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Overview of the floating offshore photovoltaic energy potential

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ABSTRACT: An overview of the state of the art of the floating photovoltaic renewable energy technology is given. The main characteristics of floating photovoltaic systems are outlined, as well as the features influencing on their preformance. Moreover, existing concepts and ongoing projects around the world are compiled and briefly described. The advantages, drawbacks and potential hazards for this technology are highlighted. Offshore solar photovoltaic systems allow upscaling the installed capacity and increment the power generation, significantly reducing greenhouse gas emissions. These systems specially contribute to boost renewable energy generation in islands with minimal land availability. The environmental risks and potential hazards for this technology are also discussed, such as water level fluctuations, severe storms, earthquakes, and tsunamis. Despite some concerning hazards, the successful performance and reliability of some existing floating solar farms has raised trustability and interest for this technology among several countries committed to a prompt energy transition.

1 INTRODUCTION

The current framework of energy transition increases the interest in investing in renewable energy technologies. They represent powerful tools to move away from the use of fossil sources (coal, oil, natural gas, etc.) and reduce environmental pollution. Despite some of the advantages of fossil fuels (generally cheaper than renewable energy sources, high energy efficiency and convenient transport), several governments around the world are engaged with the implementation of new measures that stand up for the reduction of greenhouse gas emissions given off by the excessive use of these fossil fuels (Wim *et al.* 2022). Nowadays renewable energy sources constitute about 13.5% of production energy worldwide, and this percentage raised up by about one point between 2019 and 2020 (Bellavia 2022). The offshore component of reneable energy is dominated by wind energy, which has seen a large increase in recent years (Diaz & Guedes Soares 2020).

Solar, wind, tidal, geothermal, hydroelectric and biomass energy sources have the potential to mitigate the effects of ever-rising temperatures, as they allow for the generation of energy without releasing carbon dioxide and other greenhouse gases into the atmosphere. Among them, photovoltaic (PV) modules, used all over the world for the production of solar energy, absorb sunlight by converting the energy into a usable form of electric current. The solar modules have no moving parts, which significantly reduces maintenance costs ensuring highly reliable systems (Huang *et al.*, 2023). In addition, photovoltaic systems are especially cost-effective compared to other energy sources in remote places where it is difficult and economically unfeasible to reach with traditional electric lines (Remote Energy 2021).

However, an important drawback of onshore photovoltaic systems is the scarce land availability, as they compete for space with other agricultural and industrial purposes, especially in densely populated regions. A further disadvantage is the degradation of the PV array performance caused by high operating temperatures of the PV cells within onshore systems. Some of the downsides associated with onshore PV systems can be efficiently overcome with the use of the emerging floating PV technologies (FPV). Photovoltaic panels are increasingly being installed in various places, including seas, lakes, rivers, dams, and water treatment plants.

The performance of a photovoltaics system on land and at sea has been simulated and compared by Golroodbari & van Sark (2020). The results show that the relative annual average output energy is between 13% to 18% higher at sea compared with land. However, special concerns arise regarding to the mooring lines, which must be perfectly designed to survive in extreme weather conditions, avoiding damage and displacement of the system (Cazzaniga *et al.* 2018).

This work overviews the state of the art of floating photovoltaic renewable energy technology. The main characteristics of FPV systems are described in Section 2, both offshore and inland water bodies. Section 3 outlines the features influencing the performance of FPV energy systems. Section 4 reviews some of the existing FPV concepts, while Sections 5

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and 6 put forward some ongoing projects around the world and Europe. In Section 7, the advantages, drawbacks and potential hazards of this technology have been highlighted, and Section 8 concludes with the main highlights of the overview.

2 FLOATING PV CHARACTERISTICS

The structural characteristics of floating PV panels are very similar to those of land-mounted systems, except that PV modules are mounted on floating structures. The floating photovoltaic system typically consists of floating high-density polyethylene pontoons, on which the various parts of the photovoltaic fields are positioned, including inverters, and metal frames (Figure 1).

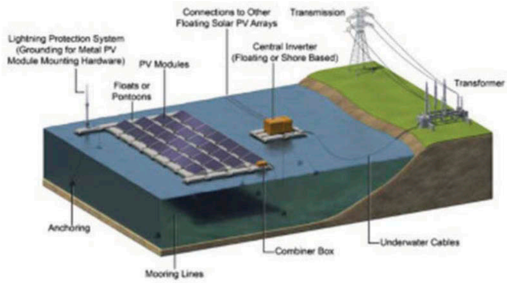

Figure 1. Typical large-scale floating PV system with its key components (Lee et al., 2020).

It is essential to correctly size a photovoltaic field to obtain high energy conversion efficiencies, also allowing to reduce the possibility of damage to the system itself (Kumar *et al.* 2021).

The inverter is a fundamental element of the photovoltaic system, as it converts the direct current derived from solar energy into alternating current destined for the public grid. The inverter can be placed both on the floating platform and on the ground and there are mainly two types: a central inverter or a multi-string inverter (Maraj *et al.* 2022).

Once produced, solar energy is taken from the panel and transferred to the ground (Figure 1). The energy produced can then be fed directly into the grid or stored in batteries. In most of the projects carried out to date, the cables are kept above the water level, guaranteeing perfectly waterproof conditions, also resisting high temperatures to avoid current leakage. High temperature resistance, water proof and robust cables are to be used to provide a long service. Other electrical components such as inverters and batteries remain on land (Sahu *et al.* 2016).

The pontoons and floats (Figure 2) represent one of the most important parts of the whole structure. They stay on the surface, floating, maintaining a constant ratio between buoyancy and own weight. They represent a fundamental part of the system as they constitute a foundation platform for the various elements. They are mainly made of high-density polyethylene (HDPE), as it has excellent characteristics, including high tensile strength, and resistance to UV rays and corrosion. Medium-density polyethene (MDPE) is also used in some applications (Sahu *et al.* 2016).

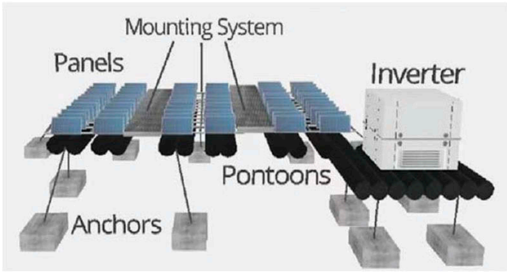

Figure 2. Pontoons and floats (Wang & Lund 2022).

The mooring and anchoring system represents a further fundamental part of the installation, as it must avoid excessive movement of the system caused by wind, changes in water level, big waves, etc. Therefore, when sizing a mooring system, it is necessary to consider the possible environmental situations that may occur during the lifecycle of the system. The mooring system is usually made with polyester nylon ropes fixed on the shore and anchored at each corner (Kumar *et al.* 2021). The approaches adopted to design mooring systems are similar to the ones used for other renewable energy devices (Xu et al. 2019).

3 PV OFFSHORE SYSTEM PERFORMANCE

The electricity production of the floating PV systems is determined by various parameters. The most important are:

- Orientation of the photovoltaic modules:

To obtain a greater performance, photovoltaic panels are generally inclined with an optimal angle of inclination relative to the horizontal surface to chase the maximum incidence of sun's rays (Figure 3). This is especially relevant for regions with a high ratio of direct to diffuse solar radiation throughout the year. In offshore parks, however, the tracking systems used in onshore conditions are not suitable, since steep angles of inclination at panels located at sea make them prone to be hit by very strong winds. Additionally, the movement of the offshore floating structure in response to incoming waves can influence the insolation on PV modules, although limited research exists quantifying this effect (Trapani *et al.* 2013, Magkouris *et al*., 21). The effects of waves on the floating PV performance was presented in (Magkouris *et al*., 21), indicating significant variations of the performance index ranging from 0 to 15% depending on the sea state.

Figure 4 shows the effect that the response of a floating structure to incoming waves can have on the effective slope of a PV module. The possible degrees of freedom of a moving offshore PV module motion are three, namely pitch, yaw and roll movements, as shown in Figure 5.

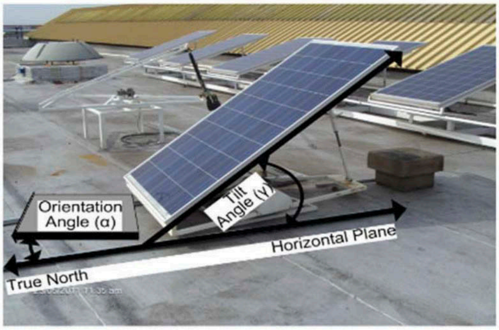

Figure 3. Orientation of the photovoltaic modules (Institute of Electrical and Electronics Engineers. 2012).

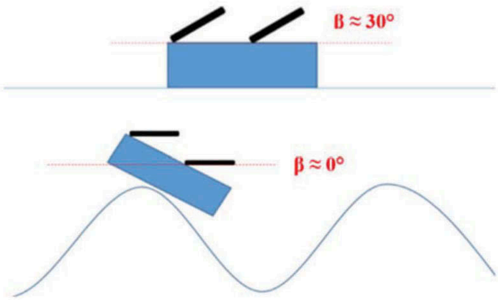

Figure 4. Floating platform at steady state (TOP) and Floating platform responding to incoming wave (BOTTOM) (Bugeja et al. 2021).

Consequently, often many offshore photovoltaic concepts have an angle of inclination equal to zero. This setup leads to a lower power production peak at noon, although a higher production in the early morning and late afternoon partially compensates for this phenomenon (Wim *et al.* 2022). Moreover, the dirt losses increase as the angle of inclination decreases, which lowers the total energy produced by the system. The dirt loss can reduce the energy produced by the PV system up to 2 Wh/Wp (El Baqqal *et al.* 2020).

- Temperature:

The output voltage, and thus the output power of PV modules decreases with increasing temperatures. However, offshore photovoltaic systems entail some advantages regarding the efficiency of the solar park, as the water acts as a natural refrigeration system, decreasing the temperature of the panels and reaching higher efficiency values (5-15% higher than

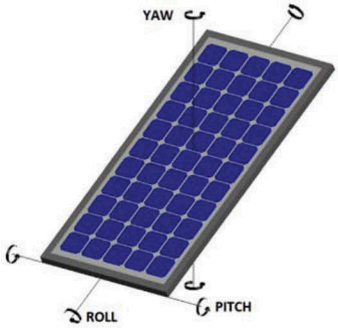

Figure 5. Solar panels (Bugeja et al. 2021).

conventional rooftop panels) (Lin 2021, Favetti 2022). The real cooling effect though is very much dependent on the construction and the materials of the floating structures on which the PV modules are mounted. Advantages also arise from an environmental point of view, if panels are installed in the right position, as it reduces the potential growth of toxic algae, as well as the evaporation effect of the water (Wim *et al.* 2022).

- Soiling and fouling:

It is essential to keep the PV panels clean as it allows the efficiency of the entire system to be kept high. Dirt accumulated on solar panels can cause a significant reduction in solar energy production. Some studies have recently confirmed that low system maintenance levels can lead to a loss of efficiency of 15-30%, thus shortening the duration of the panels' life cycle, which is usually 30 years (Wim *et al.* 2022).

4 FLOATING PV TECHNOLOGY CONCEPTS

In recent years, many increasingly sophisticated designs have been analyzed to withstand the harsh conditions present in the seas. Initially, these designs were only tested in lakes or rivers. A classification is made regarding the position of the photovoltaic modules concerning the waterline: superficial or pontoon systems. In the first case, the photovoltaic modules are installed on the water surface, in the second case, an intermediate floating platform is arranged (Claus & López 2022).

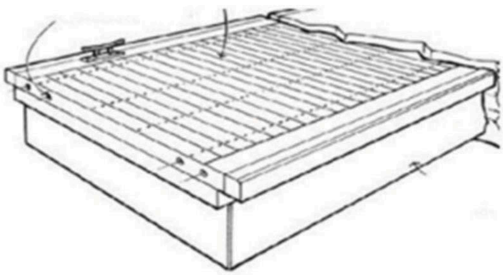

Figure 6. Schematic of a Pontoon (Wim et al. 2022).

4.1 *The Pontoon concepts*

The pontoon concept is based on floating pontoons, where the wind load on the structure is low (Figure 6). Pontoons are substructures that are mechanically coupled into a massively modular structure. The complete floating structure is moored (Wim *et al.* 2022). The main idea behind pontoon-type systems is based on designing a raft or pontoon to create a stable floating platform on which solar panels are later installed (Claus & López 2022).

4.2 *The truss concepts*

A truss structure is equipped with floats and mooring. Above the truss structure, a platform containing the solar panels is placed (Figure 7). The platform is located at a certain height above the waterline, thus avoiding direct contact with the waves and mainly allowing for the reduction of the encrustation on the solar panels due to seawater residues on the surfaces themselves. It also allows for to reduction of the mechanical load on the solar panels which is lower due to the absence of contact with the waves (Wim *et al.* 2022).

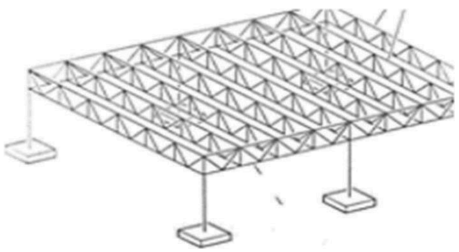

Figure 7. Schematic of a truss concept (Wim et al. 2022).

4.3 *The soft and flex concept*

The basic idea of the soft & flex concept (Figure 8) is to let the floating structure move as much as possible with the waves, to obtain a lower amount of mechanical energy on the structure, therefore reducing the mooring forces. This implies a lower cost of the structure, compared to the plant analyzed previously. Solar panels must be flexible enough as they must be able to follow the deformation of the float (Trapani *et al.* 2013).

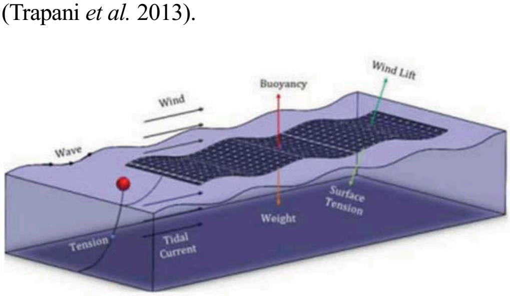

Figure 8. Schematic of a soft and flex concept (Trapani and Millar 2016).

5 OFFSHORE PV ENERGY IN THE WORLD

Although the FPV technology is increasingly getting new attention from stakeholders worldwide, not many offshore FPV systems have been installed in open water so far, while few projects are planned to be set up in the upcoming years.

5.1 *Photovoltaic systems in Asia*

- Maldives islands

The energy system in the Republic of the Maldives Islands, located southwest of Sri Lanka and India in the central Indian Ocean, relies mostly on imported fossil fuels as the primary source of energy to supply the rapidly growing economic activity (mostly boosted by the tourism industry). Nearly 80% of the petroleum product imported into the Maldives is diesel, which is used for power generation via diesel generators on the main island. Fuel transport via navigation makes the Maldives one of the regions with the highest cost of energy production in South Asia. Moreover, in the short term, the energy demand is expected to increase by about 20% (ADB 2018), compared to the current rate of consumption, thus a reliable and affordable energy supply is required for the following years.

The Maldives is naturally exposed to abundant renewable energy sources (solar, wind, ocean…), thus electricity generation using emerging renewable energy technologies may prove to be an alternative to high-cost electricity from diesel generators in the Maldives. As of the year 2020, the share of renewable energy in the total energy mix of Maldives was about 5.6 %, out of that total renewable energy generated over the country, 95 % of it is made using solar energy, 1 % using bioenergy and 4 % using wind energy (IRENA 2022).

The intensive solar radiation exposure of the region has put the Maldives in the spotlight for offshore photovoltaic energy developers. Existing research analyzed the electrical performance of floating thin-film photovoltaic systems to be installed in the Maldives Islands. Small-scale 5 MW offshore systems were designed as a compromise between energy production and environmental impact. Two PV modules were placed on the main float of the floating structure made of HDPE and connected by connecting bolts and pins, installing 6930 pontoons to support the whole PV system (SWIMSOL 2023).

As offshore solar photovoltaic modules play a fundamental role by increasing the energy supply reliability and reducing greenhouse effects, further offshore PV projects are expected to increment the solar energy penetration into the Maldivian's electric mix.

- Indonesia:

The Indonesian state-owned utility PT PLN recently started running the Indonesia's largest floating solar array up to date, a 561-kW floating solar plant built on a pond measuring 1 hectare in the Tambak Lorok coastal area of Semarang (island of Java) (Figure 9). The floating plant is part of a larger 920 kW PV project under construction, and it is expected to produce 1.4 million kWh a year, helping to reduce CO2 gas emissions by up to 1,304 tons (Meza 2023).

Figure 9. Floating solar PV plant installed on a pond in the Tambak Lorok, coastal area of Semarang (island of Java) (Meza 2023).

- Singapore

One of the world's largest floating solar PV farms, with around 60 MWp (122,000 solar panels), was installed in 2021 in the Tengeh Reservoir (Singapore) (Figure 10). It produces enough electricity to power the island's water treatment plants. The electricity generated by this plant is expected to make Singapore one of the few countries in the world to have a water treatment system powered entirely by renewable energy. Environmental impact assessments stated a reduced impact on wildlife and water quality (Lin 2021).

Figure 10. General view of one of the world's largest floating solar panel farms in Singapore (Lin 2021).

5.2 *Photovoltaic systems in Africa*

- Ghana

Following Ghana's strategy to promote access to reliable, clean, and affordable electricity, the first Hydro-Solar Hybrid power generating system in the West African subregion has been recently commissioned, which also includes a 1 MW Floating Solar PV System (Figure 11). It is of the first phase of a 250MWp solar project, which is being implemented in phases of 50MWp. The project generates renewable energy from solar resources that can operate during the day to complement existing hydropower production (Power Africa 2022).

Figure 11. One MW floating solar at Bui, Bono East Region (Ghana) (Power Africa 2022).

- The Seychelles

In the African archipelago of Seychelles, a project for the construction of a 5.8 MW floating solar power plant in the Providence lagoon, near Mahé, has been approved and is scheduled to start in the final quarter of 2023. Under the agreement, the French renewable power producer Qair will develop, build, and operate the floating solar plant to supply renewable energy to the national grid (Shetty 2023).

- Zimbabwe

The low efficiency of coal-fired power plants in Zimbabwe, which usually leads to several electricity shortages, has encouraged the government to implement a 2 GW solar energy portfolio to address the problem. An offshore photovoltaic plant is already planned to be built in the next years by the China Energy Engineering Corporation, which has proposed a project of a 1 GW floating solar plant with about 1.8 million solar modules in Zimbabwe, at the Kariba Dam on the Zambezi River. This project will be developed on the reservoir on top of the Kariba dam, which represents the largest artificial lake in the world (Norman 2023).

6 OFFSHORE PHOTOVOLTAIC IN EUROPE

6.1 *Overview of offshore floating solar systems developers in Europe*

In Europe, different developers of offshore solar panels evolved as the technology grew and spread

(Table 1). Currently, several pilot plant projects exist, which are expected to evolve towards further stages of commercialization in the upcoming years.

6.1.1 *Bluewater*

Bluewater Energy Services, a Dutch engineering consultancy, envisions building an offshore floating solar project in the North Sea with flexible, floating thin-film photovoltaic modules (Figure 12) (Santos 2022). The system consists of multiple individual floats moored to a shared mooring grid, and the floats are made of flexible, air-filled double-wall fabric. In the event of overpressure, this material combines excellent stability of the floating room and such low global stiffness that the float can follow the wave profile perfectly. Some studies state that flexible floating solar technology offers less resistance to waves, therefore facilitating the use of lighter weight floats and anchors, which greatly reduce the total cost (Wim *et al.* 2022b). If the offshore pilot project is successful, the team plans to build a commercial system ranging in size from 1 MW to 5 MW at a wind farm in the North Sea by 2024 (Santos 2022).

Table 1. Solar offshore European technology developers (Wim et al. 2022).

System Developer	Country	Concept	TRL medium exposure	TRL high exposure
Oceans of energy	NL	Pontoon	5	4
Bluewater	NL	Soft&Flex	4	4
Solar duck	NL	Truss	5	4
Tractebel-Engie	Belgium	Truss	4	4
Swimsol	Austria	Truss	8	n.a.
Moss Maritime	Norway	Pontoon	4	4
Ocean Sun	Norway	Fishfarm	8	5

Figure 12. Bluewater technology (Wim et al. 2022).

6.1.2 *Moss Maritime*

Moss Maritime, a Norwegian engineering company active in the offshore oil and renewable energy sector, has developed a concept based on floating 10 x 10 m^2 photovoltaic platforms (Figure 13). It is a classic truss concept, with square bridges and cubic floating elements. The units are flexibly connected to larger systems, allowing the system to perfectly match the surface to the longer wavelength waves (Wim *et al.* 2022).

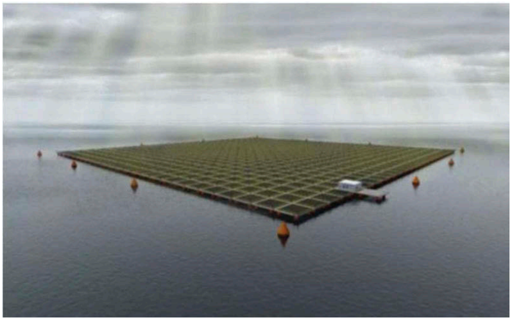

Figure 13. Moss Maritime concept (*Wim* et al. *2022*).

6.1.3 *Tractebel-Engie*

Tractebel-Engie is a well-known developer of floating photovoltaic systems on in-land water bodies. A 1 MWp plant was recently installed on a Terhills Resort reservoir near the Hoge Kempen National Park (Belgium) (TRACTEBEL- Engie 2021). In 2020, they announced the development of three floating PV panels with 30 MW capacity within the 52.2 MW Batalha Hydroelectric Project (Bellini 2020). The photovoltaic system consists of about 7,000 solar panels with a total capacity of 3 MWh. One third of the plant is to be installed on an artificial lake and the remaining part on the ground (Wim *et al.* 2022). A test model of this technology can be seen in Figure 14.

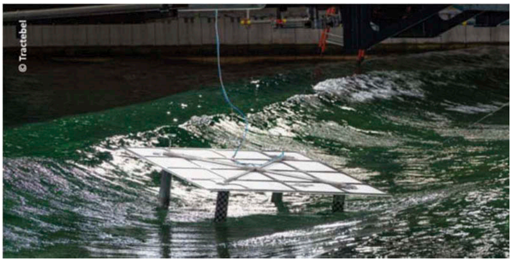

Figure 14. Model test of Tractebel system (*Wim* et al. *2022*).

6.1.4 *Solar Duck technology*

The concept of SolarDuck is based on the use of triangular platforms, mostly made of aluminum, which float a few meters above the water on cylinders (Wim *et al.* 2022). To capture a larger portion of the sun, the PV modules are mounted at an east-west angle direction. SolarDuck is developing a pilot 65 kW floating PV array to be connected to a 10-kW electrolyser to produce hydrogen. The pilot plant is being deployed on the Dutch River of Waal (Rhine), located near IJzendoorn, a village in the province of Gelderland (Solarduck 2021). The system relies on the company's own floating technology that resembles an offshore oil platform. The floating structures are triangular and measure 16 x 16 x 16 meters (Figure 15). They are connected in a flexible way to create large-scale installations. These platforms allow for the placement of photovoltaic modules more than three meters above the water surface. According to the company, this innovative configuration allows the use of conventional photovoltaic modules with high efficiency without having to obtain specially designed and excessively expensive products.

Figure 15. Solar duck system (Bellini 2023).

6.1.5 *Grafenworth technology*

The Grafenwörth floating solar power plant houses more than 45,000 PV panels and is built on the water surface of a former sand and gravel quarry. After testing the plant, the company subsequently installed 15 of them, for a total of approximately 230 MW worldwide (Figure 16) (Ajsa Habibic 2023).

Figure 16. Grafenworth System (Ajsa Habibic 2023).

6.1.6 *Protevs technology*

Protevs, developed by SolarisFloat using research and development from Portuguese universities, is a real innovation in floating solar PV (Deena 2022). Compared to fixed structures, Protevs allows dual-axis rotation of the bifacial solar panels and therefore an increase in energy production of 30 to 40%. The water also acts as a natural cooling system, lowering the temperature of the individual modules and greatly increasing efficiency.

The panel "islands" are made up of 180 panels; each platform can turn on itself and each panel individually performs a tilting movement (Figure 17). It is a very easy-to-install, modular, demountable, and reliable solution. Furthermore, Protevs states the system constitutes a reduced environmental impact.

Protevs have been successfully installed in Holland in the Oostvoornse Meer Lake. The implemented solution, with tracking on one axis, contains 130 modules of floating photovoltaic solar panels, with a capacity of 50.7 kW (Offshore Energy 2022).

Figure 17. Protevs (Favetti 2022).

7 ADVANTAGES AND DISADVANTAGES

Offshore installations entail several advantages but also some negative effects that should be assessed during any offshore PV plant design process.

- Advantages:

Space Availability: Offshore PV systems avoid the competition of land use with other conflicting users (agriculture, industry, architecture, etc. It also reduces the in-land visual impact.

Structure: The overall system features a compact structure, which is easy to move to better capture the solar energy in the different seasons of the year. Floating PV systems equipped with tracking features can increase energy by 15%-20%.

Less evaporation: FPV plants lower the percentage of evaporated water so that more water can be used for irrigation or other purposes.

Low shading: the likelihood of shading FPV is lower due to a more exposed installation environment. Furthermore, the presence of dust on the panel is significantly lower than in inland desert regions or areas with heavy traffic. This lowers the dirt losses and allows us to achieve significantly higher energy efficiencies.

Cost: Offshore photovoltaics can significantly reduce the costs of a photovoltaic plant, mainly in locations with high land management costs (Aritra Gosh 2023a).

- Disadvantages:

Durability: Traditional PV modules are made for terrestrial climates. FPV technologies are constantly exposed to the corrosive effects of salt, humidity, and intensive mechanical forces of wind, and waves, which can easily degrade the system, significantly reducing its performance.

Frozen ambient temperature: The fluctuations of ambient temperature can be problematic, especially if it varies between below zero and above zero degrees. The whole system may freeze when temperatures drop below zero. Anchoring systems can also be affected due to snow.

Marine and aquatic life: The presence of floating structures on the open sea often creates problems of light transmission through the water layers, which subsequently reduces the process of chlorophyll photosynthesis and therefore the growth of algae.

Conflicting users: Other activities performed in the same marine environment could be severely affected (such as fishing, navigation, recreation, etc) (Aritra Gosh 2023b).

8 CONCLUSIONS

An overview of the floating PV renewable energy has been presented in this paper, both offshore and on in-land water bodies. The main characteristics of FPV systems have been outlined, as well as the features influencing on their preformance. Moreover, existing concepts and ongoing FPV projects around the world, have been compiled and briefly described. Also, the advantages, drawbacks and potential hazards for this technology have been highlited.

The floating photovoltaic conversion technology is still very recent and innovative technology but is suffering a quick growth linked to the raising interest for an energy transition framework, as it allows high efficiency rates with low environmental impacts. Bringing these floating modules offshore at the sea is increasing in popularity as well, as it permits upscaling the installed capacity by avoiding some of the environmental impacts linked to the floating technology on in-land water bodies and making the most possibly efficient use of the marine space.

Offshore floating photovoltaic energy is expected to grow sifnificantly in the following decades as as land availability keeps and global energy targets become tighter. Consequently, it is important to highlight that during any design process of an offshore floating solar energy plant, there is a need to always evaluate not only the advantages, but also the potential hazards linked to each of type of novel concept at each potential location.

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