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A new Double-Layer Photovoltaic Installation: Illustration of the basic Idea and first Performance Tests

R. Carbone[1], C. Borrello[2] and F. Gioia[2]

[1] Department of Information, Infrastructures and Sustainable Energy (DIIES),
University "Mediterranea" - loc. Feo di Vito, via Graziella.
89122, Reggio Calabria, Italy.
Phone number: +39 331 6241496, e-mail: rosario.carbone@unirc.it

[2] A.M.P.S. s.r.l., Via del Gelsomino 45/C, 89128, Reggio Calabria, Italy. https://www.amps-tech.it.

Abstract. Conventional photovoltaic (PV) installations cause excessive land-use, even when built by using last-generation PV cell (and PV module) technologies. On the basis of an Italian patent (issued in 2025) and an international patent application, this study presents the new idea of a dynamic double-layer PV installation. It consists of two distinct and overlapping PV generation layers, where each layer can be (or not) equipped with independent solar tracking systems. A custom-designed and self-built scaled prototype is introduced and its main characteristics and possible operational configurations, for on-field experimental tests, are described in detail. The data of some first comparative on-field tests are presented and discussed to underline advantages and drawbacks of the proposed "dynamic" double-layer PV installation, referring to conventional "static" single-layer PV installations. Also, the proposed solution can be profitably miniaturized at the single-module level for being fully integrated into a variety of buildings (BIPVs) or greenhouses. The double-layer PV installation idea offers a new approach for optimizing the energy yield per square meter of occupied land area by PV installations, promising an increased land-use efficiency more than +40% with respect to conventional single-layer PV installations.

Key words. Land-use efficiency, PV Solar Tracker, Bifacial PV technology, BIPV, PV greenhouse.

1. Introduction

In recent years, research in the PV sector has pursued the common goal of increasing the generation efficiency of PV installations, while minimizing the land use [1-4]. In principle, this goal can be achieved through improvements in PV cell technology and "smart" electrical architectures, which have become increasingly high performing and optimized. Also, new installation paradigms could result capable of maximizing energy production and achieving a reduced environmental and territorial impact of the PV generation.

Along this direction, recent studies explicitly propose land-oriented metrics to compare PV installations and technologies, assessing annual PV electricity production per unit area of the occupied land.

The introduction of PV bifacial technology has represented a major turning point and installations based on bifacial PV modules (static and/or with solar trackers) have achieved very interesting levelized cost of electricity (LCOE) [5-14]. In parallel, installation solutions that aim to increase PV module density (and optimize yield per square meter of the occupied land) become increasingly sustainable, provided that shading and interactions among active surfaces are effectively managed. Recent reviews frame BIPVs and agrivoltaics as very promising options to increase land use efficiency and enable co-benefits in terms of reducing CO_2 emissions and of water management and crop optimization [15-17].

As a complement to all the previous technologies, several studies have further proposed multi-plane structures, to increase PV power density and exploit incident radiation as much as possible. Moreover, much of the analysis focuses on static configurations without fully exploring the potential of dynamic systems [18-23].

Based on a preliminary experimental study, this work proposes a new concept of multi-plane PV installation, with the objective of identifying a PV installation more efficient than those of the state of the art. Specifically, the idea of a "dynamic" double-layer PV installation, already covered by a recent Italian patent [24] and an international patent application [25], will be introduced, fully described and experimentally tested. Unlike the aforementioned multi-plane PV installations, the two separate layers of the proposed double-layer PV installation use independent solar tracking systems for enabling active management of mutual shading among adjacent and overlapping PV modules. By this way, the proposed double-layer PV installation reveals the capability of significantly increasing the electricity generation and the land-use efficiency. A custom-designed and home-made scaled prototype, was already operated on-field under different operating conditions and the measured data have confirmed that the proposed double-layer PV installation can increase the land-use efficiency more than +40% with respect to conventional static single-layer PV installation.

2. The double-layer scaled PV prototype

Fig.1 reports a photograph of the scaled in power PV prototype that has been custom-designed and self-built to explain both the basic idea of a "dynamic" double layer PV installation and for performing on-field experimental tests.

Fig. 1 Photograph of the scaled in power double-layer PV prototype.

Of course, the main constituent elements of the prototype are the special mini PV modules, specifically designed and manufactured for this project. They are bifacial and each of them can be rotated, independently from the others, thanks to its own stepper low power motor. The prototype counts twelve mini PV modules: six are mounted on the bottom layer of the installation (1-6) and six are mounted on the top layer (7-12).

Each mini PV module is built by connecting in series nine latest-generation bifacial half-cut PV cells measuring 182 × 91 mm. As a result, each mini PV module has a width of about 20 cm, a length of about 90 cm and a peak power of about 36 Wp, with an open circuit voltage of about 6.4 V and a short circuit current of about 7 A.

Therefore, the whole PV power installed on board of the double-layer prototype is of about: 12x36 Wp = 432 Wp, with an installed PV power density of about 400 Wp/m^2.

For achieving the maximum degree of flexibility on testing the prototype, each mini PV module is equipped with an independent low power *Nema23* stepper motor, which is independently driven by a *DM542T* driver.

The aluminium structure of the prototype was designed to be easily adjustable both in azimuth and tilt.

The two layers are perfectly aligned in plane and properly spaced in height and the mini modules of each layer are installed side by side without any empty space between them, for maximizing the PV module density on the land area occupied by the installation.

Each mini module is equipped with an ammeter that measures its short-circuit current; the choice of measuring all the PV module short-circuit currents will be better clarified in the following.

Both current acquisition and motor control are handled by an Arduino Giga R1 WiFi [26], through a custom-designed dedicated PCB (Fig.2).

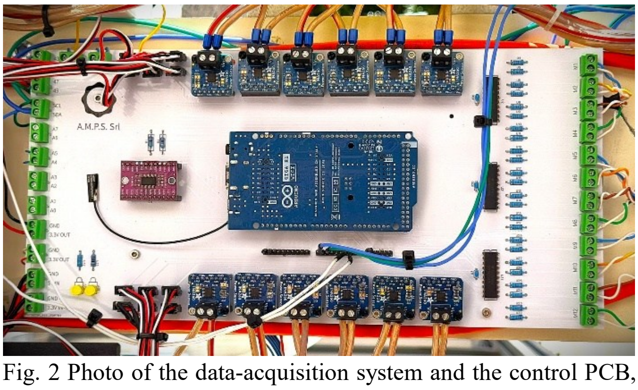
Fig. 2 Photo of the data-acquisition system and the control PCB, mounted on the double-layer prototype

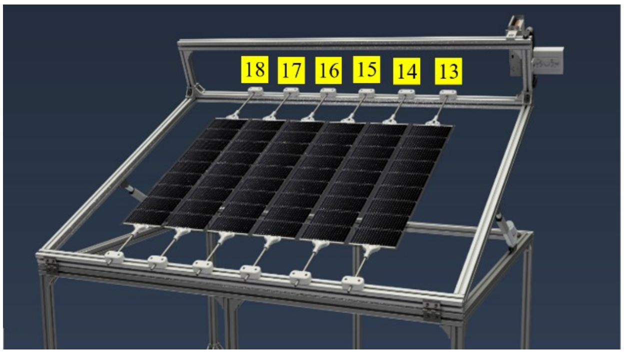

Fig. 3 CAD rendering of the conventional static single-layer prototype

The experimental setup is complemented by an additional static single layer PV installation, which is shown in Fig.3. The latter is built by using six mini modules identical to the aforementioned ones of the double layer prototype and which occupies the same land area, but with a reduced PV power density of about 200 Wp/m^2.

In practice, the prototype of Fig.3 reproduces the generation capabilities of a conventional monofacial single layer PV installation and provides a consistent comparative reference.

3. Method

In conventional static single-layer PV installation, a sensible percentage of the incident sunlight is lost by reflection; furthermore, the diffuse sunlight is also poorly absorbed and converted into electricity. As a result, nowadays the maximum conversion efficiency of bifacial last generation commercial PV modules is limited to about 25%.

Starting from the aforementioned consideration, the main objective of the proposed “dynamic” double-layer PV installation is to capture and convert into electricity the maximum percentage of the incident, reflected and diffused sunlight, per square meter of the land occupied by the installation.

By comparing (also just visually) the two different PV installations illustrated in Fig.1 and Fig.3, it can be observed that the double-layer PV installation has a superior capability of absorbing and converting the sunlight.

Furthermore, it is evident that, at a given time of the day, installation site and weather conditions, the total amount of sunlight captured and converted by the double-layer PV installation strongly depends on the reciprocal orientation of the rotating PV mini modules.

Determining the optimal reciprocal position of the mini PV modules of the two layers of the installation, at each time of the day and for each climatic and solar irradiation conditions, is complex. Future work will focus on finding and implementing the optimal control logic for rotating the mini PV modules, also considering the possibility to profitably use AI-supported methods and technologies.

Nevertheless, currently, the custom-built prototype is operational and fully equipped with a dedicated PCB and twelve fully controllable low-power stepper motors. As a consequence, all twelve rotating mini PV modules are ready to be independently driven with dedicated drivers;

also, both short-circuit current acquisition (from all the mini modules) and motor control are fully handled by the Arduino Giga R1 board. Finally, the implemented controller is able to manage also the data upload on an already working dedicated server.

Taking advantage of the previously described operability of the prototype, the latter was used for a first-stage campaign of experimental tests, which are described and discussed in the following sections.

4. On-field experimental tests

As specified in the previous section, the double-layer prototype has already been subjected to preliminary operational measurements; the conventional single-layer prototype has also been tested, in the same installation conditions, to enable a direct performance comparison. The measurements were carried out in September 2025, during some cloudless days, at the Reggio Calabria site, in the southern Italy. Both prototypes were installed in a north to south orientation and at a tilt of 20°.

The aforementioned on-field experimental tests were carried out with the main aim of obtaining a first insight into the actual generation capabilities of the proposed dynamic double-layer PV installation. The tests also enable a direct comparison with the generation capabilities of a conventional static monofacial single-layer PV installation, under identical climatic and solar irradiation conditions and occupying the same land surface.

In this paper, we implement, test, and discuss a single control logic for rotating the prototype's mini-modules. The identification of AI-based methods for optimizing the generation performance of the proposed dynamic double-layer photovoltaic installation under varying climatic, solar irradiance, and installation conditions (e.g., cloudless versus cloudy days and different surface albedo) will be addressed in future studies and publications.

Considering the fundamental concept, the structure of the proposed dynamic double-layer PV installation shown in Fig. 1, and the installation conditions specified above, the control logic selected for these first experimental tests was designed to be intuitive and readily applicable in industrial settings. This control logic governs the rotation of the mini-modules over a full day.

In practice, only the six mini modules of the top layer (7-12, in Fig.1) are rotated during the day, whereas the six mini modules of the bottom layer (1-6) remain fixed, as do the six monofacial mini modules (13-18) of the conventional single-layer prototype of Fig.3.

To maximize the electricity generation of the double-layer prototype, during all cloudless test days, the rotation of the six mini modules in the top layer was controlled so as to allow the incident solar rays to pass beyond them and reach the six fixed mini modules of the bottom layer almost entirely. In other words, in this stage of the experimental tests, for the mini modules of the top layer we implemented an unconventional solar tracking strategy for the top layer, which we refer to as "parallel solar tracking" [24, 25].

In this way, the fixed bottom layer has been used to convert only the incident solar irradiance into electricity (as in the conventional single-layer installation), while the top layer has been also used to convert into electricity additional components of solar radiation, such as diffuse and reflected irradiance.

To gain a clear understanding about the generation capabilities of all the mini modules of the top and bottom layer of the prototype, we decided to directly measure, acquire and store, the short-circuit currents of all the twelve mini modules (1-12) of the double-layer prototype. For comparative reasons, during the experimental tests, the short-circuits currents of all the six mini modules (13-18) of the conventional single-layer prototype are also contemporarily measured, acquired and stored.

All the aforementioned short-circuit current measurements were then used as a reliable index of the electricity generation capability of each tested mini module (and of both prototypes). In fact, in this way, the generation capability tests are independent of the electrical load variations and/or from the efficiency of the MPPTs while being influenced only by climatic conditions and solar irradiance that the installation under test is able to capture at any time of the day.

Using the aforementioned on-field measurements and stored data, the numerical postprocessing stage enabled the analysis of both the generation performance of the dynamic and bifacial double-layer installation and the actual interaction between its two distinct layers. It was also possible to perform a comparison with the generation performance of the conventional single-layer static and monofacial installation.

From Fig.1, it should be clear that, to correctly evaluate the generation capabilities of the proposed double-layer installation, avoiding disturbing peripheral effects, we focus on the central mini modules (i.e. mini module 3 or 4 for the bottom layer and 9 or 10 for the top layer). For this reason, to compute a reliable generation capability index of the proposed double layer installation we evaluated numerically the sum of the short-circuit currents, $\mathbf{I}sh_{(3+9)}$, of the mini modules 3 and 9 of Fig.1. To evaluate the generation capability of the conventional single-layer installation, we simply computed the short-circuit current, $\mathbf{I}sh_{(15)}$, of the mini module 15 of Fig.3.

The two diagrams of daily short-circuit currents described above are shown in Fig.4. The experiment was repeated on different cloudless days, and almost identical results were obtained.

Once the area under the two daily diagrams described above had been numerically computed, the daily electricity generation indices of the two different prototypes were also calculated to allow a direct comparison.

From Fig.4, it is clear that, at any time of the day, the total short-circuit current $\mathbf{I}sh(3+9)$ generated by the double-layer prototype is significantly higher than that generated by the single-layer prototype, $\mathbf{I}sh(15)$.

As a final result, in the double-layer prototype, the rotating and bifacial mini modules of the top layer generate a substantial additional amount of electricity compared with that generated by the fixed mini modules of the bottom layer, resulting in an approximate +42% increase in the total daily electricity generated by the double-layer installation compared with that generated by the single-layer installation.

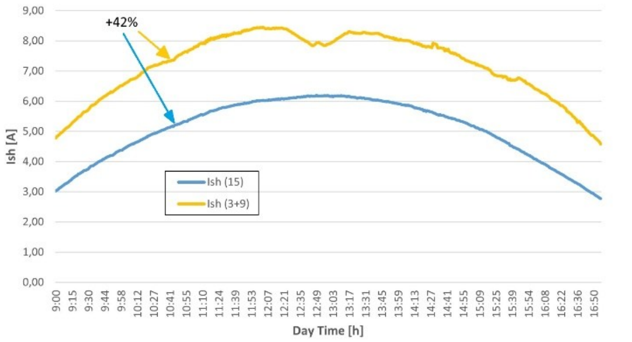

Fig. 4 Comparison of the daily short-circuit current diagrams: **I**sh(3+9) represents the sum of the short-circuit currents of the mini modules 3 and 9 of the double-layer prototype of Fig.1; **I**sh(15) represents the short-circuit current of the mini module 15 of the single-layer prototype of Fig.3. The final account of the daily electricity generation indices is also reported for a direct comparison.

5. Conclusions and perspectives for future studies and developments

After introducing an innovative idea for a dynamic bifacial double-layer PV installation, the home-made low power prototype was subjected to some first on-field experiments and measurements, to compare its efficiency with that of conventional static single-layer monofacial PV installations. The results showed that, also using a simple and easy to realize solar tracking control logic, the proposed double-layer installation can achieve a significant increase in efficiency, up to approximately +42%. In this way, in the near future, dynamic double-layer PV installations could become an optimal means to reduce the use of terrestrial land.

Nevertheless, at this first stage of our experimental study and developments, the potentialities of the proposed double-layer PV installation have not been fully explored and further studies and experiments are needed to highlight some additional and relevant features and concrete advantages. In fact, in the experiments discussed in this paper, only the mini modules of the top layer of the double-layer prototype were operated to implement a daily solar tracking, while the mini modules of the bottom layer were kept fixed.

On the other hand, it is intuitive that, by rotating also the mini modules of the bottom layer, it is possible to further optimize the use of solar irradiance that, after striking the top layer of the PV installation, pass through it and reach the bottom layer. First of all, by appropriately rotating these last mini modules, it is possible to further increase the electricity conversion ratio of the bottom layer. Furthermore, it is possible to add to the whole PV installation an additional and relevant task: i.e. the dynamic control of the natural lighting (or shading) of the underlying environment.

As a relevant example of a concrete application of this additional task, Fig.5 visually summarizes a project, we have planned for the near future, for the development and experimental study of a next-generation high-efficiency PV greenhouse. In practice, the proposed dynamic double-layer PV installation is fully integrated under the transparent cover of the greenhouse, in a miniaturized form very similar to that of the prototype of Fig.1. In that way, all the constitutive components, therein including the electrical and electronic ones, result fully protected against harmful atmospheric agents (strong wind, hailstorms, …). Furthermore, the dynamic double-layer PV installation not only guarantees a substantial generation of electricity, in any weather condition, but it also introduces the additional and relevant possibility to dynamically control the natural lighting and/or shading of the interior of the greenhouse, so making very efficient the control of its microclimate. Nevertheless, the rotating bifacial PV mini modules in the top and bottom layers of the PV installation constantly interact with each other and, determining the optimal relative position of the modules for each time and weather condition is complex. As a consequence, for this next stage of study and experimentation we expect it will be necessary to develop and implement more sophisticated AI-based control algorithms.

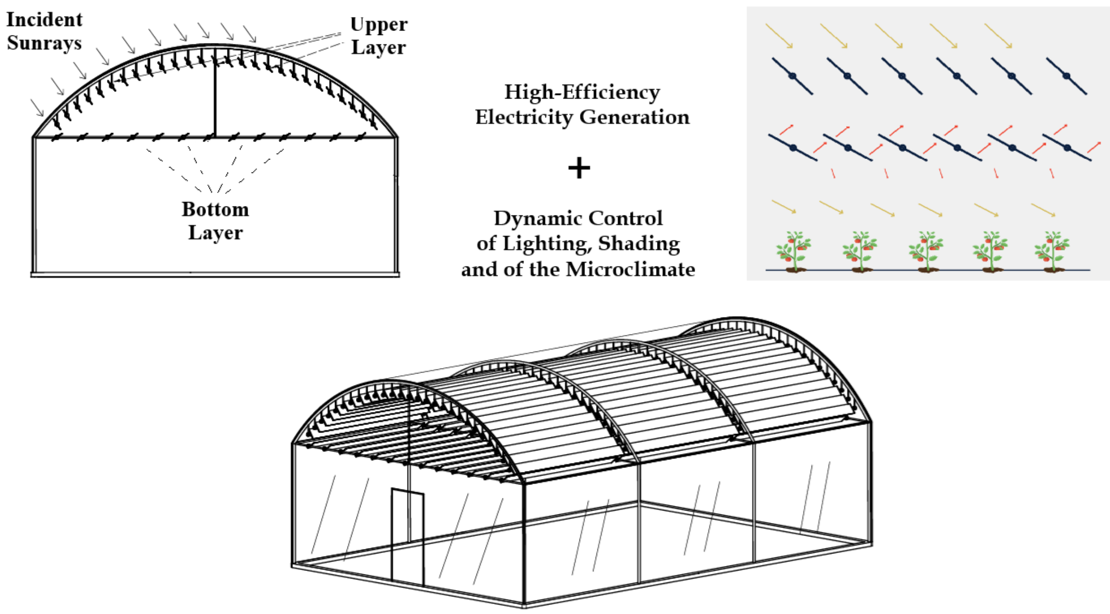

Fig. 5 Synthetic visual representation of an upcoming project for the development and experimental study of a next-generation high-efficiency PV greenhouse.

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