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FLOATING SOLAR STATIONS

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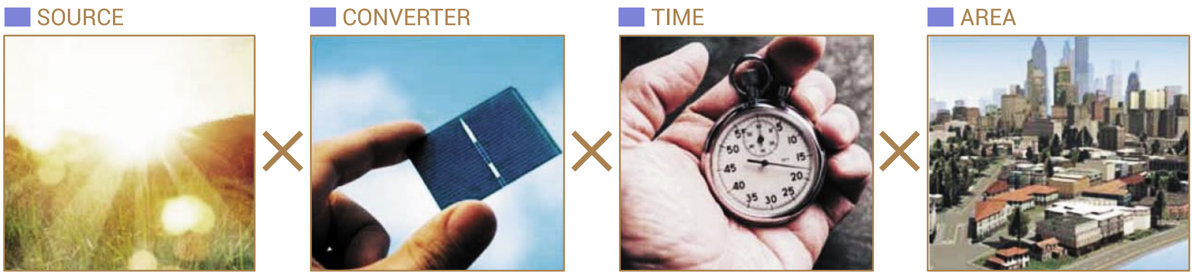
INTRODUCTION

According to International Energy Agency, solar photovoltaic deployment levels were globally high in 2020 in the midst of 90% grow in renewable electricity demand[5]. Photovoltaic (PV) can directly convert sunlight to electricity. From photovoltaic point of view, as can be seen Figure 1, there are four main factors influencing the output PV energy yield. First is the source of energy, the sunlight, then the converter which is the PV cell, further the amount of time that the PV unit can work, and finally the amount of area that PV technology is added on or integrated into. Sunlight is a given, we do not have much control on it. On top of that, PV converter efficiency is reaching its maximum theoretical efficiency[6/7]. And that is why researchers have now put more effort into investigating approaches to boost the lifetime of PV (the factor time)[8] and also looking into possibilities to add PV on or integrated it into any possible surface (the factor area)[9]. However, due to low efficiency of PV modules, they occupy considerable amount of area, which can be used for other essential needs of human kind, such as food and accommodation. World population is growing and the demand for food, accommodation, and green energy is also increasing. Therefore, agriculture and energy sectors might compete or already are competing over land. This inevitably brings the attention to another vastly available surface area, the water. Simply placing any type of PV system on top of (or even submerged into) water bodies, such as lakes, reservoirs, hydroelectric dams, industrial and irrigation ponds, and coastal lagoons, is called floating PV (FPV) or floatovoltaics.

FIGURE 1. Four key influential factors on photovoltaic energy yield.

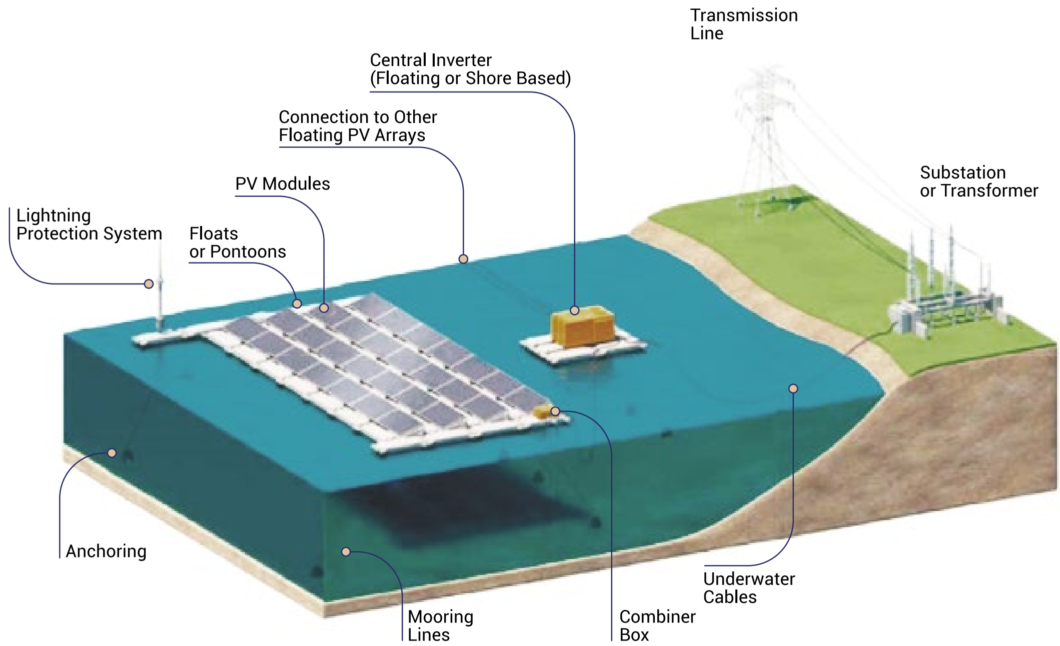


5 — World Energy Outlook 2020, International Energy Agency
6 — Yoshikawa et al., 2017
7 — Richter et al., 2013
8 — Ndiaye et al., 2013
9 — Ziar et al., 2021

TECHNOLOGY

A floating PV plant normally consists of floats, mooring and anchoring system, PV modules, and balance of system (BoS) components. Figure 2 shows a schematic of a floating PV plant and its key components. Expect for the floats, which bring the necessity for mooring and anchoring system, the rest of a floating PV plant is almost the same as ground-based installation. Floats are compartments with buoyancy to keep PV modules and supporting structures float on water. Floats should be recyclable, nontoxic, resilient to water, salt corrosion, and UV radiation that can ensure more than 20 years of operation with minimum effect of the waterbody ecosystem. There are three main types for the floats used for floating PV plants: (1) pure-floats with high-density polyethylene (HDPE) material, (2) pontoons (or hollow cubes) with metal trusses, and (3) special membranes or mats. Examples for float types are shown in Figure 3. Mooring refers to any permanent structure which is used to forestall free movement of the floating structure. An anchor mooring fixes a floating structure's position relative to a point on the bottom or sides of a waterbody. This will prevent the floating PV plant from being blown or pushed away by wind load, wave force, and or water streams or hit the banks when the water level is changing. Examples of three main anchoring types are shown in Figure 4. Rows of PV modules, either mono-facial or bifacial, produce DC electricity which is sent to the combiner box. For the first and second type of the floats, usually framed glass-glass PV modules are placed as they are more resilient to humid condition compare to glass-back sheet PV modules. However, real long-term data is missing to further prove this general expectation. For the first and second types of the floats, framed PV modules are preferred as they enable easy yet sturdy installation of the PV modules on the floating structure. Frameless PV module are also installed in a few project, especially when installing on membrane, as they are expected to experience less potential induced degradation (PID) effect. Most of the installed floating PV modules use mono-facial mono or poly crystalline silicon PV technologies. Further, the inverter, could be central or string inverter, convert the produced power to AC electricity. Usually larger FPV plants brings the necessity for putting central inverter(s) with ingress protection 67 (IP67) on a floating housing(s), whereas most of the small-size FPVs have string inverters placed on the land nearby. Underwater cables with high insulation are used to send the produced energy to the nearest grid connection point, which can be further transmitted to the grid or be used locally. As floating PV plants are placed on open waterbodies, they can be susceptible to lighting, therefore usually lightning protection is placed and surge arresters are included in the combiner boxes. A floating PV system can also be backed up by storage, e.g. batteries, if need be.

FIGURE 2. Schematic of a floating PV plant and its key components[10].



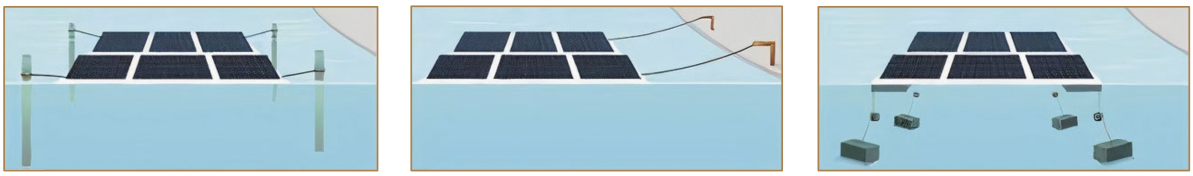
10 — Lee et al., 2020

FIGURE 3.

a. b. c.

Different floating structures used for floating PV plants, (a) small size PV system installed on a pure-float floating structure, (b) pontoons with metallic structures holding rows of rigid PV modules, and (c) PV modules placed horizontally on thick an elastic mat. Option (a) is lightweight with large water-plastic contact area. This boosts plastic defoliation possibility. The lightness of the floats makes them vulnerable to high wind loads when wave force is present[11], by increasing the chance for the wind to blow under the floats and push them upward in a cascaded manner. Option (a) has complex mooring system, hardly customisable for sun tracking and bifacial PV installation. However, it is a cost effective solution, which enables large-scale deployment. For example, this type of floats are used in the largest Europe floating PV system (17 MW) in France[12]. On the other hand, option (b) suffers from high cost and complex construction[13] but brings the possibility for vertical sun tracking, bifacial PV, and higher tilt installation. For instance, a ~450 kW floating PV installation in Swiss Alps[14] is using such floats concept with bifacial PV modules. Option (c) is less common than the other two but is a good option in regions with water scarcity as the rubber mats can entirely cover a waterbody. Since membranes in option (c) types of floating PV systems are in full contact with water, PV modules work at a lower temperature (higher efficiency). In addition, the membrane-based floating platforms are strong enough to withstand weight (for installation and maintenance) while being flexible enough to accommodate waves, which makes them a preferred solution for off-shore applications. Option (c) however, suffers from costly installation and O&M and tilted PV modules cannot be installed. The 100 KWp floating PV system installed in Norwegian west coast is a good example of implementing such floaters[15]. Also for this type, PV modules can be submerged into water. Submerged FPV is currently not considered as the mainstream solution[16].

FIGURE 4.



a. b. c.

Three common types of anchoring for floating PV plants, (a) anchoring on piles, (b) bank anchoring, and (c) bottom anchoring, which could be self-sinking or permanents fixed point[12]. The type of the anchor depends on the soil condition. A floating PV can also have a combination of different anchoring types.

11 — Bellini, 2019
12 — Floating solar: Europe's largest power plant is French, 2019
13 — Cazzaniga et al., 2018
14 — PV magazine, 2019
15 — Kyrholmen project
16 — World Bank, 2019

POTENTIAL AND COST

GLOBAL POTENTIAL OF FLOATING PV

One can quickly guess that floating PV systems have tremendous potential, simply by knowing that 71% of the Earth surface is covered by water. However, current technology of the floating PV systems are not sophisticated enough to handle harsh offshore environment, and if even so, with a huge additional cost. However, if only 10% of the man-made waterbodies, i.e. dams and man-made reservoirs, are coved by floating PV plants the global potential of FPV adds up to 4 TWp[12]. Table I shows the share of each continent in this potential.

TABLE 1. Share in global FPV potential per continent (calculated from[12])

Continent	Share in global FPV potential (%) *(10% cover of man-made waterbodies)*
Africa	25
Asia	28.6
Europe	5
North America	31.1
Oceania	1.2
South America	9

COST OF FLOATING PV

The main difference between installation costs of a floating PV with that of a ground-based PV system is on floating structure, mooring and anchoring systems, and cabling. Example MWp scale projects across the globe show the CAPEX cost of FPV between 0.8 to 1.2 $/Wp, which is around 18% more than conventional ground-based PV system. However, this extra cost is compensated as FPV systems yield more energy because of lower working temperature and more favourable free horizon for the modules. The yield gain of FPV systems has been reported differently so far[17/18], but an FPV system in warmer climates gives higher yield gain (~10%) while in colder regions the gain drops (~5%). Overall, depending on the installation region, this results in respectively 3-4% and 8-9% higher levelised cost of electricity (LCOE) for floating PV compare to ground-based PV plants[19]. Table II represents the percentage breakdown of the system components cost for a MWp scale FPV project.

TABLE 2. Share in total FPV CAPEXT per component (calculated from[15])

FPV component	CAPEX share (%)
Modules	34.2
Inverters	8.2
Mounting system (Floating structure, anchoring, and mooring system)	20.5
BOS (cables, junction boxes, switchboards, transformers, etc.)	17.8
Design, construction, testing and commissioning	19.2

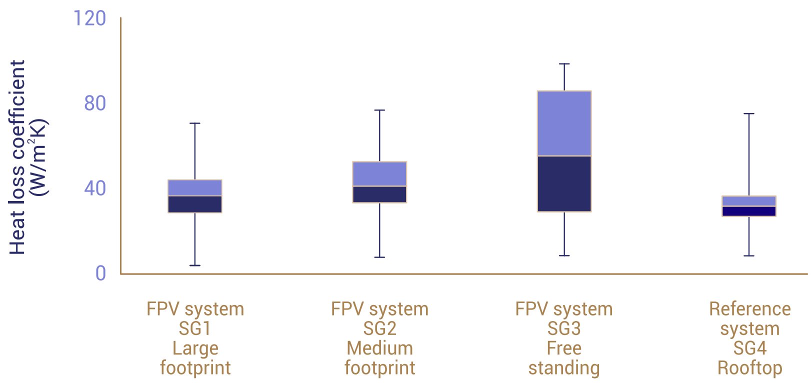
17 — Liu et al., 2018
18 — Ziar et al., 2020
19 — World Bank, 2019

CHALLENGES AND OPPORTUNITIES

There are several unique features and functionalities associated with FPV plants, which might bring both opportunities and challenges. The following tables make an overview of the opportunities and challenges come into play when one considers FPV plants.

TABLE 3. Opportunities coming along with floating photovoltaic plants.

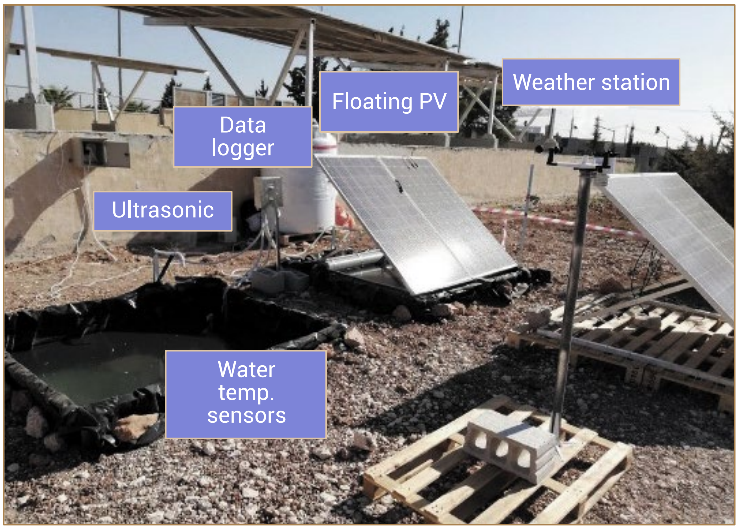
Opportunities	Comments and/or evidence to support
Saving land	Using water area, that is a non-revenue generating surface, keeps the land saved for other land-incentive markets such as housing, agriculture, tourism, mining, etc. This a trivial fact, supported by literature[20/21/22/23].
Radiation balance	Since PV modules are designed to absorb as much as light possible, they have very low albedo. Therefore, land-based PV plants strongly modify the land albedo, which depends on the type of material covering it (e.g. for vegetation is 20-30%, for desert is 40-50%)[24]. Such radiation imbalance may raise issues related to local temperature and microclimate. For the water, however, the albedo is ~6%[25/26], which goes with the low albedo of the PV modules and therefore no to low radiation imbalance will happen.
Increased efficiency	As the convection is the main cooling mechanism for PV modules[27], and the air above water area is cooled down by the air, therefore the PV modules, which have negative temperature coefficient work at higher voltage, which leads to more efficiency and total energy yield. A study showed in tropical climates, e.g. Singapore, the irradiance weighted temperature difference of floating PV can reach to 14.5 °C, while for maritime climates (e.g. the Netherlands) this value reduces to 3.2 °C. This plot shows the heat loss coefficient FPV systems compared to reference rooftop PV in Singapore[28].



20 — Rosa-Clot, 2020
21 — Trapani et al., 2015
22 — Sahu et al., 2016
23 — Ranjbaran et al., 2019
24 — Ziar et al., 2019
25 — Ziar et al., 2020
26 — Séférian et al., 2018
27 — Hasanuzzaman et al., 2016
28 — Dörenkämper et al., 2021

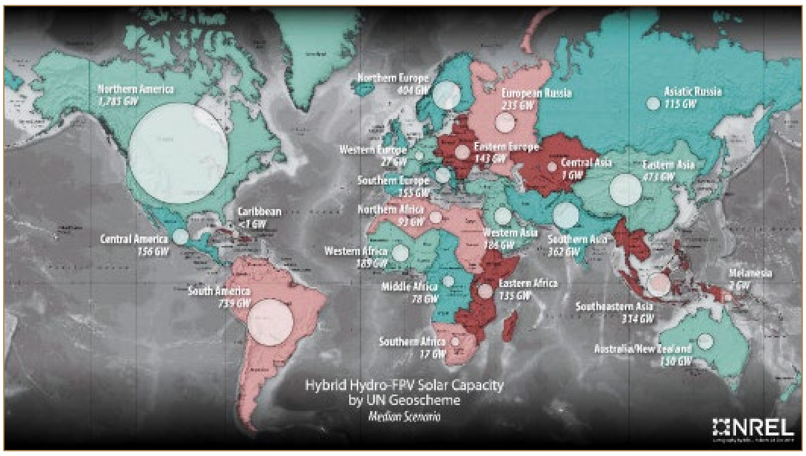
Reduced water evaporation

When deployed on sweet water reservoir, floating PV can reduce the rate of water evaporation. In some countries, such as Morocco water evaporation can reach up to 3 m^3/m^2/year. A study performed in Jordan showed that installing floating PV can reduce the water evaporation by 60%. The figure shows the platform of the experiments conducted in Jordan[29].



Synergy with hydro power plants

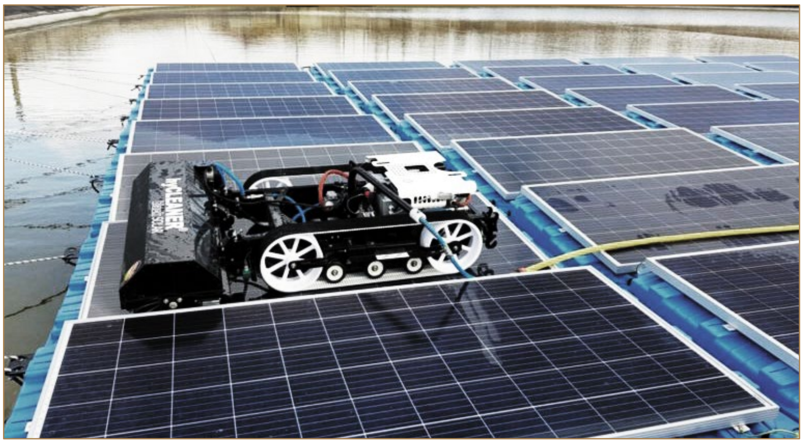
The yearly power production curve of hydropower plants (HPP) is mainly governed by water seasonal cycle, which complementary to sunlight irradiance cycle. Therefore, HPP and FPV can work complementary while FPV is benefiting from the surface of the calm water behind the dam and the already established grid infrastructure, and on the other hand HPP benefits from less water evaporation and complementary power production profile. Also with a coordinated control HPP and FPV can work together to provide stable power without the need for electrical storage. A research studied 20 largest HPPs across the World and concluded that by covering 10% of the HPP basins surface the HPPs energy production is increased by 65%[30]. The figure shows the hybrid HPP-FPV capacity around the globe[31].



29 — Abdelal et al., 2021
30 — Cazzaniga et al., 2019
31 — Lee et al., 2020

Easy and effective PV module cleaning

Due to accessibility to water, cleaning the modules for FPVs system is less expensive and can be done more frequently compared to land-based PV systems. The figure shows a snap of robot cleaning for a floating PV system installed in Spain[32].



Improved water quality

As a result of less light penetration into water, there will be lower chance for algae growth and therefore higher water quality is expected. For water quality assessment, usually total nitrogen (TN), total phosphorus (TP), chlorophyll-a, a measure of total phytoplankton abundance (Chl-a) and cyanobacterial chlorophyll, a measure of potentially toxic cyanobacterial abundance (cyano-Chl) are measured. So far, research result showed no discernible impacts on water quality as result of FPV installation[33] or even improvement reported by observation of limiting Chl-a and nitrate concentrations[26]. One-third to half coverage is recommended by the literature to preserve water quality while reducing water evaporation[34].

Longer life-time

Although land-based PV plants placed in dry areas benefit from high irradiance, but modules experience more severe thermal cycle as a result of high day and night temperature differences. This severely influence the lifetime of the modules and causes effects such as delamination[35]. However, when PV modules are deployed on water, across 24 hours they experience very low temperature deference because the water has a high heat capacity. This will help PV modules longevity.

32 — Molina, 2021
33 — Ziar et al., 2020
34 — Baradei, Sadeq, 2020
35 — Ferrara, Philipp, 2012

Ease of deployment	For type one and two of the floats, deployment of floating PV systems can be easy and quick. Leading float manufacturers reported that when supply chain is in place, a team of trained installers can deploy between 500 KWp to 1MWp per day[36]. The figure shows a team installing pure-float based FPV in modular and quick way[37].

TABLE 4. Challenges associated with floating photovoltaic plants.

Challenges	Comments and/or evidence to support
Complex mooring and anchoring	Anchoring and mooring system choice and design might change per morphology of the installation location. Key influential factors are: type of the soil at the bottom of the water basin, water depth, and maximum water level variation. Also, as the size of FPV increases the number of mooring lines increases. Around 30 mooring lines are needed per MWp of floating PV[38]. Calculating the forces on each mooring line at different wind and wave scenarios is a challenging engineering task. For instance, the figure shows Anhui CECEP's floating solar plant in China (70 MWp) which uses bottom anchoring with 1500 anchors[39].

36 — World Bank, 2019
37 — Clean Technica, 2019
38 — Solarplaza Webinar, 2020
39 — Anhui CECEP, 2021

Dirt and bio-fouling accumulation and hotspot

Although soiling is most server for PV plants in dry regions with dust events, recent researches showed that dirt and bio-fouling is a considerable effect for floating PV systems. One reason is birds visit floating PV systems quiet often. If not cleaned, dirt and bio-fouling cause hot spots and damage PV modules[40/41]. Research shows the modules with higher tilt are less likely to get fouled by birds, as it is more difficult for bird to stand for a long time on them. The figure shows heavy bio-fouling on PV modules and reflectors and hot-spot as a result of dirt[42/43].

Difficult maintenance

There are few advantages for floating PV in terms of maintenance, such as easier access to water for cleaning and lower risk of theft or vandalism. However, generally maintenance procedure, either preventive, corrective, or preventive, for floating PV plants is not as straightforward as that of the land-based systems. For floating PV, it is harder to access and replace components, which could be needed more frequently because highly-humidity environment may accelerate corrosion and components are very likely to have biofouling[44].

Impact on water eco-system

Floating PV reduces light penetration into the water and reduces underwater biomass and photosynthesis rate. Therefore, floating PV might reduce oxygen concentration of water, which can affect fishes. Low oxygen concentration (anoxia) can also increase methane release in shallow lakes. A research reported periods of anoxia is more frequent under floating PV plants compare to open water areas[38].

Less life-time of BOS component

Since cables, junction boxes, fuses, and other balance of the system components are working under very humid condition, the longevity of the components might be affected. Submerging cables and connectors into water can cause current leakage and low insulation resistance, corrosion of cables, and eventual loss of power. The figure shows biofouling on submerged connectors and cables[40].

40 — Ziar et al., 2012
41 — Ziar et al., 2017
42 — Ziar et al., 2020
43 — SERIS Thermographic Analysis of PV Systems
44 — World Bank, 2019

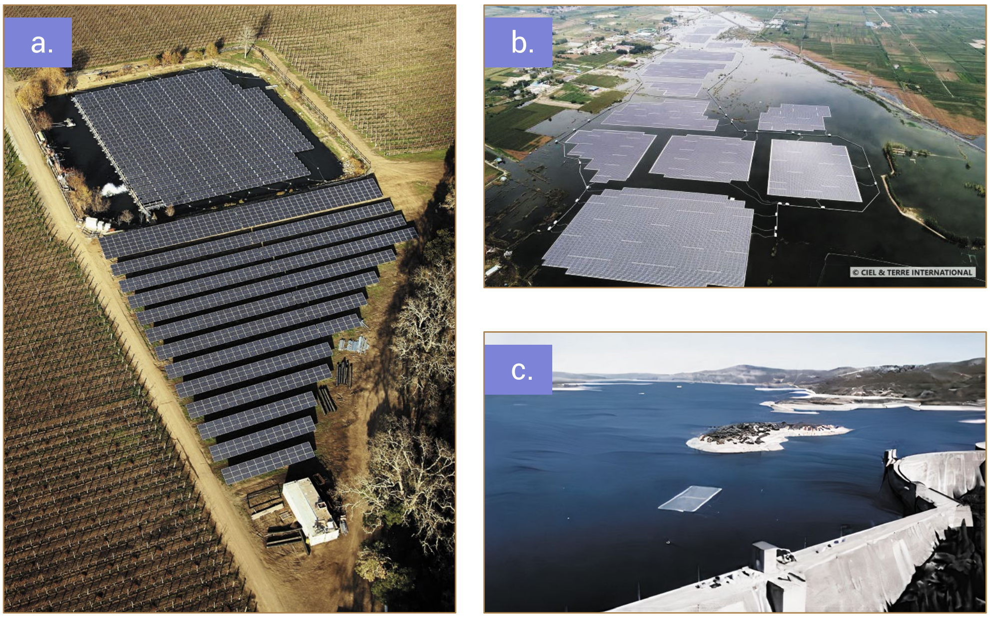
Low TRL for high-wave categories	Although floating PV plants with membranes as floating platform are installed in costal areas, the technology readiness level (TRL) of floating PV system for high wave categories is lower. There are four categories for the FPV. The first three categories are for inland water areas, respectively for negligible, 1m-, and 2m-wave heights. The fourth category is the for open seas for which the floating PV systems should withstand waves up to 10 meters of height[45]. Comparative projects running at various places in the World show that the technology readiness level is higher for the lower wave categories[46].
Lack of FPV-specific Standards	As a technology, floating PV is still in its nascent stages, and thus, there are no specific standards available at the moment. The standards written for ground-based PV systems cannot be extended for FPV as they comprises floating platform and anchoring and mooring systems placed on top of the water surface. Formulating FPV-specific standards and guidelines for designes will help to ensure that FPV system and its compoenets can survive harsh environmental conditions while retaining the quality over 20 years without causing considerable impact on water ecosystem and biodiversity[47].

45 — Folkerts et al., 2017
46 — TNO, 2020
47 — Acharya et al., 2019

NOTABLE FLOATING PV PROJECTS AROUND THE WORLD

The first floating PV system (20 kWp) was built in 2007 in Aichi, Japan for research purposes, followed by the first commercial scale (175 kWp) floating PV plant installed in California, USA in 2008[48]. Many floating PV systems were developed afterwards, mostly leading by countries with high population density and/or land scarcity[49]. Nowadays, in 60+ countries floating PV plants are either installed or planned to be installed soon. By the end of August 2020, the cumulative installed FPV capacity Worldwide was reported 2.6 GWp[50]. Figure 5 shows a few notable FPV system installed across the World. Such examples are practical proves of technological feasibility of floating PV plants and shows that floating PV has gained momentum.

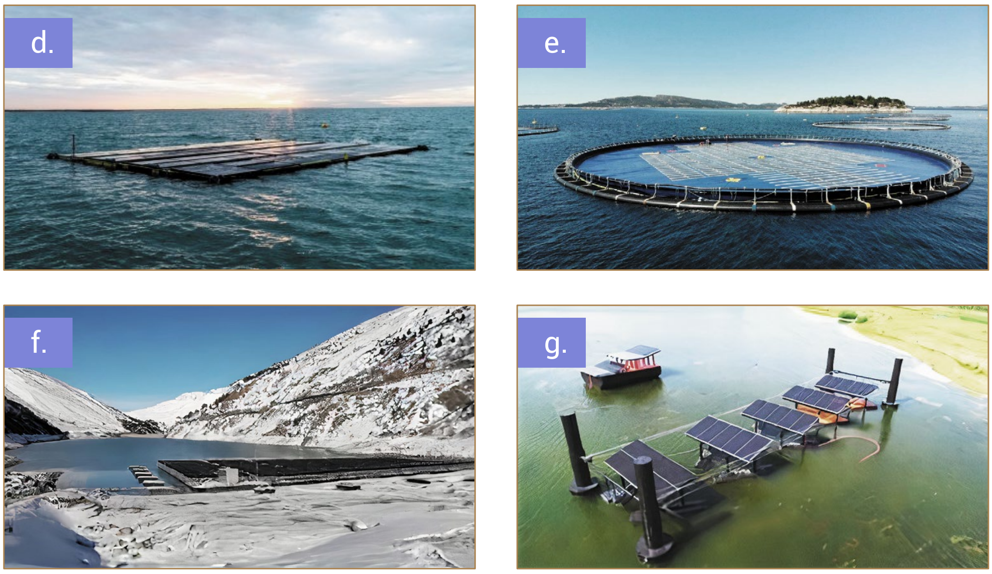
FIGURE 5.



Notable floating PV systems around the World, (a) first commercial scale floating PV plant, Far Niente wineries in California, USA. SPG Solar was contracted by the owners of the winery to install the array in 2008 with 175 kWp[51], further extend to 400 kWp[52], (b) the largest floating PV plant in the World to date, 70 MWp installed at a former coal-mining area of Anhui Province, China[53], (c) World's first combination of hydropower plant and floating PV plant, 220 kWp capacity installation on a hydroelectric dam of Alto Rabagão in Portugal in 2016[54], (d) Pilot of the first off-shore floating PV installed in 2019 in the North Sea with 8.5 kWp, then expended to 50kWp in 2020. Further expansion to 1MW is planned in a modular manner. It is claimed that the pilot module was designed to withstand 13-meter waves. The system survived storms Ciara and Dennis in February 2020[55], (e) single floater, 50 m diameter, 100 kWp floating PV demonstrator system installed for a fish farm operator in Norway in 2018. Being engineered for operations in coastal waters and on man-made reservoirs based on a design that integrates aspects

48 — Trapani et al., 2015
49 — Patil Desai Sujay et al., 2017
50 — Hauwitz, 2020
51 — Trapani et al., 2015
52 — The New York Times, 2011
53 — PV Tech, 2019
54 — Ciel Terre, 2021
55 — Oceans of Energy, 2019

of open-sea salmon farm architecture, the system uses silicon PV modules mounted on a flexible hydro-elastic floating membrane, [f] One of the first commercial scale bifacial floating PV ~450 kW installed on artificial Toules lake in Swiss Alps in 2019[56], (g) Retractable and tumbler floating PV systems, respectively enables mowing activities on waterbodies and horizontal-axis sun tracking both with bifacial PV and reflector installations. The pilot systems were installed in the Netherlands in 2019[57].



CONCLUSION

Implementation of floating PV systems can solve the land surface conflict between essential sectors of food, accommodation, and energy for growing population of the World. Moreover, floating PV has low to no effect on surface radiation balance, a feature that land-based PV plants are greatly missing by modifying land albedo. On top of that, floating PV can prevent water evaporation in dry regions. These three key features: (1) solving the surface conflict, (2) maintaining Earth surface radiation balance, and (3) preserving sweet water resources, among other advantages, makes floating photovoltaic plants a unique energy solution for the decade to come, and possibility the years after. While working on addressing the challenges with floating PV, energy-related engineering and research communities should note that FPV systems are not competitors of ground-based PV systems and can been seen as a different implementation of PV modules that brings several advantages and is multi-purpose.

56 — PV magazine, 2019
57 — Ziar et al., 2020

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