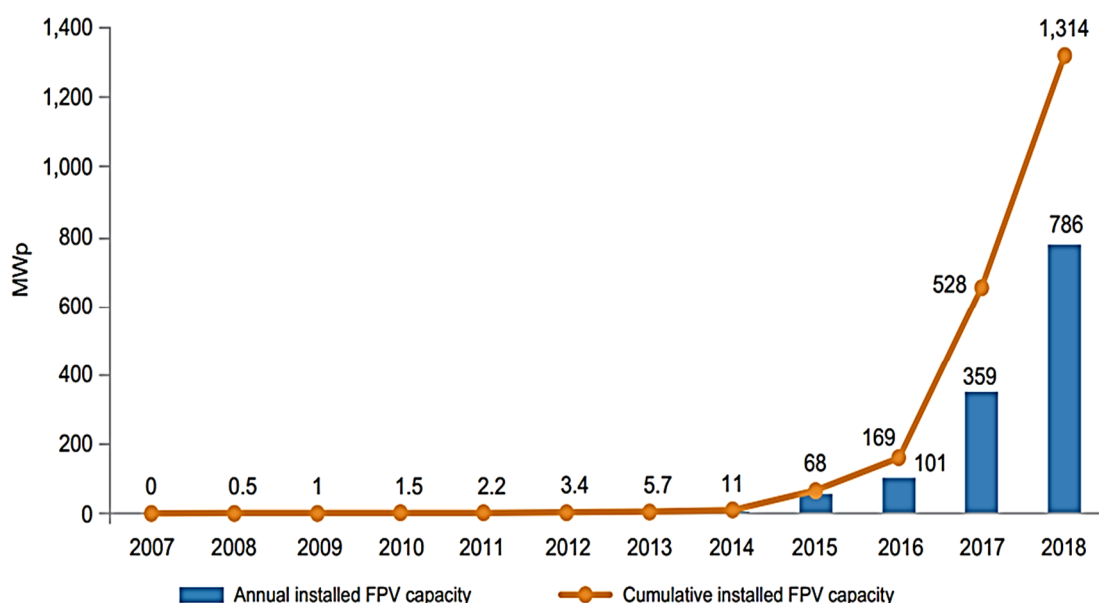


Figure 7. Installed capacity of FPV systems at a global scale [17].

2.5.1. The Increase in Land Saving

One of the major handicaps of LBPVs is the massive land occupation requirement of the power plant, and FPVs are at the center of interest to overcome this challenge. It is unequivocal that there are no negative impacts of FPVs on farmland and any other land relating to industrial or residential usage. FPVs also do not cause any problem regarding the landscape. The land saving feature of FPVs is of vital importance, and as an example from a pilot plant in Japan, a 13.7 MW FPV system installed on the Yakamura Dam water surface provides an approximate land saving of 43,000 m², which is notable. The aforesaid power plant is illustrated in Figure 9 [20].

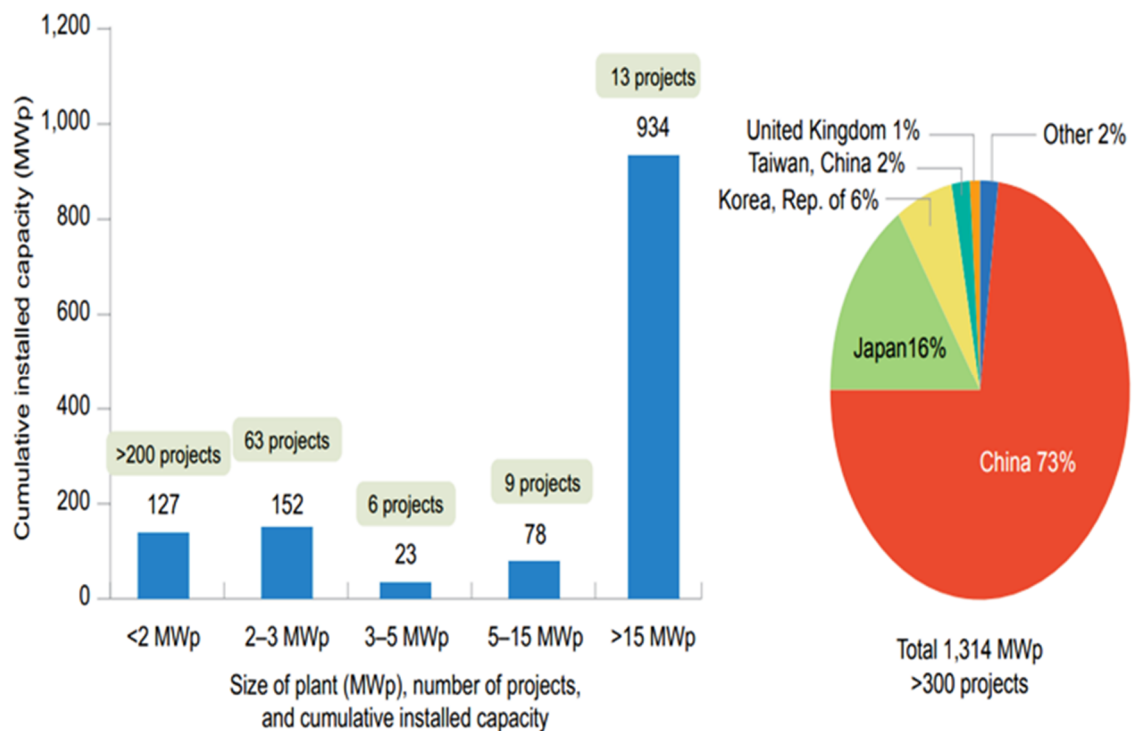


Figure 8. The worldwide distribution of installed FPV plants by 2018 [17].



Figure 9. Land-saving by large-scale FPV installation covering the water surface in Japan [20].

2.5.2. The Improvement in Energy Generation

It is well documented in literature that PV module performance is highly dependent on environmental conditions [21]. In particular, greater operating temperatures cause remarkable reductions in efficiency terms and energy generation performance due to the dependency of voltage parameters on cell temperature [22]. In addition, dust, dirt, and shadow effects considerably deteriorate the electrical performance characteristics of PV systems due to their influence on main cell parameters [23]. FPV systems are observed to give better energy generation performance on site because of several reasons. Continuous evaporation effects from the water surface keep PV modules operating in a regulated

temperature range. Dust accumulation is almost negligible on FPV systems, and it is very easy to clean the PV module surfaces when dirt occurs owing to the water source nearby.

2.5.3. The Assembly and Dismantling of the System

The installation is a costly process for LBPVs in most cases depending on locational prerequisites. When compared with LBPVs, not much effort is required to install and dismantle FPV systems. Unlike the fixed land-based solar plants with foundations, the structure can be simply mobilized anywhere due to the features of the mooring systems. Figure 10 shows the FPV installation steps on a water reservoir [17].



Figure 10. The construction process of FPV systems on a water source [17].

2.5.4. Water Saving

FPV systems are also preferred to LBPVs because of their positive influence on water saving. The findings from the practical applications reveal that a significant reduction in the evaporation on the water surface is observed when the water basins are covered by FPVs. From this point of view, especially in the regions with water scarcity, FPV systems are appropriate to consider on water sources for minimum water losses due to evaporation.

A comprehensive comparison of LBPV and FPV systems is presented in Table 1. The comparison is carried out critically over some key parameters including energy-yielding, investment, operation and maintenance, and so forth. Despite some minor challenges, it can be asserted that FPVs are ideal in most cases when energy generation performance and environmental issues are taken into consideration.

Table 1. A comprehensive comparison between FPV and LBPV systems [17].

Parameter	FPV	LBPV
Investment	Slightly higher costs on average due to floats, anchoring, mooring, and plant design Cost of floats may drop as the scale of deployment increases Higher perceived risk due to a lower level of maturity Harder to access and replace parts	Huge installed capacity and hence very established investment and financing sector Costs continue to drop
Operation and Maintenance	Biofouling Animal visits and bird droppings Harder to maintain anchoring Easy access to water for cleaning Lower risk of theft/vandalism	Easy to access More affected by vegetation growth Easier to deploy cleaning routines

Table 1. Cont.

Parameter	FPV	LBPV
Durability	Normally 5 to 10 years of warranty on floats	Key system components durable for >20 years
Safety	Close to water, tend to have lower insulation resistance to ground Constant movement poses a challenge for equipment grounding Risk of personnel falling into water	Generally safe
Regulation and Permits	More difficult for natural lakes and easier for artificial ponds Lack of specific regulations	More established permitting process Clearer regulations
Experience/Level of Maturity	Cumulative capacity as of the end of 2018: >1.3 GW Four years of experience with large-scale projects	Cumulative capacity as of end of 2018: >500 GW Thousands of projects built A range of 10–30 years of experience
Environmental	Potential to reduce algae growth Potential to reduce water evaporation Potential impact on aquatic ecosystem	Some adverse impacts during construction Potential habitat loss or fragmentation

3. The Contributions

Following a review of recent literature in FPV systems, it is understood that numerous studies focus on revealing outstanding contributions of FPVs to efficient energy harnessing from the sun and effectively reducing the losses from water sources due to evaporation. Water saving and notably better energy generating performance are the key benefits of FPVs when compared with LBPV systems.

3.1. Enhanced Energy Generation

The panel temperature of PV modules affects the main performance parameters of PV systems such as efficiency and power generation, in particular [24]. The panel temperature is changeable on the basis of the material used as panel coverages, the heat removal properties of the materials, and weather conditions, namely, solar radiation, temperature, and wind [25–27]. Panel temperature can be decreased by using a water or air-based cooling system in practice [28–30]. In the case of FPVs, it is also possible to reduce the operating temperature of PV modules via evaporative cooling [31]. FPV power plants display higher efficiency compared with LBPV systems on account of evaporative cooling effects, fewer dust particles restricting the energy generations, and so on [32]. The performance of the PV modules is mitigated due to the coverage of some substances including soiling and bio-soiling (leaves and bird droppings). The effects of bio-soiling losses on FPV energy yields are reduced with the tilt angle fixed at 5–20°, but 10° is reported as the recommended angle to provide self-cleaning via rainfall for cleaning the modules in FPV systems [17].

It is mentioned that evaporative cooling reduces the operational temperature of FPVs up to 3.5 °C when compared with LBPVs [33]. According to the findings of experimental research carried out in Spain, an FPV system with a surface area of 4490 m² installed on an irrigation water reservoir shown in Figure 11 is capable of generating 425 MWh annual electrical energy [34]. In another study, it is addressed to install a 1 MW FPV power plant at a limestone mine located in Korea. According to the simulation results, about 971.57 MWh annual energy generation can be achieved with a 40° tilt angle of PV modules [35]. Similarly, the study carried out by Kim et al. [36] focuses on the energy generation via FPV systems installed on 1134 water reservoirs in Korea by utilizing commercial software. The predicted energy generation from the FPV system covering 10% of water-basin areas is determined to be nearly 2932 GWh/year. In a recent study, the potential energy generations from FPV installation at four different lakes covering 5%, 10%, 15%, and 20% of the water basin is assessed by adopting a software program. The findings indicate that the energy generations

are found to be in the range of 5189 and 54,606 MWh/year depending on the lake and the rate of coverage [37].



Figure 11. FPV system installed on the irrigation water reservoir in Spain [34].

The possible FPV installations at Jablanica lake located in Bosnia aim to supply clean energy generation with an annual approximate potential of 36.55 GWh for the installed capacity of 30 MW [38]. FPV power plants located at Shek Pik and Plover Cove reservoirs in Hong Kong have 100 kW power capacity. It is declared that the energy generation potential of these FPV systems depicted in Figure 12 is more than 120,000 kWh per year [39].



Figure 12. 100 kW FPV power plants located at (a) Shek Pik and (b) Plover Cove reservoirs [39].

3.2. Reduction in Evaporation Rates

One of the main benefits of FPV installations on the water reservoir can be described as the water saving achieved by reducing the evaporation due to providing coverage through

FPV systems as illustrated in Figure 13 [34,40]. Based on the analysis with respect to installing FPV systems on the water reservoir, it is declared that the amount of water saving gained by reducing evaporation by means of FPV is determined to be nearly 5000 m³/year, and this amount accounts for 25% of the whole capacity of the reservoir [41]. The study conducted by Mittal et al. [37] investigated the reduction in evaporation due to FPV installation at lakes located in India. The maximum water saving owing to a 27 MW FPV covering 20% of the Man Sagar Lake surface area was determined to be 496 million liters annually as provided in Table 2.

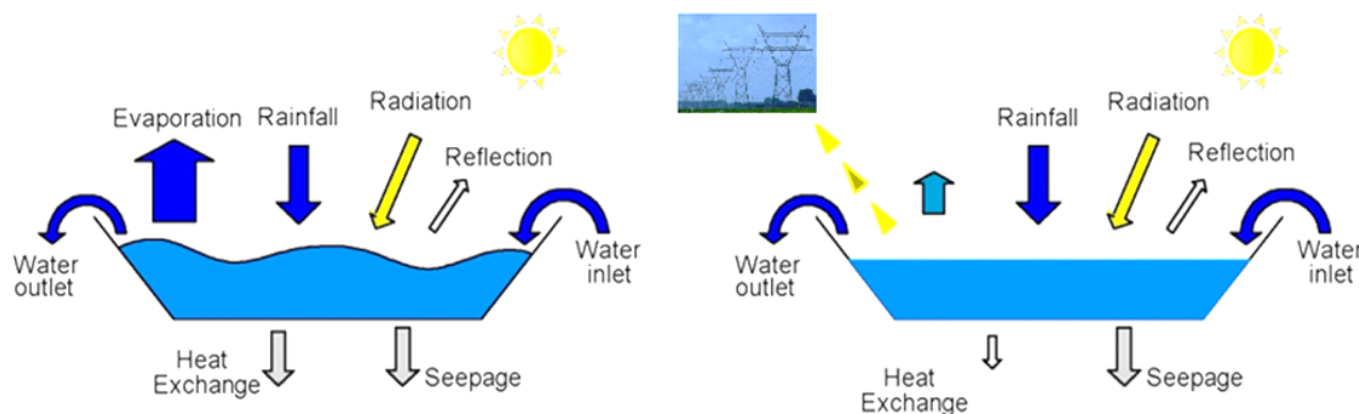


Figure 13. Illustrations of water reservoirs with/out FPV installations in terms of energy saving [34].

Table 2. Energy generation and water-saving features of the FPV system installed at the Man Sagar Lake [37].

Covered Area of Man Sagar Lake (139 ha)	Energy Generation (MWh/Year)	Installed Capacity (MW)	Evaporation without FPV (ML/Year)	Water Saving Due to FPV (ML/Year)
5%	12,135	6	177	124
10%	26,292	13	354	248
15%	40,449	20	531	372
20%	54,606	27	708	496

In another study [42], the influence of FPV installations at wastewater basins was theoretically analyzed as shown in Table 3. It should be emphasized that the water saving through FPV systems is at a remarkable level. The installation of FPVs at hydroelectric power plants (HPPs) was analyzed in China. A feasibility study was conducted for 46,758 stations regarding the role of FPVs in reducing the evaporation from the water surface [33]. The results indicate that the water saving is estimated to be approximately 2×10^{27} m³ through the covering of 2500 km² water basins. The project related to a 1 MW FPV installed at the Kota Barrage and Kishor Sagar Lake was analyzed in terms of water saving, energy generation, and the decline in carbon emissions [43]. It was reported that the water saving is expected to be 37 million liters/year from both potential installations. A similar study was performed for Kaylana Lake to reveal an increase in water saving via utilization of FPV systems [44]. According to the results, the water saving amount based on reducing the evaporation was determined to be 191,174 million liters/year with 1 MW FPV installations [45].

Table 3. Reduction in evaporation rates at wastewater basins through FPV installations [42].

Location	Surface Area (m ²)	Installed Power (kW)	Energy Generation (MWh/Year)	Water Saving (m ³ /Year)
Bolivar	640,000	75,000	133,875	1,152,000
Goolwa	68,775	9313	16,391	123,795
Lilydale	86,400	8467	13,971	138,240

4. Applications of FPV Systems

Water reservoirs can be split into three categories composed of freshwater resources (FWR), human-made resources (MMR), and basin surfaces of hydropower plants (HPPs). The data based on worldwide water resources are depicted in Table 4 [46].

Table 4. Worldwide water reservoirs [46].

	FWR, km ²	MMR, km ²	HPPs, km ²
Africa	540,030	46,499	24,197
America Central	58,801	4161	2899
America South	381,710	65,000	53,863
Asia South East	153,490	32,231	22,929
Asia South Without India	48,320	1238	1081
Australia and New Zealand	58,920	4695	1216
Canada	891,163	97,914	95,224
China	270,550	12,979	7454
Europe (North)	178,156	30,267	24,724
Europe (South)	19,612	3091	2066
India	314,00	102,775	13,361
Japan	14,430	1394	130
Middle East	140,190	26,259	10,775
Russia	720,500	85,408	84,761
Turkestan	76,110	17,247	14,582
USA	685,924	43,904	21,686
Total	4,550,906	573,377	380,948

4.1. Hydropower Plants

The integration of FPV systems with hydropower plants provides some advantages in practice. For instance, it is known that existing HPPs utilize grid connectors and power generators. The availability of this equipment leads to a reduction in the cost of FPVs. Moreover, in warm regions, the energy production from HPPs is reduced due to the seasonal water level of the dam during the summer. However, the PV modules in the said regions work with the maximum capacity to produce energy. In this way, the fluctuation in the energy generation can be compensated [47].

The research conducted by Cazzaniga et al. [47] underlines the notable growth in renewable energy generation due to the integration of FPV with HPPs. It is reported that if FPV is applied to 2.4% of the global HPP basin surfaces, the growth in total energy generation is predicted to be 35.9%. There have been many attempts to integrate FPVs with HPPs at a global scale. One such project in Brazil reveals that the FPV system installed on the Balbina Dam has an energy-generating capacity of 970 GWh/year. It is reported that the total energy generation can be enhanced by more than 35% through a hybrid FPV system without any hazardous effects on the environment [46].

4.2. Water Treatment

The basins of wastewater treatment facilities are commonly known to spread across large areas but are very shallow water surfaces compared with lakes, etc. The basins are used to transform the wastewater into irrigation water through aerobic processes. While applying FPV to the basins, water saving is provided by reducing the evaporation rate,

and the sickly smell arising from the wastewater basin can be reduced, bringing about an increase in aerobic processes [42]. An FPV station with a capacity of 6.3 MW installed at a water treatment facility in London is stated to generate energy which is roughly equivalent to the energy demands of 1800 dwellings [48]. An FPV power plant (having 4.4 MW power capacity) located at the Bordentown Avenue water treatment facility is reported to meet its own energy demand with an electricity generation capacity of 5 GWh/year [49].

4.3. Irrigation Reservoir

Compared with the rest of the applications, irrigations or drinking water reservoirs are more popular for the installation of FPV systems for generating electricity [17]. For instance, it is reported that more FPV power plants are installed on irrigation reservoirs among the other suitable water bodies in Japan. An FPV power plant located in Hyogo was deployed to the irrigation reservoir spreading over 2.8 ha. The coverage of the FPV accounts for nearly 43% of the water surface as shown in Figure 14 [50]. In Brazil, a 305 kW FPV power station covering more than 45% of the agricultural irrigation reservoir is composed of 1150 PV panels [51].



Figure 14. Hikuni Ike, 1.3 MW FPV which has been in operation since 2019 [50].

4.4. Mining Water Basins

An FPV system can be installed on water bodies belonging to active and former mining sites. For active mining sites, the consumption of energy and water attracts attention. So as to mitigate the aforesaid resource consumption, an FPV is considered as an alternative to generate clean energy and to reduce the evaporation from the water surface [52]. The abandoned quarries and mining sites are informed to have huge water bodies allowing the possibility of FPV installations to produce renewable energy and to mitigate carbon emissions [53]. In Chile, an 85 kW FPV covering 110 m² of the water surface to improve the efficiency of the facility is installed on mining water bodies placed at 3500 m above sea level. The reduction in evaporation is determined to be 80% relative to the findings [54]. A 70 MW FPV power plant is planned to be installed on 63 ha of the collapsed coal mining water basins in China. The potential energy production is expected to be equivalent to meeting the energy demand of 21,000 dwellings [53]. After examining the applications of the FPV station, the main factors in the designation of water reservoirs suitable for installation of FPV systems are depicted in Table 5.

Table 5. The factors in the designation of water reservoirs suitable for installation of FPV systems [17].

Factor	High Preference	Low Preference
Location	Near load centers and populated regions Easily accessible by road Secured Close to manufacturing facilities or ports for simplified logistics	Remote places with high transportation cost
Weather and climate	High solar irradiation Little wind or storms Calm water Dry region where water conservation	Cold regions with freezing water High winds and risk of natural disasters Seasonal flooding Drought events that lead to exposure of water bed
Water body features	Regular shape Wide opening toward south or north depending on hemisphere Human-made reservoirs	Narrow strip between mountains Presence of islands
Type of water body	Hydropower dams Industrial water bodies Mining areas	Natural lake Tourist or recreational sites
Underwater terrain and soil conditions	Irrigation ponds Shallow depth Even terrain Hard ground for anchoring Water bottom clear of any cables, pipelines, or other obstructions	
Water conditions	Freshwater with low hardness and salinity	Salty water Dirty/corrosive water Water prone to biofouling
Other site conditions	Existing electrical infrastructure Easy water access Sufficient land area for deploying electrical equipment Self-consumption loads, such as wastewater treatment and irrigation pump facilities	No existing electric infrastructures Complicated banks Extensive horizon shading from nearby mountains Nearby pollution sources (chimneys, burning crops, and quarries)
Ecology	Simple and robust ecology	Natural habitat of protected species Frequent bird activity Water species that are sensitive to water temperature, dissolved oxygen, and sunlight

5. Comparison of FPVs and LBPVs

Energy generation with respect to FPV power plants shows higher performance compared with LBPV. Depending on this circumstance, many researchers focus on the comparisons in terms of energy production from FPV and LBPV. Table 6 presents the comparison between FPV and LBPV systems in terms of energy efficiency.

For instance, the case study carried out by Choi et al. [55] investigates two different FPV plants installed in Hapcheon shown in Figure 15 [56] and an LBPV located at Haman. Moreover, the energy generation from the FPV is compared with the generation based on the LBPV. According to the results, the efficiency of the FPV is found to be 10% better than that of the LBPV. A further study conducted in Korea evaluated the energy generation and the capacity factor of FPVs and LBPVs, between July and September of 2010 [57]. The capacity factor ratio of FPVs and LBPVs was determined to be 1.1 and 0.8 from July to September, respectively.

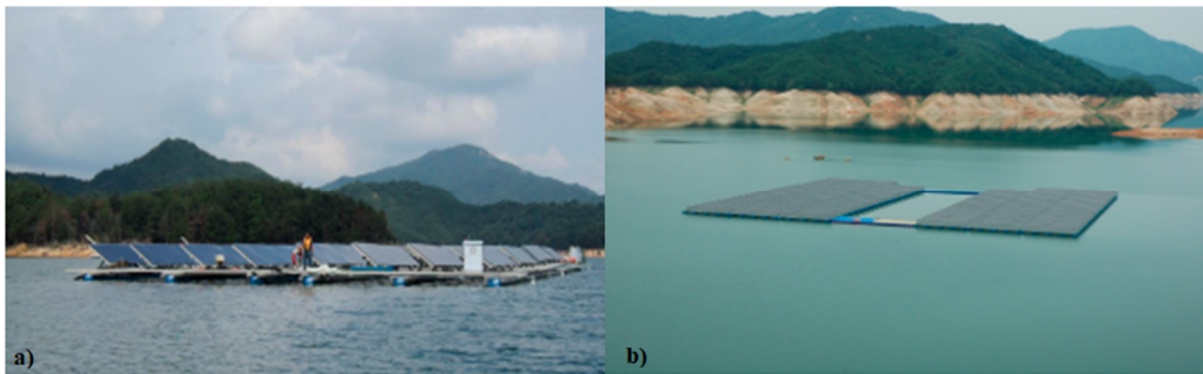


Figure 15. (a) 100 kW FPV and (b) 500 kW FPV at the Hapcheon Dam [56].

The FPV shown in Figure 16 and conventional PV panels were analyzed in three different solar radiation levels of 417, 617, and 834 W/m² [58]. The average efficiency of the FPV and PV at 417 W/m² is determined to be 4.38 and 4.22%, respectively. Moreover, in comparison with conventional PVs, the efficiency of the FPV is found to be about 3.8% higher. The increase in solar radiation has profound effects on power generation and the efficiency of the systems. In line with the results, power generation and average efficiency of the FPV are found to be 5.04 W and 5.5%. It is also stated that the efficiency belonging to the FPV reaches 14.6% at 834 W/m².

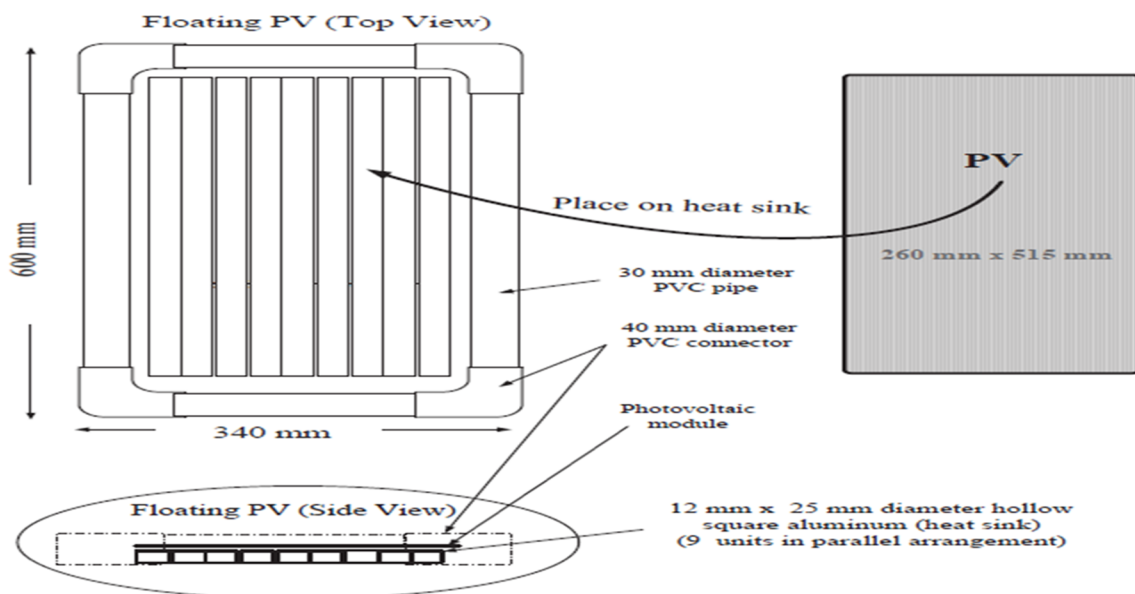


Figure 16. Schematic illustrations of FPV for experimental analysis [58].

The research carried out by Azmi et al. [58] investigates the power gain of the FPV and LBPV in a laboratory by using an experimental simulator. The results reveal that the FPV and LBPV can generate 1190 and 1030 W, respectively, when exposed to a solar intensity of 896 W/m² [59]. In another study, the capacity factor of the FPV and LBPV is investigated by Yadav et al. [60]. According to the results, the FPV performs nearly 7% better than conventional LBPVs. Annual energy generation performance is also evaluated for the FPV and LBPV. The findings indicate that the potential energy generation from FPV and LBPV is estimated to be 1715.57 and 1673.98 MWh/year, respectively [44]. A numerical attempt compares the energy generation from 8.3 kW at each of the FPV and LBPV. It is mentioned that the FPV generates nearly 2.5% more energy compared with the LBPV (12,291 kWh/year) [45].

Table 6. The comparison between FPV and LBPV in terms of energy efficiency.

Ref.	Duration	Tilt Angle	FPV	LBPV	PG _{FPV}	PG _{LBPV}	Comparisons
[55]	02/2012 01/2013	FPV, 33° LBPV, 30°	100 kW at Hapcheon	1 MW at Haman	421 kWh/day	3486 kwh/day	CF was determined to be 17.6% and 15.5 for FPV and LBPV, respectively. The efficiency of FPV is 13.5% more than LBPV 17.1% and 15.5% of the CF belongs to FPV and LBPV, respectively. The efficiency of FPV is higher than LBPV, by about 10.3%.
	10/2012 03/2013	FPV, 33° LBPV, 30°	500 kW at Hapcheon	1 MW at Haman	2044 kWh/day	3491 kWh/day	
[14]	01/2012 07/2012	FPV, 11° LBPV, 11°	2.4 kW at Juam Dam	2.4 kW at Juam Dam	—	—	The avg. CF for FPV and LBPV is 14% and 13%, respectively.
[57]	07/2010 08/2010	—	0.93 kW at Buksin Bay	20 kW at Buksin Bay	1.8 kWh/day	32.88 kWh/day	The avg. CF is evaluated to be 16% and 13.7% for FPV and LBPV, respectively. The ratio of CF is equal to 1.16
[60]	June 2016	—	0.25 kW at Manit	0.25 kW at Manit	—	—	The CF for FPV and LBPV is found to be 12.42% and 11.63%, respectively.
[44]	01/2016 12/2016	—	1 MW at Jodypur	1 MW at Jodypur	1715.57 MWh/year	1673.98 MWh/year	FPV-efficiency is higher than LBPV, up to 6.8%. The CF is found to be 19.58% and 19.11% for FPV and LBPV. The efficiency of FPV is 2.45% more than LBPV.

Golroodbari and Sark [61] carried out a simulation study for the purpose of comparing the performances of FPV and LBPVs. They developed a mathematical model for both FPV and LBPV and characterized different tilt angles. According to the results, they demonstrated that tilt angles of FPV are a very important parameter on the performance of the system. For the optimal tilt angle of FPV, the FPVs have better performance by about 12.96% than LBPVs, on average, on an annual basis.

6. FPV Market and Potential

The increase in global FPV applications depends on some parameters, notably, the solar irradiance potential, the convenience of the water resources for the FPV, and the distance between the FPV plants and the power lines. Based on the report declared by the World Bank Organization, the potential of FPV power plants were evaluated to utilize the water reservoirs existing in continents. The energy capacity and possible energy yielding are indicated in Table 7 [13]. If FPV systems are installed on 1% of the total global water surface areas, the required FPV power capacity is estimated to be 400 GW. It was also declared that the power capacity of FPV plants already in operation reached roughly 1.3 GW at the end of 2018 [17]. Briefly, the global FPV market can be deduced as a new market for the renewable energy sector.

Table 7. The potential energy generation from FPV installed on suitable water reservoirs [13].

Continent	Total Surface Area (km ²)	Number of Water Reservoirs	Total FPV Capacity (GW) (the Coverage Rate of the Water Surface Area with FPV)			Total Potential Energy Generation (GWh/Year) (the Coverage Rate of the Water Surface Area with FPV)		
			1%	5%	10%	1%	5%	10%
Asia	115,621	2,041	116	578	1156	128,691	643,456	1,286,911
Africa	101,130	724	101	506	1011	167,165	835,824	1,671,648
Europe	20,424	1082	20	102	204	19,574	97,868	195,736
N. America	126,017	2248	126	630	1260	140,815	704,076	1,408,163
Oceania	4991	254	5	25	50	6713	33,565	67,131
S. America	36,271	299	36	181	363	58,151	290,753	581,507
Total	404,454	6648	404	2022	4044	521,109	2,605,542	5,211,086

The FPV power station installed in Anhui, China, is known as having the world's largest FPV power capacity. It is reported that the payback period of this FPV station is expected to be less than 7 years [62]. Furthermore, it is stated that the carbon saving is expected to be nearly 199,500 tons annually. The energy demand of 94,000 dwellings located in urban and rural areas would be met by generated electricity from this station [63]. The FPV station is considered as an applicable technology for countries having more water bodies than land. Many countries deploy the FPV systems to generate electricity. Table 8 also demonstrates the operated FPV stations that are more than 5 MW of the installation capacity placed on the world [64–79].

Table 8. FPV (power capacity $\geq$ 5 MW) power plants in the world.

Power Capacity (MW)	Water Basins and Location	Country	Grid-Connection Year	Deployed by	Description	Ref.
150	Coal mining subsidence area, Huainan	China	2018	Three Gorges New Energy	Installation cost of \$ 23.8 million	[64]
150	Coal mining subsidence area, Huainan	China	2018	Sungrow	220 GW/year of energy generation	[65]
130	Coal mining subsidence area, Anhui	China	2018	Trinasolar	3.04 billion kWh over 25 years	[66]
102	Coal mining subsidence area, Huainan	China	2017	Sungrow	—	[67]
100	Coal mining subsidence area, Jinxing	China	2018	Sungrow	—	[67]
70	Mine lake, Anhui	China	2018	Ciel and Terre	194,731 floating solar panels	[68]
50	Coal mining subsidence area, Jinxing	China	2017	Sungrow	—	[67]
40	Coal mine, Huaibei	China	2017	Trinasolar	15 km ² of water surfaces	[69]
40	Coal mining subsidence area, Huainan	China	2017	Sungrow	—	[68]
32.6	Mine lake	China	2018	Cile and Terre	Covering 20% of water surface	[70]
31	Coal mining subsidence area, Jinxing	China	2017	Sungrow	—	[67]
27.4	Bomhofsplas, Zwolle	Netherlands	2020	Baywa	Meeting the consumption of 7800 dwellings	[71]

Table 8. Cont.

Power Capacity (MW)	Water Basins and Location	Country	Grid-Connection Year	Deployed by	Description	Ref.
20	Coal mining subsidence area, Huainan	China	2016	—	—	[13]
18.7	Gunsan Retarding Basin	Korea	2018	Scotra	Meeting the energy demand of 7450 houses	[72]
17	Piolec	France	2019	Akuo Energy	Meeting energy demands of 4773 dwellings	[73]
14.5	Sekdoorn, Zwolle	Netherlands	2019	Baywa	6465 tones of carbon saving annually	[71]
13.7	Yamakura Dam reservoir	Japan	2018	Ciel and Terre	Installed on 18 ha of water surface	[74]
9.9	Water storage reservoir, Agongdian	Taiwan	2018	Ciel and Terre	Covering 92,000 m ²	[75]
9.9	Irrigation reservoir, Pei County	China	2017	Ciel and Terre	Covering 29% of the water basin	[76]
8.4	Tynaarlo, Drenthe	Netherlands	2019	Baywa	7669 MWh/year energy production	[71]
7.5	Irrigation, Saitama	Japan	2015	Ciel and Terre	Covering 57% of water surface	[77]
6.7	Mine Lake, Shandong	China	2018	Ciel and Terre	Covering 9.5% of water surface	[78]
6.3	Drinking water reservoir, London	U.K.	2016	Ciel and Terre	Covering 5% of water surface	[79]

Many countries plan to increase energy generation based on FPV systems. Due to this, such countries are increasing commercial agreements and investments with regard to plant installations depending on the convenience of the water sources for the installation of FPV stations. For instance, the FPV project with 150 MW of power capacity being presented as the first FPV project for Malaysia is expected to be completed in 2020. The PV panels are supplied by Chinese solar panel manufacturers [80]. In another project, it is planned to install an FPV with 145 MW of power capacity on a 225 ha area of the Cirata Reservoir in Indonesia. It is also reported that the date of connecting the FPV to the grid would be in 2022 [81]. Based on the study carried out by the Energy and Resources Institute, the water reservoir of India is more than 18,000 km², and the potential of FPV power capacity is also determined to be 280 GW [82]. In addition, it is expected to improve the FPV power capacity by up to 1 GW by the Maharashtra State electricity distribution company [13]. The world's largest FPV station installation is planned on the coast of the Yellow sea in Korea. The power capacity is estimated to be 2.1 GW and the installation cost is determined to be nearly \$ 3.36 million [83].

7. Environmental Impacts

Many researchers focus on the effects of FPV on both energy generation and the environment. FPV installed on water surfaces has positive impacts on the environment such as carbon saving and water saving obtained from preventing the evaporation of water surfaces [84–86]. Al-Widyan et al. [87] conducted an experimental study to observe the effect of FPVs on water quality and energy efficiency. They tested water quality parameters by collecting samples from August 2020 to February 2021 with the help of a spectrophotometer. The results of the experimental study revealed that an increase in the total water quality was observed with a decrease in algae biomass. In addition, a decrease in the PH values measured at certain points, an improvement in clarity, and an increase in the amount of organic carbon were observed. Some studies examining the reduction in carbon emissions by installing FPV systems are presented in Table 9 including the type of water basins, covering areas, and the amount of carbon saving. On the other hand, covering

the water surfaces with FPV is stated to have possible effects on water quality and water life as follows:

- The occurrence of water layers depending on the change in temperature
- Changes in oxygen levels of the water affect aquatic habitats due to not meeting the oxygen demands
- Prevention of wind effects on the dynamic systems existing on water surfaces (providing heat transfer of the whole reservoir)
- Reduction in the growth rates of marine life
- Changes in water odor and taste and the increase in possible health problems based on the metals at the bottom of the reservoir
- The systems do not harm biodiversity, and in particular, birds are not harmed, in addition to establishing a good balance with aquatic fauna [84,85].
- Blue-green algae result in the corrosion of metals because of the existence of dissolved oxygen levels [88,89].

Table 9. Carbon saving by virtue of FPV installations.

Ref.	Research	Covering Area (m ²)	Water Basin	Carbon Saving
[41]	Experimental	4490	Irrigation water reservoir	1454.19 tons of CO ₂ saving over the lifetime of FPV
[35]	Simulation	87,650	Open-pit limestone mine	471.21 tons of CO ₂ /year
[36]	Simulation	—	1134 water reservoirs in Korea	1,294,450 tons of CO ₂ /year
[43]	Simulation	10,000 each of them	Lake and barrage	1773 and 1714 tons of CO ₂ /year
[45]	Simulation	50	Lake	14.44 tons of CO ₂ /year
[39]	Power plants	—	Water reservoir	Nearly 85 tons of CO ₂ /year

When the life cycle of the FPV systems is evaluated, the possible effects of FPV on the environment are pointed out as demonstrated in Table 10 [17].

Table 10. Possible environmental impacts of FPVs during construction and operation [17].

Stage	Effects
Installation and decommissioning (short and long-term effects)	Short-term air pollution from project construction equipment Noise, affecting people and wildlife, from project construction equipment Turbidity from installation and dismantling of mooring and anchoring systems Potential release of oil and lubricant spills related to project construction equipment Loss of habitat and marine species The increase in waste during construction and delivery of the equipment The failure in water quality: Increased temperature Decreased dissolved oxygen Limited mixing
Operation and Maintenance (long-term effects)	Leaching/chemical risk Loss of benthic habitat Impact on primary production Loss of avian wildlife Loss of marine species Loss of aesthetic value

8. Challenges

Although the performance of the FPV is greater than LBPV in terms of energy production, the installation cost of FPVs is reported to be more than \$ 100,000 per MW. So it is highlighted that the cost is considered as the main drawback of FPV systems [90]. Based on the report conducted by the Fraunhofer Institute for solar energy systems, the potential of FPV installation in Germany is estimated to be nearly 56 GW. The handicap is

that the installation cost of FPV is 10–15% more than the LBPV. This obstacle avoids the increase in FPV systems which could be overcome by providing incentive packages [91]. In terms of capital investment, FPV and LBPV that are assumed as operating under the same conditions are theoretically compared. On the basis of the findings, it is indicated that the FPV cost is roughly 18% more expensive than the LBPV cost [13]. In this investigation, the power capacity of the systems is considered to be 50 MW. The analyses of total capital investments pointed out in Table 11 are carried out by using this assumption.

Table 11. The capital expenditures (CAPEX) of FPV and LBPV [13].

CAPEX Component	FPV 50 MW (\$/W)	LBPV 50 MW (\$/W)
Modules	0.25	0.25
Inverters	0.06	0.06
Mounting system	0.15	0.10
Balance of the systems	0.13	0.08
Design and construction	0.14	0.13
Total CAPEX	0.73	0.62

The degradation of FPVs is regarded as being crucial due to the effects of humidity on the PV panels compared with LBPVs [90]. As remembered, environmental conditions profoundly influence the performance of PVs. These conditions consist of humidity, snow, cold, heat, etc., result in product failure. It is also stated that the degradation of FPVs can increase depending on temperature and humidity such as corrosion, ribbon fatigue, and back sheet hydrolysis. Although the evaporative cooling has a positive effect on the improvement in energy efficiency, and the longevity of FPV modules, the closeness to water surfaces of FPV leads to a huge increase in the exposure to humidity [17]. The degradations are called failure modes and can consist of potential induced degradation (PID) [92], back sheet degradation caused by chemicals descending from solar panels [93], and cell deformation and hotspots. Relative to the research with respect to PV performance, micro cracking on cells causes power losses determined to be in the range of 0.9 and 42.8% caused by the increase in hot spots [94]. Nevertheless, the drawbacks impacting the energy performance of FPVs can be lessened by the methods presented in Table 12 [17].

Table 12. Potential degradation modes and mitigation methods [17].

Environmental Stress	Failure Mode	Mitigation Strategies
Moisture	Corrosion	Moisture-hardened materials
	Hydrolysis	Back sheet: glass, aluminized
	PID	PID-resistant cells
Mechanical stress	Interconnect fatigue Cell cracking	System-level PID compensation
		Increase module stiffness
		Cells and string on the neutral axis
Hot spot/shading	Arcing/melting/cracking Diode failure	Cut cells
		Lower modulus encapsulants
		Multi-wire interconnections
		Less cells per bypass diode
		Higher RTI materials
		Anti-soiling coatings

9. Concluding Remarks

Within the scope of this review, floating PV power plants are evaluated critically in terms of several performance-related aspects such as electricity production, system efficiency, reliability and sustainability, operation cost, water and carbon saving, market potential and challenges. The following bullet points can be drawn from the research:

- Floating PVs are installed on water bodies. Owing to the direct and passive cooling effects, they keep cool in operation which yields to greater power generations compared with conventional land-based PV systems.
- Floating PV power plants have a great potential to bring down energy production expenses and to provide remarkable savings on land prices especially in island counties such as the U.K., Japan, Taiwan, and the Republic of Korea. In the aforesaid countries, valuable lands are primarily preferred for different purposes such as agriculture and livestock. Installing PV systems on water bodies such as lakes, rivers, ponds, and reservoirs also narrows the gap between conventional and solar power systems.
- Floating PV power plants perform more than 10% compared with conventional land-based PV systems. In addition, they mitigate water evaporation from water bodies by about 70%. However, it needs to be noted that the investment cost of floating PV systems is slightly higher than conventional PV systems. Figures are expected to change from plant to plant since they are dependent on many environmental and operational parameters such as solar intensity, ambient temperature, wind velocity, water mass, dirt and dust level, and tilt angle of PV modules, etc.
- The floating power station installed in Anhui, China, which is known as the world's largest FPV-power capacity is reported to have a payback period of fewer than 7 years. The said plant is expected to save nearly 199,500 tons of carbon emissions annually. The energy demand of 94,000 dwellings located in urban and rural areas would be met by the electricity produced by this station.
- The influence of salt water on PV modules and the module performance are of vital importance which needs to be investigated. The degradations of floating PV systems are reported to increase depending on temperature and humidity such as corrosion, ribbon fatigue, and back sheet hydrolysis.
- Optimizing tilt angle for the PV modules in floating systems plays a notable role in annual electricity generation and system efficiency. Alternatively, floating PV systems can be operated with solar tracking units for better power generation performance.
- Offshore floating PV systems are expected to be economically feasible in the near future as a consequence of remarkable advancements in large-scale solar farms on water bodies.
- Algae growth is limited in floating PV power plants because of mitigated solar radiation, which yields to better water quality.
- Thin film PV cells have long, narrow, and rectangular cells connected in series. In addition to allowing two-dimensional current flow due to the internal structure of the cells connected in series, they are at lower temperature values in operating conditions [95]. For this reason, rather than conventional crystalline silicon PV cell technologies, thin film PV cells can be preferred to be utilized in floating PV systems which are more capable of withstanding harsh water environments.
- Geographic information systems and remote sensing techniques which are the technique of detecting and monitoring physical characteristics by measuring the radiation emitted or reflected from an area from a controlled distance, can be considered for feasibility analyses of floating PV power plant projects.
- Prior to projecting floating PV power plants at any location, temperature and solar radiation data, maximum wind speed, snow load, water current, cyclone, and typhoon risks need to be analyzed.
- Anchoring cables require periodic inspection and maintenance in floating PV power plants.

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