Dynamic photovoltaic greenhouse: Energy efficiency in clear sky Conditions

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Abstract

This paper assesses the energy efficiency of a prototype of a dynamic photovoltaic (PV) greenhouse that has an asymmetric cross section and allows the rotation of the PV modules around their longitudinal axis throughout the day to select the degree of shading inside the structure. The goal of this research is to study the production of energy and the microclimate inside the structure with different tilt angles of the PV panels to improve the information available to support the farmers and to create a PV greenhouse capable of producing income from electrical and agricultural activity. The average values of the internal air temperature and relative humidity, measured during the hottest period and on days with clear skies, are within the optimal ranges for major vegetable species (17–27 C and 60–90%, respectively). The values of the solar radiation available for the plants were always sufficient for normal agricultural opera tions, except for the last two days of the experiment (values lower than 5 MJ m——2) in which the shading percentage analyzed was too high for normal production. When the shading percentage was highest (78%), the maximum value of PV power (102 W m——2) was recorded and when the shading percentage was equal to 0%, the minimum value of PV power (20 W m——2) was recorded. The results show that it is possible to balance the electricity production using photovoltaic panels and the agricultural production as a function of the type of crop grown, latitude, operating season, and characteristics of the greenhouse.

Nomenclature

A	altitude (km)
A_0	adimensional parameter
A_1	adimensional parameter
h	hour days
I_{MMP}	nominal power current (A)
I_{oc}	short circuit current (A)
K	adimensional parameter
n	Julian day
P_{max}	rated power (Wp)
R	solar radiation (W m^{-2})
RH	relative humidity
V_{MMP}	nominal power voltage (V)
V_{oc}	open circuit voltage (V)

Subscripts

b	direct
d	diffuse
e	extraterrestrial
g	glass
p	panel

Greek letters

α	solar altitude angle (°)
β	tilt angle of the photovoltaic panels (°)
δ	declination angle (°)
φ	latitude of the location (°)
ρ	reflectance
θ	angle of incidence (°)
θ_z	zenith angle (°)
ω	solar hour angle (°)
τ	atmospheric transmittance

Abbreviations

NIR	near infrared
PV	photovoltaic

1. Introduction

Greenhouse plant production is one of the most intensive forms of agriculture [1], both in terms of the energy consumption [2–5] and the operating costs [6,7]. Greenhouses are used to grow plants of higher quality and protect plants against natural environmental effects, such as wind or rain [8], and to enable out of season cultivation [9].

To reduce costs and energy consumption, various types of greenhouses and cover materials have been offered to farmers [10,11].

In Mediterranean areas, a considerable benefit to the develop ment of greenhouse cultivation was achieved with the introduction of plastics as cover materials [12]. This led to the creation and spread of the ‘‘Mediterranean greenhouse”, which is characterized by its simple structure, economic covering materials, and lack of heating [13–15]. However, in the winter, the internal microclimate is suboptimal for the production of vegetable crops [16–18].

Greenhouses covered with plastic film have become popular in areas with mild climates during the winter and in hot areas of the world [19] with high solar radiation. The solar energy available to typical greenhouses in Mediterranean areas is more than sufficient to satisfy the energy requirements for the air conditioning of the internal environment. By contrast, in limited extreme cases, there is a need for heating [20]. Artificial heating systems are usually not used for structures in these areas because they are not considered economically viable [17]. An alternative is the use of passive solar heating methods and devices to enhance the greenhouse's energy efficiency [12]. In a typical plastic greenhouse with a bare gravel mulched soil, Baille et al. [21] found that the soil acted as a substantial source of air heating during winter nights (approximately 20 W m^{-2} on average in February). They suggested that simple passive solar systems increasing the solar heat storage in the soil during the day and releasing the energy during the night could significantly enhance the overall greenhouse efficiency, especially in areas that receive a significant input of solar radiation in the winter.

During the summer season, however, due to the intense solar radiation and high air temperature, most greenhouses located in Mediterranean areas difficult to use [22]. While blocking excess solar radiation is easy with shading [22], preventing high air temperatures is difficult using only natural ventilation [16].

Shading performed by passive means, such as the use of shading nets of different types or heat shields, has the simple purpose of intercepting or reflecting the solar radiation in such a way as to reduce the energy input. To maintain the inside air temperature, there is a need to use ventilation with air-cooling (e.g., evaporative filters), water nebulization, or the complete opening of the cover (sky system). In all these cases, it is necessary to supply artificial energy to operate the fans, pumps, and servomechanisms, with a considerable increase in the production costs.

In the last decades, different studies have focused on the possibility of replacing energy sources, such as fossil fuels, with renewable energy to heat greenhouses [23,24]. Chou et al. [25], Tong et al. [26], Nayak and Tiwari [27], and Özgener and Hepbasli [28] used renewable energy, such as ground or air source heat pumps [29], photovoltaic/thermal systems [30], and biomass energy [23,31], to control the temperature in greenhouses to decrease fossil fuel consumption.

The sun's energy that is intercepted or reflected by the shading systems is essentially lost and unused.

Controlling the microclimate inside greenhouses using electricity produced by solar radiation in excess of the needs of the cultivated plants leads to a significant reduction in production costs and could lead to a ''zero-impact greenhouse", a perfect green house that does not require any input of energy from conventional sources.

The generation of photovoltaic energy is envisaged as an efficient, natural, clean, and valuable energy source [32]. It has been applied to multiple applications [33,34], both indoor [35] and outdoor [36,37]. The optimal size of a photovoltaic system depends on many parameters, such as orientation, shading, photovoltaic surface, insolation, ambient temperature, wind speed, and PV/inverter sizing ratio ('sizing ratio') [38].

In Italy, the first installations of photovoltaic panels usually covered the entire roof, with a single pitch, and were therefore highly opaque. This created almost insurmountable difficulties for the cultivation of plants in the environment below the cover due to excessive shading.

It was then decided to cover the pitched roof facing south with photovoltaic panels in place of glass. In this case, the shading of the internal environment was also often excessive, as is illustrated in Figs. 1 and 2. The direct radiation only reaches the floor in thin strips, compromising its uniformity.

To increase the solar radiation available to the crop and to make it more uniform, it was decided to partially cover a single pitch of the greenhouse with photovoltaic panels in a checkerboard formation (Fig. 3).

Different studies [39–41] have focused on this arrangement of photovoltaic panels. Yano et al. [39] studied the electricity gain and shading in an east–west oriented greenhouse on which a 720 W maximum-rated-power PV array covering 12.9% of the roof area was mounted. Two PV array configurations were tested: straight-line and checkerboard arrangements. The two arrangements created quite different sunlight distributions in the greenhouse, even though their electrical energy generation was comparable. However, the annual solar-irradiation distribution in the checkerboard PV greenhouse was more uniform than that of the straight-line PV greenhouse because the checkerboard PV array intermittently cast shadows in the greenhouse.

Urena-Sanchez et al. [40] studied the effect of the checkerboard arrangement on photovoltaic modules with a cover pitch of approximately 10%. The results indicated that the shading due to the PV modules did not affect the yield or cost of the tomatoes, despite some negative effects on the size and color of the crop.

Most studies have focused on the use of a semi-transparent photovoltaic film on the roofs of greenhouses to balance the pro duction of electricity with agricultural production [14,42–44].

These studies have shown that it is possible to generate enough electricity for the greenhouse environment control equipment using PV systems without compromising the plant cultivation [40,45–47].

Al-Shamiry et al. [48] studied a hybrid photovoltaic system, consisting of two photovoltaic sub-systems that were connected to each other, to cool a tropical greenhouse. This system included 48 photovoltaic solar Panels with 18.75 W each, one inverter, one charge controller, and a battery bank (including 12 batteries) and was located at the University Putra Malaysia (UPM) Research Park.

The load consisted of two misting fans to cool the greenhouse. The results showed that the PV system would be suitable to supply electricity to cover the load requirement demands without using energy from the grid.

Nayak and Tiwari [49] performed energy and exergy analyses to predict the performance of a photovoltaic/thermal (PV/T) collector integrated with a greenhouse in I.I.T, Delhi, India. These analyses were conducted to validate the developed thermal model with experimental values for a typical day with clear conditions. It was observed that the theoretical values of the solar cell, Tedlar back surface, and greenhouse room air temperatures were approximately equivalent to the experimental values.

Sonneveld et al. [50] proposed a new type of greenhouse that combines the reflection of near-infrared radiation (NIR) with power generation using photovoltaic/thermal hybrid modules.

The reflection of the NIR produces improved climate conditions in the greenhouse and, in addition, produces electrical and thermal energy. The result of this work showed a yield of 20 kW h m——————— 2 for electrical energy and 576 MJ m————————————2 for the thermal energy.

Perez-Alonso et al. [51] reported the results of an experiment carried out in Almería (Spain) with a 1.024 m2 pilot photovoltaic greenhouse. They studied a photovoltaic greenhouse covered with 24 flexible thin film modules (coverage ratio 9.79%) installed in two different checkerboard configurations. The results indicated that the yearly electricity production normalized to the greenhouse ground surface was 8.25 kW h m——— 2, in agreement with previous findings for this type of module.

Cossu et al. [52] assessed the climate conditions inside an east-west oriented greenhouse in which 50% of the roof area was replaced with photovoltaic modules and described the solar radiation distribution and the variability of the temperature and humidity. The test crop consisted of tomatoes. The south-oriented roofs were completely covered with multicrystalline silicon PV modules. This study quantified the resulting reduction of solar radiation as an average of 64% on a yearly basis, up to 82% for the areas under the PV covers and 46% under the transparent covers.

This condition decreased the tomato yield compared to conventional greenhouses while generating a large income from the PV energy.

The majority of photovoltaic applications on the covers of greenhouses described in the literature result in low levels of shading, generally less than or equal to 50%. However, these percentages do not correspond to practical applications because these structures are configured with the goal of maximizing the energy production to the detriment of the agricultural production. Therefore, the majority of existing structures have a coverage ratio of 50% (checkerboard) or 100%, which accounts for approximately 85% of the photovoltaic market [36,53].

Moreover, all the photovoltaic greenhouse solutions studied so far are characterized by a static shading of the internal environment. Stationary photovoltaic panels can limit the development of crops because they drastically reduce the solar radiation that plants need. To facilitate energy production and agricultural production on the same unit of land, it is necessary to make compromises.

The low impact of cultivation, compared to energy production, on total income has forced farmers to cover the roofs of greenhouses with as much photovoltaic panels as possible, neglecting the primary goal of these structures. Therefore, national and European legislation have forced farmers to prove income from agricultural activity to receive the incentive tariff. Therefore, it is necessary to find a solution to improve the sustainability of such photovoltaic greenhouses and to find the optimal balance between energy production and agricultural production.

Therefore, this paper describes the concept of a dynamic solar greenhouse. With this solution, the shading inside the greenhouse is continuously variable in accordance with the instantaneous physiological needs of the crops, based on the latitude and the month of the year, unlike the photovoltaic greenhouses previously reported in the literature. Panels can rotate at any moment of the day to admit the proper quantity of solar radiation required for the crops, and, at the same time, to produce energy from the photovoltaic panels with the surplus solar radiation. The result is a greenhouse with panels constantly moving in search of the optimal distribution of solar radiation between the panels and plants.

Furthermore, the possibility to select the level of shading most suitable for a crop allows this system to be used as a method of passive cooling. During the cold seasons, when the plants need a certain amount of energy to grow and develop, the photovoltaic panels should not be present on the cover to avoid possible shading. Conversely, during the hot seasons, or when there are no crops in the greenhouse, the use of photovoltaic panels would be a great advantage to both passively protect the structure from heat and capture energy excesses that generate income when the structure is unused.

Different degrees of shading are possible due to the rotation of the photovoltaic panels and the projection of their shade inside the greenhouse. To limit the decrease in energy production due to a non-optimal tilt angle of the photovoltaic panels, highly reflective aluminum mirrors (98%) can be installed, the objective of which is to reflect the solar flux lost by the panels due to reflection.

Following the above discussion, this paper aims to evaluate the production of electricity by photovoltaic panels installed on the south-facing roof of an iron and glass prototype greenhouse and to study the internal microclimate (air temperature, relative humidity, and solar radiation) with different shadow rates on days with a completely clear sky. In particular, this study aims to produce scientific evidence of the energy sustainability of this innovative structure and to provide data to support the grower in large scale applications of this technology.

The innovations in this paper can be summarized in the following four points. (1) It achieves a variable shading level of greenhouse coverage. The shading will be adjusted depending on the weather conditions and crop requirements, including the cultivation period, the type of crop, and the parameters that influence the solar radiation, such as the time of day, day of the year, latitude, altitude, and degree of sky coverage. The photovoltaic green houses implemented so far exhibit fixed shading degrees, which, if they become too great, can reduce the growth and development of the crops and productivity. However, if they are too small, they can reduce the electricity production. (2) It strikes a balance between photovoltaic energy production and agricultural production on the same land unit, with the aim of optimizing the economic productivity of the mixed system. (3) It significantly reduces losses by reflection of the photovoltaic panels, which, to reduce shading, will need to have a non-optimal tilt angle. The reflected solar energy will be almost completely recovered, thanks to the presence of highly reflective mirrors, which are made of aluminum and aligned with the rays of the sun. (4) It installs a photovoltaic surface on nearly 100% of the roof area and reduces the projection of the panels on the ground through the rotation of the photovoltaic panels upwards to remove shading and therefore allows the greatest flexibility for the total use of the structure.

2. Materials and methods

2.1. Location

The study was carried out at the ‘‘N. Lupori” didactic-experimental farm of Tuscia University (Lazio, Italia, 42°25’38’’N, 12’04’51’’E, 306 m altitude) using a prototype of the solar photovoltaic greenhouse with an east–west (E–W) orientation, specially designed for photovoltaic power generation. The period considered was from August to October 2014 and consisted of days with completely clear skies.

2.2. Greenhouse

The prototype possesses an asymmetrical cross-section (Fig. 4) and is made of iron and glass with a polycarbonate transverse vertical wall.

The dimensional parameters of the prototype are:

– Length: 3.79 m
– Width: 2.41 m
– Ridge height: 2.05 m
– Eave height (south wall): 0.94 m
– Eave height (north wall): 1.36 m
– Photovoltaic surface: 8.15 m^2
– Photovoltaic pitch slope (south): 33°
– Non-photovoltaic pitch slope (north): 51°
– Glass thickness: 3 mm

The greenhouse was equipped with a fan (1000 m^3 h^{-1}) set on the vertical wall facing west and an aluminum grid on the opposite vertical wall for mechanical ventilation. Moreover, there were six openings for natural ventilation (three on the south vertical wall and three on the north pitch). The fan was connected to a thermostat that powered it when the internal air temperature exceeded 26 °C.

2.3. PV system and handling system

The south-oriented roof was covered with 24 polycrystalline silicon photovoltaic panels (SYM 30P-7V, Sunenergy, Zollino, Lecce, Italy) with the characteristics listed in Table 1. The system was composed of three strings of eight panels each, connected in series. The energy produced by the photovoltaic panels was stored in two batteries (12 V, 100 A) and used locally to power all the electrical systems used in the greenhouse system.

Each string had a system of manual handling, which allowed rotation along the longitudinal axis to adjust the shading inside the structure.

The main problem with this rotational system was possible losses due to the reflection of solar radiation caused by non-optimal inclinations of the photovoltaic panels. To overcome this drawback, the PV panels were fitted with 24 highly reflective aluminum mirrors (Vega SP Energy, Almeco group, San Giuliano Milanese, Milano, Italy) (reflectance 98%; Fig. 5) that could be manually rotated around the longitudinal axis. The highly reflective mirrors were always oriented according to the solar rays to avoid shadowing inside the greenhouse or on the photovoltaic cells.

They were used when the angle (a) formed between the mirrors (and consequently the solar rays) and the photovoltaic panel was less than 60° (Fig. 6). The more this angle decreases, the greater the importance of the mirrors. At 55° (Fig. 7), the portion of the PV panel that allows the mirrors to be useful for the recovery of solar radiation is equal to 30%. At 45° (Fig. 8), only one reflection occurs from the mirror; however, the portion of the panel that allows the mirror to recover solar radiation is equal to 100%. For angles smaller than 45° (Fig. 9), the number of reflections increases proportionally to the decrease in the incidence angle.

The reflection losses are closely related to the angle of incidence. For this type of photovoltaic panel, they are estimated to be approximately 20% for angles of incidence between 0° and 70° [54].

The photovoltaic modules, if parallel to the pitch, allow a shading of 78% to be obtained inside the greenhouse. This degree of shading is given by the ratio between the projection of the panel length including a frame (21 cm) on the pitch and the distance between the panel rotation points (27 cm).

Rotating the panels allows the percentage of shading to be reduced as a function of (1) the physiological needs of the crop in production; (2) the angle of incidence of the solar rays on the photovoltaic modules in different seasons; (3) the time of the day; and (4) the latitude. By rotating the panels along the longitudinal side, it is possible to reduce the panel projection on the pitch and therefore reduce the degree of shading.

The relative tilt angles of the photovoltaic panels, necessary for obtaining certain shading levels, has been calculated by relating the solar altitude for days with the following percentages of shading:

– 78%;
– 75%;

– 70%;
– 60%;
– 50%;
– 40%;
– 30%;
– 20%;
– 10%;
– 0%.

In this study, the panel tilt angle (Fig. 10) is defined by Eqs. (1)–(17) [55] to obtain the shading percentages previously listed at 12.00 pm (daylight savings time) on each day of the experiment [56]. The inclination of the photovoltaic panels depends on the latitude, the Julian day, the time of day, and consequently the position of the sun at different times of the day.

$$R_e = 1367 \times \left[1 + 0.033\cos\left(\frac{360}{365} \times n\right)\right] \tag{1}$$

$$\tau_b = A_0 + A_1 e^{\frac{-K}{\cos\theta_z}} \tag{2}$$

$$\tau_d = 0.271 - 0.294\tau_b \tag{3}$$

$$A_0 = [0.4237 - 0.00821(6 - A)^2]\left[1 + 0.03\sin\left(\pi\frac{91 + n}{182}\right)\right] \tag{4}$$

$$A_1 = [0.5055 - 0.00595(6.5 - A)^2]\left[1 + 0.01\sin\left(\pi\frac{91 + n}{182}\right)\right] \tag{5}$$

$$K = [0.2711 - 0.01858(2.5 - A)^2]\left[1.01 + 0.01\sin\left(\pi\frac{91 + n}{182}\right)\right] \tag{6}$$

$$\cos\theta_z = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega \tag{7}$$

$$R_b = R_e\tau_b\cos\theta_z \tag{8}$$

$$R_d = R_e\tau_d\cos\theta_z \tag{9}$$

$$\omega = \frac{360}{24}(12 - h) \tag{10}$$

$$\delta = 23.45\sin\left[\frac{360}{365}(284 + n)\right] \tag{11}$$

$$\alpha = \sin^{-1}(\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega) \tag{12}$$

$$\psi = \alpha + \text{Photovoltaic pitch slope } (33^\circ) \tag{13}$$

$$X = 0.27 \times \text{shade} \quad (14)$$

$$\varepsilon = 180 - \psi \quad (15)$$

$$\gamma = \sin^{-1}\left(X \times \frac{\sin \varepsilon}{0.21}\right) \quad (16)$$

$$\beta = 180 - (\varepsilon + \gamma) \quad (17)$$

2.4. Instrumentation and measurements

The outside and inside climatic conditions (air temperature, relative humidity, and solar radiation on the horizontal plane) were detected from four sensors (Thermo-hygrometer CS215 + Pyranometer CS300, Campbell Scientific INC, USA), of which three (S1, S2, and S4) were placed inside the facility and the fourth (S3) was placed outside to measure external climate data. The internal sensors were collocated at a height equal to the south eaves (0.94 m) to detect only the microclimatic interior values below the photovoltaic pitch (Fig. 11) and, therefore, to avoid the edge effect. The use of three internal sensors is necessary to collect data in areas with different shade conditions (sunny-shady).

To measure the values of the current and voltage, the following sensors were used:

- CE-IZ04-35A2-1.0/0-50A DC Current Transducer (Phidgets, Canada) and
- CE-VZ02-32MS1-0.5 DC Voltage Sensor 0–200 V (Phidgets, Canada).

The sensor accuracies are reported in Table 2.

All sensors were connected to a Campbell CR1000 data acquisition system (accuracy of ±0.06% of reading + offset, at 0–40 C), which recorded values at intervals of 15 min.

3. Results and discussion

3.1. Internal climatic condition

Table 3 shows the cloudless days during the experiment period, the photovoltaic panel tilt angles calculated to obtain the established percentages of shading, and the shading percentages.

Fig. 12 shows the air temperature values measured at intervals of 15 min both outside (S3) and inside (S1, S2, and S4) the photovoltaic greenhouse on cloudless days.

Table 4 shows the minimum, maximum, and average air temperature values recorded inside and outside the greenhouse. During this time, the outdoor air temperature never ever exceeded 32 °C, reaching a peak of 31.1 C on August 10.

The air temperature measured indoors was always greater than 30 C in the central hours of the day. August 29 registered the maximum temperature during the entire measurement period (45.4 °C). The high internal air temperature values are due to the lack of natural ventilation. During the trial days, only mechanical ventilation was used.

The indoor and outdoor temperature difference was lower at night and in the early hours of the day (2–4 °C), while during the central hours, the differential was higher (9–15 C) because of the greenhouse effect created in the confined structure.

For most vegetable species grown in a protected environment, the required average air temperature is 17–27 C, with approximate lower and upper temperature limits of 10 C and 35 C [57], respectively, depending on the phenological phase of the crop.

The values measured for the indoor air temperature are quite high, especially during the central hours of the days in August. During the hot season, to be able to cultivate inside this structure, it is necessary to use natural ventilation. The trend in the internal air temperature during the period of the experiment decreases with the increase in the percentage of shading. This suggests that the photovoltaic system placed on the roof acts as a passive cooling system. The impact of photovoltaic panels on heat flow has been extensively studied and used to reduce the cooling load inside buildings [58,37,59]. Conversely, it may have a negative effect during the winter, increasing the energy needed for heating [52].

For the relative humidity (Fig. 13) recorded outside the greenhouse, on three days (August 10, September 9, and September 28), the air saturation average values were between 55% and 85%. Inside the prototype greenhouse, the maximum value recorded was 91.7% (September 9), with average values that ranged from 45% to 70%.

Relative humidity within the range 60–90% is suitable for plant growth [57]. Values below 60% may occur during ventilation in arid climates, or when plants are young with small leaves, and this can cause water stress. Serious problems can occur if the relative humidity exceeds 95% for long periods, particularly at night, as this favors the rapid development of diseases and reduces plant tran spiration [57]. During the day, humidity can usually be reduced using ventilation.

3.2. Photovoltaic production

Fig. 14 shows the outside global solar radiation (direct + diffuse) on a horizontal surface (W m——————2) on the completely clear days and the hourly photovoltaic energy generated per unit area (W m^{-2}) listed by the ascending order of the percentages of shading.

On the experiment days, the maximum outside solar radiation varied between 700 W m^{-2} and 940 W m^{-2}. The measured peak was 932 W m^{-2}, which was recorded in the central hours (2:15 pm) on August 17.

As mentioned earlier, on each day, a different tilt angle of the panels was used to obtain a different shading percentage.

The maximum values of the photovoltaic energy (102 W m^{-2}) were obtained when the shading percentage was higher (78%) and the tilt angle of the panels was coincident with that of the photovoltaic roof (β = 30°). When the solar panels were positioned horizontally (β = 0°, September 9) the energy produced was reduced by approximately 30%. At negative values (β < 0°) the photovoltaic cells were exposed to the north with a consequent decrease in the energy production.

On the experiment day without internal shading (August 17), the tilt of the panels took on a position almost perpendicular to the photovoltaic roof. This position deviated significantly from the one optimal for photovoltaic energy production at the latitude of the site, and the energy produced experienced a reduction of approximately 75% (approximately 20 W m^{-2}) compared to that produced by the photovoltaic panels parallel to the photovoltaic roof (October 5). The annual electrical energy consumption per unit greenhouse ground area with various greenhouse locations and electrical loads were reported to be 2–20 kW h m^{-2} yr^{-1} for Mediterranean greenhouses [43,60,61].

The highly reflective plates allow electricity to be produced even when the inclination of the photovoltaic panels differs, sometimes significantly, from the optimal value thanks to a recovery of part of the solar radiation lost by reflection from the PV panels.

This is true for the clear sky conditions and climatic conditions considered here.

Table 5 shows the daily values of the external solar energy and the photovoltaic energy produced in relation to the tilt angle of the panels calculated to obtain the previously established shading percentages.

The average daily efficiency of the photovoltaic modules (Fig. 15) was variable during the experimental period, ranging from 2.5% on August 17 to a value of 13.8% on October 5. The main cause of these fluctuations was the different inclinations of the photovoltaic panels on different days, deviating considerably from the optimal value for the latitude of the site. In addition, it is important to consider the variation of the external radiation, the temperature of the photovoltaic panels, and the degree of filth, all of which greatly affect the conversion percentage and therefore the energy produced.

As investigated by Hussein et al. [62], the efficiency of the photovoltaic panels is affected by the angle of their inclination.

Increasing the tilt angle increases the efficiency of the system. Moreover, the tilt angle has an effect on the monthly average maximum output energy, similar to its effect on the monthly average incident solar energy.

3.3. Solar radiation availability inside the greenhouse

Fig. 16 shows the daily values of the external solar energy and the available solar energy inside the dynamic photovoltaic greenhouse in ascending order of shading percentage.

The values of the inside solar radiation were obtained by weighting the values recorded by the three internal sensors and by distinguishing the values recorded when the sensors were exposed to solar radiation and those recorded when the sensors were shaded. The percentage ratio between the internal and external solar radiation was slightly lower than those previously established because part of the solar radiation was lost to transmission in the cover material.

The solar radiation available to plants varies considerably with different shading percentages. The highest values of energy available within the structure were recorded on August 17, when the shading percentage was zero (22.7 MJ m^{-2}).

The lowest values of internal solar radiation were recorded on the last two days (October 3 and October 5), when the shading percentages were 75% and 78%, respectively. In both cases, the measured values were lower than 5 MJ m^{-2}. This amount of energy is not sufficient for the normal development of agriculture [52,63–66]. In Mediterranean areas, during days in the cold seasons with clear skies, the amount of solar radiation is greatly reduced compared to days in the hot seasons. Therefore, it is advisable to set the shading percentages to very low values, if not zero, during the cold seasons to allow for the entrance of the greater quantity of solar radiation necessary for the normal development of agriculture within the structure. The reduced solar energy input suggests that the PV array had a cooling effect on the internal environment and that the transmitted solar radiation falling on the transparent north-oriented covers did not contribute to the thermal heating of the greenhouse [67].

The high opacity of the photovoltaic panels can be a huge problem in the cold season or in latitudes characterized by a low level of solar radiation, generating low crop yield and low crop quality.

Currently, there are many solutions that can remedy this problem.

Reducing the photovoltaic surface installed on the cover allows for a greater entry of solar radiation available for the plants, however, at the same time reduces the income from energy production.

The use of some technologies, such as semitransparent photo voltaic film [14,42,43,60,68] thin films [40], spherical micro-cells [69], or CIS and CIGS semiconductors, can increase the solar radiation available to plants [52], however, their low efficiency and high cost make these technologies premature for large-scale applications, and they require further investigation to test their performance in the field and their impact on crops.

In this study, the possibility of the rotation of the panels throughout the day showed that their use on a greenhouse as a cooling passive system could be an advantageous solution, in economic and energy terms, because it allows the crop to be shaded during periods with high irradiation and, at the same time, produces energy from the photovoltaic panels for the electrical systems of the greenhouse [70]. Rotating the panel during the day allows the farmer to find the optimal balance between energy production and agricultural production.

However, the use of these cover materials also leads to an increase in the cost for PV greenhouse construction or modification, which may not be convenient.

The concept developed in this research has not addressed the economic market, i.e., the production of electric energy for sale, rather, it addressed the realization of a completely energy independent greenhouse. The electricity produced by the greenhouse is used to satisfy the energy needs of the greenhouse facilities and automated control systems. Greenhouses made in this way can be located in areas with hot climates without a connection to the electricity grid.

3.4. Simulation of internal solar radiation and photovoltaic production

On the basis of measured data during the experimentation and with direct and diffuse solar radiation calculated with Eqs. (8) and (9), the annual trend of external and internal solar radiation and PV energy production were simulated. For this simulation were considered the 15th of each month with completely clear sky.

Fig. 17 shows the monthly average daily values of the external solar energy and the available solar energy inside the dynamic photovoltaic greenhouse with the different shading percentage considered (0%, 20%, 50% and 78%).

The available solar energy inside the greenhouse with shading percentage of 78% was always lower than 5 MJ m 2 day————1. These values create problems for the normal development of agricultural activity for the major horticultural species with the consequent reduction of product quality (size, color, shape, etc.) [52,63–66].

When the shading percentage was 50%, the months of the year with these problems were January (3.3 MJ m 2 day————1), February (4.6 MJ m————2 day———— 1), November (3.7 MJ m————2 day————1) and December (2.9 MJ 2 day————1). During this period, because of the low intensity of external solar radiation, it is preferable to adopt a smaller shading percentage allowing the entry inside the structure of the greater quantity of solar radiation reducing, in part, the photovoltaic energy production.

When the shading percentage was 20% the months with insufficient solar radiation available for the plants were January (4.8 MJ m————2 day————1) and December (4.2 MJ 2 day————1). In this period, shading percentage of 0% is adequate.

Unlike, during the spring and summer seasons the external solar radiation exceed the needs of the major vegetable species.

Therefore it is necessary to adopt high shading percentages using photovoltaic panels as a passive protective system.

The results obtained shows that a shading percentage of 20% is favorable for the spring and autumn periods while for the periods with a percentage of 50% is extremely adequate for the summer period.

Fig. 18 shows the external solar radiation and PV energy production obtained with considered shading percentages in the monthly average daily with completely clear sky.

During all periods the PV energy was more than sufficient to satisfy [43,60,61] the energy demands of the greenhouse electrical systems with the exception of January (0.2 MJ m————2 day— 1), February (0.3 MJ m————2 day————1), November (0.2 MJ m 2 day————1) and December (0.2 MJ m————2 day———— 1) with shading percentage of 0%, and in the months of January (0.2 MJ m————2 day 1) and December (0.2 MJ m————2 - day————1) when the shading percentage was 20%. The reason is that the PV panel, at this particularly conditions, are perpendicular in relation to the PV pitch of the greenhouse, exposed to the north (b < 0) and the solar elevation is low. The amount of energy produced is due mainly to the action of the reflective aluminum mirrors and the diffuse radiation.

3.5. Economic analysis

Payback periods estimate the length of time (in years) required to recover the cost of an investment, which is calculated by dividing the amount of the initial investment by the cumulative net cash flow for each period. The costs analyzed include the cost of the greenhouse (structure, photovoltaic panels, mirrors, glass, handling system, and storage batteries) and the maintenance and insurance costs (1% of the initial cost [71,72]).

The cost of the dynamic photovoltaic greenhouse was 3500 €. The duration of this structure was taken to be 20 years, equal to the number of years that are guaranteed public incentives from the national authorities.

The estimated annual output of photovoltaic power supplied to the dynamic photovoltaic greenhouse is difficult to assess because the solar panels have different positions during a single day. Therefore, a constant optimum tilt angle (30) was assumed throughout the year at a Mediterranean latitude, resulting in a yearly sum of solar electricity generated by a 1 kWp system optimally inclined is equal to 1400 kW h kWp———— 1 [73,74]. The energy production of the PV system was 1120 kW h, which is equivalent to 137.4 kW h m—— 2 year————1.

The annual incentive income, derived from the feed-in tariff system (0.327 €kW h−1), was 366.24 € for all the PV energy produced, regardless of the final use of the electricity (consumption or sale).

Moreover, income was also indirectly generated through the consumption of energy that did not require purchase, which amounted to 201.6 € (average electricity price: 0.18 €kW h^{-1}) [52].

The eventual increase in the tariff of the annual incentive was assumed to be 0%, the rate of increase in energy prices was assumed to be 3% (by evaluating the latest I.S.T.A.T. data and noting that there is a proportionality but not an equivalence, between the rate of general inflation and the rate of increase in the energy price). The reduction of annual energy production, due to reduced efficiency, was set to 1%.

Consequently, the calculated payback period was 6 years.

The economic results are variable depending on the crop culti- vated, crop rotation and the climatic conditions.

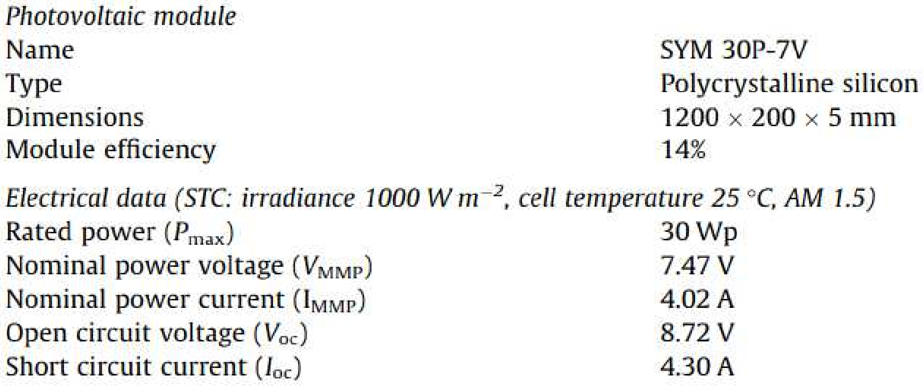
4. Conclusions

This study proposed an innovative solution for a photovoltaic greenhouse to reconcile energy production by photovoltaic panels and agricultural production. The possibility of rotating the photovoltaic panels throughout the day allows the user to adjust the shade inside the structure according to the instantaneous needs of the plants, outside weather conditions, day of the year, and cloudiness. The continuous rotation of the panels is required to allow the entry of the solar radiation required by the crop and, especially on days with completely clear skies in the hot season, to produce energy with the excess solar radiation. The presence of highly reflective mirrors allows electricity production, even with non-optimal angles, due to the recovery of the solar radiation lost by reflection from the photovoltaic panels.

The study of the internal microclimatic parameters (air temperature, relative humidity, and solar radiation) provides support parameters for the choice of crop most suitable to cultivate. During the experimental period, these parameters are within the optimum ranges (17–27 C and 60–90%, respectively) for most plant species grown in greenhouses. In addition, the lowering of the air temperature and solar radiation available inside the structure with increased shading percentage suggests how this solution can be used as a passive cooling system and, at the same time, produce energy from the photovoltaic panels, especially in geographical areas characterized by high solar irradiation. The microclimate and energy parameters obtained are encouraging for a large-scale application of this structure. All these aspects can contribute to better information to support the farmer and help achieve the optimal balance between agricultural income and energy income.

References

Table 1
Technical specifications of the photovoltaic modules.



Photovoltaic module	
Name	SYM 30P-7V
Type	Polycrystalline silicon
Dimensions	1200 × 200 × 5 mm
Module efficiency	14%
Electrical data (STC: irradiance 1000 W m^{-2}, cell temperature 25 °C, AM 1.5)	
Rated power (P_{max})	30 Wp
Nominal power voltage (V_{MMP})	7.47 V
Nominal power current (I_{MMP})	4.02 A
Open circuit voltage (V_{oc})	8.72 V
Short circuit current (I_{oc})	4.30 A

Table 2
Sensor accuracies.

Sensors	Accuracy
Hygrometer	(at 25 °C) ±2% (10–90% range) ±4% (0–10% range)
Thermometer	±0.3 °C at 25 °C ±0.4 °C (+5 °C to +40 °C) ±0.9 °C (−40 °C to +70 °C)
Pyranometer	±5% for daily total radiation
DC Current transducers	1%
DC voltage sensor	0.50%

Table 3
Experimentation days, PV tilt angles, and shading percentages.

Experiment day	PV tilt angle (°)	Shading percentage (%)
August 10, 2014	3	70
August 17, 2014	−61	0
August 29, 2014	−39	30
September 9, 2014	0	60
September 13, 2014	−11	50
September 26, 2014	−43	10
September 27, 2014	−35	20
September 28, 2014	−10	40
October 3, 2014	25	75
October 5, 2014	30	78

Table 4
Minimum, maximum, and average outside and inside air temperatures.

Experiment day	Outside air temperature (°C)			Inside air temperature (°C)		
	Min.	Max.	Mean	Min.	Max.	Mean
August 10, 2014	17.1	31.1	23.7	19.0	41.7	29.1
August 17, 2014	13.9	29.4	21.1	15.1	42.4	27.3
August 29, 2014	17.6	30.6	23.4	18.4	45.3	29.4
September 9, 2014	15.9	28.3	21.3	17.5	39.4	26.4
September 13, 2014	11.5	26.1	18.0	12.3	37.4	22.8
September 26, 2014	11.9	24.4	17.4	12.4	36.3	22.0
September 27, 2014	12.4	27.1	19.0	13.1	38.6	23.5
September 28, 2014	13.9	27.0	19.5	14.8	36.4	23.6
October 3, 2014	14.1	25.9	18.6	14.5	33.0	21.8
October 5, 2014	12.8	25.3	17.6	13.3	32.8	21.0

Table 5
Daily values of the outside solar energy and the PV energy produced in relation to the panel’s tilt angle and respective shading percentage.

	Outside solar radiation (MJ m^{-2})	PV energy (MJ m^{-2})	Tilt angle (°)	Shading percentage (%)
August 10, 2014	26.0	2.1	3	70
August 17, 2014	26.9	0.7	−61	0
August 29, 2014	24.0	0.9	−39	30
September 9, 2014	21.5	1.8	0	60
September 13, 2014	21.9	1.5	−11	50
September 26, 2014	19.7	0.7	−43	10
September 27, 2014	19.2	0.8	−35	20
September 28, 2014	19.1	1.6	−10	40
October 3, 2014	17.0	2.2	25	75
October 5, 2014	17.2	2.4	30	78

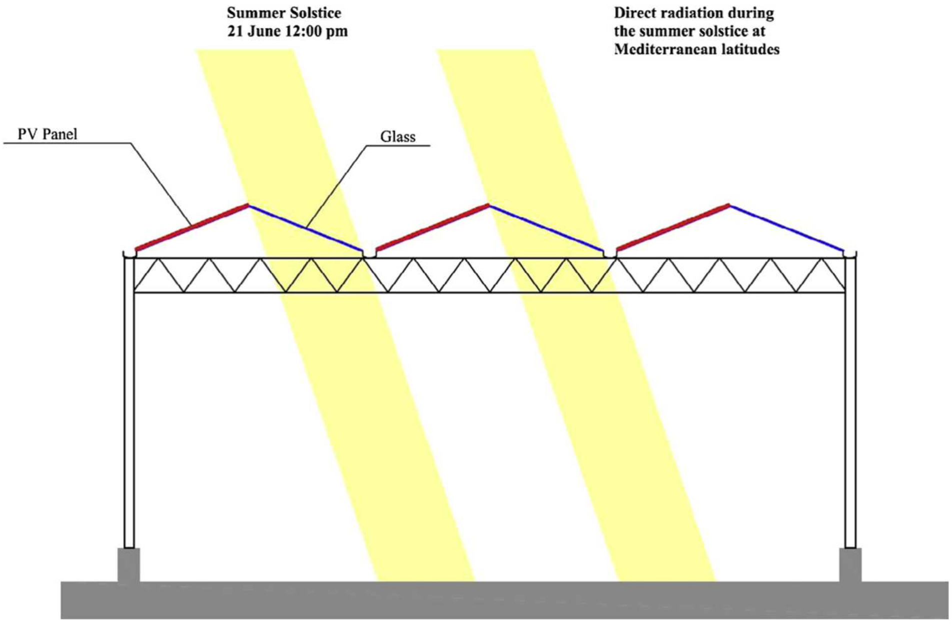


Fig. 1. Direct radiation during the summer solstice at Mediterranean latitudes.

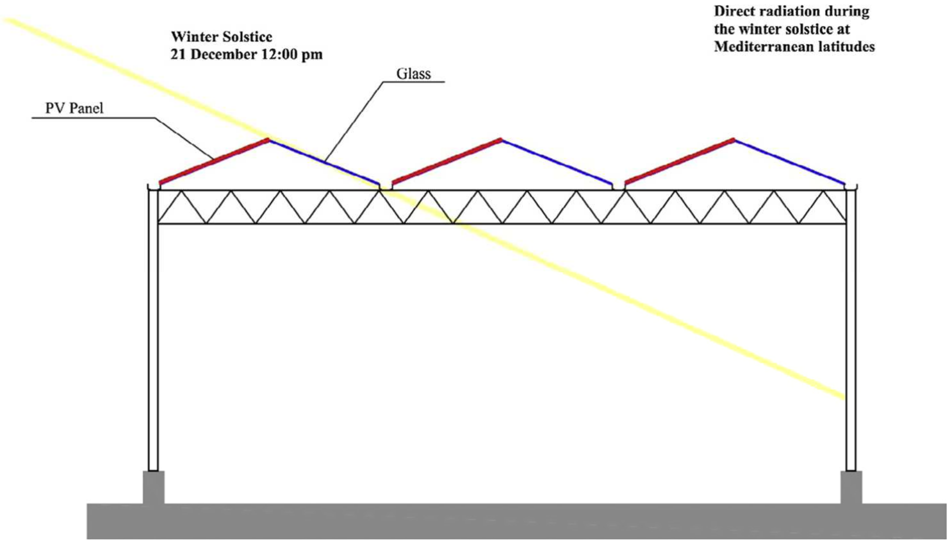


Fig. 2. Direct radiation during the winter solstice at Mediterranean latitudes.

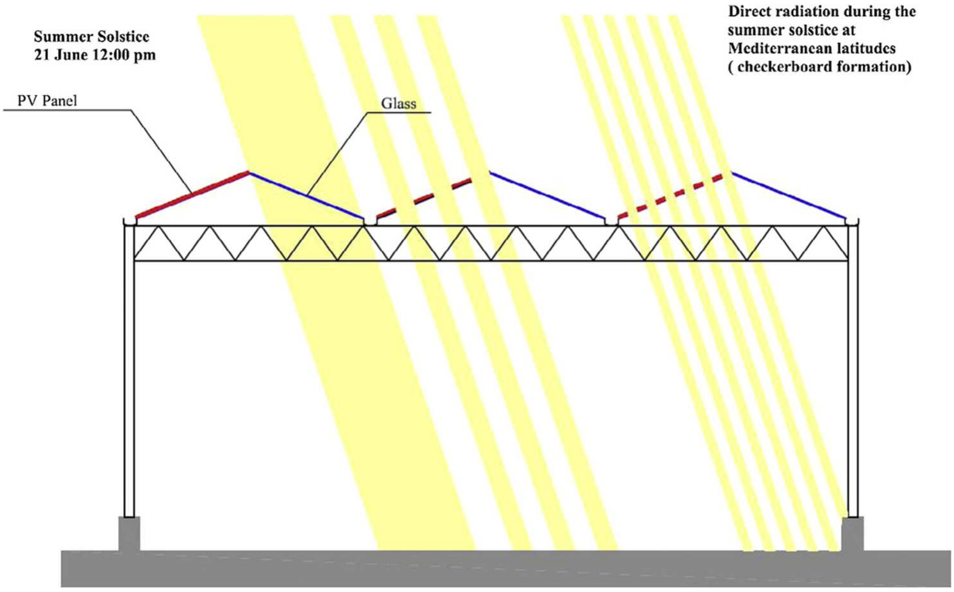


Fig. 3. Direct radiation during the summer solstice at Mediterranean latitudes (checkerboard formation).

Fig. 4. Iron and glass prototype of the dynamic photovoltaic greenhouse.

Fig. 5. Movement system of the photovoltaic panels and highly reflective aluminum mirrors.

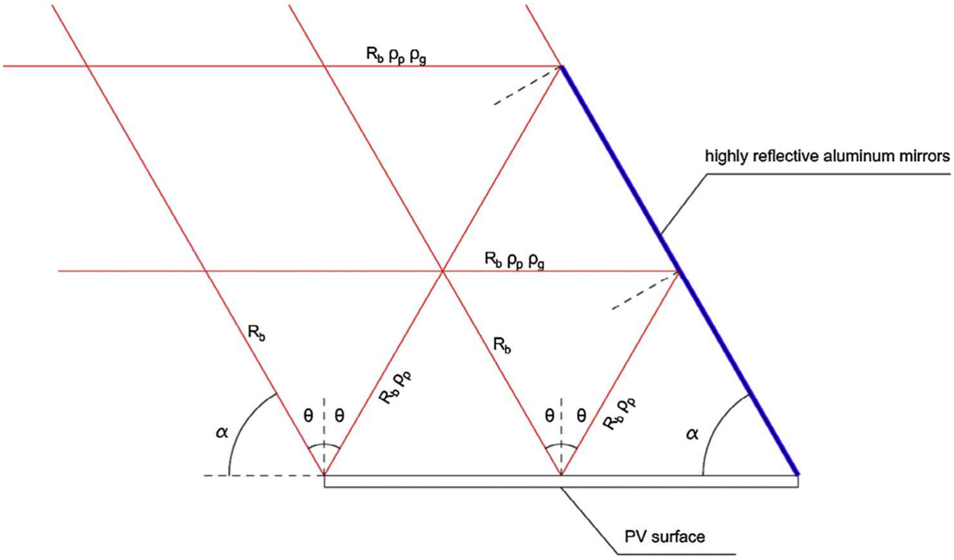


Fig. 6. Schematic diagram of the solar reflections between the PV panel and the mirror with a solar elevation angle (a) equal to 60°.

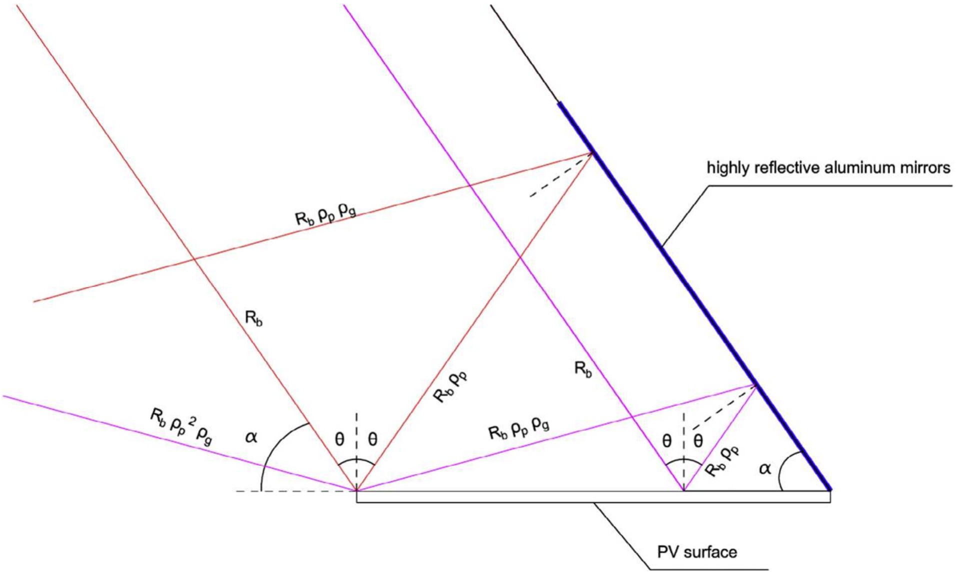


Fig. 7. Schematic diagram of the solar reflections between the PV panel and the mirror with a solar elevation angle (a) equal to 55°.

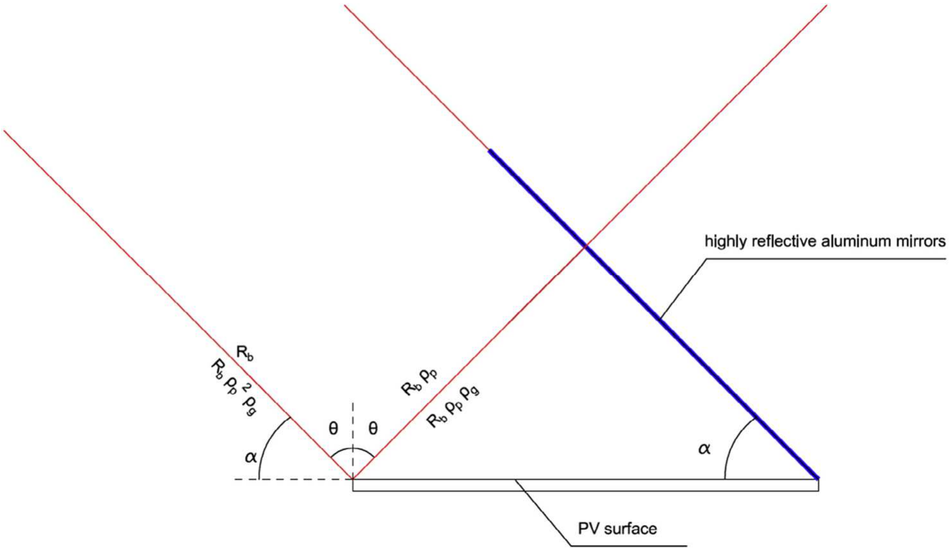


Fig. 8. Schematic diagram of the solar reflections between the PV panel and the mirror with a solar elevation angle (a) equal to 45.

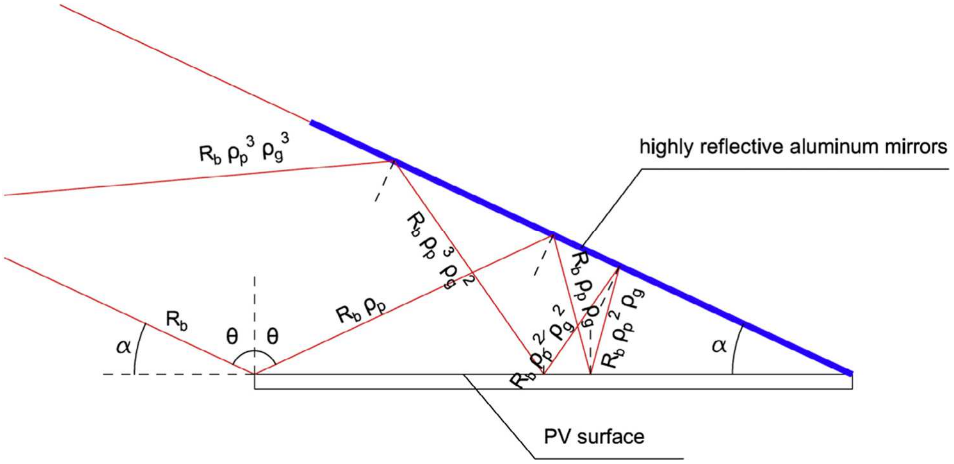


Fig. 9. Schematic diagram of the solar reflections between the PV panel and the mirror with a solar elevation angle (a) equal to 25.

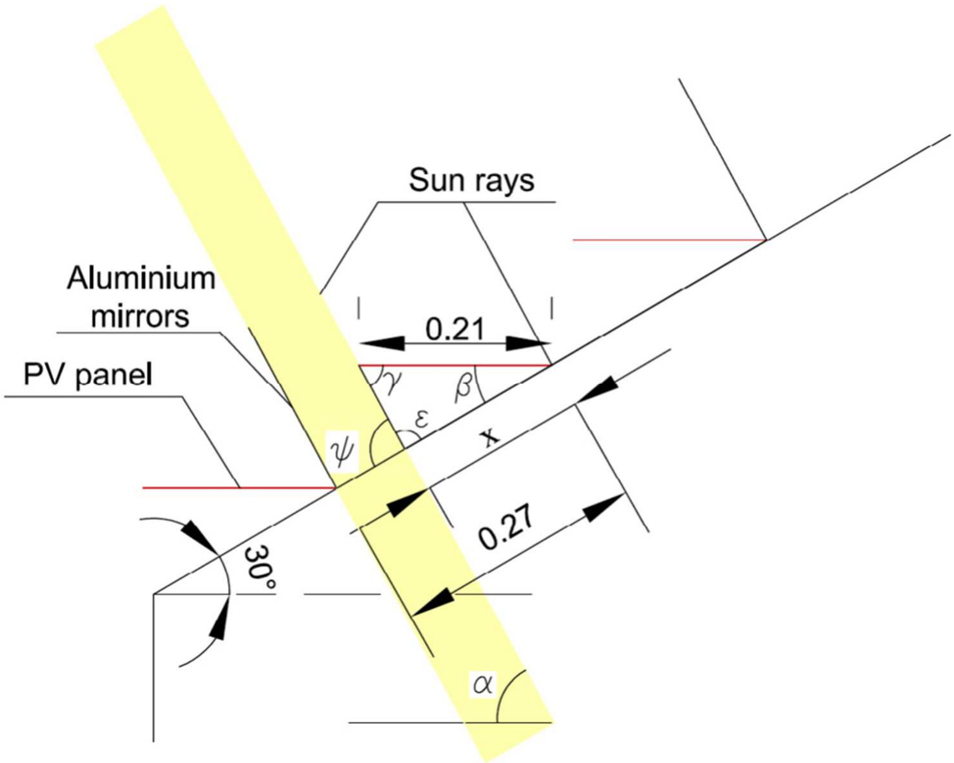


Fig. 10. Schematic with the values to calculate the inclination of the photovoltaic panels.

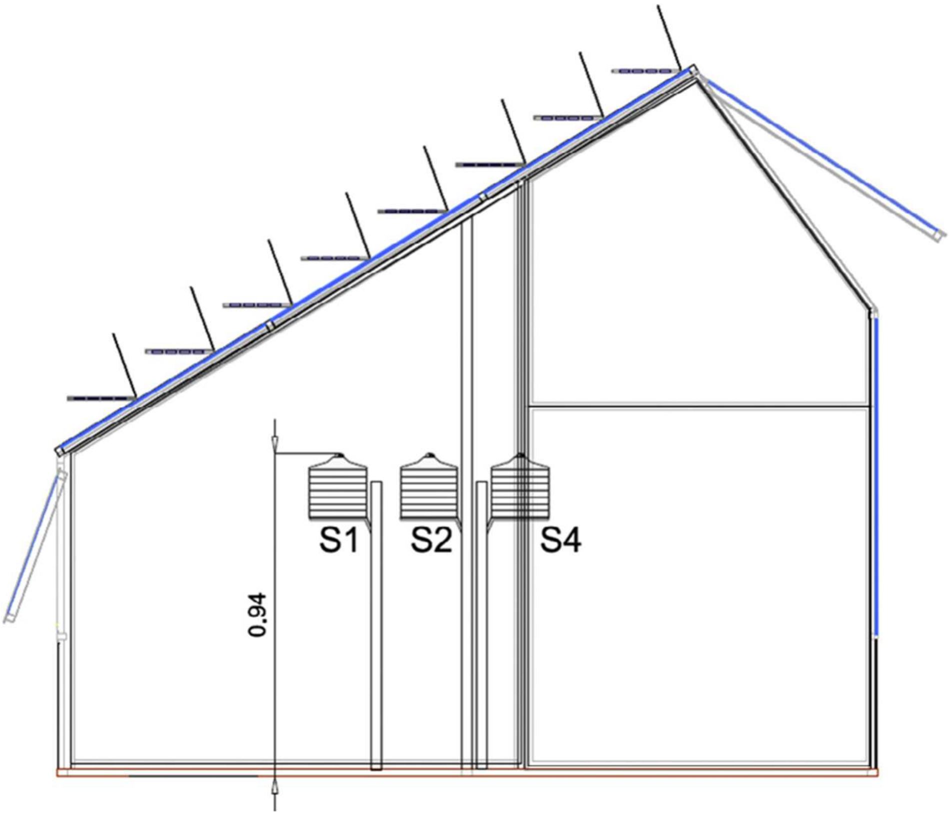


Fig. 11. Cross-section of the prototype and the meteorological sensor positions.

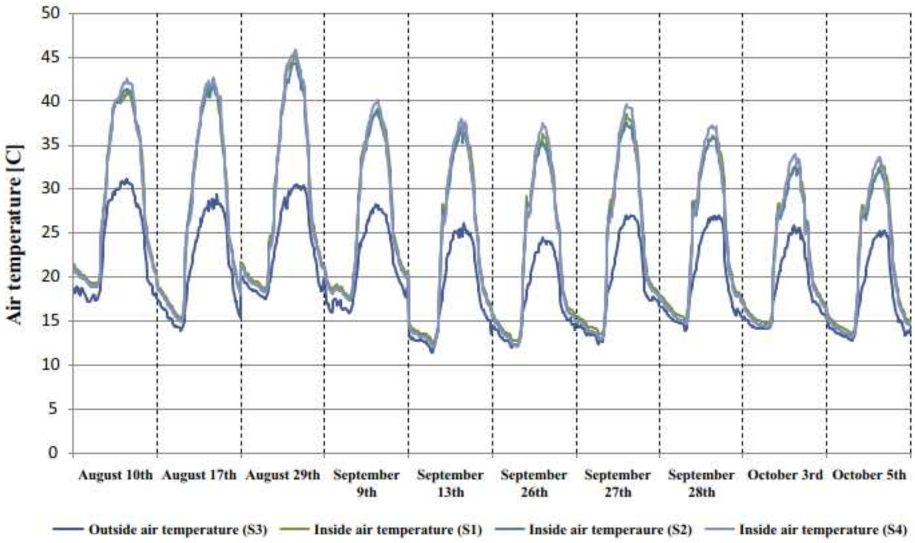


Fig. 12. Outside and inside air temperatures recorded with four sensors (S1, S2, S3, and S4).

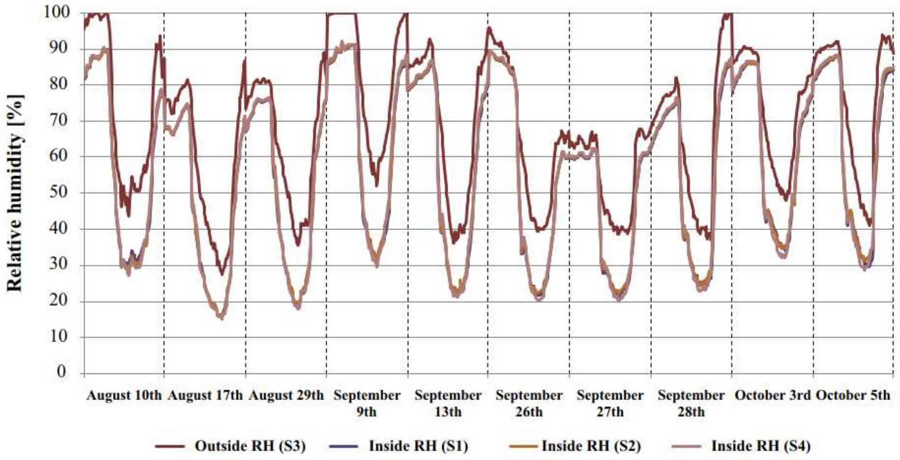


Fig. 13. Relative humidity inside and outside the greenhouse.

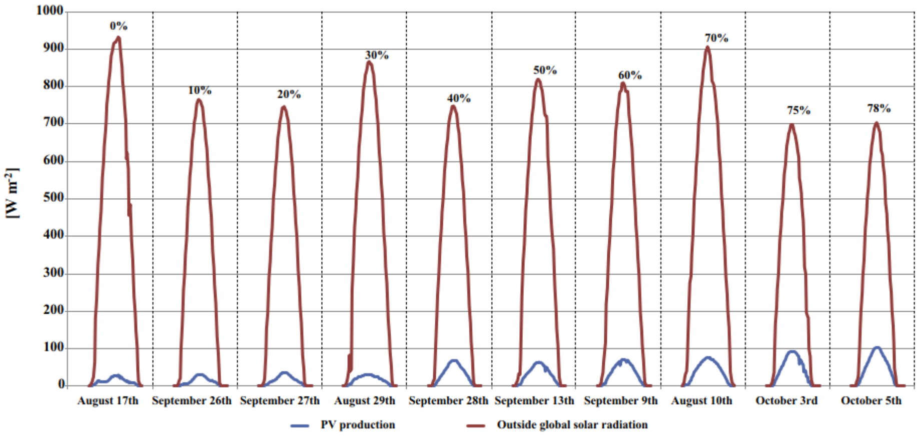


Fig. 14. Outside global solar radiation and PV production in ascending order of shading percentage.

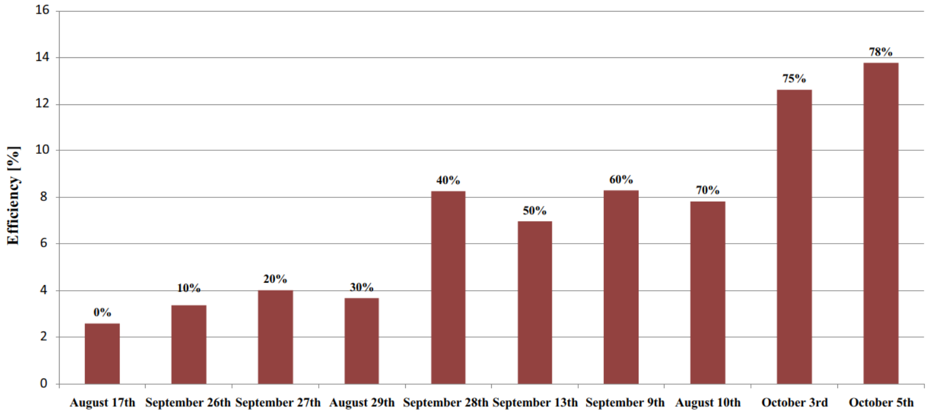


Fig. 15. Calculated photovoltaic panel efficiency in ascending order of shading percentage.

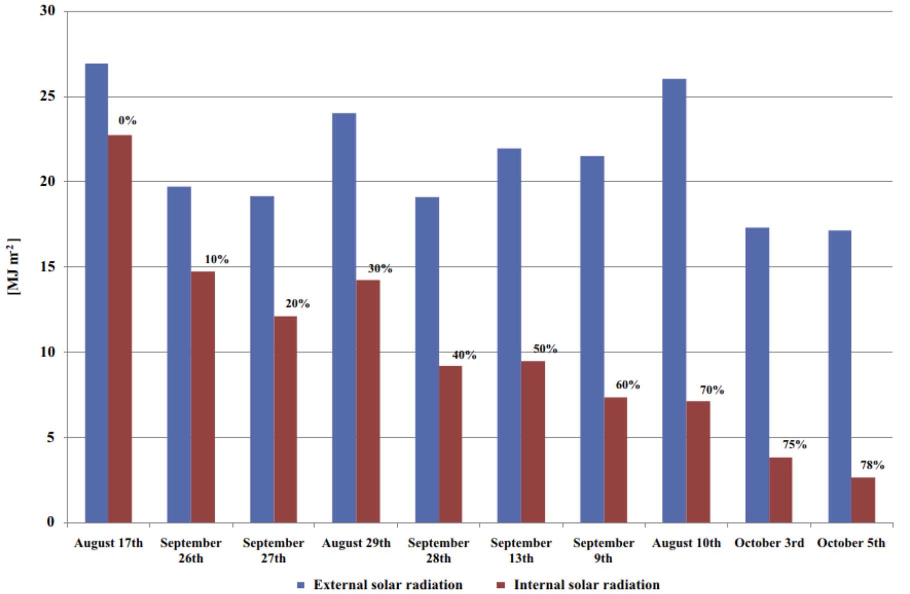


Fig. 16. Outside and inside solar radiation in ascending order of shading percentage.

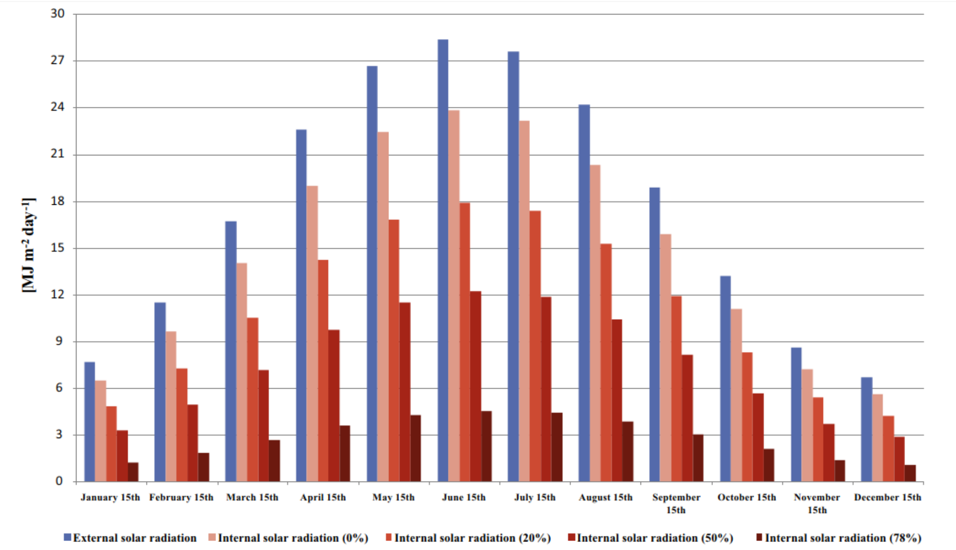


Fig. 17. Simulation of internal solar radiation.

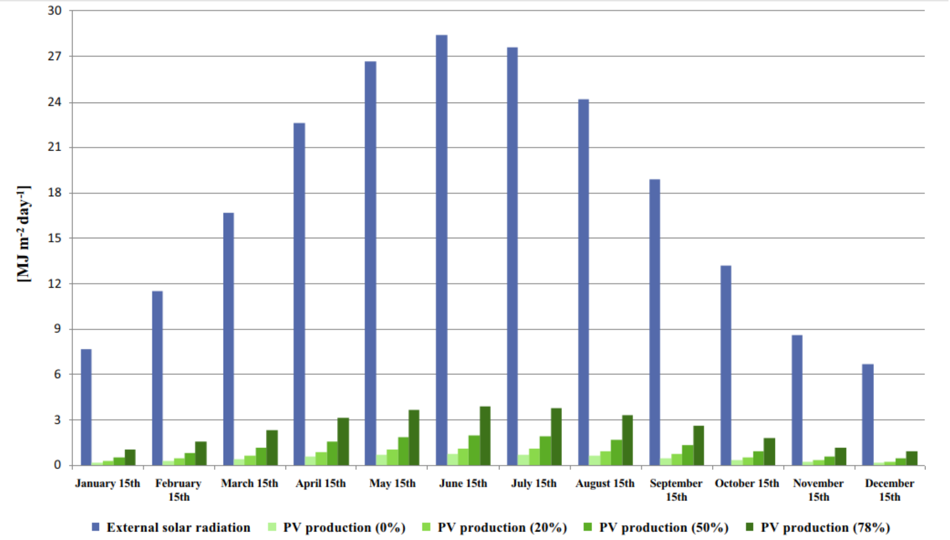


Fig. 18. Simulation of photovoltaic production.