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Floating photovoltaic plants: Performance analysis and design solutions

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ABSTRACT

The analysis of the performance of photovoltaic (PV) installations mounted on a floating platform is performed. Different design solutions for increasing the efficiency and cost effectiveness of floating photovoltaic (FPV) plants are presented and discussed. Specifically, FPV solutions that exploit the advantages of additional features such as tracking, cooling and concentration, are presented. The results of experimental tests are reported and they show a considerable increase in efficiency due to the positive tracking and cooling effects. Gains due to the use of flat reflectors are also analyzed. Finally, the possibility of exploiting the floating structure on water in order to develop an integrated air storage system is presented.

1. Introduction

The installed Photovoltaic (PV) capacity has increased rapidly in the last few years, and in 2015 the PV market experienced a further worldwide expansion with an installed capacity of over 230 GW while the major development moved from Europe to Asia (China, Japan, India) and USA [1]. In particular, the strong exponential increase is driven by a reduction of PV system costs which for a utility scale system was about 1.8 $/Wp and it is forecast to range from 1.5 to 1.7 $/Wp for 2016 [2,3].

There are several factors that can limit the further development of such technology:

1. Invasiveness and environmental impact: large-scale deployment of PV energy has a potentially significant land use. According to real data reported in [4] for USA, the capacity-weighted average land use for utility scale PV plants ranges between (in ha/MWac): 2.39 (fixed) ÷ 3.81 (2-axis) for medium size PV (> 1 MW, < 20 MW) and 2.35 (fixed) ÷ 3.64 (1-axis) for large PV (> 20 MW).
2. Loss of efficiency at high operating PV cell temperature depends on the technology. Each PV technology is characterized by a specific maximum power thermal coefficient expressed in %/°C that gives the variation of the efficiency for the variation of one degree Celsius in the PV cell temperature. This thermal parameter for the commercial PV technologies is always negative and reaches the maximum value of 0.4–0.45%/°C for the Silicon crystalline PV technology, whereas for a-Si it is about 0.2%/°C [5]. However, nowadays Si-wafer based PV technology is the most used in the world. It accounted for about 93% of the total production in 2015 and it will continue to be the prevalent technology in the near future. In 2016 the share of multi-crystalline technology decreased but it is still 69% of total production [6]. In this context, it is important to search for design solutions of PV plants that can keep the operating temperature of crystalline silicon PV module low and constant, such as floating and submerged PV systems.
3. The cost of the land tracking system has been strongly reduced in the last few years, mainly for one axis tracking; this solution is suggested only when large land surfaces are available [3]. In this case an increase in costs of 7–8% is balanced by a gain in energy harvesting of 15–20% and by an increase in the land occupancy of 50–60%.
4. Intermittency and availability for a limited time, ranging between 1000 and 2000 h per year. Actually, such systems have an impact on the management of national power grids, especially in regions weakly connected with the main national grid such as island power systems [7].

The main static and dynamic parameters to be evaluated to understand the impact of “Renewable Non Programmable PV power systems“ are related to the local load and to the contribution of programmable generators, e.g. Thermoelectric or CCGT (combined cycle gas turbine) [7] as well as to storage systems [8].

The aforementioned problems can be partially or totally solved by an emergent solar technology known as floating PV, which tries to break the paradigm that mounting solar panels on water surfaces is an

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expensive and complicated process (as reported by IEA annual report in 2014). This technology is now being deployed in projects across the world [1]. FPV systems are generally comprised of a racking assembly mounted on top of floating structures (rafts or pontoons) which are installed in 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 Ref. [9] a review of the main floating 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. Ref. [10] 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 announce that India's ambitious target of 100 GW within 2022 will get a wide contribution from floating plants.

Notwithstanding the efforts made for building PV plants on water (more than 20 plants ranging from 10 kWp up to several MWp are at present grid-connected at a worldwide level), very little information is given about the real advantages and tests of the technology.

The goal of this paper is to expand and deepen this analysis by showing the advantages, potentialities and limits of this technology. Physical aspects are analyzed in detail whereas engineering aspects as well as economics are postponed to later investigations. Here we simply mention that the higher cost of the raft structure compared to the standard land panel support is partially compensated by the lower installation and maintenance costs.

For the installation, the costs of buying and preparing an equivalent area of land nearby (civil works and foundations) are avoided. For operation and maintenance costs, weeding is avoided and cleaning is drastically reduced due to availability of water.

Of course the problem of corrosion should be considered but the impact depends on where the floating system is installed. If the floating PV systems is sited on freshwater bodies such as lakes and reservoirs the problem is limited, if it is sited on salt water ad hoc solutions have to be adopted.

Furthermore, gains in energy harvesting from cooling and tracking mechanism can bring the kWh cost below the price of the kWh produced with land-based plants.

The paper is organized in sections where the followings topics are discussed:

- A qualitative comparison between submerged and floating PV systems.
- A general review of the raft system and the platform structure in terms of materials and geometry.
- The cooling techniques based on water use are presented and the solution adopted for floating systems is discussed.
- Low radiation concentration based on reflectors is presented. The main differences between tracking solutions for on-shore and floating platforms are outlined and original solutions are presented.
- Storage system integrated in a modular raft based on compressed air storage system (CAES) technology is reported. This possibility is described in its physical aspects.
- In the last section, measurement campaigns data on two experimental platforms built and tested in Pisa (Colignola, Pisa, Italy) and Suvereto (Livorno, Italy) are presented. Field tests cover five years, during which energy harvesting under different conditions (tracking, cooling and reflectors) has been measured.

2. From submerged to floating PV systems

There are many possibilities to exploit water as an energy vector, both in freshwater (hydroelectric) and seawater (waves and tides, now under rapid techno-economic development). All these sources of energy can provide a considerable contribution to satisfy the local electricity demand.

In this scenario, the use of PV systems in a water context can create a positive synergy increasing the cost effectiveness of such systems (e.g. reduction of thermal drift), satisfying the local demand for energy (distributed generation) and creating positive effects on water (e.g. limiting evaporation and algae bloom problem). Of course, PV systems do not use the water as energy vector (aside from photovoltaic/thermal, PV/T systems [11]), but they can exploit the water effectively as operating ambient. In this context, they can be classified according to different criteria, such as:

- position in relation to the water surface: i.e. over (floating system) or under (submerged);
- type of water: fresh (lake, river) or salt (sea water);
- type of PV module: rigid or flexible.

Submerged PV plants are suggested as a solution of minimal environmental impact, as they avoid or reduce the cleaning problem and increase efficiency owing to the elimination of the thermal drift effect. The literature provides only one analysis of the efficiency of submerged modules, of which two cases can be listed: PV module in deep water [12] and PV module in shallow water [13]. In 2008 two of the authors filed an Italian patent about the use of submerged PV plants or floating plants with veil water [14] subsequently extended to Europe [15] and USA. The optical, thermal and electrical effects of water on submerged PV modules are presented in [16,17], where the concept of a Submerged PV solar module (SP2) is discussed and checked experimentally. The possibility to combine the use of both shallow and deep design options for SP2 systems has been studied (see Fig. 1 which shows a graphic view of a SP2 equipped with a sinking system, a safety operation adopted during days of strong wind and high waves).

Pure water is a strong light absorber; the absorption mainly depends on the wavelength of incident solar radiation. It behaves like high-pass filter, specifically the water blocks the photon with long wavelength (red-infrared region), whereas the light transmission in pure water reaches its maximum in the wavelength interval between 350 nm and 550 nm (in the visible spectrum), where the main

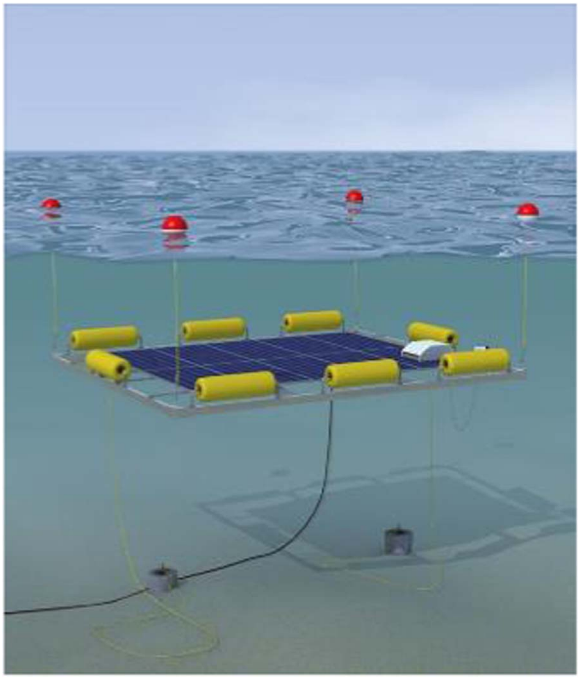

Fig. 1. Submerged SP2 plant with sinking system.