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A Photovoltaic Greenhouse with Variable Shading for the Optimization of Agricultural and Energy Production

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Received: 11 June 2019; Accepted: 3 July 2019; Published: 5 July 2019

Abstract: The cultivation of plants in greenhouses currently plays a role of primary importance in modern agriculture, both for the value obtained with the products made and because it favors the development of highly innovative technologies and production techniques. An intense research effort in the field of energy production from renewable sources has increasingly led to the development of greenhouses which are partially covered by photovoltaic elements. The purpose of this study is to present the potentiality of an innovative prototype photovoltaic greenhouse with variable shading to optimize energy production by photovoltaic panels and agricultural production. With this prototype, it is possible to vary the shading inside the greenhouse by panel rotation, in relation to the climatic conditions external to the greenhouse. An analysis was made for the solar radiation available during the year, for cases of completely clear sky and partial cloud, by considering the 15th day of each month. In this paper, the results show how the shading variation enabled regulation of the internal radiation, choosing the minimum value of necessary radiation, because the internal microclimatic parameters must be compatible with the needs of the plant species grown in the greenhouses.

Keywords: dynamic photovoltaic greenhouse; variable shading; renewable source; passive cooling system

1. Introduction

Cultivation in greenhouses allows us to satisfy the growing demand for vegetables and fruits by the growing global population by extending the production window both geographically and seasonally [1]. The use of greenhouses allows for the control of the microclimatic parameters that characterize the internal environment (i.e., air temperature, relative humidity, lighting level, CO_2 concentration) [2–5], influencing both crop quality and quantity [6,7] and the spread of pathogens and diseases [8].

Greenhouses use solar radiation input, but the control of the internal environment takes place thanks to energy supplied from different sources, including fossil fuels and the electricity network [9]. These systems that take advantage of the greenhouse effect require high amounts of energy for the operation of forced cooling, heating, and lighting systems [10]. Given the need to reduce human pollution, the combination and use of renewable energy sources (e.g., solar energy) seems to be the best solution to follow [11,12]. Some studies have shown that solar panels can produce energy for the operation of heat pumps in Italy [13,14], fog cooling systems in Malaysia [15] and in Saudi Arabia [16], and for fan and pad cooling systems in Arizona [17].

By appropriately positioning solar panels on greenhouse roofs, it is possible to obtain multiple advantages: using the solar energy produced to make the agricultural production independent of traditional energy sources [18,19]; reducing the environmental impact and production costs; not subtracting from the land useful for crops [20,21] (since both agriculture and photovoltaic panels need sunlight and available land, and these two practices are in conflict [22]); and using the panels as a passive cooling system thanks to the shading produced [23,24], as an alternative to special shading systems such as nets [25–27] and reflective coatings [25,28].

Depending on the latitude and weather conditions, cultures must be protected from low temperatures in winter and/or autumn and at night and from high temperatures in spring and/or summer. These low- and high-temperature conditions occur easily in Mediterranean countries [25].

To correct the excessively high temperature values that can occur inside the greenhouse, there are several methods; among them, shading is an advantageous practice—especially in regions of high insolation such as Spain [29] and Saudi Arabia [30].

Shading reduces the level of solar radiation, the air temperature, and the rate of evapotranspiration, reducing water consumption—a fundamental aspect for countries where this resource is scarce [31,32]. Furthermore, it has been shown that shading combined with evaporative cooling is more effective in arid regions and in hot seasons, while shading combined with thermal screens reduces the energy consumption used for heating in cold regions, maintaining the temperature of the internal air at 5 °C higher than outside air [33].

Shading is important to improving crop growth, extending the crop cycle, and delaying ripening [33,34], and its benefits have been demonstrated by some studies conducted in Japan [35] and in the Mediterranean regions [26]. When placing the solar panels on the roof of the greenhouse, the shading depends on the inclination of the solar rays (and therefore on the latitude, altitude, time of day, and season) [36], their arrangement on the roof, their degree of transparency, and their inclination.

Some studies have analyzed the effect of the panel arrangement on cultures, and highlighted how this aspect drastically influences plant growth and energy production [7,37–39]. Controlling the panels' disposition seems to be a good solution to reducing the lack of lighting uniformity [35].

Photovoltaic panels can be opaque, semitransparent, or transparent, and can let different amounts of solar radiation pass, influencing crop growth [25]. Opaque panels have negative effects on production, reducing the crop growth in the case of tomatoes or reducing the amount of biomass in the case of maize [40–45]. Meanwhile, in the experiments conducted so far, semi-transparent panels such as DSCs (dye-sensitized solar cells) [46,47], OPVs (organic photovoltaics) [48–50], and PVs based on the latest generation of luminescent solar concentrators have been shown to have great potential for improvement in terms of biomass production, plant morphology, and nutritional content, since they allow the wavelength used by plants for photosynthesis and morphogenesis to pass through [49]. Li et al. say that "the installation of semi-transparent PV modules on a greenhouse roof surface can be beneficial when crops require moderate shading under high-irradiation conditions" [9] and, for example, tomato [10,38], lettuce [51,52], wild rocket [53], and Welsh onion [37] were cultivated correctly under semi-transparent panels [9]. The arrangement of the semi-transparent panels varies from checkerboard to conventional planar PV modules [7,54,55] or cells [39,56,57] to dispersed PV micro-cells [58,59].

One important aspect to be analyzed for shading concerns the inclination of the panels [60]. By placing the solar panels on the roof of the greenhouse and creating a static system, independent of time, their inclination will be equal to that of the greenhouse cover. In this way, the shading system is not very dynamic and not very adaptable to the needs of the plants, which are influenced by excessive shadowing when it is not necessary [36,61].

Considering that the amount of solar radiation reaching the Earth varies according to the time of day, season, latitude, weather conditions, and altitude, a compromise must be found between electricity production and agriculture, making the solar panel system dynamic over time, exactly like irradiation.

In other words, until today the research has developed fixed-shading photovoltaic greenhouses.

A fixed shading value can work well in some months of the year, but not others; it can be optimal in clear skies but not in partially or totally cloudy sky conditions. Additionally, during the day, the shading should vary with higher values in the central hours of the day.

The research gap can be filled only with photovoltaic greenhouses with variable shading by PV panels.

This article describes the experimental results obtained by applying a dynamic photovoltaic greenhouse prototype where shading inside the greenhouse was continuously changeable according to the demand of the crops for light and external weather conditions [62]. The panels' position could change at any time of the day, optimizing the production of electricity and agriculture.

When the irradiation was at a maximum, during the hot season and in the central hours of the day, the panels could be positioned in such a way as to shade the crop and obtain maximum energy production; when the level of radiation was reduced, such as in the cold season and in the first and last hours of the day, the panels could be positioned in such a way as to allow more solar radiation to pass through.

Thanks to the rotation of the panels, it was possible to vary the degree of shading from a minimum of 0 degrees to a maximum of 78 degrees. Furthermore, it is important to underline that with this panel movement system, when it was necessary to let in more solar radiation because the sky was covered, the roof remained closed and the crop continued to be protected from any precipitation.

When the optimal inclination of the solar panels to produce electric energy was lost, causing a reduction in energy production, reflective aluminum mirrors reflected the otherwise-lost radiation back on the panels and in this way the electricity production was improved [62].

This innovative system is able to

(1) Continuously vary the shading according to the weather conditions, the period of the year, the time of day, and the type of harvest. The mobile system (panels and mirrors) makes the structure dynamic and flexible based on the needs of the situation;
(2) Optimize energy and agricultural production consuming the same land unit, without filling areas adjacent to the greenhouse for the positioning of the panels at the expense of crops;
(3) Totally recover the amount of energy lost by reflection when the inclination of the direct solar radiation moves away from the optimal one thanks to the use of aluminum mirrors constantly aligned with the sun's rays;
(4) Use a large part of the greenhouse roof for the installation of photovoltaic panels, leaving the crop protected from precipitation.

In this paper the variation in shading obtained from the dynamic prototype of the photovoltaic greenhouse is analyzed and discussed in order to maintain certain minimum internal solar radiation thresholds expressed in terms of both global daily radiation (5 MJ m^{-2} day^{-1}) and energy flow (400 Wm^{-2}).

2. Materials and Methods

The prototype used in this research was realized at the Tuscia University in Viterbo, Italy. The length and width of the greenhouse were 3.79 and 2.41 m, respectively; it had an asymmetric cross section specifically designed for photovoltaic energy generation.

The photovoltaic panels occupied an area of 8.15 m^2 and were positioned on the south pitch, inclined at 33°. The north pitch without photovoltaic panels had a slope of 51° (Figure 1).

Figure 1. The experimental prototype used for this search.

The prototype was made of iron and glass, with a transverse vertical polycarbonate wall.

More details about the geometrical characteristics and technical data of the prototype are reported in Marucci et al. [62].

This innovative system arose from the observation of shaded greenhouses where the pitch of the south-facing roof was partially covered by photovoltaic panels. This solution has become the most popular one. If we consider the latitude of the Mediterranean areas, knowing the inclination of the sun's rays at 12:00, it is possible to observe that the portion of the illuminated floor is poor and not uniform. Figure 2 shows the distribution of the partial shadows from June 21st. When the height angle of the solar rays decreases, the internal solar radiation is also reduced, as shown in Figures 3 and 4.

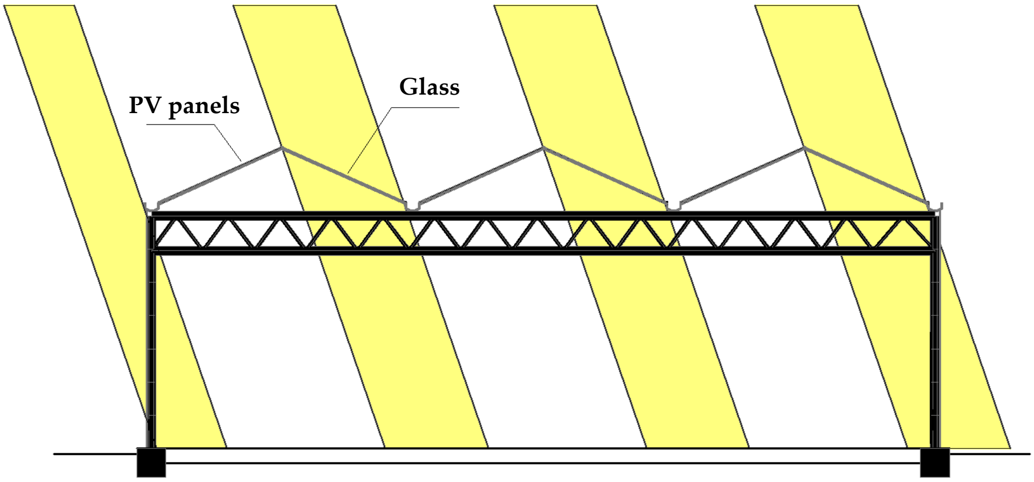


Figure 2. Direct solar radiation at Mediterranean latitudes: 21 June, 12:00 pm. (PV: photovoltaic).

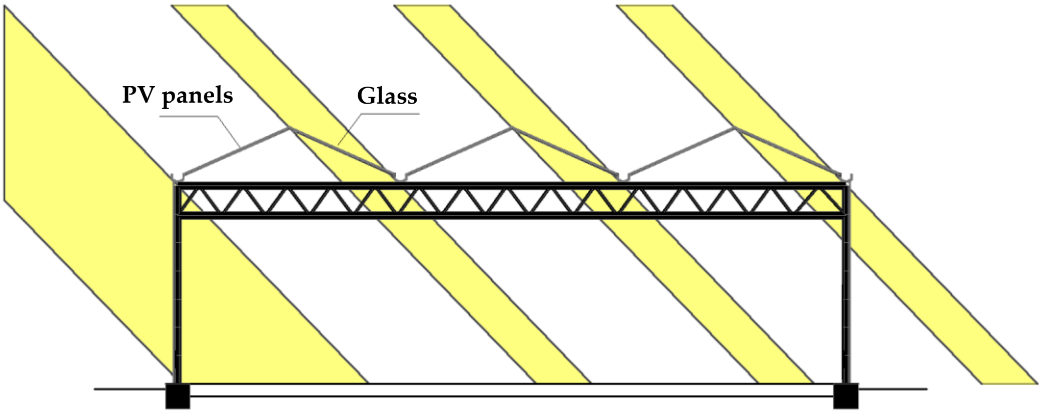


Figure 3. Direct solar radiation at Mediterranean latitudes: 21 September, 12:00 pm.

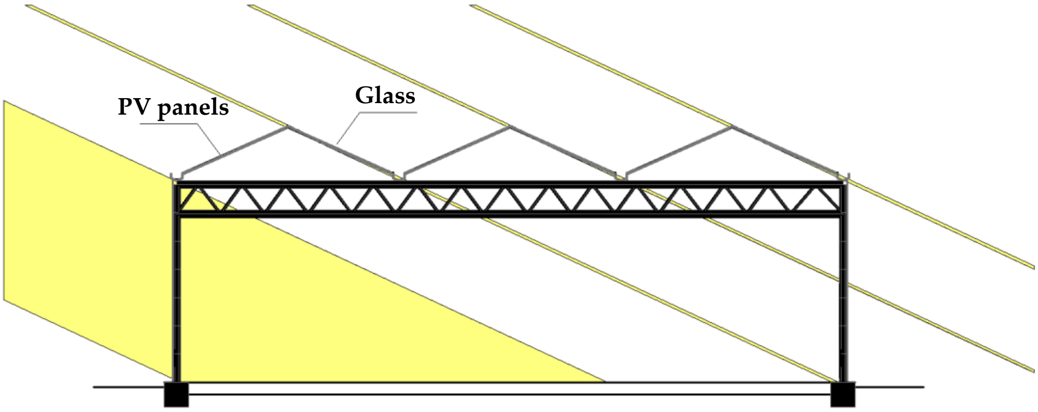


Figure 4. Direct solar radiation at Mediterranean latitudes: 21 December, 12:00 pm.

Under these conditions, most of the direct solar radiation enters the protected environment from the vertical wall facing south. Finally, Figure 5 shows that the checkerboard formation allows greater uniformity of lighting and therefore is much more efficient for the growth of crops.

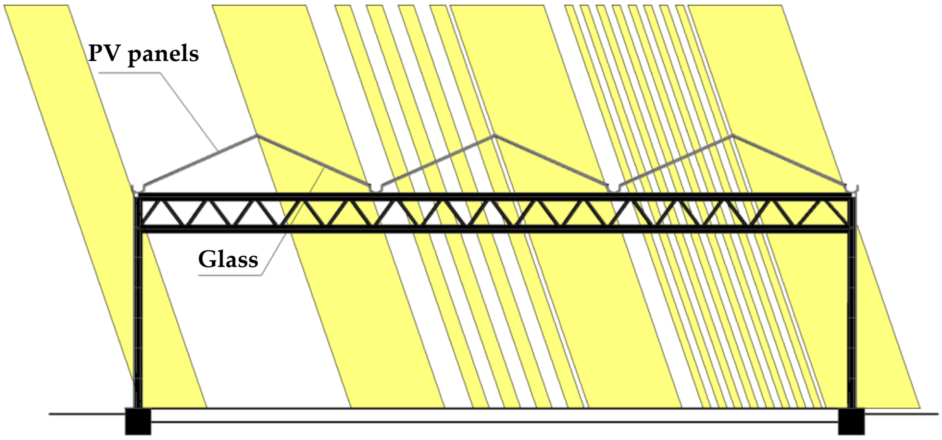


Figure 5. Direct solar radiation at Mediterranean latitudes for a different checkerboard formation of photovoltaic panels: 21 June, 12:00 pm.

These solutions are expensive to implement, and as they are "static", they are good for limited periods of the year and day, and only for certain crops. It is necessary to consider that under clear sky conditions solar radiation varies considerably during the year in terms of intensity of energy flow (Wm^{-2}) and in terms of duration of solar radiation (day length).

For example, in the absence of clouds, at the latitude of 42° north and at an altitude of 300 m, the global daily radiation ranges from 7.3 MJ $m^{-2}d^{-1}$ on 21 December to 29.4 MJ $m^{-2}d^{-1}$ on 21 June—an approximately four-fold increase.

To make the dynamic system, it was decided to move the panels.

A mechanical system allowed the rotation of the panels along the longitudinal axis and regulated the shading inside the structure (Figure 6).

Figure 6. PV panels and mirrors on the prototype.

However, the dynamic system caused the loss of the optimal inclination for the production of energy with photovoltaic panels, resulting in losing part of the solar radiation useful for reflection.

This problem was partially solved by placing mirrors (Figures 6 and 7) [62].

Figure 7. Detail of the movement system of the PV panels and mirrors.

To reflect part of the lost radiation, the mirrors must always be aligned with the sun's rays. Defined with α the angle between the mirrors and the panels, the importance of the mirrors is greater the smaller the angle α. At 55°, the area of the photovoltaic panel that allows the mirrors to be efficient for the recovery of solar radiation is 30%. At 45°, only a reflection occurs on the mirror, but the area of the panel that allows the mirror to recover the solar radiation is 100%. As studied by Marucci et al. "For angles smaller than 45°, the number of reflections increases proportionally to the decrease in the incidence angle" [62].

If the photovoltaic panels are parallel to the roof, they allow a maximum shading degree of 78%. Marucci et al. defines the degree of shading as "as the ratio between the projection of the length of the panel including the frame (21 cm) on the pitch and the distance between the points of rotation of the panel (27 cm)" [62].

The percentage of shading could be modified thanks to the panel movement system. If the portion of the panels projected on the ground is reduced, the shading is reduced.

The degree of shading must be selected based on

(1) The kind of crop;
(2) Latitude;
(3) The time of day; and
(4) External weather conditions.

3. Results and Discussion

Figure 8 shows the values of the external and internal global solar radiation measured on clear days and with different values of shading by the PV panels and the values of the transmittance of the photovoltaic cover.

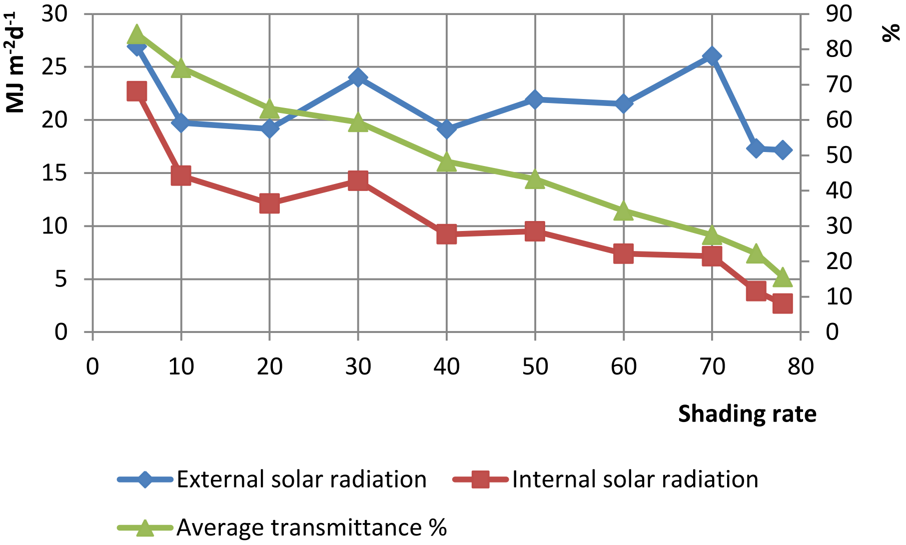


Figure 8. Outside and inside global solar radiation at different shading percentages.

The values of internal solar radiation were obtained by processing the data measured by internal sensors [62]. It can be seen that the internal solar radiation decreased as the percentage of shading increased, and that the system was very effective in adapting to external radiation levels. From the measured data shown in Figure 8 and with the direct and diffuse solar radiation levels calculated [36,63], the annual trends of external and internal solar radiation were simulated for different shading percentages (20%, 40%, 60%, and 78%). For this simulation, the 15th of each month in clear sky conditions was considered (Figure 9).

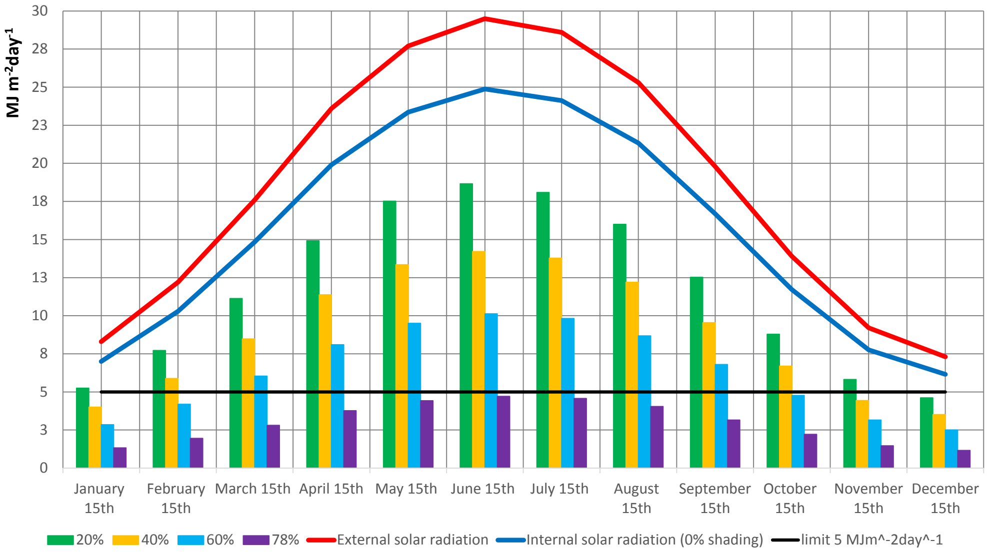


Figure 9. Levels of external and internal solar radiation under different levels of shading (0%, 20%, 40%, 60%, and 78%).

Values of internal solar radiation below 5 MJ m^{-2} day^{-1} are not sufficient for the optimal growth of most crops, and this is reflected in the poor quality of the final products in terms of size, quantity, color, and nutritional properties.

This threshold value would never be reached if the shading percentage reached 78%. According to the simulation, for 60% of the shading, the critical months are January, February, October, November, and December. For the months of January, November, and December, 40% of the shading was not allowed to reach the lower limit of 5 MJ m^{-2} day^{-1}. Finally, the month of December did not exceed the threshold, even with the shading percentage at 20%. Thus, in the months of January, February, October, November, and December, thanks to the mobile panels, it is possible to allow more solar radiation to pass, reducing the shading. During spring and summer, on the other hand, it is possible to use the panels as if they were a passive cooling system, because the available solar radiation exceeds the demand of most plants, at the same time producing electricity that could eventually be entered in the electricity network. Figure 9 clearly shows that in the spring and autumn season it is sufficient to shade to 20%, while in the summer period a value of 50% is sufficient.

This new dynamic photovoltaic greenhouse was also designed and built to achieve instantaneous shading variations. When we set an optimal limit (constant or variable) of internal solar radiation for the plant cultivated (for example, 400 Wm^{-2}), all the PV panels, initially aligned with the mirrors to the solar rays, could begin to rotate to increase the shading in such a way that the internal solar radiation was maintained at the established optimal value.

On June 21, with clear sky and at 42° north latitude, in order to maintain the greenhouse at the fixed level of solar radiation (400 Wm^{-2}), the PV panels should begin to produce shade three hours after sunrise and stop shading three hours before sunset (Figure 10). In addition, the shading is not constant and must gradually increase up to a maximum of 47% in the middle of the day.

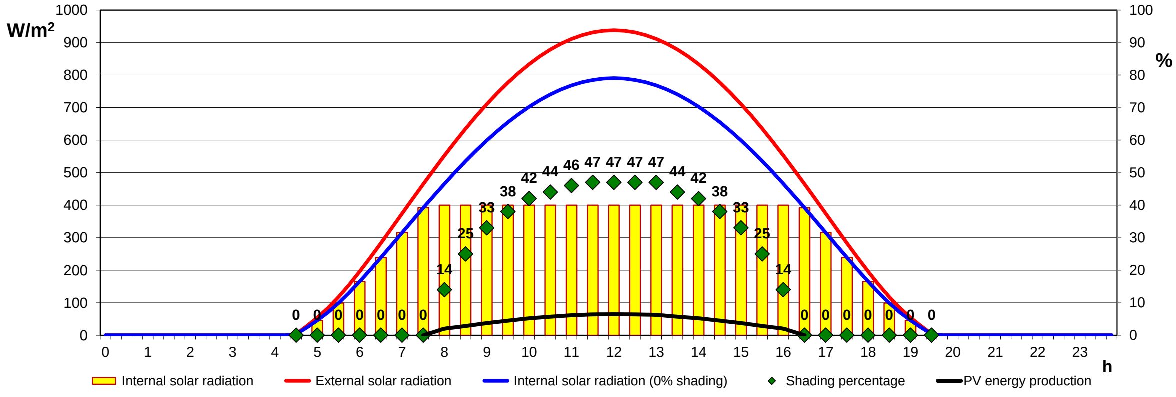


Figure 10. Daily trend of shading percentages so that the internal solar radiation is kept lower than or equal to the set limit on June 21.

On March 21, the PV panels should begin to produce shade three hours after sunrise and stop producing shade three hours before sunset (Figure 11). The shading in this case should gradually increase to a maximum of 35% in the middle of the day.

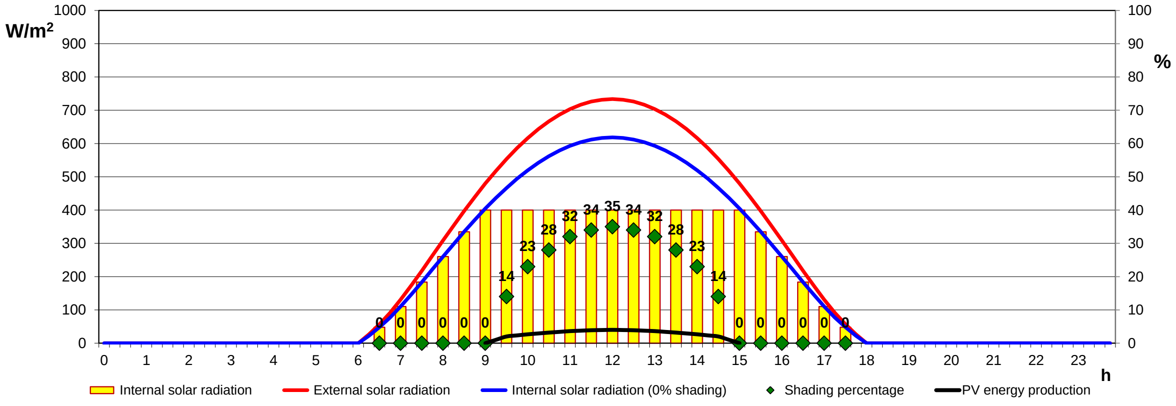


Figure 11. Daily trend of shading percentages so that the internal solar radiation is lower than or equal to the set limit on March 21.

Lastly, on February 21, the maximum shading must not exceed 18% (Figure 12).

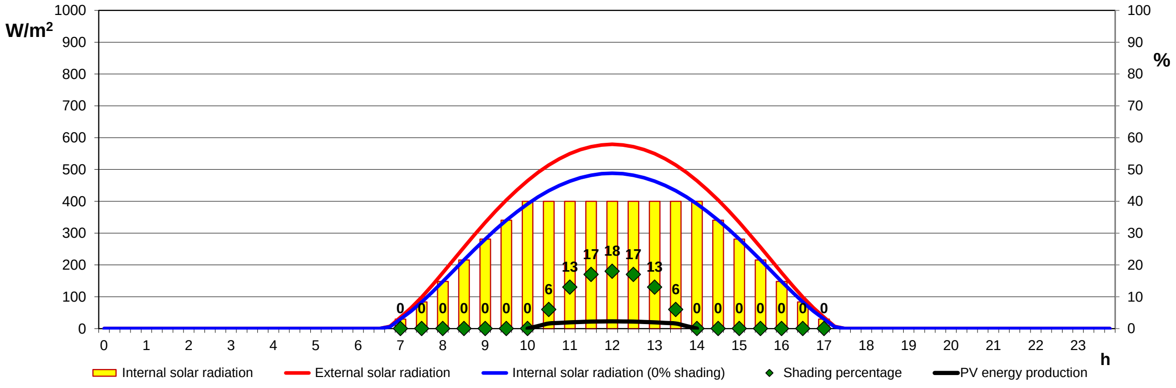


Figure 12. Daily trend of shading percentages so that the internal solar radiation is lower than or equal to the set limit on February 21.

On the three days considered, the panels must begin to shade about three hours after sunrise and stop shading about three hours before sunset; these intervals do not vary much during the year, but they can be changed by modifying the limit for the internal solar radiation. However, one factor that does vary greatly during the year is the percentage of shading required to have the same internal solar radiation. On days with a partly cloudy sky (Figure 13), the shading by the PV panels must be instantly adapted to the external solar radiation and the set limit for the internal solar radiation.

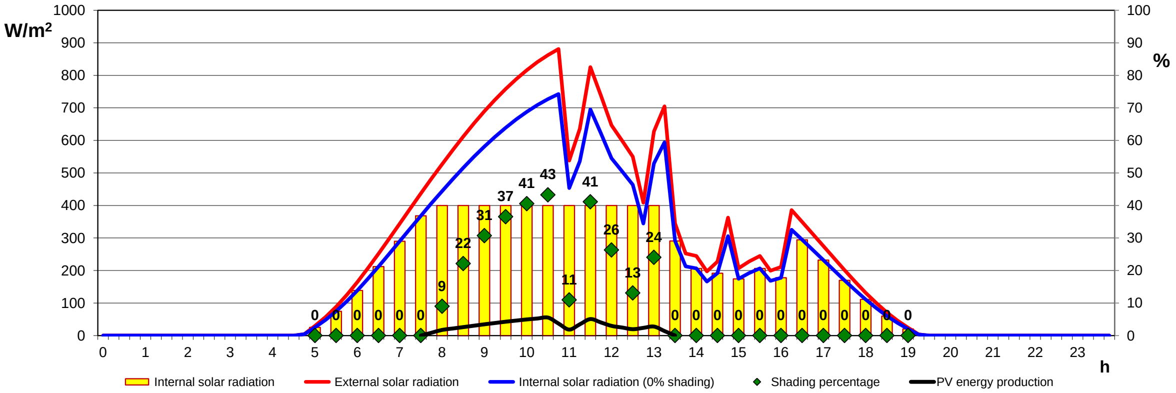


Figure 13. Daily trend of the shading percentage with partly cloudy sky on May 23.

The shading of the PV panels adapts instantaneously to the variations in the external solar radiation: it must be null when the internal solar radiation is less than or equal to the set limit, and must gradually increase to remain equal to the set limit for the internal solar radiation.

The trends in the electricity production of the PV panels on representative days (sunny days of different lengths and partly cloudy days) are shown in the corresponding figures, depending on the external solar radiation and above all on the shading of the panels. The electricity production of the PV panels is null in the first and last hours of the day, where the panels are aligned to the rays of the sun like mirrors; it grows with increasing shading up to about 65 Wm^{-2} in the central hours of the day on the summer solstice. Table 1 shows the total daily values of the electricity produced by the PV panels expressed in MJ $m^{-2}d^{-1}$.

Table 1. External and internal solar daily radiation of the prototype and electricity production of the PV panels.

Day	External Solar Radiation (MJ $m^{-2}d^{-1}$)	Internal Solar Radiation (MJ $m^{-2}d^{-1}$)	PV Energy Production (MJ $m^{-2}d^{-1}$)	PV Energy Efficiency (%)
June 21, clear sky	29.5	16.8	1.44	4.9
March 21, clear sky	18.8	12.7	0.63	3.3
February 21, clear sky	13.3	10.4	0.25	1.9
May 23, partly cloudy sky	20.6	13.8	0.67	3.2

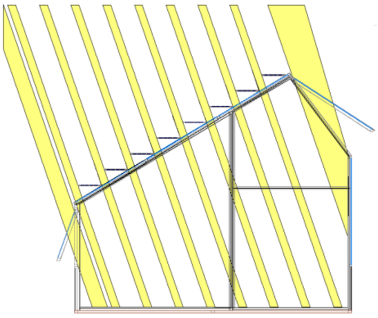
On clear days, with the internal threshold of 400 Wm^{-2}, the daily electricity production varied from 0.25 to 1.44 MJ $m^{-2}d^{-1}$ with a maximum efficiency percentage of 4.9%. In cloudy conditions the production of electricity was lower and in any case extremely variable with the distribution and intensity of cloudiness. To immediately adapt the shading to the required conditions, the panel movement system (manual in the prototype) could be easily automated and associated with the centralized greenhouse management system. The value of internal solar radiation was established based on the needs of the cultivated plants. Based on the value of external solar radiation measured, the automatic control system obtained the percentage of shading and therefore the angle that the panels must take with respect to the pitch. The automated management system also controlled the angle of the mirrors, which must always be aligned with the sun's rays.

The energy exchanges of the proposed prototype, including the radiative exchanges in the night period, were studied in the energy balance [36]. In the winter months, shading and electricity production were drastically reduced to become negligible, as the solar energy that reaches the ground is just enough for cultivated plants. Without plant cultivation, however, the shading would be the maximum possible (78%), as would the production of electricity.

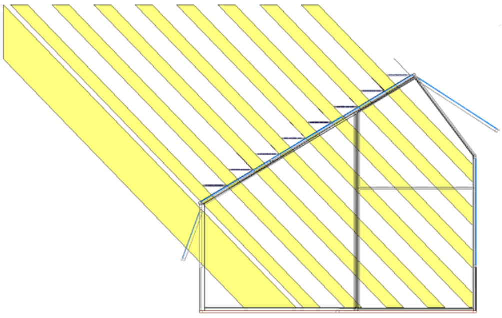
Another possible use of this prototype could be to entrust the modification of the shading to the strong variation of the angle of the solar rays, keeping the photovoltaic panels fixed and horizontal.

This working method of the prototype will be the subject of further studies and research.

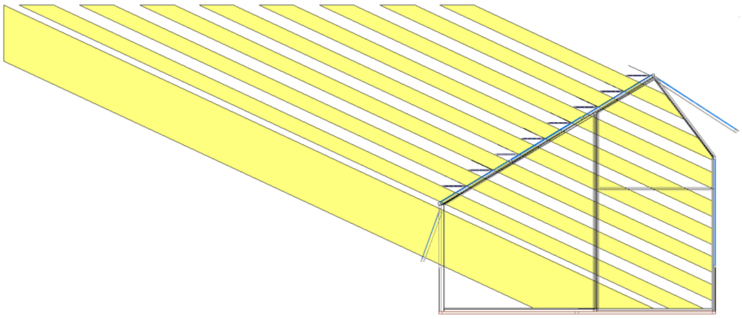
Rotation is still necessary for the mirrors, which must always be aligned to sunlight. It is a variation of passive shading, without energy consumption for the control and handling systems (Figure 14).



Latitude 42°N - June 21, 12:00 pm



Latitude 42°N - September 21, 12:00 pm



Latitude 42°N - December 21, 12:00 pm

Figure 14. Shading in clear sky conditions with horizontal PV panels.

The shading obtained is favorable for crop requirements: maximum in summer, minimum during the winter.

4. Conclusions

This study shows the feasibility of changing the degree of shading inside a greenhouse based on the available solar radiation and on plant needs, thanks to a dynamic system of photovoltaic panels. The advantages of this innovation are evident, because the mobile photovoltaic panels positioned on the roof allow optimization the agricultural production (varying the amount of solar radiation that reaches the plants) and the production of electrical energy (thanks also to the presence of the mirrors). Finally, the shading can be almost completely removed: the photovoltaic panels can rotate to cancel their projection on the floor and not interfere with the lighting.

With a set optimal limit of internal solar radiation for the plant cultivated, all the PV panels, initially aligned with the mirrors to the solar rays, can begin to rotate to increase the shading in such a way that the internal solar radiation is maintained at the established optimal value (constant or variable). With a partly cloudy sky, the shading by the PV panels can be instantly adapted to the external solar radiation and the set limit for the internal solar radiation.

Therefore, this prototype is a dynamic and flexible system that easily adapts to agricultural and energy production demands.

Author Contributions: Conceptualization, S.M. and A.M.; methodology, A.M.; software, S.M.; validation, S.M.; formal analysis, S.M. and A.M.; investigation, S.M. and A.M.; resources, A.M.; data curation, S.M.; writing—original draft preparation, S.M.; writing—review and editing, S.M.; visualization, S.M.; supervision, A.M.; project administration, A.M.; funding acquisition, A.M..

Funding: This research received no external funding.

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

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