Title: A Review of Floating PV Installations: 2007 - 2013

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Abstract: The paper gives a review of the various projects which have been realised in throughout the years. These have all been in enclosed water bodies such as reservoirs, ponds and small lakes. The main motivation for the floating photovoltaic (PV) panels was the land premium, especially for agricultural sites were the land was more valuable for growth of the crops (in these cases grapes since the sites were wineries). The PV panels of the existing projects are mounted on a rigid pontoon structure and vary between horizontal and tilted installations. Future concepts proposed for marine and large lacusterine sites are envisaged to incorporate laminated thin film PV, which would allow the structure to be flexible and able to yield with the oncoming waves, and submergible arrays which would be submerged in harsh weather conditions. Interest and research has been developing in this niche field throughout the years and has currently reached the megawatt scale with even bigger plans for the future.

1 Introduction

The 21st century has seen a shift towards redevelopment of the energy sector, with the aim of featuring more renewable energy technologies within in. This was primarily brought upon by protocol agreements and legislative requirements, such as the Kyoto Protocol. EU country members also have binding agreements to produce a percentage of their energy from renewable energy technologies by 2020 [1], or they would stand to pay penalties. Most renewable energy technologies, biomass, solar etc., require large footprint areas for MW scale electricity generation, and hence put restriction on land use for agricultural purposes. This has brought forth the debate of land use for energy versus food debate [2, 3] and has intensified efforts for research in offshore renewable technologies [4], and so the development of the floating photovoltaic (PV) array concept for commercial electricity generation. For which economics of the concept have been developed by the author [5, 6].

The developed floating PV projects include conventional PV arrays, as well as concentrated PV arrays which benefit from the surrounding water body to prevent overheating of the solar cells. The review given here within is limited to only conventional PV arrays for the novel floating application. The pre-mature stages of this technology application limit the projects which have been developed around the world. The review provided will aim to illustrate each of the projects in existence, and the installation and technological variations between each. For the most part, these installations are mounted upon a pontoon-based floating structure and are installed in either reservoirs or ponds which are used mainly for irrigation purposes (motivated by increasing demand for energy in modern irrigation systems and agriculture). Common benefits from these installations was a reduction in water evaporation from the reservoir/pond [7] and decreased algal growth (due to the reduction in sunlight penetration within the water body)[8]. Also electrical yields were slightly improved, in most reported cases, probably due to the cooling benefit offered by the underlying water surface as illustrated by Bahaidarah *et al*. [9] while testing a photovoltaic panel which was in direct contact with water.

2 Floating PV Installations

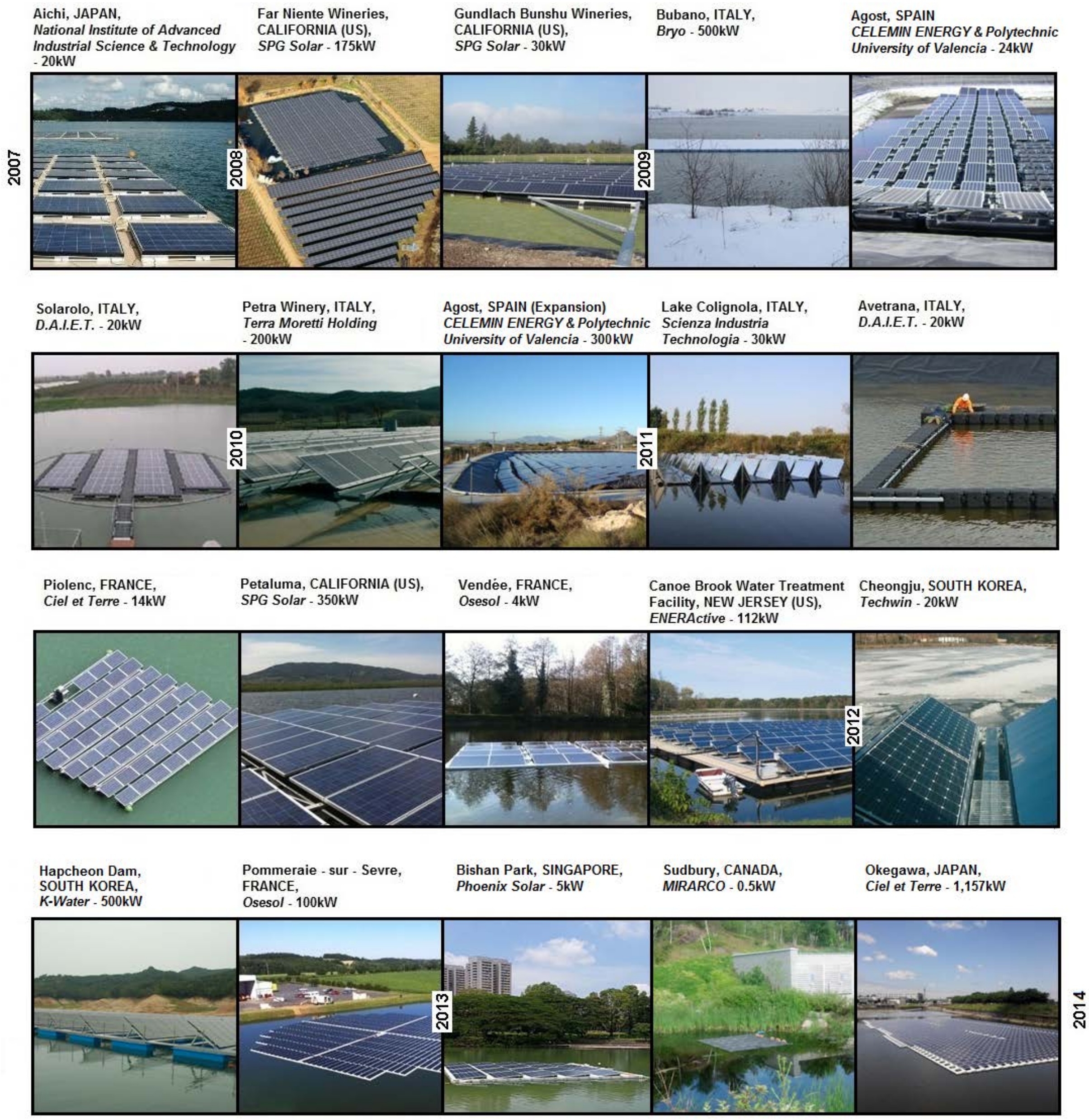

Figure 1: Floating PV projects timeline

The propriety nature of the technology somewhat limits the literature available on floating PV installations. Through online research and direct contact with the developers (commercial and academic) Figure 1 was compiled. This figure illustrates the floating PV projects developed worldwide to date for electricity generation, tallying the installations to 19 in total.

2.1 Projects 2007 – 2009

The project which has received most news coverage and usually claimed as being the first realisation of a floating PV project (although a research floating PV project had been installed the previous year in Aichi, Japan) was that of Far Niente wineries in California, USA. SPG Solar were contracted by the owners of the winery to install the array in 2008[10]. Their motivation for the deployment of the PV panels on top of their water reservoir was not to displace land which was used to grow the vines – and so a more precious resource for their business. The installation was based on modular crystalline PV panels which were mounted at an optimal tilt on top of individual pontoons. The mounting structure, included walkways between the rows of panels and along the sides to facilitate cleaning and maintenance of the panels. Having this effective cover from the pontoon and the PV panels on the reservoirs resulted in reduction of water evaporation from the reservoir, research in Australia suggests that 40% of open reservoir's water could be lost through evaporation [11]. This could be correlated to water loss in the Napa Valley region since world radiation maps indicate that they have similar mean solar radiations. So a significant reduction in water evaporation is definitely positive for the farming business.

Later in the same year, 2007, a research team from the National Institute of Advanced Industrial Science and Technology in Japan developed their own floating PV prototype. The aim of their research was to compare the electricity output from an array which was water-cooled and another which was air-cooled [12]. The panels in this case were installed as an array lying at a slight tilt (1.3° south facing) on top of foam polystyrene board floating on top of the water body. The major variance between the two systems was because of the accumulation of bird dropping over the air-cooled PV system (where the water cooled system was kept clean due to the 10min regular water coverage). Hammond *et al.* [13] estimate an 8% reduction in efficiency due to bird dropping, which could be recovered to a 3% loss after a heavy rainfall.

The installation in Gundlach Bunchu Wineries (2008) also in California is very similar to that in Far Niente (even in motivation, it being on a winery too), the project was designed and executed also by SPG Solar. The main difference between the two is the array size, with that of Far Niente being much bigger at 175kW$_p$ rated, while that of Gundlach Bunchu being just 30kW$_p$.

One of the biggest projects developed is that of Bubano, Italy at 500kW$_p$. This was realised by Byro, in 2009, which is a collaboration of four local companies which retain equal shares in the project. This system is grid connected and takes revenue from the feed-in tariff. Prior to installation, a preliminary environmental impact assessment was required to outline any potential hazards to the ecosystem and lake fauna. The buoyancy for the installation is maintained with hollow polymer cubes at the two opposite edges and through which struts for the PV panel mounting are ran through. The array is modular with four buoyancy cubes of either side holding 4 PV panels mounted horizontally above the water. An interesting feature of this project is that, this was the first floating PV project which was exposed to snow and ice. The impact was only to the surface panels, since the climate it was set in was not cold enough for the surrounding waters to freeze. Thus consideration for the mooring and structure, for the thaw/freezing conditions needed not to be taken into consideration. The developers claim a 20-25% increase in electricity output due to the cooling effect from the water, consistent with the negative temperature notion for PV modules (higher temperatures leading to lower efficiencies and lower temperatures leading to higher efficiencies).

Further on the topic of evaporation of water reservoirs, a research team in Spain developed a 24kW$_p$ floating PV array in 2009 with the primary array of reducing water evaporation, which was expanded to a 300kW$_p$ array later the following year due to its good performance. This project is a collaboration between the Polytechnic University of Valencia and the company CELEMIN ENERGY. The array is made up of a number of modules each holding 2 panels, tilted at 10° (facing south) and fabricated by rotomoulding using medium density polyethylene [14]. The platform has inserts for the electrical cables and the metal struts from the top, while from the base it is smooth and rounded to protect the reservoir's geomembrane and they are connected together with metal pin links, creating a flexible elastic system able of deforming to the conclave profile of the reservoirs according to the changing water levels. Annual electrical yield of the PV array was averaged at just under 30GWh since 2009 [7], giving it a capacity factor of approximately 13.5%. Economics given by Ferrer-Gisbert *et al.* [7] indicate that almost 45% of the costs were pontoon associated costs. The economic analysis highlighted in the same paper indicates profitability of the array installation, with an internal rate of return of 12.65%, not including any economic savings from the reduction in water loss.

The Solarolo project (2009), also in Italy, was designed by D.A.E.I.T. on top of an irrigation pond where they elected to only tilt them at 8° to maximise the power density output by footprint of the array. The design realised by D.A.E.I.T. consisted of a modular array unit, of $20kW_p$. The array unit construction is very similar to the structure in Bubano, except that the panels are mounted at a slight inclination rather than flat. The design logic behind this (and the installation in Bubano) is to minimise the structure components and also to create a channel through which the panels can be air-cooled from underneath (since there is no gap behind the panels, as those by SPG Solar, by which the panels can be air-cooled). Also the buoyancy at the sides rather than underneath allows a channel by which any individual panel can be physically reached. At the Solarolo site the cubic buoys are extended to the edge of the reservoir allowing continuous access to the installation (access to the Bubano site is solely by boat).

2.2 Projects 2010 – 2013

The only project realised in 2010 was that at Petra Winery in Italy, which was grid connected later in 2011. A special feature of this installation is that it includes a tracking system which rotates the system according to the sun`s motion. This was designed and constructed by

Terra Moretti Holdings, while the research group at *Scienza Industria Technologia* (SCINTEC) were responsible with the tracking and safety systems. The motivation for this installation is similar to that Far Niente, since it is also situated in a winery. The structure of the array is made almost entirely of metal struts, with buoyancy (and integrated tracking system) underneath maintaining the whole structure afloat. The structure is designed to hold the crystalline panels at an optimal orientation of 40°, while tracking the solar motion.

Following the Petra Winery installation, SCINTEC developed the installation at Lake Colignola in 2011. This was developed at a prototype, 30kW$_p$ in size and similar to the Petra Winery installation with a motor running the tracking system and was constructed entirely of metal struts with low lying tabular buoyancy keeping it afloat. The interesting aspect of this development was the utilisation of mirrors to reflect additional solar radiation onto the PV panels, this being experimentally tested for ground-mounted installations [15, 16]. So the PV panels rather than being mounted tilted they were installed horizontal with mirrors positioned on the south and north face of the panel. The mirrors were placed at an angle of 60° and -60° respectively [17] and is expected to increase the solar radiation effective on the PV panels by a factor of 2. The proximity of the PV panels to the water is key in allowing the panels to cool in order to maintain the panel`s efficiency. Testing estimates a 60-70% increase in annual yield compared to a conventional fixed-ground mounted installation [18].

SCINTEC's next contribution to the field of floating PV was thanks to their partnership with the French company Osesol. Osesol have installed a 100kW$_p$ floating PV array at Pommeraie-sur-Sevre (2012), in France, following the initial success they had with their 4kW$_p$ prototype in Vendée (2011), also France. The Osesol installations are mounted on a structure constructed entirely from PVC, which resulted in effective cost reductions in comparison to the installations in Italy which required metal struts for the PV panel mountings. The other project SCINTEC helped design was in Korea, Cheongju (2012), built by Techwin in collaboration with Koinè Multimedia and SCINTEC. This project was especially challenging because of the climatic conditions the project was set in, were the surrounding waters were subject to freezing temperatures during the winter months. Special consideration was taken in the choice of the individual components within the installation, since they had to be able to withstand the seasonal freezing and thawing.

In 2011, D.A.E.I.T. and SPG Solar added two new projects to their repertoire. D.A.I.E.T. installed a replica of their Solarolo project in Avetrana, also in Italy, at the same $20kW_p$ scale. In the case of SPG Solar they changed their design to accommodate the larger installation scale at Petaluma, California with an installed capacity of $350kW_p$. Instead of using the modular design similar to that at Far Niente, they adopted a singular large pontoon structure on which the tilted PV panels were mounted and with on-board inverters placed. The pontoon was tension tied to four buoys at each side of the rectangular floating structure, which were moored to the reservoir's bottom.

The majority of the projects discussed within are installed in ponds and reservoirs used for irrigation, while a couple are in small lakes. The Canoe Brook Water Treatment Plant in New Jersey, USA, was installed floating in a water treatment reservoir (like the Negret reservoir in Spain). This is a $112kW_p$ installation designed by ENERActive and their main challenge was to adjust the mooring (which was subcontracted to Seaflex) to changing levels in water within the reservoir and keeping the polystyrene floating structure (holding the tilted array of PV panels) in place during the freezing/thaw cycles.

The Piolenc site in France was originally an abandoned quarry which has since been flooded. The PV panels (installed in 2011) are held tilted towards the sun with metal struts, which also links the array together, and is kept afloat with buoyancy underneath each row within the array. The site developers, Ciel et Terre, have submitted an application for a 12MW installation at the same site which would make it the larger installation to date. Ciel et Terre have also established bases in other countries, mainly Japan and India and have submitted application for multi-megawatt installations in those countries on top of dams and lakes. Their last accomplishment was in Okegawa, Japan (2013) which holds the title for the largest floating installation at almost 1.2MW_p. The array is the similar to that in Piolenc and was constructed as modular panel units (consisting of 4,530 260W solar panels) in France and then delivered to site.

Matching the installation at Bubano is the 500kW_p installation at Hapcheon Dam, South Korea in 2012. This project is the first of a planned series of investments by Korea Water Resources Corporation (K-Water), who plan to build an installed capacity of 1,800MW_p by 2022 jointly with private companies. One of the motivations for the project was the lack of available ground and rooftop spaces for the large scales of photovoltaic installations envisaged and in the case of the ground installations also the limitations due to environmental planning. The crystalline PV panels of the arrays are mounted on metal struts which are tilted at the optimal solar radiation angle and kept afloat by mini-platforms. The materials chosen in the design had enhanced water and moisture resistance to decrease the chances of freezing and cracking.

On smaller scales in 2013 there were two additional projects one in Singapore and the other in Canada, both for research purposes. The one in Canada will be discussed in the following section, because differently from all the other projects it is not mounted on a rigid pontoon but mounted directly onto the water surface utilising a laminated thin film PV product. The project in Singapore is located in Bishan Park and was developed by Phoenix Solar as a test project, being monitored for one year, with data being recorded for research. The outcome of this project could potentially lead to larger installations in Singapore. The panels here are mounted on a single pontoon with the crystalline panels at a slight incline, due south.

3 Floating PV Concepts

3.1 Flexible Floating PV Concepts

The projects realised throughout the 2007-2013 period are exclusive to self-contained water environments such as reservoirs, ponds and small lakes. This means that the requirements for the structure and mooring do not have to abate to the higher component requirements of a marine (or large lacustrine) environments which would endure additional loading from the tides, high winds and waves. The two concepts which have been proposed for such offshore environments have a similar logic in design and differently from the existing floating PV installations, which incorporate mainly crystalline PV panels which are rigid, they utilise flexible thin film PV (Figure 2) to generate electricity. This is so that the structure yielded with the wave motion, rather than withstand its force, and hence allowing the moorings to be subjected to significantly less loading force (which are a huge issue in reliability of offshore structures) [19].

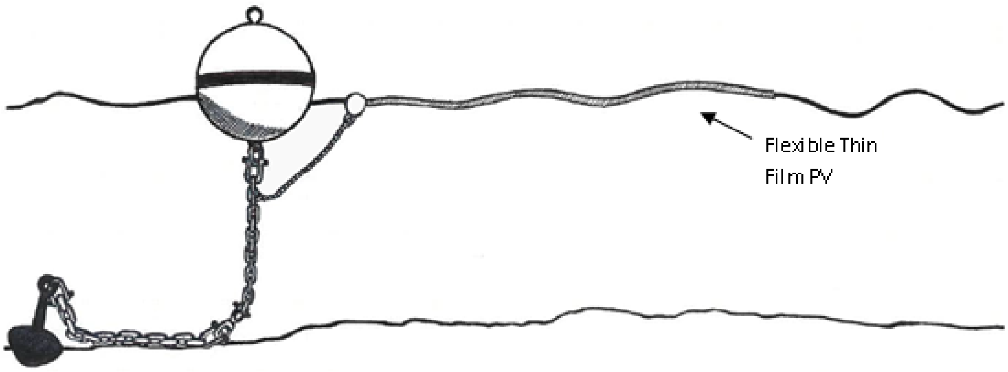

Figure 2: Schematic of the thin film floating PVs

3.1.1 MIRARCO's Floating PV Project

The first of these offshore floating PV concepts discussed here within was developed at MIRARCO (2010), a mining research company in Sudbury, Canada, with the aim of providing an alternative method for electricity generation for remote mines. This concept features a single scalable array (either with larger panels and/or a greater number of panels). The system is designed to have the terminal connectors connected to each other within the array, with the number of panels connected in series and parallel depending on the required output voltage. Buoyancy is designed to be incorporated within the laminated thin film PV panels themselves with air pockets trapped within the lamination. The design is aimed to decrease the number of components within the project to maintain procurement and O&M (operations and maintenance) costs down and also increase the project's reliability (less components available to fail). Also the aim is to have the panels in direct contact with the water surface to enhance the direct cooling by the water and allow self cleaning.

MIRARCO have recently launched a 0.5kW$_p$ test project on a small pond in Sudbury, Canada (as featured in Figure 1) for data collection and analysis. For this prototype it was not feasible to integrate the buoyancy within the laminate, so thin strips of neoprene were glued to the back of the array. The neoprene strips allowed the panels to be linked together into array, hence not requiring further components for linking of the panels. Identical PV panels were installed as a control on the ground nearby in order to allow comparison between the two setups (Figure 3).

Figure 3: MIRARCO's Floating PV Prototype (Left) and the control ground mounted nearby panels (Right) – Sudbury, Canada

3.1.2 DNV's Floating PV Project

The other flexible floating PV concept is called SUNdy (2012), realised by DNV – Det Norske Veritas. The overall design is as described by Figure 4, and consists of a series of thin film PV panels connected together and then onto the electrical bus lines running through the hexagonal vertices. The panels themselves are envisaged to be laminated and adhered to a flexible foam surface which would give the panels buoyancy and structure. The panels are each rated at 560W and embedded within the underneath flexible foam is a 3 phase micro-inverter which converts the electricity from dc to ac directly. At the edge of the float embedded is also a marine grade connector which allows the panels to be connected to each other both mechanically and electrically. A transformer is located at the center of the hexagonal structure from which the electricity is delivered to shore. Plans are for walkways and water cannons, for the cleaning of the panels, to be located between the center and the vertices to allow access to the equipment. The structural design is inspired from a spider web and is designed to be compliant with the waves while still being structurally strong and capable of maintaining its shape. The whole structure is designed to be kept in place thanks to catenary mooring at each of the vertices.

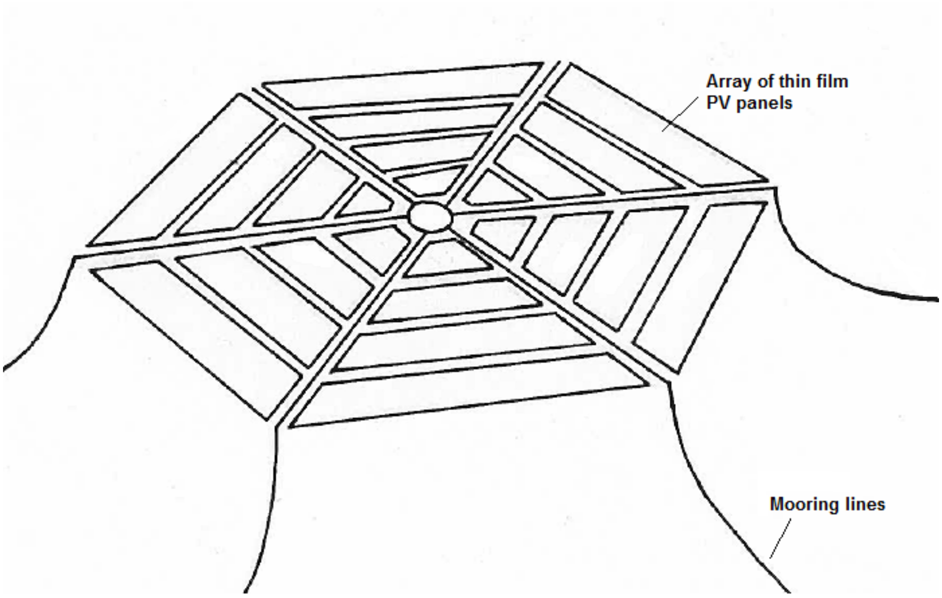

Figure 4: Schematic of the 2MW$_p$ SUNdy concept, the hexagonal design consisting of 4,200 individual panels

3.2 Submerged PV Concept

The invention by M. Rosa Clot, P. Rosa Clot and S. Carrara [20] (SCINTEC) has some elements from both the existing projects and the concepts mentioned in Section 3.1. This is since it utilises a rigid concept which is also in direct contact with the water as illustrated in Figure 5. The system cannot undulate with the oncoming waves due to it being rigid, so instead to withstand rough sea conditions it is designed to be able to submerge up to 2m. The submersion and floating of the array is achieved by pumping in and out water respectively in surrounding enclosed buoys. For normal operating conditions the array is designed to be under just 0-2mm of water which according to research undertaken by SCINTEC will not deter the solar radiation effective on the PV panel's surface [21], while also help the cooling of the panels to improve its electrical efficiency.

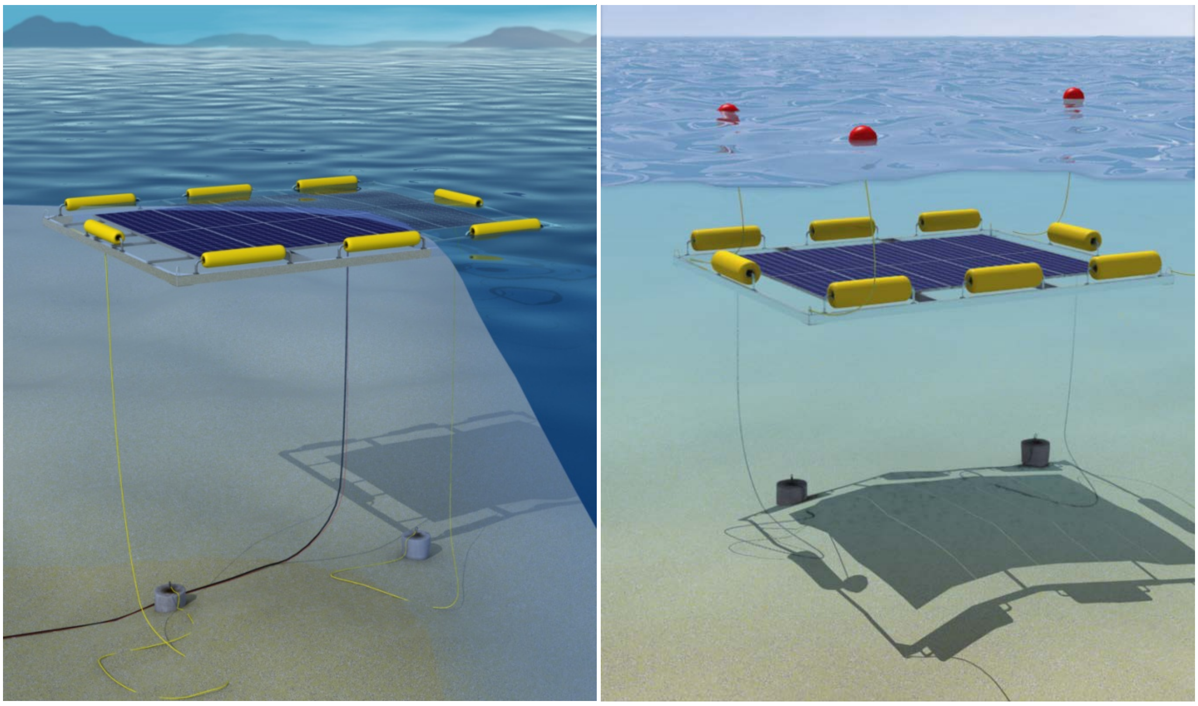

Figure 5: SCINTEC submergible floating PV concept

4 Conclusion

The review given herein gives a timeline of the projects which have been realised to date. All of the projects in existence are kept afloat using some kind of pontoon structure and incorporate rigid PV panels. Also these projects are installed in small water bodies such as reservoirs, ponds and small lakes. The large number of projects which have been developed in the short five year period since floating PV installations have started to crop up, is a clear indication of the interest and niche need of such a technology.

Concepts for future develops are looking at larger expansions of water on which to introduce this technology to. This would mean that such an installation would be subjected to larger loads by the harsher sea wave environments. The concepts proposed for such environments envisage a flexible thin film structures able of undulating with the waves or else conventional rigid PV arrays which could be submerged in rough water conditions. Further research and proven demonstration larger installations in this technological field will be required before floating PV technology can be considered alongside the more established offshore renewable technologies.

The trend exposed by the projects timeline has indicated significant research towards the establishment of the floating PV technology and the development of multi-megawatt scale floating PV arrays. Interest and current negotiations mostly in Asia indicate that we will be seeing larger installations cropping up in the near future. Floating PV arrays could become a front runner in renewable energy technology installations.

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