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Article

A Building-Integrated Bifacial and Transparent PV-Generator Operated by an “Under-Glass” Single Axis Solar Tracker

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Abstract: Nearly Zero Energy Buildings (NZEBs) play a key role in the world energy transition and this is motivating the scientific community to develop innovative electrical and thermal systems, characterized by very high efficiency to specifically address the energy needs of modern buildings. Naturally, the integration on buildings of latest generation PV-systems helps to satisfy this need and, having in mind this objective, an innovative and highly efficient BIPV-system is presented and discussed in this paper. First, the proposed PV-system is purpose-built to be fully integrated into a variety of buildings and, preferably, into their rooftop. It is based on a certain number of innovative rotating and bifacial PV-modules which are specifically made to be installed “under-glass”, within a likewise custom-made transparent casing. Each of the aforementioned PV-module has the form of single row of bifacial PV-cells and is equipped with two special terminations; the PV-modules are then installed inside their transparent casing, side by side and suitably spaced from each other. Thanks to the aforementioned properties, the PV-modules can rotate around their central longitudinal axis, by using a very low-power, reliable and efficient mono-axial solar tracking system. Finally, by the aforementioned way, the proposed PV-system assumes – de facto - the form of a transparent BIPV-generator (PV-skylight), equipped with an innovative “under-glass” single axis solar tracking system. Once the proposed PV-generator is fully integrated into a building, it generates electricity and, additionally, helps to improve both the whole energy performances and the aesthetic appearance of the building. The electricity generation and illuminance performances of the proposed BIPV-generator are experimentally tested by using a low-power home-made prototype driven by different solar tracking logics and under different operating conditions; the most relevant results are summarized and extensively discussed.

Keywords: NZEB; transparent BIPV; bifacial PV-cells; solar trackers; PV-skylights

1. Introduction

In order to limit the rise in global temperature to 1.5 °C, a number of countries in the world have already pledged to reach net-zero emissions by 2050. In this contest, the international agency of energy (IEA) have recently published the report “*Net Zero by 2050: A roadmap for the global energy system*” [1]. The report sets out clear milestones for what needs to happen, and when, to transform the global economy from one dominated by fossil fuels into one powered predominantly by renewable energy, like solar and wind. In the building sector, the report estimates that the floor area worldwide will increase till 75% by 2050 and the electricity demand for appliances and heating/cooling equipment will continue to grow. This is because electrification, together with energy efficiency, is considered one of the main drivers of decarbonization of the building sector. In fact, despite the growth of the electricity demand, total CO₂ emissions from the building sector are expected to decline from almost 3 Gt in 2020 to around 120 Mt in 2050, thanks to the pledged net zero pathway. Anyway, to achieve this, more than 85% of buildings worldwide need to comply with the zero-carbon-ready energy code by 2050 and - whenever possible - they should integrate locally available renewable resource, e.g. geothermal, solar thermal and solar PV. About the PV-generation

of electricity, the contribution of building integrated PV-generators (BIPVs) is expected to grow from 320 TWh in 2020 to 7500 TWh in 2050.

BIPVs are, at the same time, integral/structural components of the building envelopes and generators of electricity (from the sunlight); these solar systems are thus “*multifunctional construction materials*” [2]. One of the most relevant issue of BIPVs is, of course, related to major costs of a building PV-solar cladding construction, with respect to a conventional (non-PV-solar) cladding construction. Nevertheless, the cost of a BIPV installation is very difficult to be assessed, as it is strongly influenced by a variety of factors such as the part of building skin under consideration (roof or façade), the local market characteristics, the complexity of legal and administrative procedures, etc. which are strongly variable moving from one country to another in the world. Furthermore, when the BIPV design and its installation are carried out simultaneously with other building interventions, it is possible to optimize the economic feasibility of the whole installation by reducing significantly the extra costs of BIPVs. For all these reasons, the costs of BIPVs vary widely. In particular, among the 25 real examples of BIPV realized worldwide and described in [3], the costs of a BIPV can range from 255 €/m² (for an in-roof installation in the Netherlands) up to 2,500 €/m² (for the artistic façade of the Harbourfront Centre Theatre, in Toronto). In the aforementioned report, by differentiating between roofs and façades and by excluding the most expensive examples due to their singularity, it is estimated that for a BIPV roof the costs range from 250 €/m² to 660 €/m², while for a BIPV façade the costs range from 280 €/m² to 850 €/m². The aforementioned prices consider not only the cost of the façade/roof BIPV components but also the cost of sub-structures and of materials needed to guarantee that the building is itself energy-efficient and also the installation costs. Finally, the report also examines what happens when a BIPV cladding is installed instead of regular cladding, by considering both energetic and economic benefits of BIPVs and it summarizes that, while the costs per m² are much higher for a BIPV cladding - after 20 years – “*the total cost difference between the two solutions can almost cover the cost of a new BIPV cladding system*”. Of course, assessing the real price of a BIPV component remains very difficult, but the cost reduction target for BIPVs is certainly one of the keys to success in enlarging their diffusion. On the other hand, in [4], to enable a wider diffusion of innovative solutions of BIPV, for both roof and façade applications, the authors highly recommend to achieve also high levels of ease-of-installation of BIPV elements. Furthermore, in [5] the authors presented a summary for the future development of aesthetically appealing building integrated photovoltaic system. While in [6] the authors investigate the case of a real-time adaptive BIPV shading system and its ability, in comparison with traditional static building integrated photovoltaic façade systems, to perform as regards visual comfort and energy generation potential simultaneously. Finally, in [2] the authors underline that an additional fundamental step to achieve the same goal is to maximize energy efficiency of BIPVs, within the building’s energy demand, because the more the energy efficiency of the BIPV-systems the more also their economic benefits during its life-time. From this last point of view, in [7–10] the authors also underline how innovative semitransparent BIPV-solutions can offer relevant advantages over conventional opaque PV modules.

Starting from the aforementioned considerations, it is intuitive to understand that the attractiveness (and success) of a BIPV-system substantially depends on some very relevant factors such as: its initial cost, its electrical efficiency, its thermal and lightning performances and also its aesthetic appearance. Unfortunately, with respect to the land installed PV-generators or to the building applied photovoltaic generators (BAPVs), BIPV-systems generally have a significantly greater installation cost together with a significantly lower electrical generation efficiency. This is because they need more sophisticated constructive materials but also because they are forced to be installed inefficiently in terms of their exposition to the incident sunlight. Even if BIPVs located on building façades are becoming more and more popular thanks to their major visibility from the aesthetic point of view, some studies [11–13] testify that the most preferred/convenient installation location for a BIPV is the rooftop of a building. This is essentially due to both the lower installation costs and the better energy efficiency of the roof located BIPVs with respect to the façade located BIPVs. In fact, due to its better solar exposition and the lower presence of shadowing phenomena, with respect to façade located BIPVs, roof located BIPVs are characterized by a good energy

efficiency, especially in terms of the electricity generation. Nevertheless, roofs of buildings clearly offer a minor surface availability for the installation of BIPVs and, as a consequence, the energy efficiency improvement of the roof-installed BIPVs plays a role of primary relevance.

As well known, solar tracking systems are potentially able to improve the electricity generation efficiency of a PV-generator up to +50%, compared to the same PV-generator installed in a fixed manner [14,15]. In particular, dual axis solar tracking systems are a sophisticated and very efficient solution; nevertheless, they are expensive, complex and could have many out of order during their lifetime, especially due to their complexity and also their exposure to aggressive atmospheric agents (wind, hail, rain, humidity, ...). On the other hand, single axis solar tracking systems are simpler, less sophisticated and cheaper; also, they show a greater degree of reliability and of availability. On the contrary, single axis solar tracking systems have a lower electricity generation efficiency that, however, can go up to +30%, compared to an equivalent fixed PV-generator. Considering all the aforementioned respective characteristics, today single axis solar tracking systems appears to be the most widespread; even if, their utilization is again limited due to expensive maintenance problems and frequent out of orders, substantially caused by the aforementioned action of adverse atmospheric agents.

Bifacial photovoltaic cell and module technologies are rapidly increasing their market shares and it seems now possible that much of the future bifacial PV-cell production will be used even in monofacial modules paired with white back encapsulant and/or reflective backsheets to enhance its front side power rating [15–18]. In [16] the authors presented a comparative analysis on the yield potential and cost effectiveness of different kind of PV-plants installed worldwide. In particular, data validated from real worldwide PV-installations and additional results from literature have been utilized to perform a comparative analysis of installation and maintenance costs and performances between fixed-tilt PV-Plants and PV-plants based on single and dual-axis tracking systems, by referring to both monofacial and bifacial PV-cell technologies. The results of the comparative analysis reveal that bifacial PV-cell technology paired with a single axis solar tracking installation can increase energy yield by 35% and that this solution reaches the lowest LCOE for the majority of the world locations (93.1% of the land area). On the contrary, although dual-axis solar tracking installations achieve the highest energy generation, their costs and complexity are still too high and are therefore not as cost effective.

Regardless their category, when speaking about solar tracking systems, in our opinion, it is important to underline also an additional and very relevant issue. That is to say, if on one hand solar tracking systems promise a relevant improvement of the PV-generation efficiency (in comparison with an equivalent fixed PV-generator), on the other hand they need - in practice - to occupy a greater available surface, for installing the same PV-modules of its equivalent fixed PV-generator (i.e. in the case of a multi-string PV-generator). In fact, when a certain rotating PV-generator is made up by using a certain number of PV-strings (which have to be rotated in unison for tracking the sun), in order to avoid reciprocal shading phenomena during their daily rotations, the PV-strings have to be sufficiently distanced from each other. By this way, starting from a fixed total number of PV-modules, the realization of a PV-generator which uses a single axis solar tracking system needs of a greater installation land surface, if compared with that needed for realizing a fixed installation with the same number of PV-modules. Obviously, this clearly corresponds to install less PV-power per m² of available land surface. As an example, to obtain the +30% of the yearly electrical energy promised by a single axis solar tracking system, the PV-strings of the PV-generator are typically installed (along the north-south terrestrial direction) in the form of side by side “rows” distanced from each other, so that they overall occupy about +30% (or more) of the available land surface, in comparison with the fixed installation. As a consequence, the yearly energy generation obtained by means of the PV-installation based on the single axis solar tracking system - per m² of the occupied land surface - is about equal (or lower) with respect to that obtained by the fixed PV-installation. Obviously, this last aspect has a great relevance in the sector of BIPVs, where the available installation surfaces well exposed to the sunlight are a very precious and rare resource.

That said, this paper introduces an innovative transparent BIPV-system, daily operated by using a special single axis solar tracking system which is specifically made up for being easily and effectively integrated within the roof of a variety of buildings, repaired “under-glass” from the adverse atmospheric agents. First, this BIPV-system is made up on the basis of a number of custom-designed bifacial PV-modules which are made in the form of a single row of a certain number of bifacial PV-cells. Then the bifacial PV-modules are installed side by side within a special transparent casing, which is specifically made up to be a structural part of the rooftop of a building. This transparent casing is designed for containing inside also all the electro-mechanical constitutive elements of the single axis solar tracking system, for eliminating the main issues deriving from aggressive actions of atmospheric agents. By this way, the proposed transparent BIPV-system clearly assumes the form of a photovoltaic skylight (PV-skylight).

If feasible, an entire available surface of a rooftop of a building can be fully utilized for the installation of more of the proposed PV-skylights, depending on the specific building energy and aesthetic needs.

In the following sections, the constitutive characteristics of the proposed PV-skylight are detailed and discussed together with its potential energy, illuminance and aesthetic performances. Finally, a low-power home-made prototypes is introduced and described and the results of a campaign of experimental tests are exposed and deeply discussed.

2. Constitutive characteristics of the proposed PV-skylight

The basic idea for obtaining a transparent PV-system that can be fully integrated in a variety of buildings, also by taking advantage of the well-known benefits of a single axis solar tracker, has been already introduced by the authors within an Italian patent [19]. Starting from the contents of this last, in this section, we introduce the executive design and the constitutive characteristics of an innovative PV-skylight, which is specifically made for being fully integrated on the rooftop of a building. Differently from conventional PV-skylights, which are its direct competitors, the proposed one is equipped with a special single axis solar tracker protected “under-glass” and, as already underlined, it is based on the utilization of a certain number of special single-row rotating and bifacial PV-modules characterized by a very low thickness.

2.1. *The rotating and bifacial, single-row and low-thickness PV-modules*

In order to obtain, at the same time, a transparent PV-generator fully-integrable in a variety of buildings and equipped by a single axis solar tracker, first of all, as basic components, we decided to use a certain number of custom-designed rotating and bifacial single-row PV-modules. These PV-modules are realized in the form of a single-row of certain number of series-connected bifacial PV-cells; once realized, they are installed side by side within a likewise custom-designed transparent casing, which is made to be fully integrated in a building (preferable, in its rooftop). Within the same transparent casing, are also installed all the electro-mechanical components of the special single axis solar tracking systems, which is able to rotate the aforementioned single-row bifacial PV-modules, in a controlled way and all together in unison.

For making possible an experimental investigation about the potential contribution of the bifaciality of the rotating PV-modules, we decided to realize each bifacial PV-module of the prototype by using two separate single-row PV-strings of mono-facial PV-cells that are properly encapsulated, shoulder to shoulder; by this way, the currents generated by the two faces of the bifacial PV-module (the front face and the rear face) can be independently measured and analyzed. In other words, only for experimental study purposes, when constructing our prototypes, we decided to avoid the use of commercial bifacial PV-cells, and we used instead commercial monofacial PV-cells assembled in the aforementioned “shoulder to shoulder” special way. In practice, for constructing each of our bifacial PV-modules, we used two PV-strings each based on three series-connected PV-cells, so utilizing, de facto, six mono-facial PV-cells. Once constructed the two separate and identical PV-strings, they have been glued shoulder to shoulder with each other, so obtaining the desired bifacial PV-module, having its front face and its rear face physically separated and characterized by the same generation capacity.

Thanks to this, during our experimental tests, for each bifacial rotating PV-module we had the possibility to separately analyze the attitude of its front face and of its rear face in generating electricity, under certain (and variable) sunlight exposition conditions.

Figure 1 graphically summarizes the construction process of the home-made prototype of a bifacial single-row PV-module.

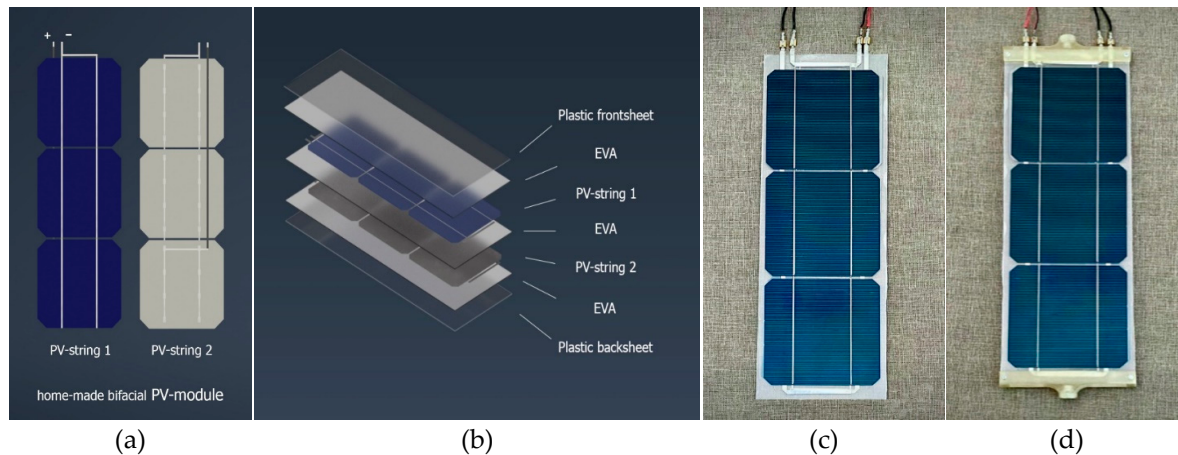


Figure 1. Realization of a prototype of a single-row bifacial PV-module, based on two separate and identical monofacial PV-strings glued shoulder to shoulder with each other, where each PV-string is realized by using three series-connected monofacial PV-cells: (a) the two PV-string of three series-connected monofacial PV-cells, before they are glued shoulder to shoulder with each other; (b) constitutive stratigraphy of the bifacial PV-module; (c) a picture of the bifacial PV-module prototype before the mounting of its special terminations; (d) a picture of the bifacial PV-module prototype in its final form.

Figure 1(a) refers to the first step where two identical and separate single-row PV-strings are realized by using three series-connected monofacial PV-cells, before they are glued shoulder to shoulder with each other.

Figure 1(b) refers to the second step where the two PV-strings are encapsulated, shoulder to shoulder, between two transparent plastic thin films (a frontsheet and a backsheet) by using, as glue in the middle, the well-known EVA material.

Figure 1(c) is a first picture of the bifacial single-row PV-module prototype before the mounting of its special terminations while Figure 1(d) is a second picture which shows the PV-module in its final form.

By the construction procedure described above, we can obtain a single-row bifacial PV-module which is, at the same time, light, slim, semi rigid and ready to rotate (around its fictitious central axis) when mounted within its transparent casing; additionally, the currents generated by its front face and by its rear face can be measured, monitored and analyzed independently, at each time.

Please note that, outside the specific objectives of this academic experimental study, for the construction of the proposed bifacial single-row PV-modules, for eventual commercial purposes, we obviously suggest to use, single PV-strings realized on the basis of most efficient commercial bifacial PV-cells. Furthermore, in order to avoid the consequent realization of a too thick transparent casing (and of a too thick PV-skylight), we also suggest to use, as much as possible, commercial bifacial PV-cells characterized by a somewhat small surface (i.e. (5x5)" PV-cells, instead of larger (6x6)" PV-cells).

2.2. Installing the single-row bifacial PV-modules within its transparent casing

Once a certain number of single-row bifacial PV-modules have been made, they have to be installed inside its custom-designed transparent casing. As it can be easily deduced from Figure 1(d), each single-row PV-module simply appears able to rotate around their fictitious central longitudinal axis which is identified by the imaginary line that connect the central pins of its special terminations. This characteristic makes very simple the realization of a reliable and cheap mono-axial solar tracking

system also inside the same casing which are now discussing. Basically, the geometry and the constitutive materials of the transparent casing have to be designed and selected so that it can be easily and fully integrated on the structure of a certain building (i.e. its rooftop). Furthermore, its perimeter shoulders and its transparent cover have to be designed in order to guarantee the installation of all the single-row bifacial PV-modules, in the form of side by side rows spaced one from each other, so that two important factors are always guaranteed during a day and during the daily rotations of the PV-modules, and this two factors are: (i) the generation of the maximum available electrical power; (ii) a certain degree of semitransparency of the PV-skylight to the incident sunlight. From this point of view, the optimal solution should be that to live an empty space, between two PV-modules installed side by side within the PV-skylight, and this empty space should be large enough to avoid any reciprocal shading among the PV-modules during their daily rotations, even for a large rotation angle. In fact, by this way, one can maximize both the electricity generation capacity and the degree of transparency to the incident sunlight of the PV-skylight. Once defined the approximative sizing of the transparent casing, considering the total number of the single-row PV-modules to be installed inside to it and the width of the aforementioned empty interspaces, its geometry has to be executively defined also considering the characteristics (materials and sizes) of all the components of the single-axis tracking system. Thanks to the reduced number, dimension and weight of the rotating PV-modules, we estimate that a single low-power (just few watts) stepper motor could be enough for rotating (in unison) all the PV-modules of a “medium-size” PV-skylight. Furthermore, as better detailed in the section dedicated to the description of our prototypes, also the electronic components (microcontroller, motor drivers, sensors, ...) are few and occupy a low volume. As a consequence, we evaluated that the motor, the electronic and also the additional components of the mechanical transmission system of the PV-modules can be installed altogether within a little dedicated “service box”, which is located just below one of the two sides of the casing, perpendicular to the rotation axes of the PV-modules. Figure 2 shows the final aesthetic appearance of an example (with only three single-row PV-modules) of the proposed PV-skylight and it should better explain also the constitutive characteristics of its transparent casing.

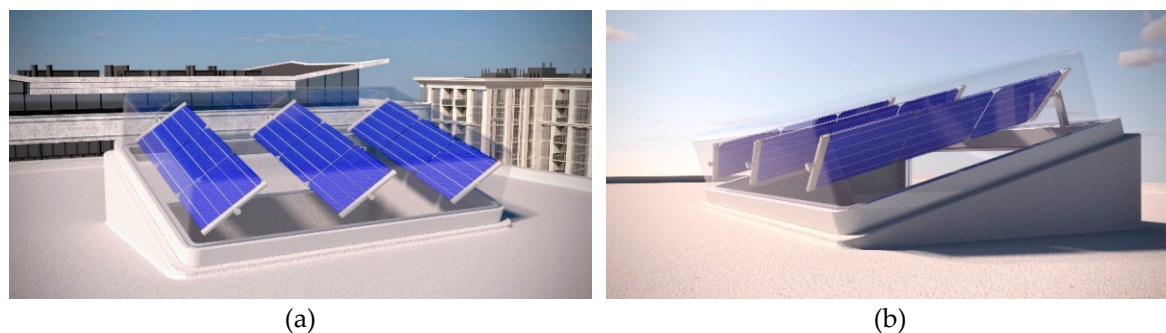


Figure 2. A photo-realistic representation of an example of the proposed PV-skylight, based on three single-row rotating PV-modules.

Finally, with the help of Figure 3, we would like to give an idea on the feasibility and the practical utilization of our BIPV-solution, by showing as the proposed PV-skylight can be integrated in a building for improving both its energy and illuminance performances and its aesthetic appearance.

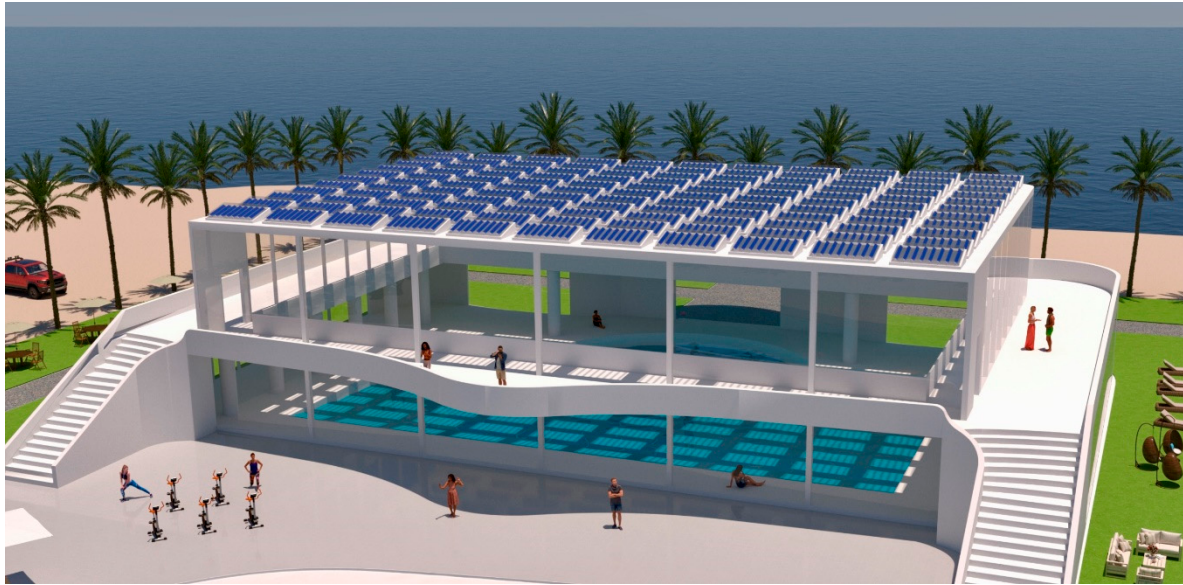


Figure 3. A photo-realistic representation of an example of integration of the proposed PV-skylight on the rooftop of a building.

3. The home-made prototype and the experimental investigation on the performances of the proposed PV-skylight

3.1. Premise

Before introducing a detailed description of the prototype which we have designed and realized for developing our experimental tests, we would like to share some basic theoretical considerations about the evaluation criterion of a PV-skylight performances when it has to be integrated in a building.

Obviously, the main objective of installing a PV-skylight in a building is the improvement of both the energetic and illuminance performances and its aesthetic appearance.

Starting from this assumption, one of the most important performance parameters of a PV-skylight is certainly its maximum generable electrical power, accordingly with the exposition to the sunlight of the building.

Nevertheless, there are some additional performance parameters that, in our opinion, are likewise relevant for a PV-skylight; that is to say: (i) the percentage of the incident sunlight that the PV-skylight lets through inside the building and (ii) the degree of controllability of the sunlight intensity that the skylight lets through inside the building.

That said, considering that we planned to include within the proposed PV-skylight also a single-axis solar tracking system, in principle (as well known and as already underlined also in the Figure 2) the more intuitive solution for obtaining the best performances of the PV-skylight is to construct it by installing on its available surface area only a limited number of rotating PV-modules, for guarantying an enough empty space between two side by side rotating PV-modules. By this way, in fact, it is possible to guarantee both the maximum electrical power generations (by avoiding mutual shading effects among rotating PV-modules) and also the maximum intensity of the sunlight that the PV-skylight lets through inside the building. On the other hand, this solution could have also some shortcomings. First, limiting the number of the rotating and bifacial PV-modules mounted on the available surface area of the PV-skylight (as compared with the maximum number potentially installable, by avoiding the aforementioned empty spaces) limits also the whole electrical power generable by the PV-skylight, when the PV-modules are facing the sun. Furthermore, if the rotating PV-modules are obliged to always track (in unison) the sun position (to maximize the electrical power), no control is dedicated to the sunlight that the PV-skylight lets trough inside the building, as well as no control is dedicated to the aesthetical exploitation of the aforementioned “passing

through" sunlight. Finally, from the academic point of view, limiting the number of the PV-modules mounted on the PV-skylight would not give us the possibility to directly compare the electrical performance of the proposed PV-Skylight mounting a solar tracker with those of a conventional (fixed and/or opaque) PV-skylight (that is to say, with its whole surface area partially or fully covered by fixed PV-modules). For these reasons, because it is difficult to theoretically predict what is the best practice solution for conceiving a PV-skylight efficient and also with a high functional flexibility, we decided to realize a flexible PV-generator prototype able to experimentally emulate – even outside from its design installation site – the behavior of the proposed PV-skylight, under different exposures to the sunlight, for different number of the rotating single PV-modules installed on its available surface area and for different sun tracking control logics. Some more details, on the constructive and functional characteristics of the prototype and on the experimental investigation we have planned and performed for the aforementioned purposes, are specified and discussed in next subsections.

3.2. Constitutive characteristics of the PV-generator prototype

Figures 1 and 2 have already illustrated what should be the constitutive components and the construction steps for realizing our proposed PV-skylight. In particular, Figure 2 shows what should be the structural characteristics of its transparent casing, in order to make possible the fully integration of the PV-skylight on the rooftop of a building. Figure 2 also advises the readers about the "reasonable" prospect to not fully cover the entire available surface area of the PV-skylight, in order to preserve a significant degree of its transparency to the incident sunlight and also to avoid mutual shading effects on its rotating PV-modules. Nevertheless, as underlined in the previous subsection, for the identification of the optimal constructive procedure of the PV-skylight and also for the identification of the optimal control logic of its rotating bifacial PV-modules, we decided to perform a campaign of experimental measurements by using a custom-made PV-generator prototype, quite different in its structure from the photorealistic representation of Figure 2 but, at the same time, eligible for emulating its behavior and its main characteristics under different operating conditions.

In practice, our objective is that of experimentally investigating how some important design parameters can affect the global performances of the proposed PV-skylight. With some more details, we want to experiment how the number of rotating and bifacial PV-modules and their respective sun tracking control logic affect: (i) the generation of the maximum electrical power; (ii) the degree of transparency to the incident sunlight; (iii) the degree of controllability of the incident sunlight passing through the PV-skylight.

As a consequence, for making possible the aforementioned experimental investigation, we have designed and realized the PV-generator prototype illustrated in Figure 4 with the help of two pictures.

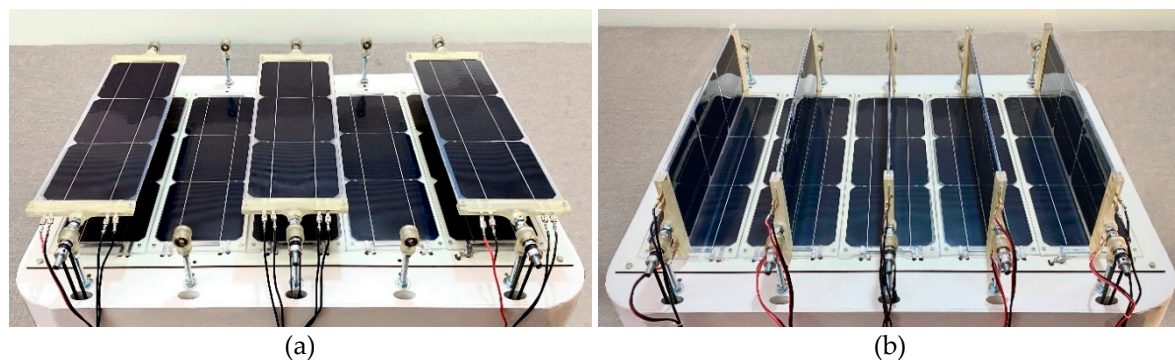


Figure 4. Two different pictures of the PV-generator prototype utilized for the experimental tests.

From Figure 4, it is possible to underline the following main constitutive characteristics of the test prototype:

- the prototype is based on a total of five identical single-row rotating and bifacial PV-modules;

- each rotating and bifacial PV-module has two identical (and separate) faces (the front and the rear), each of one is realized by connecting in series three (5x5)'' mono-crystalline PV-cells and these two faces can be electrically monitored separately;
- the five rotating and bifacial PV-modules can be installed side by side with no an empty space from each other and the prototype exposes to the sunlight a total surface area equal to five times that of a single PV-modules;
- for test purposes, each of the five PV-modules is equipped with its respective low-power stepper motor, it can be rotated independently from each other and it can fulfil a rotation from 0° to 180° and, if desired, also in unison with all the remaining PV-modules;
- each rotating and bifacial PV-module can be simply removed from the prototype, in order to make possible any desired change in their number and in their reciprocal position on the PV-skylight.

Some additional characteristics and specifications about its main components are reported in Table 1.

Table 1. Technical specifications of the main components of the prototype.

Component	Description
PV-cells	$I_{SC} = 6.03\text{ A}$, $V_{OC} = 0.64\text{ V}$, $P_{mpp\text{ (STC)}} = 3.07\text{ W}_p$, $\eta_{max} = 19.2\text{ \%}$
Terminations	3D custom printed, with clear resin
Motors	Nema mod. 17HS08-1004S
Transmission	Based on GT2 belts and pulleys

3.3. *Characteristics of the data acquisition system and of the electronic control system*

As well known, for fixed environment conditions (intensity of the sunlight, ambient temperature, cloudiness, ventilation and so on) the power that can be generated by a PV-module is directly proportional to its short circuit current: the more its short circuit current the more its generable electrical power. Obviously, the electrical power actually generated by the PV-module also depends from its electrical load condition. Nevertheless, if one assumes that the load condition is always made optimal by an ongoing and uninterruptible operation of a specific maximum power point tracker (MPPT) - as is normally the case - the measurement of the short circuit current of a PV-module corresponds also to an indirect measurement of the maximum electrical power that the PV-module can generate.

Starting from the aforementioned assumption, first, the two PV-strings of each rotating PV-module (mounted on its front face and on its rear face) are permanently short-circuited and its respective short-circuit currents are constantly measured, acquired and stored. This means that, for measuring all the short-circuit currents, our prototype counts ten amperemeters (two for each of the five rotating PV-modules). These short-circuit currents are constantly acquired and stored and they are also made accessible on the web, for any numerical and/or graphical postprocessing need.

Concerning the tracking of the solar position during each day and the consequent control of the daily rotation of the PV-modules, we would like to remind that the main objective of our experimental investigation is to understand how the position of the rotating PV-modules affect the performance of the proposed PV-skylight not only in terms of the maximum electrical power it can generate but also in terms of incident sunlight that can pass through it (i.e. in terms of its semitransparency) and also in terms of controllability of this last performance parameter.

For this reason, we decided to implement a “special” control logic for the rotation of the five PV-modules during a day, which we are now going to explain with some more details. First, please remember that the solar tracker mounted on the proposed PV-skylight has only one axis and, as a consequence, the prototype is installed with a fixed tilt angle and with a fixed north-south terrestrial direction; the five step motors of the solar tracker are then controlled so that the corresponding five rotating PV-modules of the prototype daily rotate in unison, from east to west.

Nevertheless, with the help of a home-made electronic board, we decide to implement the special control logic we are going to explain in detail.

This control logic is based on a certain number of special “rotation sequences”, which are imposed to all the five rotating PV-modules. The first rotation sequence starts at the sunrise while the last rotation sequence ends at the sunset. In practice, during a whole day, the first rotation sequence is periodically repeated about every five minutes until the end of the day.

Each rotation sequence consists of four different steps, which are specified in detail below.

At the step (i), the five PV-modules are placed with their surfaces parallel to the ground, with an angular position of 90°, as in the Figure 4(a) and like a conventional fixed PV-skylight (with no solar tracker); the five PV-modules stay in this position for about two minutes.

At the next step (ii), all the five PV-modules start in unison a “quick” counterclockwise rotation that ends when their surfaces are perpendicular to the ground, with an angular position of 0°, as in the Figure 4(b).

At the next step (iii), all the five PV-modules start a new and “slow” clockwise rotation (from 0° to 180°) and it ends when the surfaces of the five PV-modules are perpendicular to the ground again.

At the next step (iv), all the five PV-modules “quickly” come back to the initial parallel position to the ground and they stay there for about two minutes, before repeating the steps (ii), (iii) and (iv).

The aforementioned rotation sequences are repeated daily, from the sunrise until the sunset.

During the aforementioned daily rotation sequences, the ten short-circuit currents (two for each of the five rotating PV-modules) are constantly measured, acquired and stored for being numerically post processed off-line; by this way, one can read, analyze and understand how the position of the PV-modules, during a whole day, affects: (i) the electricity generation of its front face and of its rear face (and also of their sum), (ii) the semitransparency of the PV-skylight and (iii) the controllability of the sunlight that the PV-skylight lets passing through it.

Some additional characteristics and specifications about the main components of the embedded system utilized for the motor driving, for the measurements, and for the data acquisition and upload, are reported in Table 2.

Table 2. Technical specifications of the main components of the home-made embedded system.

Components	Model
Microcontroller	ESP32-WROOM 32
Amperemeters	ACS712 20 A
ADCs	Ads1115 16 bit
Motor drivers	TMC2209 v1.2

Some further considerations about the practice relevance of this kind of experimental analysis will be done in the following sections, together with the discussion of the main results.

3.4. Description of the home-made illuminance sensor, realized for estimating the semitransparency degree of the PV-skylighth

In the previous sections we have cited and underlined two additional and important performance parameters of a PV-skylight, that is to say its semitransparency to the incident sunlight and the degree of controllability of this last. For experimentally investigating the variation of the aforementioned performance parameters during the aforementioned daily rotation sequences imposed to the five rotating PV-modules, we have conceived and constructed a useful home-made illuminance sensor, for estimating the level of the incident sunlight passing through the PV-skylight. This illuminance sensor is practically based on five additional fixed (and monofacial) PV-modules, identical one from each other. Each of these additional PV-modules has also a geometry and a surface area identical to each of the aforementioned rotating and bifacial PV-modules. Furthermore, these additional PV-modules are constructed starting from the same (5x5)'' mono-crystalline PV-cells already utilized for the construction of the rotating and bifacial PV-modules. First, the five additional monofacial PV-modules are glued on a low-thickness rigid plastic foil, side by side and with no empty spaces from each other; furthermore, they are maintained electrically independent. By this way, they realize a monofacial plane PV-surface identical to the front surface realized by the five rotating bifacial PV-modules when they are placed at the angular position of 90° (parallel to the ground).

Finally, as shown in the Figure 4, this resulting plane PV-surface can be installed exactly under the surface area of the PV-skylight (also at different heights, if necessary for study purposes). Figure 5 specifically illustrates the aforementioned home-made plane PV-surface with the help of a picture.



Figure 5. A picture of the home-made illuminance sensor (PV-surface), utilized for estimating the level of the sunlight passing through the PV-skylight (on the underlying surface area), in five different zones.

Similarly to what was already done for the five bifacial and rotating PV-modules, also the five additional monofacial PV-modules are permanently short-circuited and its additional five short-circuit currents are permanently measured, acquired and stored, by using five additional amperemeters and the already cited data acquisition system.

In practice, for estimating the intensity of the sunlight that passes through the PV-skylight and its uniformity, we measure the five different short-circuit currents generated by the five fixed and monofacial PV-modules of our PV-surface, that is installed exactly under the PV-skylight surface area. De facto, we are assuming that, by passing through the PV-skylight, the sunlight that strikes the five fixed and monofacial PV-modules of our underlying PV-surface is proportional to their respective measured short-circuit currents.

4. Experimental results and discussion

As briefly disclosed in the previous sections, with the help of our home-made prototype, we have performed a campaign of experimental tests, for emulating the behavior of the proposed PV-skylight and its potential performances under different operating conditions, both in terms of electricity generation and controllability of its transparency degree to the incident sunlight. In particular, considering that the prototype can mount at maximum five rotating and bifacial PV-modules on its available surface area exposed to the sunlight, we paid attention to two different operating conditions: in the first case-study, we considered the possibility to realize a PV-skylight by installing only three rotating and bifacial PV-modules, interspaced one from each other (as shown in the Figure 4(a)); in the second case study, we considered the possibility to realize a PV-skylight by installing all the five PV-modules, side by side with no empty spaces between them (as shown in the Figure 4(b)). Please consider that all the following experimental tests have been performed on a terrace of a building located in the city of Reggio Calabria, in the south of Italy. The aforementioned case-studies are discussed in detail in the following two separate sub-sections.

4.1. first case-study: testing the prototype based on three rotating and bifacial PV-modules interspaced one from each other.

The Figure 4(a) illustrates with a picture the operating conditions of the prototype (emulating a PV-skylight), when it is ready for being utilized for performing a first set of experimental tests.

In practice, on the whole surface area of the prototype (equal to five time the surface area of a single PV-module), we installed only three rotating and bifacial PV-modules. In particular, between the first lateral (M1) and the second central (M2) rotating PV-module and between the second (M2) and the third lateral (M3) rotating PV-module we left an empty space equal to the width of each

rotating PV-module itself; that is to say, only the 3/5 of the whole surface area of the PV-skylight was utilized for installing the three rotating PV-modules while the 2/5 of it was left empty. This is for guaranteeing very reduced reciprocal shadowing phenomena between the three rotating PV-modules during their daily rotations and, as a consequence, for guaranteeing, as much as possible, the improvement of the electricity generation of them, together with a high degree of transparency of the PV-skylight to the incident sunlight.

As already specified in the subsection 3.3, thanks to the single axis solar tracker and its electronic control system, all the three rotating PV-modules (M1, M2 and M3) are daily rotated in unison, by implementing a four-step repetitive rotation sequence, conceived ad hoc.

At the first step of the aforementioned rotation sequence, the PV-modules are parallel to the ground (as the PV-modules of a conventional semitransparent fixed PV-skylight) and they remain in this 90° angular position for about 2 minutes.

At the second step, all the PV-modules rapidly rotate counterclockwise (in just few seconds) to reach the 0° angular position, where they are perpendicular to the ground.

During the third step, all the PV-modules slowly rotate clockwise from the 0° angular position to the 180° angular position, until they are perpendicular to the ground again. This step takes about two minutes and, during the rotation, all the eleven short-circuit currents, of all the eight PV-modules installed on the prototype, are constantly measured, acquired and stored, by the home-made data acquisition system. Please note that, the prototype mounts three rotating and bifacial PV-modules and this means we have six (2x3) short-circuit currents to measure; additionally, our home-made illuminance sensor (the PV-surface shown in the Figure 5) consists of five additional monofacial PV-modules (M4, M5, M6, M7 and M8) and this means we have five additional short-circuit currents to measure, for a total of eleven short-circuit currents.

At the fourth step, the PV-modules rapidly rotate counterclockwise (in just few seconds) to reach the 90° initial angular position (parallel to the ground) and they remain in this position for about two minutes, before restarting again the same four-steps rotation sequence.

In practice, during a single day, each rotation sequence is repeated every 5 minutes, from the sunrise to the sunset.

First, in order to appreciate the practical usefulness of the implemented rotation sequences, the Figures 6 shows an excerpt of the whole waveforms of some of the measured and registered short-circuit currents. In particular, the excerpt of the Figure 6 specifically refers to the central (M2) rotating and bifacial PV-module of the prototype and, also, of the of the central fixed and monofacial PV-Module (M6) of the underlying PV-surface (that is, de facto, our illuminance sensor); the data was measured and registered during the cloudless day of July 21 2023.

With some more details, for all the four steps of the already specified rotation sequence, the Figure 6 reports the waveforms of: (a) the short-circuit current of the front face of the central M2 rotating bifacial PV-module, I_{sh-F} ; (b) the short-circuit current of the rear face of the M2 rotating bifacial PV-module, I_{sh-R} ; (c) the sum of the two aforementioned currents, I_{sh-S} ; (d) the short-circuit current of the fixed and monofacial central PV-Module M6 of the underlying PV-surface, I_{sh-U} . As specified also in the time axis of the figure, this excerpt refers to a single rotation sequence operated in the early morning of the test day.

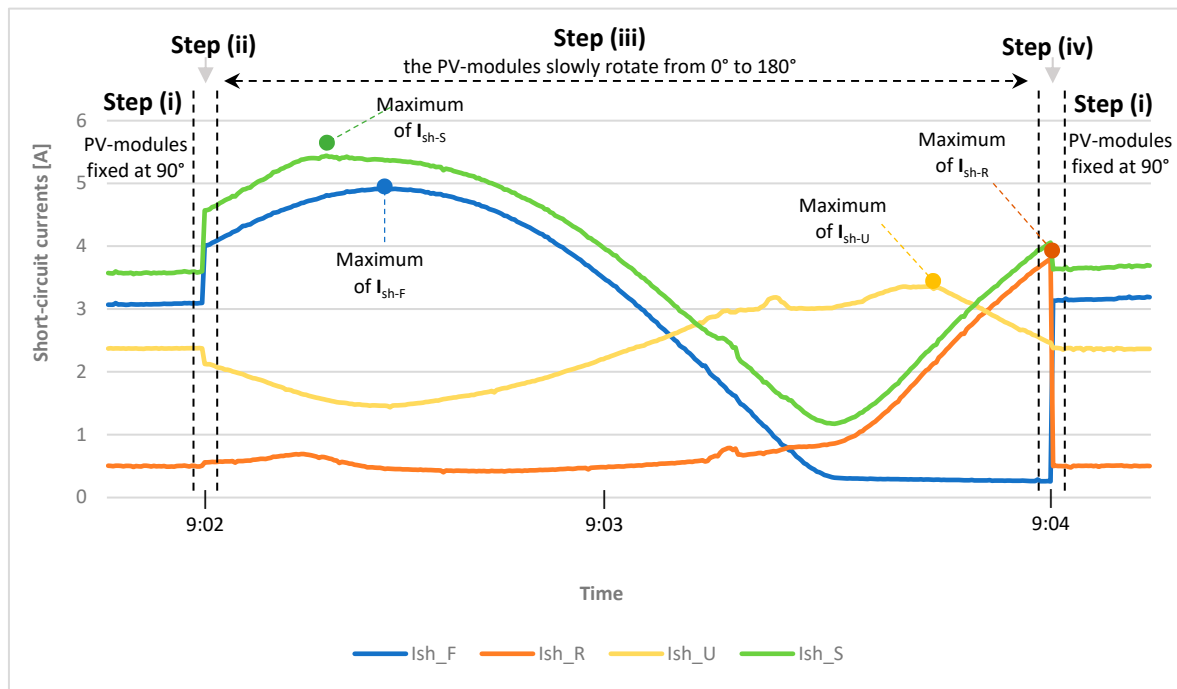


Figure 6. Waveforms of the short-circuit currents of the central rotating PV-module M2 (I_{sh-F} , I_{sh-R} , I_{sh-S}) and of the central fixed PV-module M6 of the underlying PV-surface (I_{sh-U}), during the duration time of a single and complete (four steps) rotation sequence, implemented in the early morning of the cloudless day of July 21 2023, as extracted from the respective whole daily waveforms.

From the analysis of the waveforms reported in the Figure 6 it is possible to develop some first interesting considerations. During the step (i) of the rotation sequence, when the central rotating and bifacial PV-module of the prototype, M2, is parallel to the ground (as the fixed PV-modules of a conventional semitransparent PV-skylight), its front face generates about 3.1 amps while its rear face generates a very reduced current of about 0.5 amps. This means that the contribution of the bifaciality of the M2 PV-module, in this position and at this time, results to be of about a +16%. At the same step, thanks to the “large” empty space between the PV-module M1 and the PV-module M2, on the central zone of the underlying PV-surface the illuminance level is relatively high (the respective central PV-module M6 generates about 2.3 amps, that is to say almost the 75% of the short-circuit current generated by the front face of the rotating PV-module M2). At the end of the quick step (ii), the rotating and bifacial PV-module M2 reaches the position perpendicular to the ground and its front face increases the generated current from 3.1 amps to 4 amps while the current generated by its rear face practically remains constant. At the same time, the illuminance on the underlying PV-module M6 decreases a little (the respective current decreases from 2.3 amps to 2.1 amps). During the slow step (iii), the current generated by the front face of the rotating PV-module M2 continues to increase and it reaches its maximum value of about 4.9 amps in the new angular position of about 40°. Please note that, because the angular speed of the motors is constant, the rotation angle varies (from 0° to 180°) linearly with the time. Also, at the early morning, the position at which the current generated by the front face of the rotating PV-module M2 reaches its maximum value is not that perpendicular to the position of the sunrays, because, at this time, the first lateral PV-module M1 projects a sensible shadow on the PV-module M2 (under analysis). On the other hand, when the PV-module M2 reaches the angular positions (40°) in which the aforementioned shadow disappears, it generates an actual current sensibly lower with respect to the theoretical maximum value that it could have generated in absence of the PV-module M1 at the angular position perpendicular to the sunrays of 33° (for instance, the front face of the lateral PV-module M1, at the angular position perpendicular to the sunrays of 33°, generates a maximum short-circuit current of about 5.3 amps). About the contribution of the bifaciality of the rotating PV-module M2, to its whole generation capacity, please note that the maximum value of I_{sh-S} (the sum of the two short-circuit currents I_{sh-F} and I_{sh-R}) doesn't occur at the

same angular position of the maximum of I_{sh-F} and it results equal to about 5.4 amps, that is to say a +10% with respect to the maximum value of I_{sh-F} . Furthermore, the illuminance level on the underlying PV-surface (I_{sh-U}) results at its minimum value, of about 1.45 amps, just in correspondence of the maximum value of I_{sh-F} , while it assumes a sensible higher value, of about 1.55 amps, in correspondence of the maximum value of I_{sh-S} . Finally, please note that the illuminance level of the underlying PV-module M6 reaches its maximum value of about 3.4 amps in correspondence of the angular position of about 150°; in this angular position, the aforementioned PV-module practically results “parallel” to the incident sunrays and its whole electricity generation (I_{sh-S}) results equal to the noteworthy value of about 2.5 amps (46% of its maximum value). During the step (iv), the rotating PV-modules quickly return to the initial 90° angular position (parallel to the ground) and they remain there for about two minutes, before restarting a new rotation sequence.

For giving a more complete representation of what happened during the whole day, in the Figure 7 are reported four additional excerpts from the whole daily waveforms of the same aforementioned short-circuit currents; these additional excerpts refer: (a) to the late morning, (b) to the midday, (c) to the early afternoon, and (d) to the late afternoon. Even if the waveforms are sensibly different from that of the Figure 6, it is easy to extend independently also to them the detailed analysis we have already developed for the previous waveforms.

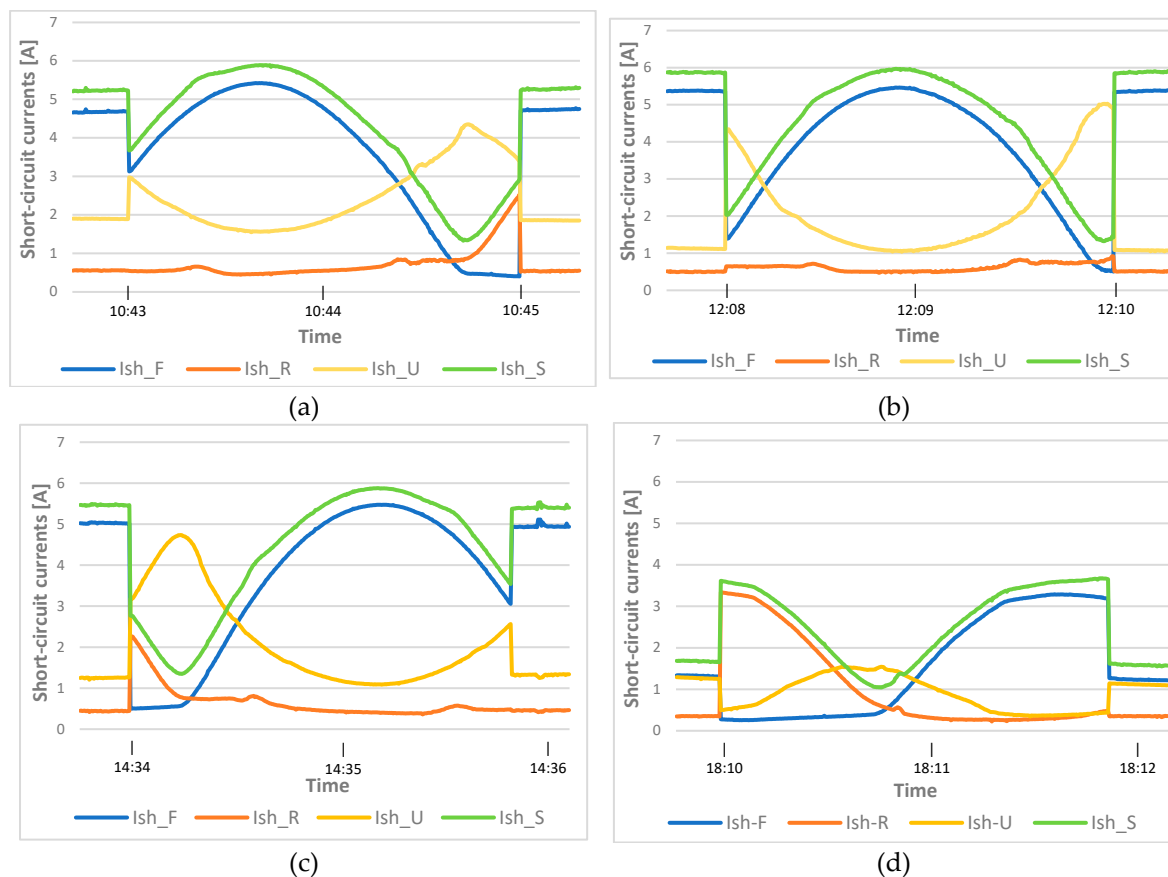


Figure 7. Waveforms of the short-circuit currents I_{sh-F} , I_{sh-R} , I_{sh-S} and I_{sh-U} already defined in the Figure 6, during the duration time of a single and complete rotation sequence: (a) in the late morning; (b) in the midday; (c) in the early afternoon; (d) in the late afternoon.

Once we have measured, acquired and registered the daily whole waveforms of all the short-circuit currents (of all the rotating bifacial PV-modules and of all the fixed monofacial PV-modules of the underlying PV-surface) and after having analyzed their contents during each four-step rotation sequence, we proceeded to perform also their numerical postprocessing, in order to derive some additional and important information about the potential performances of the introduced PV-

skylight, we are experimentally emulating. The main results of this last analysis are reported in the following Figure 8.

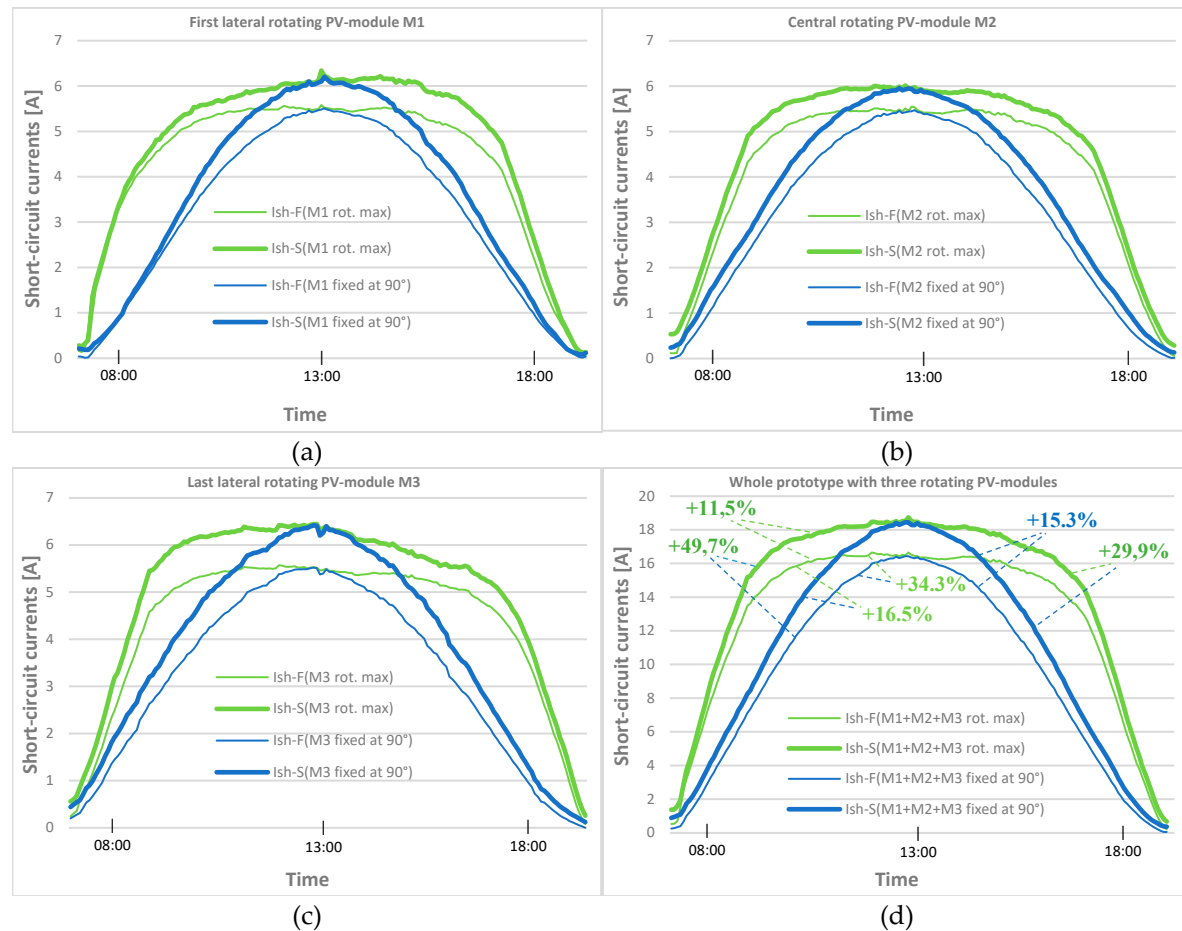


Figure 8. Daily curves of the short-circuit currents of the three rotating PV-modules M1, M2 and M3, from the picture (a) to the picture (c), and of their sum, in the picture (d). Each picture reports the waveforms of: (i) the short-circuit current of the front face of the i -th rotating and bifacial PV-module, when it is fixed at the 90° angular position (parallel to the ground), $I_{sh-F}(M_i \text{ fixed at } 90^\circ)$; (ii) the sum of the short-circuit currents of the front face and of the rear face of the i -th rotating and bifacial PV-module, when it is fixed at the 90° angular position, $I_{sh-S}(M_i \text{ fixed at } 90^\circ)$; (iii) the maximum value of the short-circuit current of the front face of the i -th rotating and bifacial PV-module, measured during the step (iii) of each rotation sequence, $I_{sh-F}(M_i \text{ rot. max})$; (iv) the maximum values of the short-circuit current of the sum of the front face and of the rear face of the i -th rotating and bifacial PV-module, measured during the step (iii) of each rotation sequence, $I_{sh-S}(M_i \text{ rot. max})$.

The Figure 8(a) reports the daily curves of different short-circuit currents of the first lateral M1 rotating and bifacial PV-module of the prototype; in particular, the figure contains the daily waveforms of: (i) the short-circuit current of its front face when it is fixed at the 90° angular position, $I_{sh-F}(M1 \text{ fixed at } 90^\circ)$; (ii) the short-circuit current of the sum of its front face and of its rear face, when it is fixed at the 90° angular position, $I_{sh-S}(M1 \text{ fixed at } 90^\circ)$; (iii) the maximum values of the short-circuit current of its front face measured during the step (iii) of each rotation sequence, $I_{sh-F}(M1 \text{ rot. max})$; (iv) the maximum values of the short-circuit current of the sum of its front face and of its rear face, measured during the step (iii) of each rotation sequence, $I_{sh-S}(M1 \text{ rot. max})$. The Figures 8 (b) and (c) report the daily curves of the same short-circuit currents defined above but, respectively, for the central rotating and bifacial PV-module M2 and for the last lateral rotating and bifacial PV-module M3. The Figure 8(d) reports the daily curves of: (i) the sum of the short-circuit currents of the front faces of all the three rotating and bifacial PV-modules of the prototype (M1, M2 and M3), when they are fixed at the 90° angular position (parallel to the ground, as for a fixed PV-Skylight), $I_{sh-F}(M1+M2+M3 \text{ fixed at } 90^\circ)$; (ii) the sum

of the short-circuit currents of the front and of the rear faces of all the three rotating and bifacial PV-modules of the prototype (M1, M2 and M3), when they are fixed at the 90° angular position, $I_{sh-S(M1+M2+M3 \text{ fixed at } 90^\circ)}$; (iii) the maximum value of the sum of the short-circuit currents of the front faces of all the three rotating and bifacial PV-modules of the prototype (M1, M2 and M3), measured during the step (iii) of each rotation sequence, $I_{sh-F(M1+M2+M3 \text{ rot. max})}$; (iv) the maximum values of the sum of the short-circuit currents of the front and of the rear faces of all the three rotating and bifacial PV-modules of the prototype (M1, M2 and M3), measured during the step (iii) of each rotation sequence, $I_{sh-S(M1+M2+M3 \text{ rot. max})}$.

The most relevant outcomes can be deduced from the Figure 8(d), and it emerges that: (i) for a fixed semitransparent and bifacial PV-skylight, the bifaciality of the PV-modules guarantees an improvement of the generable electricity of +15.3%, with respect to the same fixed and monofacial PV-skylight; (ii) for the rotating semitransparent and bifacial PV-skylight, the bifaciality of the PV-modules guarantees an improvement of the generable electricity of +11.5%, with respect to the same rotating and monofacial PV-skylight; (iii) the rotating semitransparent and monofacial PV-skylight can generate +34.3% more electrical power with respect to a fixed semitransparent and monofacial PV-skylight and +16.5% with respect to a fixed semitransparent and bifacial PV-skylight; (iv) the rotating semitransparent and bifacial PV-skylight can generate +49.7% more electrical power with respect to a fixed semitransparent and monofacial PV-skylight and +29.9% with respect to a fixed semitransparent and bifacial PV-skylight.

Even if the most performing rotating semitransparent and bifacial PV-skylight promises a great improvement of the electrical power generation with respect to a fixed semitransparent and bifacial PV-skylight, it is interesting to underline that it doesn't reach the value of the electrical energy that could be generated by installing, on the same available surface area fully occupied by the PV-skylight, five fixed and monofacial PV-modules, that it to say by installing an almost "opaque" fixed PV-skylight. In fact, also considering just the medium generation capacity of each fixed and monofacial PV-module of the tested prototype, it is easy to estimate that the electrical power generable by the aforementioned opaque fixed and monofacial PV-skylight realized with five fixed PV-modules could be more than +11% higher than that generable by the most performing rotating semitransparent and bifacial PV-skylight.

That said, it remains evident that the global advantage of a rotating semitransparent and bifacial PV-skylight, with respect to a fixed "opaque" and monofacial PV-skylight has to be brought back to its degree of transparency to the incident sunlight and to its controllability.

From this last point of view, the next Figure 9 reports the waveforms of the five short-circuit currents of the corresponding five fixed and monofacial PV-modules of the underlying PV-surface utilized as illuminance sensor, as numerically postprocessed starting from the respective whole waveforms we have measured, acquired and registered during the entire test day. In particular, in the in the Figure 9(a) we plotted the waveforms of the five short-circuit currents of the aforementioned five PV-modules of the underlying PV-surface (M4, M5, M6, M7 and M8) when all the three rotating and bifacial PV-modules (M1, M2 and M3) are rotated (controlled) for catching the maximum electrical power, during the entire test day. From these waveforms it is possible to give evidence of what could be the illuminance degree and its variation on the five respective zones of the underlying surface, during an entire day. In the same figure we also reported the waveform of the whole short-circuit current (sum of the front and rear faces) generated by all the three rotating and bifacial PV-modules, in order to have an insight also about the maximum daily generation capacity of this kind of PV-skylight. In order to make possible a comparative analysis, in the Figure 9(b) we plotted the waveforms of the five short-circuit currents of the same five PV-modules of the underlying PV-surface (M4, M5, M6, M7 and M8) when all the three rotating and bifacial PV-modules (M1, M2 and M3) are maintained fixed at the 90° angular position (parallel to the ground, as the PV-modules of a semitransparent and fixed PV-skylight), during the entire test day; the picture reports also the curve of the corresponding daily whole generation of electricity of the three rotating and bifacial PV-modules. Furthermore, in the Figure 9(c) we plotted the waveforms of the five short-circuit currents of the same five PV-modules of the underlying PV-surface (M4, M5, M6, M7 and M8)

when all the three rotating and bifacial PV-modules (M1, M2 and M3) are rotated (controlled) for obtaining the maximum transparency degree of the PV-skylight, during the entire test day; the picture reports also the curve of the corresponding daily whole generation of electricity of the three rotating and bifacial PV-modules. Finally, in the Figure 9(d) we plotted the waveforms of the five short-circuit currents of the same five PV-modules of the underlying PV-surface (M4, M5, M6, M7 and M8) when all the three rotating and bifacial PV-modules (M1, M2 and M3) are rotated (controlled) for obtaining the minimum transparency degree of the PV-skylight (that is to say, also the maximum shadowing of the underlying surface) during the entire test day; the picture reports also the curve of the corresponding daily whole generation of electricity of the three rotating and bifacial PV-modules.

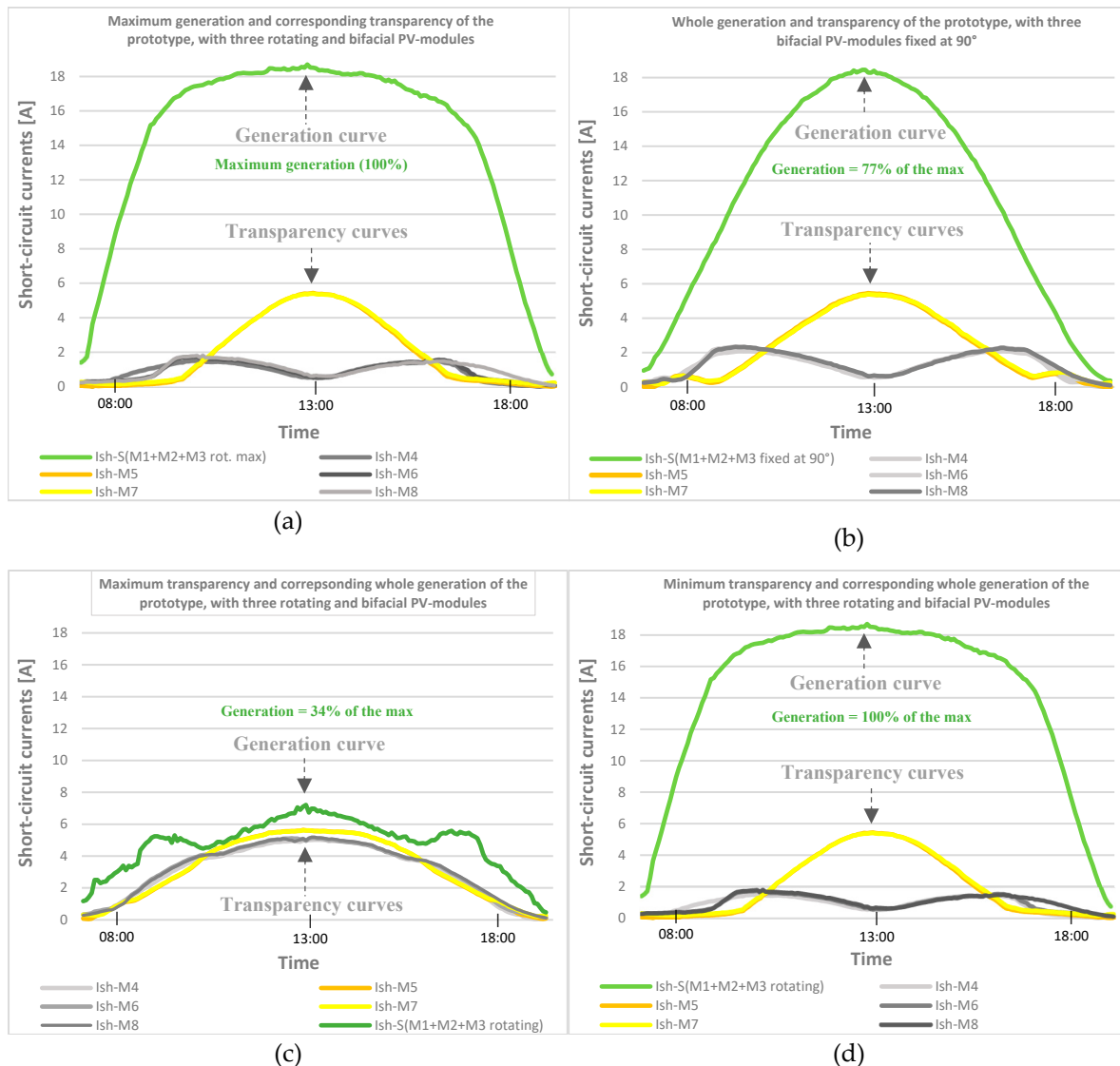


Figure 9. Daily curves of the five short-circuit currents, I_{sh-M4} , I_{sh-M5} , I_{sh-M6} , I_{sh-M7} , and I_{sh-M8} , of the five fixed and monofacial PV-modules of the underlying PV-surface (M4, M5, M6, M7 and M8). The figure reports also the daily whole bifacial short-circuit current generated by the three rotating PV-modules of the prototype, $I_{sh-S(M1+M2+M3 \text{ rot. max})}$. The picture 9(a) refers to the operating condition in which the three rotating PV-modules are rotated for catching the maximum electrical power, during the entire test day. The picture 9(b) refers to the operating condition in which the three rotating PV-modules remained fixed at the 90° angular position (parallel to the ground) for the entire test day. The picture 9(c) refers to the operating condition in which the three rotating PV-modules are rotated for catching the maximum transparency of the prototype, during the entire test day. The picture 9(d)

refers to the operating condition in which the three rotating PV-modules are rotated for catching the minimum transparency of the prototype, during the entire test day.

The main outcomes of the analysis of the Figures 9, from (a) to (d), can be summarized as in the following.

The prototype controlled for specifically obtaining the maximum generation of electricity (Figure 9(a)) shows that the corresponding PV-skylight has also a good medium degree of transparency to the incident sunlight. Nevertheless, the corresponding illuminance level on the underlying surface is not uniform; in fact, the three zones exactly under the three rotating PV-modules are less illuminated with respect to the two zones below the two empty spaces of the overlying surface, that result to be very illuminated.

The prototype that emulates a semitransparent fixed PV-skylight (Figure 9(b)) shows that this last generates only the 77% of the maximum generable electricity. Furthermore, its degree of transparency to the incident sunlight and the uniformity of the corresponding illuminance level on the underlying surface are practically the same of those of the rotating PV-skylight generating the maximum electrical power.

The prototype controlled for specifically obtaining the maximum degree of transparency (Figure 9(c)) shows that it is really possible to make “full transparent” the prototype (like a conventional “glass skylight” with no PV-generation) by specifically controlling its rotating PV-modules. In fact, the curves of the short-circuit currents of the PV-modules (M1÷M5) of the underlying PV-surface show that they can practically generate the same currents of the overlying rotating PV-modules when these last are fixed at the 90° angular position (parallel to the ground). Please note that, this operating condition can be simply obtained by controlling the angular position of all the rotating PV-modules so that they are constantly “parallel” to the incident sunrays. Nevertheless, please also note that, in this operating condition, the electricity daily generation of the PV-skylight decreases to about a 34% of the whole maximum generable value.

Finally, the prototype controlled for specifically obtain the minimum degree of transparency (that is to say, the maximum shadowing of the underlying surface) reveals that this specific PV-skylight it is not capable of becoming “opaque” to the incident sunlight. In fact, for obtaining this performance, the only possibility is that of controlling the rotating PV-modules so that they are constantly “perpendicular” to the incident sunrays, anyway, because of the presence of the two empty spaces between the three rotating PV-modules, this is not sufficient to prevent incident sunlight from passing through the PV-skylight. Furthermore, please note that this operating condition practically coincides with that of the maximum generation of electricity.

From the considerations developed above, we can conclude this experimental subsection by summarizing that the prototype endowed with only three rotating and bifacial PV-modules, installed side by side an empty space from each other:

- (i) can generate almost +50% more electricity than a fixed semitransparent PV-skylight based on three monofacial PV-modules and almost +30% more electricity than a fixed semitransparent PV-skylight based on three bifacial PV-modules, with the same transparency degree;
- (ii) its maximum generation of electricity results almost -11% lower than that generable by an “opaque” fixed and monofacial PV-skylight, occupying the same available surface with five fixed and monofacial PV-modules;
- (iii) its medium degree of transparency is always very good; nevertheless, it doesn’t guarantee a good uniformity of the illuminance on the underlying surface; furthermore, because of the presence of the two empty spaces between the three rotating PV-modules, it is not capable of becoming sufficiently opaque to the incident sunlight for profitably controlling the illuminance level on the underlying surface.

Starting from these last outcomes, in the next section, we introduce a new campaign of measurements developed for exploring the possibility to improve the whole performances of the proposed PV-skylight, by installing on the prototype two additional rotating and bifacial PV-modules, occupying the aforementioned two empty spaces on its available surface.

4.2. second case-study: testing the prototype based on five rotating and bifacial PV-modules, installed side by side with no empty spaces.

The Figure 4(b) illustrates with a picture the operating conditions of the prototype (emulating a PV-skylight), when it is ready for being utilized for performing a new set of experimental tests. In particular, also considering the theoretical premise reported in the subsection 3.1, these new experimental tests are finalized to understand if the performances of the proposed PV-skylight can be improved, when compared with those of the previous semitransparent PV-solution based only on three rotating PV-modules, both in terms of maximum electricity generation and of profitable control of the sunlight passing through the PV-skylight. In practice, on the whole surface area of the prototype (equal to five time the surface area of a single PV-module), we installed exactly five rotating and bifacial PV-modules (M1, M2, M3, M4 and M5). Obviously, this time, the aforementioned PV-modules are installed on the prototype side-by side with no empty spaces from each other; that is to say, all the 5/5 of the whole available surface area of the PV-skylight was occupied by the rotating PV-modules.

As specified in the subsection 3.3, thanks to the single axis solar tracker and its electronic control system, all the five rotating PV-modules are daily rotated in unison, by implementing the four-step repetitive daily rotation sequence already described in detail in previous sections. The same home-made PV-surface, based on five additional fixed and monofacial PV-modules (now called, M6, M7, M8, M9 and M10), is again utilized for analyzing the sunlight illuminance level on the surface under the PV-skylight. Also, the performed daily rotation sequences, together with the measurement method and the data acquisition system are the same of the previous case-study.

First, in order to appreciate also in this operating condition, the practical usefulness of the implemented rotation sequences, the Figure 10 shows an excerpt of the whole waveforms of the rotating and bifacial PV-module M2 of the prototype and, also, of the of the underlying fixed and monofacial PV-Module M7; the data was measured and registered during the cloudless day of July 22 2023 on the same site of the previous case-study.

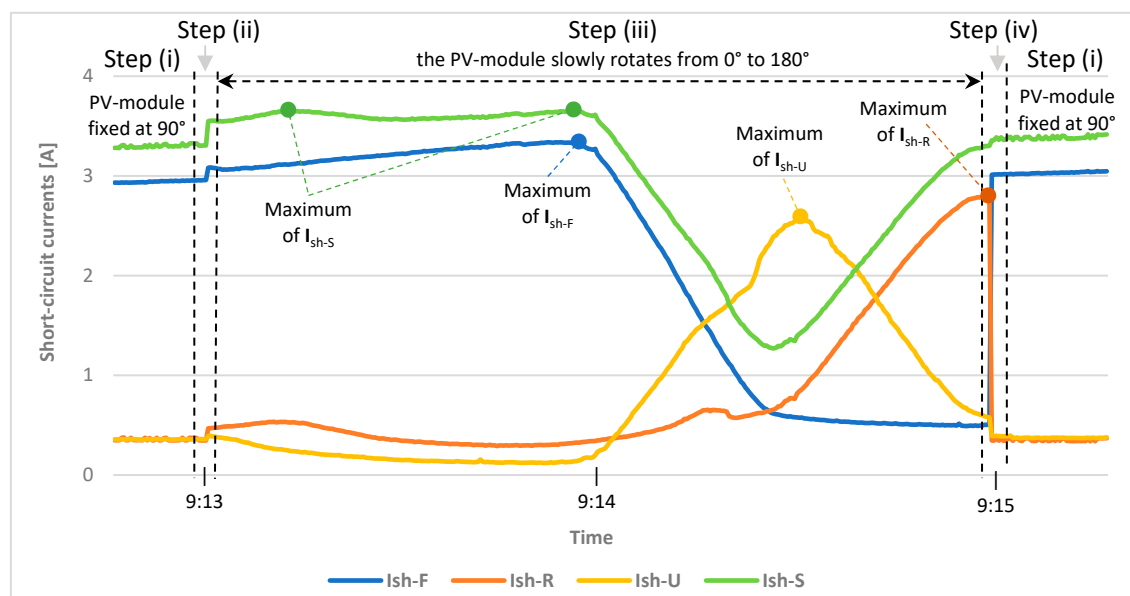


Figure 10. Waveforms of the short-circuit currents of the rotating PV-module M2 (I_{sh-F} , I_{sh-R} , I_{sh-S}) and of the fixed PV-module M7 of the underlying PV-surface (I_{sh-U}), during the duration time of a single and complete (four step) rotation sequence, implemented in the early morning of the cloudless day of July 22 2023, as extracted from the respective whole daily waveforms.

With some more details, for all the four steps of the already specified daily rotation sequence, the Figure 10 reports the waveforms of: (a) the short-circuit current of the front face of the rotating bifacial PV-module M2, I_{sh-F} ; (b) the short-circuit current of the rear face of the rotating bifacial PV-

module M2, I_{sh-R} ; (c) the sum of the two aforementioned currents, I_{sh-S} ; (d) the short-circuit current of the fixed and monofacial PV-Module M7 of the underlying PV-surface, I_{sh-U} . As specified also in the time axis of the figure, this excerpt refers to a single rotation sequence operated in the early morning of the test day.

Also for this case-study, from the analysis of the waveforms reported in the Figure 10, it is possible to develop some first interesting considerations.

During the step (i) of the rotation sequence, when the rotating and bifacial PV-module M2 of the prototype is parallel to the ground (as the fixed PV-modules of a conventional “opaque” PV-skylight), its front face generates about 2.9 amps while its rear face generates a very reduced current of about 0.4 amps. This means that the contribution of the bifaciality to the whole generation of the M2 PV-module, in this position and at this time, results to be of about a +14%. At the same step, considering that this time there are not empty spaces between the five rotating PV-modules, on the underlying zone of the PV-surface the illuminance level is very low, in fact, its respective PV-module M7 generates about 0.4 amps.

At the end of the quick step (ii), the rotating and bifacial PV-module M2 reaches the position perpendicular to the ground and its front face increases a little the generated current, from 2.9 amps to 3.1 amps, and also the current generated by its rear face increases a little, from 0.4 amps to 0.5 amps. At the same time, the illuminance level on the underlying PV-module M7 practically remains constant, in fact, its respective current remains at the low value of 0.4 amps.

During the slow step (iii), the current generated by the front face of the rotating PV-module M2, I_{sh-F} , increases very slowly and it reaches its maximum value of about 3.4 amps in the new angular position of about 88°. This means that the rotation of the PV-module M2 contributes a little to the improvement of its generation capacity, because, at this time, the first lateral PV-module M1 projects a strong shadow on the PV-module M2 (under analysis); on the other hand, when the aforementioned shadow disappears, the actual current generated by the PV-module M2 registers a relevant loss with respect to the theoretical maximum value that it could have generated in absence of the shadowing PV-module M1 in the angular position perpendicular to the sunrays (for instance, at the same step, the front face of the first lateral PV-module M1 generates a maximum short-circuit current of about 4.7 amps, at the angular position perpendicular to the sunrays of about 35°). About the contribution of the bifaciality of the rotating PV-module M2 to its whole generation capacity, please note that the maximum value of I_{sh-S} (the sum of the two short-circuit currents I_{sh-F} and I_{sh-R}) doesn't occur at the same angular position of the maximum of I_{sh-F} and it results equal to about 3.7 amps, that is to say it increases of about a +9% with respect to the maximum value of I_{sh-F} . Furthermore, in this position, the illuminance level on the underlying PV-surface (I_{sh-U}) results at its minimum very low value, of about 0.15 amps. Finally, please note that the illuminance level of the underlying PV-module M7 reaches its maximum and relevant value of about 2.6 amps in correspondence of the angular position of about 137°; in this angular position, the aforementioned PV-module practically results “parallel” to the incident sunrays and its whole electricity generation (I_{sh-S}) results equal to the noteworthy value of about 1.5 amps (that is to say, the 40.5% of its maximum value).

During the step (iv), the rotating PV-modules quickly return to the initial 90° angular position (parallel to the ground) and they remain there for about two minutes, before restarting a new rotation sequence.

For giving a more complete representation of what happened during the whole day, in the Figure 11 are reported four additional excerpts from the whole daily waveforms of the same aforementioned short-circuit currents; these additional excerpts refer: (a) to the late morning, (b) to the midday, (c) to the early afternoon and (d) to the late afternoon. Even if the waveforms are sensibly different from that of the Figure 10, it is easy to extend to them, independently, the detailed analysis we have already developed for the previous waveforms.

After having analyzed the waveforms of the daily short-circuit currents (of all the five rotating bifacial PV-modules and of all the five fixed monofacial PV-modules of the underlying PV-surface), which have been measured and registered during each four steps rotation sequence of the test day, we proceeded to perform also their numerical postprocessing, in order to derive some additional and

important information about the potential performances of the introduced PV-skylight under test. The Figure 12(a) reports the daily curves of different short-circuit currents of the first lateral M1 rotating and bifacial PV-module of the prototype; in particular, this figure contains the daily waveforms of: (i) the short-circuit current of its front face when it is fixed at the 90° angular position, $I_{sh-F(M1 \text{ fixed at } 90^\circ)}$; (ii) the short-circuit current of the sum of its front face and of its rear face, when it is fixed at the 90° angular position, $I_{sh-S(M1 \text{ fixed at } 90^\circ)}$; (iii) the maximum values of the short-circuit current of its front face measured during the step (iii) of each rotation sequence, $I_{sh-F(M1 \text{ rot. max})}$; (iv) the maximum values of the short-circuit current of the sum of its front face and of its rear face, measured during the step (iii) of each rotation sequence, $I_{sh-S(M1 \text{ rot. max})}$. The Figures 12 from (b) to (e) report the daily curves of the same short-circuit currents defined above, respectively, for the rotating and bifacial PV-modules M2, M3, M4 and (the last lateral) M5. The Figure 12(f), instead, refers to the whole five PV-module prototype and it reports the daily curves of: (i) the sum of the short-circuit currents of the front faces of all the five rotating and bifacial PV-modules of the prototype, when they are fixed at the 90° angular position (parallel to the ground, as for a fixed PV-Skylight), $I_{sh-F(M1+M2+M3+M4+M5 \text{ fixed at } 90^\circ)}$; (ii) the sum of the short-circuit currents of the front and of the rear faces of all the five rotating and bifacial PV-modules of the prototype, when they are fixed at the 90° angular position, $I_{sh-S(M1+M2+M3+M4+M5 \text{ fixed at } 90^\circ)}$; (iii) the maximum value of the sum of the short-circuit currents of the front faces of all the five rotating and bifacial PV-modules of the prototype, measured during the step (iii) of each rotation sequence, $I_{sh-F(M1+M2+M3+M4+M5 \text{ rot. max})}$; (iv) the maximum values of the sum of the short-circuit currents of the front and of the rear faces of all the five rotating and bifacial PV-modules of the prototype, measured during the step (iii) of each rotation sequence, $I_{sh-S(M1+M2+M3+M4+M5 \text{ rot. max})}$.

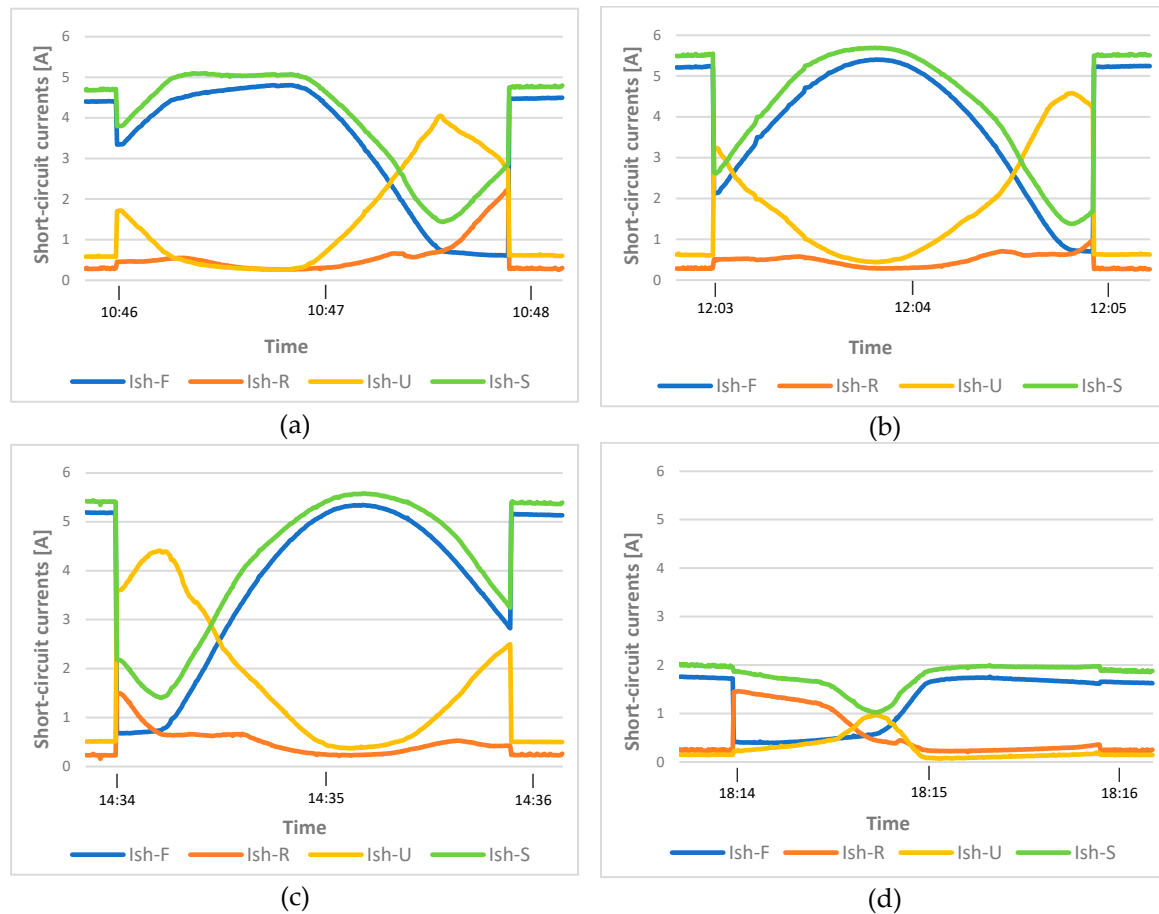


Figure 11. Waveforms of the short-circuit currents I_{sh-F} , I_{sh-R} , I_{sh-S} and I_{sh-U} already defined in the Figure 10, during the duration time of a single and complete rotation sequence, as extracted from: (a) the late morning; (b) the midday; (c) the early afternoon; (d) the late afternoon.

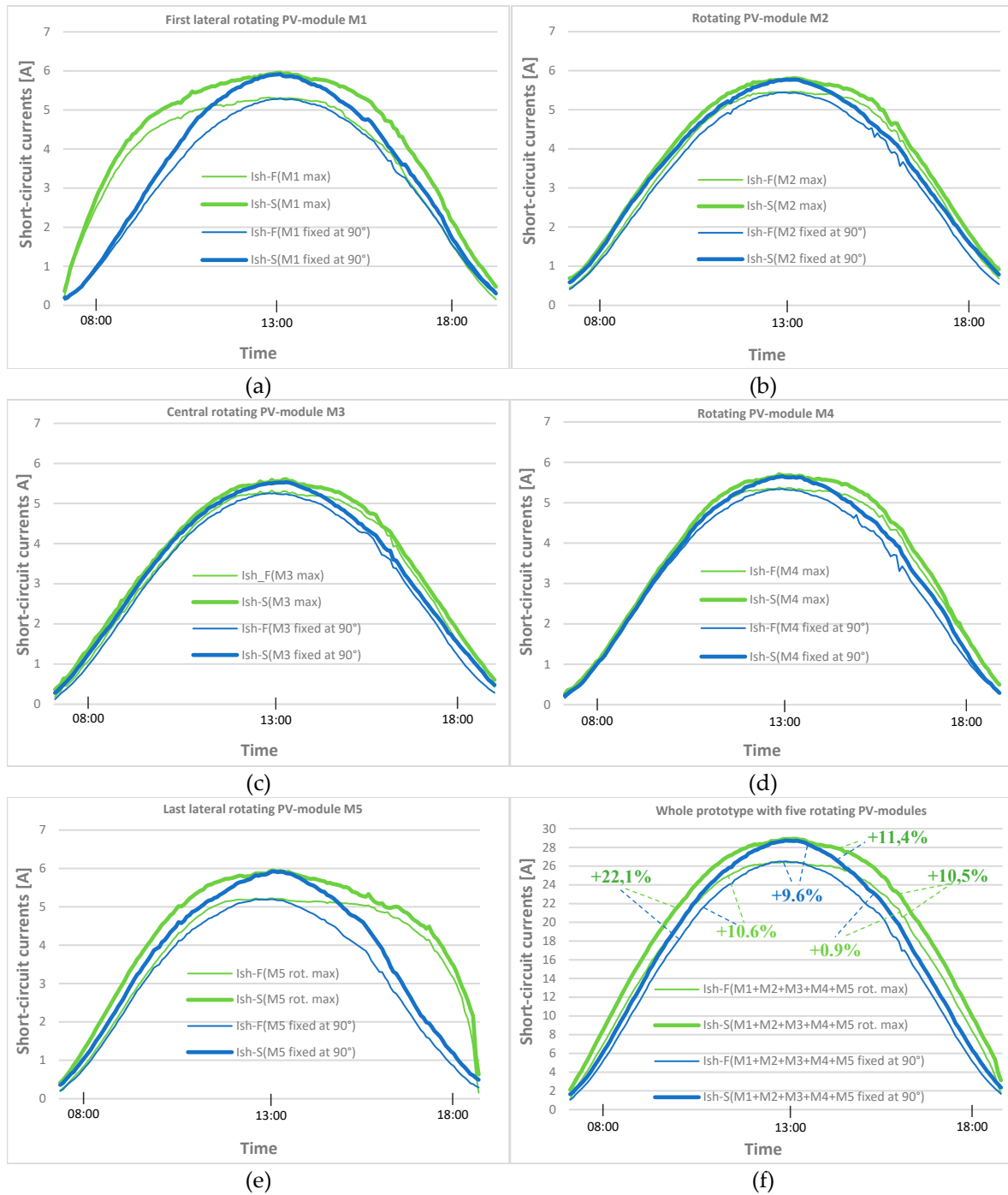


Figure 12. Daily curves of the short-circuit currents of the five rotating PV-modules M1, M2, M3, M4 and M5, from picture (a) to picture (e) respectively, and of their sum, picture (f). Each picture reports the waveforms of: (i) the short-circuit current of the front face of the i -th rotating and bifacial PV-module, when it is fixed at the 90° angular position (parallel to the ground), $I_{sh-F}(M_i \text{ fixed at } 90^\circ)$; (ii) the sum of the short-circuit currents of the front face and of the rear face of the i -th rotating and bifacial PV-module, when it is fixed at the 90° angular position, $I_{sh-S}(M_i \text{ fixed at } 90^\circ)$; (iii) the maximum value of the short-circuit current of the front face of the i -th rotating and bifacial PV-module, measured during the step (iii) of each rotation sequence, $I_{sh-F}(M_i \text{ rot. max})$; (iv) the maximum values of the short-circuit current of the sum of the front face and of the rear face of the i -th rotating and bifacial PV-module, measured during the step (iii) of each rotation sequence, $I_{sh-S}(M_i \text{ rot. max})$.

From the Figure 12(f), it emerges that: (i) for a fixed and bifacial PV-skylight, the bifaciality of its PV-modules guarantees an improvement of the generable electricity of +9.6%, with respect to the same fixed and monofacial PV-skylight; (ii) for the rotating and bifacial PV-skylight, the bifaciality of

its PV-modules guarantees an improvement of the generable electricity of +10.5%, with respect to the same rotating and monofacial PV-skylight; (iii) the rotating and monofacial PV-skylight can generate +10.6% more electrical power with respect to a fixed and monofacial PV-skylight and +0.9% with respect to a fixed and bifacial PV-skylight; (iv) the rotating and bifacial PV-skylight can generate +22.1% more electrical power with respect to a fixed and monofacial PV-skylight and +11.4% with respect to a fixed and bifacial PV-skylight.

With some more details, the PV-skylight realized by using five rotating and bifacial PV-modules, installed side by side without any empty space from each other, promises a relevant improvement of the generable electricity with respect to both the monofacial fixed five PV-module ("opaque") PV-skylight (+22%) and the bifacial fixed five PV-module ("opaque") PV-skylight (+11%). Furthermore, if compared with the rotating and bifacial PV-skylight realized by using three PV-module, already analyzed on the previous subsection, the five PV-module PV-skylight promises an improvement of the maximum generable electricity of +40.5%. As a consequence, the PV-skylight realized by five rotating and bifacial PV-modules results the most performant solution in terms of maximum electricity generation.

For experimentally analyzing also its degree of transparency to the incident sunlight and its controllability, the next Figure 13 reports the waveforms of the five short-circuit currents of the corresponding five fixed and monofacial PV-modules of the underlying PV-surface utilized as illuminance sensor, as numerically postprocessed starting from the respective whole waveforms we have measured, acquired and registered during the entire test day of July 22 2023.

In particular, in the in the Figure 13(a) we plotted the waveforms of the five short-circuit currents of the aforementioned five PV-modules (now numbered as M4, M5, M6, M7 and M8), when all the five rotating and bifacial PV-modules (M1, M2, M3, M4 and M5) are rotated (controlled) for catching the maximum electrical power, during the entire test day. From these waveforms it is possible to give evidence of what could be the illuminance degree and its variation on the five respective zones of the underlying surface, during an entire day, in the aforementioned operation condition. In the same figure we also reported the waveform of the whole short-circuit current (sum of the front and rear faces) generated by all the five rotating and bifacial PV-modules, in order to have an insight also about the maximum daily generation capacity of the PV-skylight in the same operating condition.

In order to make possible a comparative analysis, in the Figure 13(b) we plotted the waveforms of the five short-circuit currents of the same five PV-modules of the underlying PV-surface (M4, M5, M6, M7 and M8) when all the five rotating and bifacial PV-modules (M1, M2, M3, M4 and M5) are maintained fixed at the 90° angular position (parallel to the ground, as the PV-modules of a fixed PV-skylight), during the entire test day; the picture reports also the curve of the corresponding daily whole generation of electricity of the five rotating and bifacial PV-modules in the same operating condition. Furthermore, in the Figure 9(c) we plotted the waveforms of the five short-circuit currents of the same five PV-modules of the underlying PV-surface (M4, M5, M6, M7 and M8) when all the five rotating and bifacial PV-modules (M1, M2, M3, M4 and M5) are rotated (controlled) for obtaining the maximum transparency degree of the PV-skylight, during the entire test day; the picture reports also the curve of the corresponding daily whole generation of electricity of the five rotating and bifacial PV-modules in the same operating condition. Finally, in the Figure 13(d) we plotted the waveforms of the five short-circuit currents of the same five PV-modules of the underlying PV-surface (M4, M5, M6, M7 and M8) when all the five rotating and bifacial PV-modules (M1, M2, M3, M4 and M5) are rotated (controlled) for obtaining the minimum transparency degree of the PV-skylight (that is to say, also the maximum shadowing of the underlying surface), during the entire test day; the picture reports also the curve of the corresponding daily whole generation of electricity of the five rotating and bifacial PV-modules in the same operating condition.

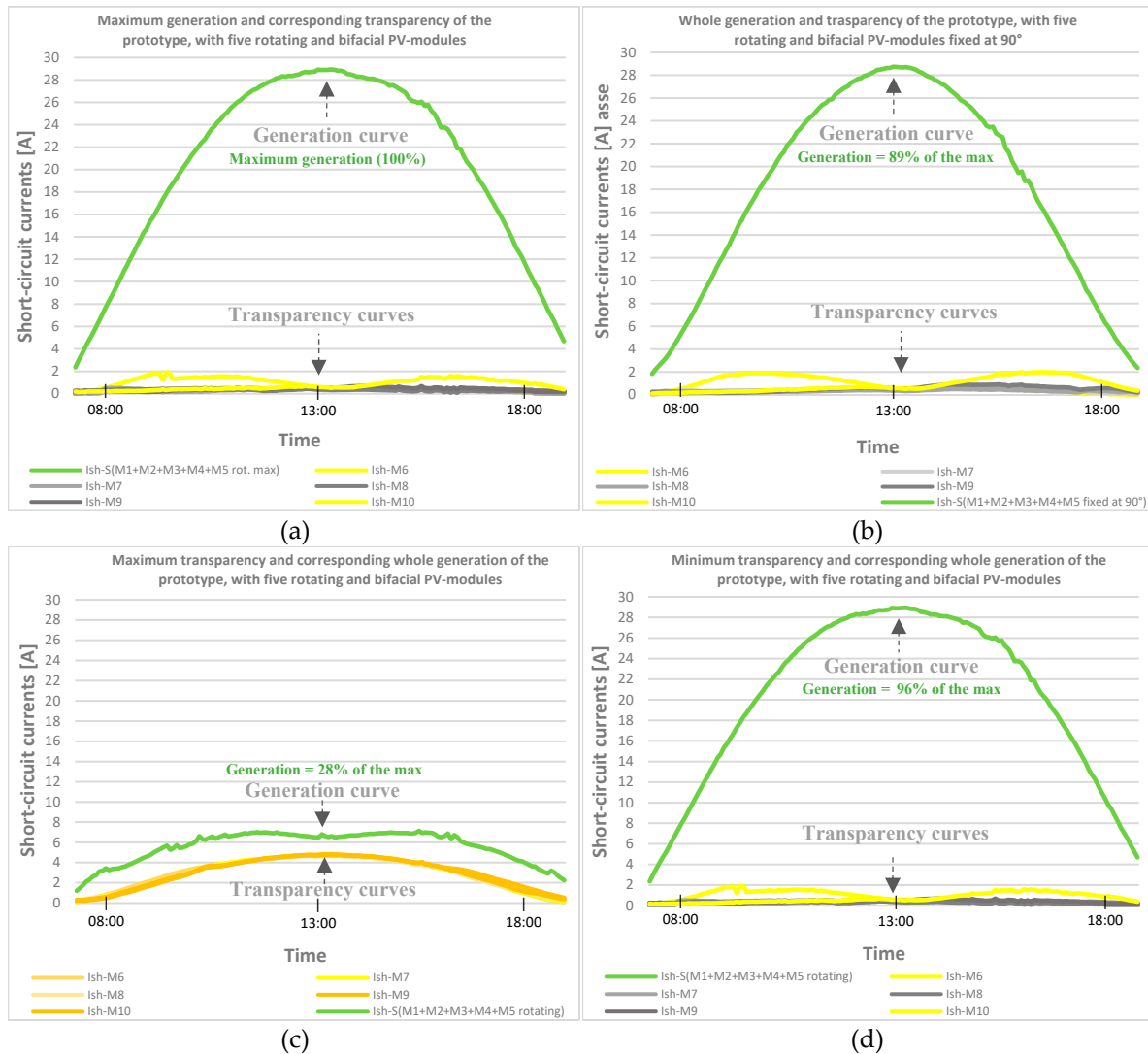


Figure 13. Daily curves of the five short-circuit currents, I_{sh-M4} , I_{sh-M5} , I_{sh-M6} , I_{sh-M7} , and I_{sh-M8} , of the five fixed and monofacial PV-modules of the undelaying PV-surface (M4, M5, M6, M7 and M8). The figure reports also the daily whole bifacial short-circuit current generated by the five rotating PV-modules of the prototype, $I_{sh-S(M1+M2+M3+M4+M5 \text{ rot. max})}$. The picture 13(a) refers to the operating condition in which the five rotating PV-modules are rotated for catching the maximum electrical power, during the entire test day. The picture 13(b) refers to the operating condition in which the five rotating PV-modules remained fixed at the 90° angular position (parallel to the ground) for the entire test day. The picture 13(c) refers to the operating condition in which the five rotating PV-modules are rotated for catching the maximum transparency of the prototype, during the entire test day. The picture 13(d) refers to the operating condition in which the five rotating PV-modules are rotated for catching the minimum transparency of the prototype, during the entire test day.

The main outcomes of the analysis of the Figures 13, from (a) to (d), can be summarized as in the following.

The prototype controlled for specifically obtaining the maximum generation of electricity (Figure 13(a)) shows that the corresponding PV-skylight has also a very low degree of transparency to the incident sunlight. Furthermore, the corresponding illuminance level on the underlying surface is quite uniform; only in the early morning and on the late afternoon, on the first and on the last lateral zones of the underlying surface, the illuminance degree results a little higher, because of the sunlight passing through from the bottom of the lateral sides of the PV-skylight.

The prototype that emulates an “opaque” fixed PV-skylight (Figure 13(b)) shows that this last generates only the 89% of the maximum generable electricity. Furthermore, its degree of transparency

to the incident sunlight and the uniformity of the corresponding illuminance level on the underlying surface are practically the same of those of the rotating PV-skylight generating the maximum electrical power.

The prototype controlled for specifically obtaining the maximum degree of transparency (Figure 13(c)) shows that it is really possible to make “full transparent” the prototype (like a conventional “glass skylight” with no PV-generation) by specifically controlling its rotating PV-modules. In fact, the curves of the short-circuit currents of the PV-modules (M1÷M5) of the underlying PV-surface show that they can practically generate the same currents of the overlying rotating PV-modules. Please note that, this operating condition can be simply obtained by controlling the angular position of all the rotating PV-modules so that they are constantly “parallel” to the incident sunrays. Nevertheless, please also note that, in this operating condition, the electricity daily generation of the PV-skylight decreases to about a 28% of the whole maximum generable value.

Finally, the prototype controlled for specifically obtain the minimum degree of transparency (that is to say, the maximum shadowing) reveals that this specific operating condition of the PV-skylight practically coincides with that of the maximum generation of electricity.

From the considerations developed above, we can conclude this experimental subsection by summarizing the following performance considerations about the prototype endowed with five rotating and bifacial PV-modules, installed side by side without any empty space from each other (practically occupying the whole available surface of the PV-skylight):

- (i) it can generate about +11% more electricity than a fixed and bifacial “opaque” PV-skylight, about +22% more electricity than a fixed and monofacial “opaque” PV-skylight and about +40% more electricity than a semitransparent PV-skylight realized with three rotating and bifacial PV-modules;
- (ii) it can guarantee a high degree of controllability of its transparency, from the maximum value of a conventional transparent skylight (without any photovoltaic generation capability) to the very low value of a conventional almost opaque skylight;
- (iii) it can also guarantee a very good uniformity of the illuminance level on the underlying surface.

5. Conclusions

In the paper, we introduced an innovative BIPV-system, which substantially assumes the form of a PV-skylight. Its construction is based on a certain number of unconventional bifacial PV-modules, each of which consists of a single-row of a certain number of bifacial series-connected PV-cells. Each bifacial PV-module is also endowed with two special terminations which make easy the rotation around its central axis. A certain number of rotating and bifacial PV-modules are installed within a custom-made and full-transparent casing, specifically built to be full-integrable on a variety of buildings and, especially, on their rooftops. For experimentally testing the overall performances of the proposed PV-skylight, we performed different experimental tests using a home-made prototype, emulating the proposed PV-skylight under different operating conditions. First, we emulated and tested a semitransparent PV-skylight, based on only three rotating and bifacial PV-modules, installed side by side and distanced from each other, without fully occupying its available surface area. Then, we also emulated and tested a different PV-skylight, based on five rotating and bifacial PV-modules, which fully occupy its available surface area. After having analyzed all the experimental results, we can finally draw the following conclusions.

The semitransparent PV-skylight based on three rotating and bifacial PV-modules promises very good generation performances, especially with respect to a conventional semitransparent fixed PV-skylight. Nevertheless, it does not make the most of the entire surface well exposed to the sun it occupies and this sensibly reduces its whole generation with respect to a fixed and “opaque” PV-skylight which, on the contrary, fully occupies the available surface area with five fixed and monofacial PV-modules. Furthermore, its very good degree of transparency is not uniform and its controllability is very limited (e.g. it is not able to significantly shadowing the underlying surface).

The PV-skylight based on five rotating and bifacial PV-modules, which fully occupy its available surface area, promises optimal generation performances. In fact, it shown to be able to generate +40%

more electricity with respect to a semitransparent PV-skylight realized with three rotating and bifacial PV-modules and +22% more electricity with respect to a fixed and “opaque” PV-skylight realized with five monofacial PV-modules. Furthermore, its very good degree of transparency is characterized by a rightly uniformity and a very good controllability (e.g. it is able to control the illuminance of the underlying surface from almost the maximum level of the available natural sunlight to almost the complete opacity).

Considering all the aforementioned characteristics and performances of the test prototype, next studies and experiments could be addressed to its utilization also in the field of photovoltaic greenhouses and/or some innovative double layer PV-panels.

6. Patents

This experimental study was realized by making explicit reference to an “industrial invention” whose details are fully specified within the documents of the Italian patent n. 0001430077, issued by the Italian Ministry of the “Sviluppo Economico” on October 02, 2018; the aforementioned patent is referred on [19]. Also, some new additional ideas have been experimented by taking advantage of the contents of a new pending Italian Application Patent N. 102023000011895, submitted by the authors on June 09, 2023; this additional application patent is referred on [20].

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Conflicts of Interest: The authors declare no conflict of interest.

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