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Floating photovoltaic plants and wastewater basins: an Australian project

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Abstract

Floating photovoltaic is a new design solution for photovoltaic (PV) power plants; Floating PV systems (FPVSs) are normally installed on water bodies such as natural lakes or dams reservoirs, and offshore solutions are also investigated. Such technology has attracted increased worldwide attention since 2007 and medium and large FPVSs have already been deployed in several countries, such as Japan, South Korea, India and USA. The cost effectiveness of FPVS increases dramatically if the floating structure performs also other tasks, for instance the reduction of water evaporation.

In this context, the possibility to integrate PV plants with the existing basins for wastewater treatment is explored; a compact FPVS without tracking with optimal orientation and distance among rows is suggested as the most simple and economic design solution. Some test cases in South Australia are suggested and analysed.

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Keywords: photovoltaic system; floating system; water basin; evaporation

1. Introduction

The use of land by photovoltaic (PV) plants can be partially or totally avoided by implementing an emergent solar technology known as floating PV, which tries to break the paradigm that mounting solar panels on water surfaces is an expensive and complicated process (as reported by IEA annual report in 2014). This technology is now being

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deployed in projects across the world [1]. FPVSs are generally comprised of a racking assembly mounted on top of floating structures (FS), such as rafts or pontoons, which are installed on enclosed water bodies such as reservoirs, ponds and small lakes. Due the novelty of these PV solutions, most systems are proprietary and of small-medium size. However, many different models and systems of varying scales (up to megawatt scale) have been created with even bigger plans for the future. In reference [2] a review of the main floating PV plants in the period 2007-2013 is reported as well as a general analysis of the main technologies: submerged systems, thin film floating systems and floating systems either fixed or with tracking. Reference [3] further develops this analysis extending it to 2016. In the past 2 years about 100 MW were installed around the world. The authors forecast a very large expansion of the sector and maintain that India's ambitious target of 100 GW within 2022 will get a wide contribution from floating plants.

In the last ten years, the floating photovoltaic systems (FPVSs) installed on water bodies such as natural lakes or dams reservoirs, have been attracting more and more worldwide attention and have already been deployed in several countries, including Japan, South Korea and USA. The floating PV plant is an emerging technology proposed by the authors almost 10 ago and several studies confirm their quick growing [2].

Several technical advantages that have been attributed in literature to FPVSs are listed and discussed in [4] from a practical point of view, specifically:

(1) the evaporative cooling of PV modules and cables caused by the water body increases the efficiency of the system;
(2) FS reduces the evaporation off the free surface of the water, conserving the volume of stored water;
(3) FS reduces algae growth;
(4) FS reduces the formation of waves and, thus, the erosion of the banks of the reservoir;
(5) the fact that the floating system does not use a land area is a great economic advantage;
(6) the reflectivity (albedo) of the water increases the incidence of radiation in the PV array and, therefore, its energy generation.

In case of installation of FPVS on an existing generation structure (e.g. hydroelectric power plant) or supplied structure (e.g. pumping station) the following advantages can be listed:

(7) a floating PV system installed on the reservoir of a hydroelectric power plant saves water in that reservoir, replacing part of its generation;
(8) a floating PV system installed on the reservoir of an already electrically connected structure does not require investment in transmission infrastructure, since the existing infrastructure can be shared.

In this paper, we want to analyze in detail the second point, that is the impact of FS on evaporation rate in the water basin. Two main factors together contribute to the reduction of water evaporation: 1) the shading provided by the floating structure reduces the incidence of solar radiation on water, and therefore its temperature, 2) the FS partially covers the free surface of the water and so it reduces the effect of the wind on this surface.

How much water would be lost without the FPVS depends on the place and local climate and has to be carefully calculated to evaluate this critical advantage.

On the other hand, it should also be mentioned that this effect is physically conflicting with the previous one, that is, the less evaporation in the reservoir, the lower the evaporative cooling caused by the water body and the lower the efficiency increase of the photovoltaic array.

In this report we explore how the coupling of FPVSs to the standard wastewater treatment basins is a very interesting integration, with environmental advantages and economic gain for both sectors: energy production and water saving.

We apply this study to Australia since, as evident from map in Figure 1 and in Figure 2, it is a continent where an interesting level of solar radiation is coupled to a rather arid climate so that the opportunity to save water is an important target.

Specifically, in Fig. 1 the radiation map for the full continent is shown. Very interesting values are reached in most of the inhabited areas except in the very deep South. Data are taken from the Government Bureau of meteorology [5].

The same Bureau also supplies a map of the evaporation rate showing very large losses of water from 2 to 4 meters, which implies that the basin depth is reduced by this amount in one year (see Figure 2).

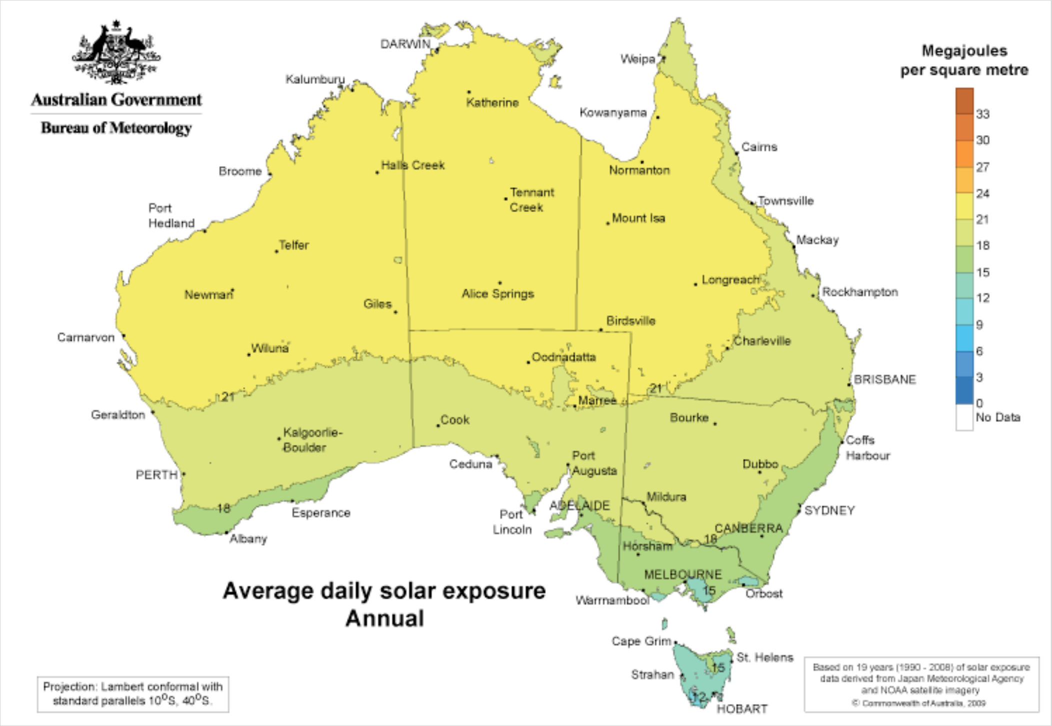

Figure 1 Australian map: annual daily solar radiation (MJ/m^2)

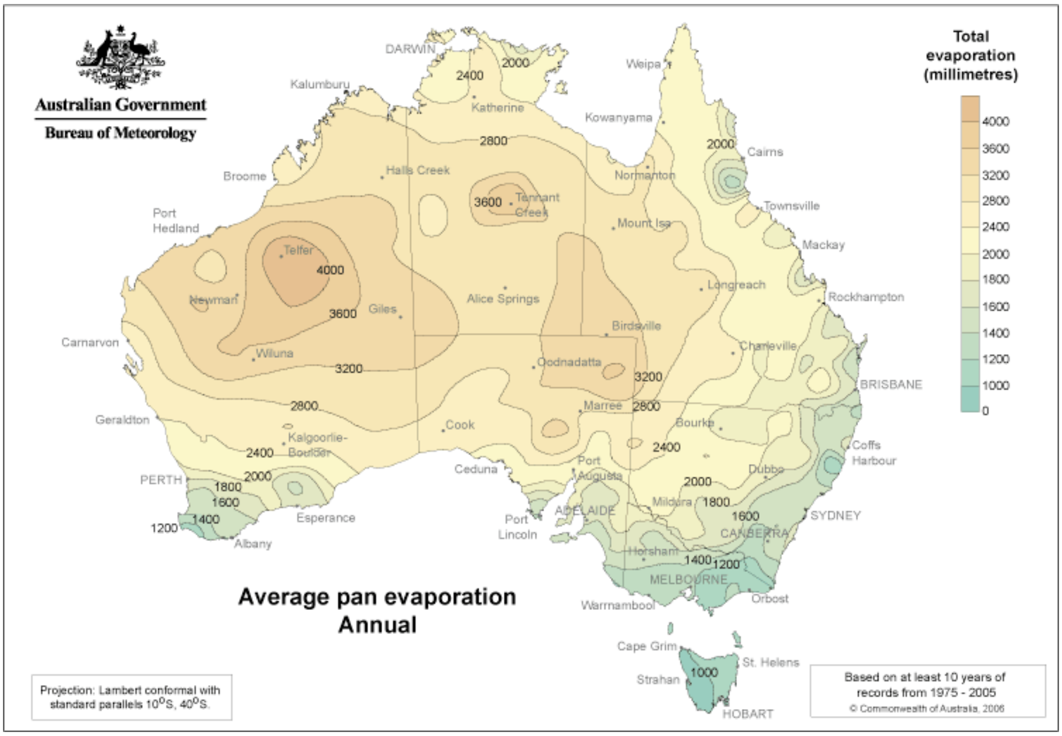

Figure 2 Australian map: yearly evaporation (mm)

These two maps suggest the idea of covering the artificial basin surface but in order to be specific two further elements are important: cost and location.

Covering a basin is a costly operation but using a system that can cover the basin producing at the same time energy, like the floating PV plant, can solve this problem.

The basin must be near a town, to reduce the cost of electrical energy transmission, and this always happens for wastewater treatment basins. These are normally large shallow water surfaces where with aerobic process the wastewater of the town is stored, treated naturally with bacteria and transformed into water usable for irrigation purpose.

Covering these basins with floating PV plants will strongly reduce evaporation, reducing at the same time the smell and improving the bacteria activity.

The paper is organized in the following sections: the evaporation mechanism, the radiation yield for different locations, a short list of possible locations for some important Australian towns, technical aspects and basic costs.

2. Evaporation model

Evaporation rate in open water surfaces has been studied and parameterized in the literature using several different models. In this paper we refer to the work of reference [6] (McJannet, Webster, Stenson, & Sherman, 2008). The evaporation rate R_{evap} is given by the following equation:

$$\boldsymbol{R_{evap}} = \frac{1}{\lambda} \cdot \left\{ \frac{\Delta_w \, (Q^* - N) + 86400 \, \varrho_a C_a (e_w^* - e_a)/r_a}{\Delta_w + \gamma} \right\} \quad (1)$$

Where

- λ (MJ kg^{-1}) is the latent heat of vaporisation
- Δ_w (kPa °C^{-1}) is the slope of the water vapour curve for temperature saturation
- Q^* (MJ m^{-2} d^{-1}) is the net radiation
- N (MJ m^{-2} d^{-1}) is the change in heat storage in the water body
- ρ_a (kg m^{-3}) is the air density
- C_a (MJkg^{-1} °K^{-1}) is the specific heat of the air
- e_w* (kPa) is the saturated pressure at water temperature
- e_a (kPa) is the vapour pressure at air temperature
- r_a (s m^{-1}) is aerodynamic resistance
- γ (kPa °C^{-1}) is the psychometric constant

where aerodynamic resistance, r_a (s m^{-1}), is calculated using the following equation

$$r_a = \frac{\varrho_a C_a}{\gamma (\frac{f(u)}{86400})} \quad (2)$$

The wind function f (u) (MJ m^{-2} d^{-1} kPa^{-1}), is calculated for wind speed at 10 m, 10 U (m s^{-1}), and area, A (km^2)

$$f(u) = \left(\frac{5}{A}\right)^{0.05} (3.80 + 1.57 \cdot U_{10}) \quad (3)$$

Using equation (1), which successfully matches experimental findings, it is possible to verify that the most important parameters which determine evaporation rate R_{evap} are:

- e_a (kPa) : vapour pressure at air temperature
- U_{10} : wind speed at a height of 10 m

Also other parameters affect the final results but they are responsible for small corrections and at a first analysis they can be safely neglected. Therefore the main results can be summarized in the plot in Figure 3(a) which gives the evaporation rate in mm/day; evaluation is done for standard values of other parameters, in particular a sunny day has

been chosen (radiation 2.2 MJ) with a good transfer of energy to the water basin (heat storage 1.7).
Variation of these parameters does not affect results in a noticeable way.
Conversely, variations of the vapour pressure and wind speed can change the evaporation ratio by a factor 10.
If the water surface is occupied by a floating PV platform we note the following:

1. Wind speed at water surface is strongly reduced since only convective motions are allowed
2. Thermal energy arriving at the water surface is reduced by approximately a factor 2, due to the reflection and conversion efficiency of PV panel
3. In the cavity created between water and platform the vapour pressure approaches that of the saturated vapour.

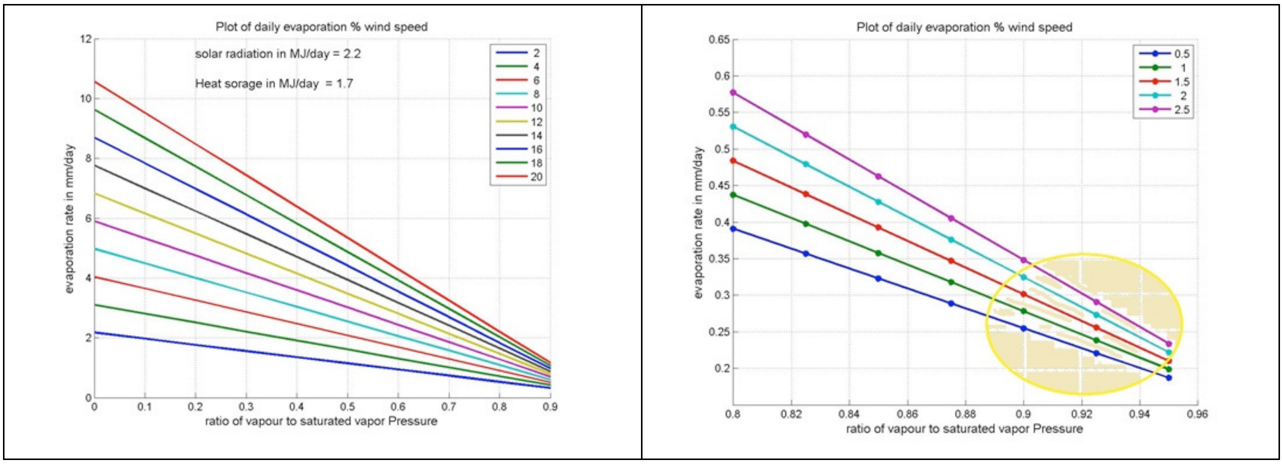

Figure 3 Evaporation rate with saturated vapour pressure with respect to the parametric wind speed (m/s) : (a) 2≤wind speed≤20 ; (b) 0.5≤wind speed≤2.5

Point 2, as said before, only slightly modifies the final result but 1 and 3 strongly affect the evaporation ratio. In Fig. 3 (b), the evaporation ratio is analysed for values of wind speed and of vapour pressure suitable for these conditions. The yellow circle identifies the range of parameters characteristic of these operational conditions. It is easy to see that the evaporation rate is reduced to a fraction of mm per day and so we can safely claim that reduction is more than 90%. The situation changes if a cooling mechanism with water layer is operational on the PV panels [7]. In this case parameters are essentially the same as those used for an open water surface when the cooling is switched on.
This however happens only in the sunny hours (typically 6-8 hours on a sunny day) and for a surface which is approximately 2/3 of the platform surface.
Water layer temperature in this case is higher than the basin temperature and this slightly favours evaporation, but it never exceeds 30°C. We want to stress that cooling takes place mainly by convection leaving the evaporation mechanism untouched.
So assuming that evaporation takes place for 1/3 of the time (on a sunny day) and for 2/3 of the surface, we can state that evaporation is about 30% less than on a free open surface. This rough result probably overestimates the evaporation rate and should be considered only as an upper limit.
We can conclude that

a) in the absence of cooling, evaporation is hindered by more than 90%
b) if cooling is active, evaporation is reduced by more than 75%.

Recently an experimental test has been performed on pools of limited size and the statement a) has been confirmed [8].

3. Locations in South Australia for FVPSs

In this section we analyze some possible locations for the installation of floating PV plants. In particular, we study four basins in South Australia. The Bolivar basin is an important basin for the wastewater treatment located in

Bolivar, an outer northern suburb of Adelaide, South Australia. It is located in the City of Salisbury, 20 km from Adelaide. It has a very large surface of approximately 3 km^2 and is a good example of the advantages that can be gained by installing a floating plant. In Figure 4(a), a photovoltaic floating plant with tracking of 42.4 MWp in the Bolivar basin is shown: the 53 floating platforms are one axis tracking of 800 kWp each and the diameter of a single platform is 100 meters. An alternative is shown in Figure 4b where North oriented fixed platforms are shown. Meteorogical data (solar radiation) for the Bolivar basin (lat. 34.75 °; long. 138,58°), taken from the NASA web site [9], show that this place has an important yearly energy harvesting, about 1854 kWh/y for m^2, with average monthly daily values that rise to 8 kWh/day in the winter period.

Figure 4 A schematic drawing of two different solutions for Bolivar wastewater basin.

Figure 5 shows the variation of the yearly energy production per kWp of a floating PV system considering the tilt of the PV modules. The following four cases have been considered: systems with and without tracking (Vertical axis tracking) and with and without cooling. To evaluate the energy production of the PV system, losses in inverters and cables have been considered, as well as the gain due to the cooling which has been estimated to be 12%.
Yellow dots suggest the optimal slope. The slope must be fixed, taking into account shadow effects and finding a reasonable trade-off between energy yield and platform surface.

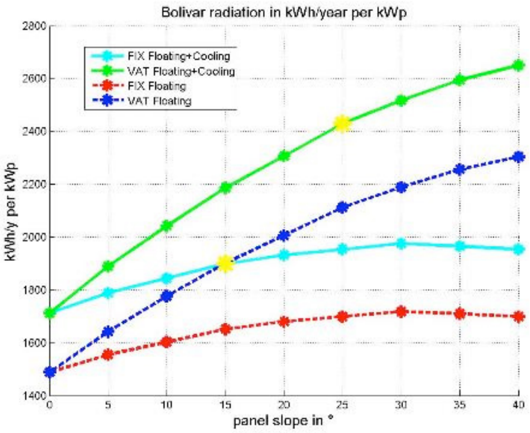

Figure 5 Annual radiation yield per kWp in Bolivar

In conclusion for a fixed panel slope we get an energy yield of 1785 kWh/kWp per year (2000 kWh/kWp if cooling is operative) and for vertical axis tracking with slope 25° we get a value of 2110 kWh/ kWp per year which rises to 2430 kWh/ kWp if cooling is present. Using these data and assuming a reduction in the evaporation as quoted in section 3, we get the results reported in Table 1.

Table 1 FPVS in Bolivar (lat. 34.75 °; long. 138,58°) first basin, yearly values

	Surface (m2)	PV Plant (kWp)	PV Energy (MWh)	Water Saved (m3)	PV Energy w/ Cooling (MWh)	Water Saved (m3)
Fixed 15°	640,000	75,000	133,875	1,152,000	150,000	1,024,000
VAT 25°	420,000	42,400	89,464	756,000	103,032	672,000

It is quite evident that, even if the fixed system has a minor energy yield, it allows a more rational coverage of the basin surface and in conclusion a greater energy production and a higher amount of saved water.

In the case of the first North basin of Bolivar wastewater treatment plant, a fixed system will allow a saving of more than 1 million of cubic meter per year. Furthermore the full coverage of the three wastewater basins will increase water saving to almost 3 million of cubic meters per year and energy production to 500.000 MWh/year.

Hereafter we will discuss only the option with north-oriented fixed plant, since the vertical axis tracking solution is not suitable for this kind of basins.

Table 2 synthesizes the basic data for the 4 sewage basins near Goolwa. The form of the basin is a rectangle, so a full exploitation of the surface forbids the use of tracking system. We limit the analysis to the solution with a fixed plant without cooling and with a slope of 15°. In this case we get the results reported in Table 2.

Table 2 FPVSs (fixed and tilt angle 15°) in Goolwa (Lat. 35°30’05”S, Long. 138°46’54”E) yearly values

	Surface (m2)	PV power (kWp)	PV Energy (MWh/y)	Water Saved (m3/year)
Basin 1	25,900	3,507	6,173	46,620
Basin2	18,700	2,532	4,457	33,660
Basin 3	15,400	2,085	3,670	27,720
Basin4	8,775	1,188	2,091	15,795
Total	68,775	9,313	16,391	123,795

Figure 6 Goolwa project: first basin

The effect of an almost complete coverage with FTC plant would be a strong reduction of evaporation which in this region reaches 2 meters per year. On the 7 ha surface of the basins it is possible to install 8 MWp with a production of almost 14 million of kWh per year. Furthermore there will be water saving of about 130,000 m3/year. The final structure will be a raft realized in galvanized iron and the final appearance is reported in the rendering of Figure 6. An analogous project is shown for the 4 main lagoons for water treatment in Lilydale.

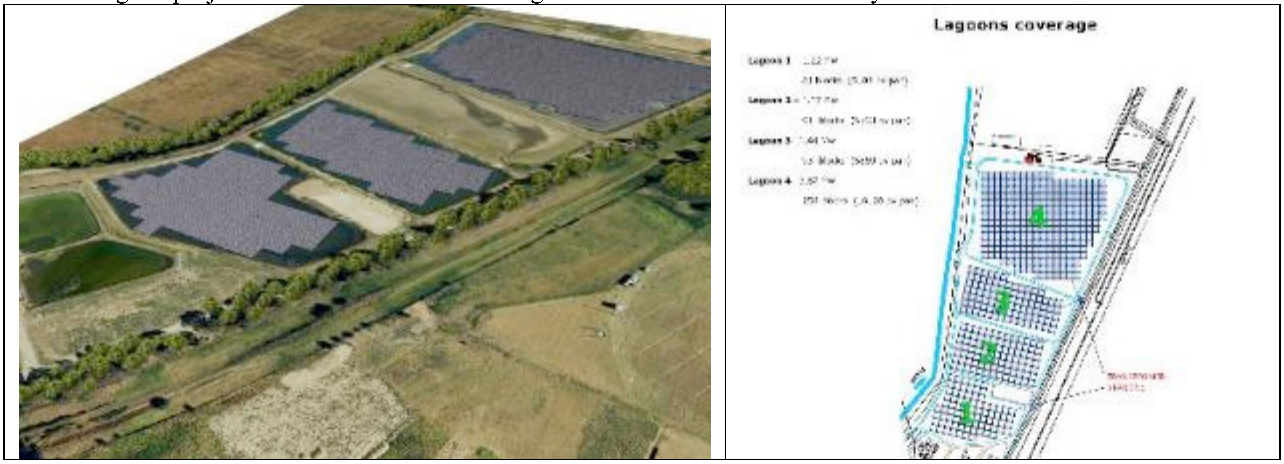

Figure 7 Lyliday basins and scheme of a full coverage

Table 3 summarizes the main parameters of the general layout for the four lagoons drawn in Figure 7.

Table 3 FPVSs (fixed and tilt angle 10°) in Lylidale (Lat. 37°45'29"S Long. 145°20'60" E) yearly values

	Surface (m^2)	PV power (kWp)	PV Energy (MWh/y)	PV Energy w/ cooling (MWh/y)	Water Saved (m^3/y)
Lilydale 1	13,200	1,294	2,134	2,391	21,120
Lilydale 2	13,600	1,333	2,199	2,463	21,760
Lilydale 3	15,600	1,529	2,523	2,825	24,960
Lilydale 4	44,000	4,312	7,115	7,969	70,400
Total	86,400	8,467	13,971	15,647	138,240

We have limited the analysis to a few basins in South Australia but, of course, every town has its own wastewater treatment plant. In Figure 8 a proposal for Canberra is shown through a basic rendering.

Figure 8 A rendering of wastewater plants with a FPV in Canberra

4. Mooring system, demonstrator, costs

The structure of basins is in general rather regular and a mooring system can be managed using cables fixed periodically to stakes planted on the edge (outside the liner limit). A qualitative scheme of the mooring is given in Fig. 9.

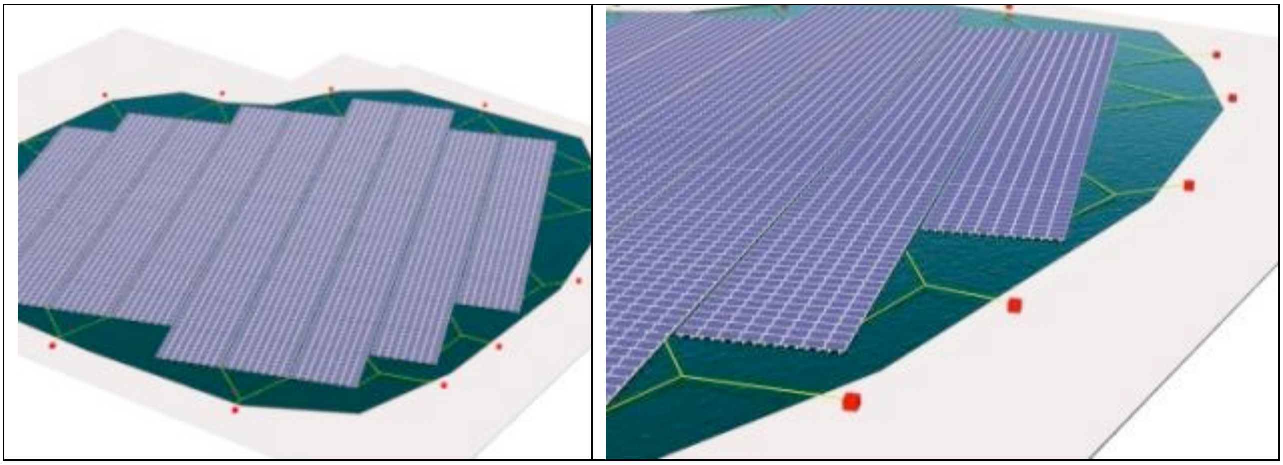

Figure 9 Scheme of mooring system

The platform is moored with steel cables fixed symmetrically in several points (from 5 to 10) on each side of the platform. Steel cables have a diameter 5/32” (3.97 mm) with break strength of 1300 kg (cost of 0.5 €/m). Since we plan to have 10 mooring cables on each side of the platform with an average 10 m length we estimate that the full length will be 400 meters with a limited cost of about 200 $.

From the evaluation of wind load forces, we note that each of the mooring cable is able to absorb the maximum wind load charge. The wind load however is distributed on the whole structure even if in an inhomogeneous way so that no doubt can subsist as to the robustness of this mooring system.

This approach has been used in Tiengeh reservoir (Singapore) where, following these criteria, a 100 kWp plant was realized.

Figure 10. Floating photovoltaic system (rating 100 kWp) in Tiengeh reservoir in Singapore

Finally a comment on the cost. A typical cost for 1 MWp (3200 PV module, PV module rating 320 Watt) plant is given, on the basis of the Singapore experience, and is synthetized in Table 4. The whole system is made of 160 rafts and in each raft there are 4 tubes (made of Polyethylene, PE, each 12 m long)

Table 4 Cost of 1 MWp (1048 kWp) fixed photovoltaic floating plant

	Quantity	Cost (€)
Raft carpentry (number of rafts)	160	200,000
PE pipes (number of pipes)	640	160,000
PV Modules (number of module)	3200	420,000
Cable &Inverter	-	140,000
Site preparation	-	30,000
Work (hour)	3000	40,000
Total costs		990,000

The project and the EPC fees should be added to this cost, but it is in any case competitive with the land based plants. The final investment should be compared with the two products of the PV floating plant per year: energy production and water saving. A rough estimate suggests that with a kWh cost of € 0.1 the payback time should range between 3 and 4 years.

5. Conclusions

The possibility of a full coverage of wastewater basins has been explored. Two main advantages were pointed out:

- Production of energy
- Strong reduction of evaporation rate and water saving

Both these quantities depend on latitude, and mainly on weather conditions. However, the basic concept is that for each MWp installed a large quantity of water, normally lost for evaporation, is saved. A rough estimation gives numbers ranging between 15,000 and 25,000 cubic meter of water saved for each MWp installed and this of course is very important in arid zones with scarcity of water. Furthermore, even if the cost is the same as for a land based plant, the energy harvesting is larger, due to the cooling effect which can improve the yearly energy yield up to 10%. The solution with tracking systems and with fixed systems were discussed and we concluded that on wastewater basins the fixed solution gives greater advantages. Three locations of South Australia were explored showing the quantitative gains in energy and in water.

In conclusion this technology is opening a new line of investment where several factors contribute to the costs reduction and to the improvement of the environment.

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