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Solar radiation distribution inside a greenhouse with south-oriented photovoltaic roofs and effects on crop productivity

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HIGHLIGHTS

- The solar radiation distribution inside photovoltaic greenhouses has been studied.
- A greenhouse with 50% of the roof area covered with solar panels was considered.
- The yearly solar light reduction was 64%, with a transversal north–south gradient.
- The reduction was 82% under the solar panels and 46% under the plastic cover.
- We provided suggestions for a better agronomic sustainability of PV greenhouses.

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ABSTRACT

This study assessed the climate conditions inside a greenhouse in which 50% of the roof area was replaced with photovoltaic (PV) modules, describing the solar radiation distribution and the variability of temperature and humidity. The effects of shading from the PV array on crop productivity were described on tomato, also integrating the natural radiation with supplementary lighting powered by PV energy. Experiments were performed inside an east–west oriented greenhouse (total area of 960 m^2), where the south-oriented roofs were completely covered with multi-crystalline silicon PV modules, with a total rated power of 68 kWp. The PV system reduced the availability of solar radiation inside the greenhouse by 64%, compared to the situation without PV system (2684 MJ m^{-2} on yearly basis). The solar radiation distribution followed a north–south gradient, with more solar energy on the sidewalls and decreasing towards the center of the span, except in winter, where it was similar in all plant rows. The reduction under the plastic and PV covers was respectively 46% and 82% on yearly basis. Only a 18% reduction was observed on the plant rows farthest from the PV cover of the span. The supplementary lighting, powered without exceeding the energy produced by the PV array, was not enough to affect the crop production, whose revenue was lower than the cost for heating and lighting. The distribution of the solar radiation observed is useful for choosing the most suitable crops and for designing PV greenhouses with the attitude for both energy and crop production.

1. Introduction

During the last decade solar photovoltaic (PV) greenhouses became widely spread in southern Europe, especially in Spain and Italy. The fast penetration of this technology was facilitated by the combination of the abundance of solar energy and the advantageous public policy support for renewable electricity generation. This fact has led to an impressive growth rate of new PV installations whose number, in Italy, has been more than double every year over the last 5 years [1]. Currently, the total PV power installed in Italy has achieved 16.4 GW: about 48% of this capacity is installed on buildings and 6% on greenhouses and platform roofs, while 41% refers to ground-mounted modules. The incentives provided for the energy production of grid-connected systems vary depending on the nominal power and usually increase when modules are integrated on buildings or structures (rooftops, walls). According to this, PV greenhouses appear to be an interesting

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option to diversify the agricultural activities and improve the economy of the horticultural sector. They can also contribute to secure the energy access also in rural and decentralised territories, using electricity locally produced and reducing the dependence of agricultural farms and communities on foreign and fossil fuels [2].

The electricity generated from the PV panels can be injected into grid, providing an additional income to the farm, or consumed for powering climate control appliances of the same greenhouse, thus contributing to a better environmental sustainability of greenhouse cultivations [3–8].

The main challenge that this technology poses is to conciliate energy and food production on the same land unit, with the goal of optimizing the economic productivity of this mixed system [9]. This aspect is strictly connected to the positioning of the PV array on the greenhouse roof and becomes more critical as the roof coverage factor increases. In fact, replacing the existing glazing surface with a PV array leads to an internal shading which affects growth, development and productivity of the cultivated crops. These effects are strongly related to the shading level, type of crop, cultivation season, climate characteristics.

The inhibitory effect of shading caused by PV modules on the accumulation of fresh and dry-weight was observed on welsh onion cultivated under a 13% PV roof coverage, with an average crop yield loss of 25% [10]. Solar modules covering 9.8% of the greenhouse roof did not affect the marketable production of tomatoes, but they had a negative effect on fruit size, hardness and color [11]. No significant effects on biomass production and yield were detected on basil and cucumber when the PV area on the greenhouse roof was lower than 20% [12]. Furthermore, a high tolerance to PV shade up to 70% was observed on lettuce, which compensated the light shortage by modifying the leaf development. However, this crop performance was observed in a ‘‘agrivoltaic-system’’, where the PV array was installed above a field crop, therefore they should not be strictly compared to a PV greenhouse [13].

Most of the literature data is referred to low shading level on the crops, which are not actually common in commercial PV greenhouses. These structures are often configured as large-scale investments to maximize the electricity generation. For this reason, most structures have been designed covering 50% or 100% of the roof area with conventional silicon PV panels, which concern about 85% of the PV market [14,15], without properly considering the sunlight needs of cultivated crops. Given the huge initial investment required, the high financial profits from PV energy production in the greenhouse sector will be sustainable only until conspicuous public subsidies are available. Furthermore, they often occupy large abandoned agricultural areas, replacing conventional activities and changing the initial land use or vocation. To limit this speculative trend in rural areas in Italy, the national and regional administrations have introduced some restrictions for PV greenhouses, such as: (1) prevalence of the agricultural income, which should be equal or higher than the revenue deriving from energy production, when the PV power exceeds 200 kWp; (2) percentage of PV coverage, whose ground projection must not exceed 50% of the total greenhouse area [16–20]. Furthermore, the suitable crops and cultivation techniques should be specified before the construction, and subsequently the conduction of agricultural activity has to be proved. These constraints potentially prevent the investor from building structures without the proper greenhouse technologies. However, at present no characterization of the microclimate inside PV greenhouses with high levels of shading can be found in literature. This makes difficult for the grower to identify the most profitable crops, which revenue allows to fully abide by the government policy. For this reason, the study of the greenhouse climate conditions is crucial for choosing the best combination of solar panels and crops, in order to optimize both the energy and crop production [9]. Particularly, the knowledge of the spatial distribution of the microclimate parameters is essential for modeling both the greenhouse environment and the crop growth [21,22].

According to the remarkable spread of greenhouses with 50% PV cover, this paper aims to study the microclimate conditions inside these already existing structures and produce the scientific information about their agronomic sustainability. More specifically, the spatial and temporal distribution of solar radiation, temperature and humidity inside a greenhouse are described in order to quantify the variability of the internal climate conditions and provide data for cultivation support purposes. The agronomic and economic feasibility, with and without supplementary lighting powered by PV energy, was assessed on tomato, chosen as a test crop.

2. Materials and methods

2.1. Location

The experiment was carried out at Decimomannu (Sardinia, Italy, 39°19′59″N, 8°59′19″E) in a commercial east–west (E–W) oriented greenhouse (Fig. 1) for horticulture, thus not expressly designed for PV energy generation.

2.2. Greenhouse

The preexisting pitched-roof greenhouse had an area of 960 m^2, with two spans (50.0 m long and 9.6 m wide each), gutter height of 2.5 m and roof slope of 22° even though, according to the latitude of the place, the optimal slope should have been around 30°. The walls and the north (N)-oriented roofs were made with PVC (Ondex Bio, Renolit, France), with up to 90% global transmissivity declared by the manufacturer, while the openings, positioned only in the side walls, were clad with a polyethylene film (PE). The cladding materials and the PV panels were supported by a steel structure.

2.3. PV system and inverters

The south (S)-oriented roof of each span was replaced with 144 multi-crystalline silicon PV modules (REC 235PE, REC Solar, USA), resulting in 50% of the roof area covered with PV modules (Table 1). The total PV area was 475 m^2 total PV area (238 m^2 per PV roof), while the total active cell area was 420 m^2.

The peak rated power of the PV system was 68 kWp, provided using four inverters (Sinvert PVM17, Siemens AG, Germany). The daily electric energy produced by the PV system was recorded by the inverters.

2.4. Layout of experiment

Four experimental areas have been set up in order to describe the variability of the internal microclimate conditions: A (N-W oriented), B (N-E), C (S-E), D (S-W), 103 m^2 each (13.0 m long and 7.9 m wide), placed at the center of the greenhouse, two in each span (Fig. 1). The distribution of the solar radiation was studied by identifying six observation points (from 1 to 6) in each area, placed 1.5 m above the ground level at the center of the crop rows (see paragraph 2.6 for crop details) and spaced 1.33 m. The observation points from 1 to 3 were under the plastic roofs, while points from 4 to 6 were under the PV roofs.

The solar radiation distribution was investigated both on the longitudinal (E–W) and transversal (N–S) direction, calculating the solar radiation incident in each observation point and area (average of the six observation points).

Table 1
Technical specifications of the modules and inverters. Data of the module is referred both to the standard test conditions (STC) and the nominal operating cell temperature (NOCT).

Photovoltaic module		Inverter	
Name	REC 235 PE	Model	Sinvert PVM 17
Type	Multi-crystalline silicon	Rated power	17 kW
Number of cells	60	Efficiency	98%
Dimensions	1665 × 991 × 38 mm	Cost	0.9
Active cell area	1.46 m^2	Grid connection	3AC 400 V; 50/60 Hz
Module efficiency	14.2%		
Weight	18 kg		
Electrical data (STC: irradiance 1000 W m^{-2}, cell temperature 25 °C)			
Rated power	235 Wp		
Nominal power voltage (V_{MMP})	29.6 V		
Nominal power current (I_{MMP})	8.0 A		
Open circuit voltage (V_{oc})	36.7 V		
Short circuit current (I_{oc})	8.5 A		
Electrical data (NOCT: irradiance 800 W/m^2, cell temperature 20 °C)			
Rated power	173 Wp		
Nominal power voltage (V_{MMP})	27.1 V		
Nominal power current (I_{MMP})	6.4 A		
Open circuit voltage (V_{oc})	33.8 V		
Short circuit current (I_{oc})	6.9 A		
Temperature ratings			
Nominal operating cell temperature (NOCT)	47.9 °C		
Power temperature coefficient	−0.46 %/°C		
Voltage temperature coefficient	−0.33 %/°C		
Current temperature coefficient	−0.074 %/°C		

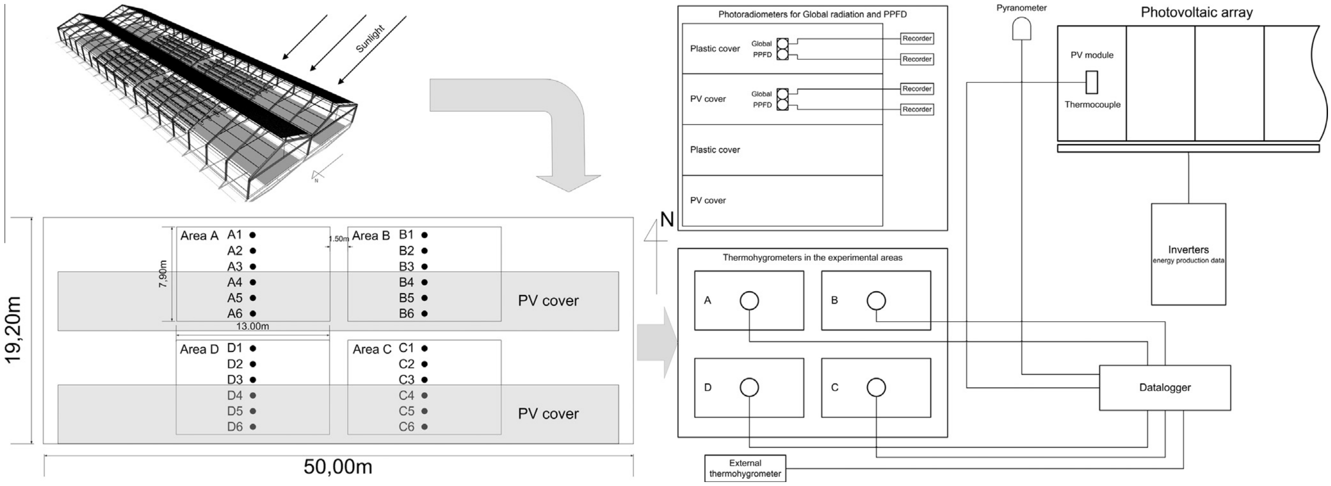

Fig. 1. Experimental setup and sensors positioning.

2.5. Supplementary lighting and air heating

A supplementary lighting system powered by the PV array was designed with the software RELUX [23] and tested as an experimental factor to evaluate its agronomic and economic convenience in PV greenhouses. The system was switched on calibrating the energy consumption according to the expected PV energy generated by the panels above the lighted areas. For this reason, it was used for 8 h/day to increase the natural light only during the months of minimum irradiation, thus the harvest period in cycle 1 (86 days, from November 1st to January 25th) and the first growth stages in cycle 2 (92 days, from January 26th to April 26th).

High pressure sodium lamps (HPS Plantastar 400 W, Osram, Germany) were placed on areas A and C, attached to horizontal steel bars connecting the trusses at a height of 3.05 m, providing a PPFD of 84 μmol m^{-2} s with a distribution uniformity of 0.77. The HPS type is commonly used on greenhouse vegetable crops, due to the high energy efficiency in PPFD conversion, with recommended levels around 55–111 μmol m^{-2} s [24], which are lower than that commonly distributed for greenhouse tomato in Canada and Northern Europe (100–150 μmol m^{-2} s [25]).

Heating was provided only in winter using a 174 kW hot air generator (Mabre 175 PK, Italy). The thermal efficiency was 90.8%, the oil flow was 14.7 kg h^{-1} and the generator was provided with hour meter. The air heating was used as defense mechanism against occasional very low temperatures during the night time and was limited to the winter months (from December to February). A low set point temperature was established (ignition below 5 °C till 6 °C), in order to limit the heating expense, according to the management of Mediterranean low cost greenhouses, which are without thermal screens and not properly airtight.

2.6. Experimental crop

Tomato was chosen as a test crop to validate the greenhouse solar radiation distribution, due to its high sensitivity to light variability [26]. Two six-month cherry tomato cycles were performed (*Solanum lycopersicum* L., cv. Shiren) with a plant density of 2.3 plants m^{-2}, spaced 0.33 m within the row and 1.33 m between the rows, each one 13.0 m long. This density, although slightly low, was comparable to that averagely adopted in Italy for cherry tomato, averagely 2.5 plants m^{-2} [30].

Plants were sown in a nursery using styrofoam multi-cell plateaux before transplantation in the greenhouse, where they were grown hydroponically using coconut fiber substrate (Coir EnGreen, Sri Lanka) and drip fertigation system. In cycle 1, the crop was transplanted on August 22nd 2011, 30 days after the sowing, the tip of the main stem was removed (topping) on October 10th 2011 at the 8th cluster in bloom and the last harvest was on January 25th 2012. In cycle 2 the crop was transplanted on January 26th 2012, 45 days after the sowing, topped on May 18th 2012, when the 8th cluster was in bloom, and uprooted on July 12th 2012. Total and marketable production (number and weight of the fruits) and the fruit dry matter content were measured on 4 rows (rows 2–5, 12 plants per row), excluding the border rows of each span, in order to avoid effects of the solar radiation coming from the side walls on crop growth. The marketable production was determined through the entire harvest period in both cycles, excluding fruits outside the commercial size range, showing blossom end rot, split and immature. The fruit dry matter content was determined three times during the harvest period in every crop cycle, drying samples in a 70 °C oven until constant weight.

2.7. Instrumentation and measurements

The internal global radiation (W m^{-2}) and photosynthetic photon flux density (PPFD in μmol m^{-2} s) were measured using four photoradiometers (HD 2012.2, Delta Ohm, Italy): two of them were equipped with global radiation probes (LP 471 RAD, Delta Ohm, Italy), the other two with quantum radiometric probes for PPFD (LP 471 PAR, Delta Ohm, Italy). Sensors were placed at gutter height, in order to avoid the shading from the crop. A couple of photoradiometers (one for global radiation and the second for PPFD) were placed under the PV cover, thus under permanent shading, while the second couple was placed under the plastic cover.

In order to quantify the solar radiation reaching each observation point, the direction of the incident sunrays was determined using the algorithm proposed by Yano et al. [27], which calculated the solar declination and azimuth angles for the whole year at the latitude of the greenhouse site. When both the angles were within the interval intercepted by the PV coverage, the observation point was considered under shade and consequently the value of the global radiation and PPFD measured under the PV roof was attributed. On the contrary, when at least one of the angles was outside the interval, the observation point was considered under direct light and it was assigned with the global radiation and PPFD measured under the plastic roof. Another available method to calculate the solar radiation input is the Auto-Cad 3D-shadow analysis, through the determination of the total solar fraction for different greenhouse orientations [28].

Temperature and humidity were measured at the center of each experimental area through four thermohygrometers (Mela KPC2-ME, Galtec, Germany), placed 1.50 m above the ground level.

The external global radiation was measured through a pyranometer (LP Pyra 03, Delta Ohm, Italy), mounted coplanar to the S-oriented PV roofs. External environmental parameters were measured using a thermohygrometer (HOBO U10-003, Onset, USA), placed inside an instrument shelter, about 15.0 m far from the greenhouse. All data were recorded at 10 min intervals using a universal data logger (Squirrel SQ2020, Grant Instruments, UK), except the photo-radiometers and the external thermohygrometer, provided with their own acquisition memory. All parameters were measured for a whole year (from August 22^{nd} 2011 to August 22^{nd} 2012).

The temperature of the PV modules was measured using a RTD platinum sensor (Flexible RTD Stikon surface sensor mod. 22810, Rdf, USA), placed at the center of a module back cover.

2.8. Formulae and agronomic terms explanation

The overall power efficiency (η_g) was calculated with the following formula:

$$\eta_g(\%) = \frac{E_P}{G_r \cdot A} = \frac{E_P}{E_r}$$

where E_p is the yearly energy production of the PV system (kWh) measured from August 22th 2011 to August 22th 2012, G_r the annual global irradiation (kWh m^{-2}) and A the PV area (m^2), which can be used to calculate the yearly solar energy incident on the PV array (E_r, kWh). This formula is based on the common calculation of the PV system solar electric efficiency [29–31].

The greenhouse transmissivity was calculated as the ratio between the internal global radiation measured under the plastic cover and the external global radiation [11]. The external radiation incident on the N-oriented roofs was calculated by correcting the data measured on the S-oriented roof using the PVGIS web software [32]. The thermal energy emitted from the back cover of the PV modules was calculated considering the main exchange factors, thus convection and irradiation, with the methods described by Jones and Underwood [33].

The earliness of the harvest was assessed by adopting a modified index developed by Faedi et al. [34]. Earliness was calculated by multiplying each picking day ordinal number and the percent of 1^{st}, 2^{nd}...till the last week yield as given below:

$$EI(\%) = \frac{\frac{Nt-N1}{Nt} \cdot P1 + \frac{Nt-N2}{Nt} \cdot P2 + \cdots + \frac{Nt-Nn}{Nt} \cdot Pn}{PT} \cdot 100$$

where P1, P2, P3 and Pn were the yield of tomato collected during 1^{st}, 2^{nd} and n^{th} week; Pt and Nt respectively the total number of harvested weeks and the total yield.

This index weights weekly yields according to the week of harvest. Moreover, an economic evaluation of the fruit yield was conducted to compare products obtained by each area and row in terms of yield (kg m^{-2}) and commercial value. Subsequently, the fruit yield of each row was weighted through the market prices occurred at the harvest and sale dates. Real unit prices, referred to the 2013–2014 yield were considered [35,36], and gross marketable yield was determined by multiplying the weekly marketable yield and relative price.

Tomato plants come in two growth varieties: determinate and indeterminate. Indeterminate plants such as ‘cherry’ tomatoes, continue growing until fall frost. Cutting off the top of the plants (topping) is a common agronomic practice that prevents upward growth, leading to a plant easier to support.

2.9. Statistical analysis

The variability of solar radiation among rows (N–S gradient) was checked for normality and then analyzed using one-way ANOVA, with six treatments (rows 1–6) and four replication (experimental areas) over thirteen months and LSD procedure for pair comparison among means (months × row) [37]. The solar radiation differences between the experimental areas and the spans, as well as the effect of supplementary light were analyzed using the T-Student Test, considering row mean as elementary observation. Temperature and humidity differences between experimental areas were analyzed using one-way ANOVA, monthly data as replication and LSD procedure for pair comparison among means. Analysis of variance of crop productivity data between rows 2 and 5 was carried out according to a randomized complete block design with four replicates (experimental areas) and LSD procedure for means discrimination.

3. Results

3.1. Internal temperature and humidity

The yearly average temperature was significantly higher inside the greenhouse (19.8 °C) compared to the outside temperature was (17.0 °C). This difference was higher during winter and spring (from November to April), reaching up to 6.5 °C in February, due to the low ventilation rate (Fig. 2). The lowest difference was observed in summer and early autumn, particularly in June, where it was around 0.8 °C, due to the increase of ventilation through the windows. On the contrary, the outside average humidity, equal to 76% on yearly basis, was significantly higher than the average value of 60% observed inside the greenhouse. The hot air generator, assuring at least 5 °C, worked for 107 h and consumed 1573 kg oil, corresponding to 2 L m^{-2} (69.7 MJ m^{-2}). The internal average temperature in winter was 13.2 °C in December (min. 7.6 °C; max 21.9 °C), 12.5 °C in January (min 6.7 °C; max 19.9 °C) and 12.5 in February (min 5.8 °C; max 23.6 °C). The experimental areas showed a similar trend concerning temperature and humidity and no significant differences were observed among areas.

For the most usual horticultural species cultivated in greenhouse the requirements in terms of average air temperature and relative humidity range respectively between 10 °C and 30 °C and 70–90% RH. In crops such as tomato, with medium thermal requirements, temperature values around 16–30 °C during the day and 13–18 °C during the night are recommended. The temperature requirements change with the age of the plant and are higher in the first stages of development. A night temperature around 15 °C, lower than the day value, reduces the respiration losses and is considered optimal. When temperatures are frequently lower than the recommended values, as occurs in unheated greenhouses during the night, some physiological and development processes may be slowed down, such as the distribution of assimilates to the fruits or the duration of vegetative and productive stages, with a decrease in the yield and production quality [24].

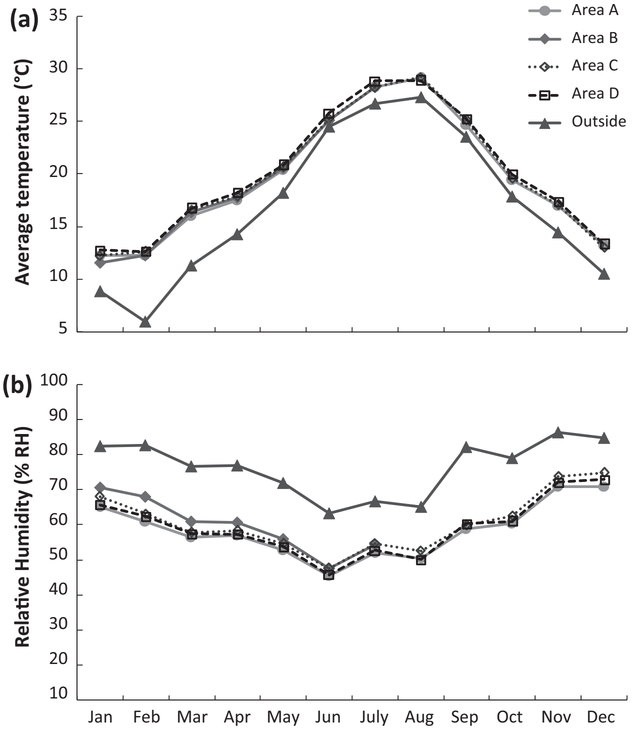

Fig. 2. Average monthly temperature and humidity in the experimental areas. Area B data was available only from January 2012 to August 2012.

In our experimental greenhouse, the “greenhouse effect” was reduced by the limited solar radiation and heating, applied only to avoid frost damages (cold greenhouse). As a consequence, the average temperature observed during the coldest months of the year was frequently lower than the minimum threshold, probably becoming a limiting factor for the fruit ripening (in cycle 1) and the vegetative growth stages (in cycle 2).

3.2. Solar radiation distribution inside the greenhouse

The yearly average global radiation under the PV modules in the central part of the day (from 10:00 h to 14:00 h) was 84% lower than that observed under the plastic roof. The lowest difference was found in December (75%) and it increased during the seasons, till reaching the maximum in June and July (92%). The global radiation under the plastic glazing was affected by the shading of the structural components of the greenhouse roof, causing fluctuations in the daily distribution curve (Fig. 3). The solar light measured under the PV roof, characterized only by diffuse radiation, had a low but regular distribution curve within the day. The PPFD under the plastic cover expressed in W m^{-2} (multiplying the value in μmol m^{-2} s by the conversion factor for natural light 0.217 [38]) was averagely 71% of the global radiation during the year. The overall greenhouse transmissivity measured under the plastic roof amounted to 55%, reaching higher values in winter (averagely 66%) and lower in summer (45%), according to what reported by Castilla in a greenhouse with symmetrical roof and E–W orientation [24].

The distribution of the global radiation and PPFD was similar in all experimental areas, following a transversal N–S gradient among the rows, changing throughout the year due to the shadows casted by the PV roofs. The rows under the plastic roof (1, 2 and 3) received averagely three times more radiation on yearly basis (1453 MJ m^{-2}) than rows 4, 5 and 6, placed under the PV roof (477 MJ m^{-2}), showing a not uniform distribution of the solar radiation inside the greenhouse (Table 2). The yearly average reduction under the plastic and PV roof was respectively 46% and 82%, compared to the potential solar radiation input without PV system (2684 MJ/m^2). This value was calculated using the data of the photoradiometer under the plastic cover, whose measurements were not affected by the shadow of the PV modules. The yearly reduction due to shading in the whole greenhouse amounted to 64%. One of the studies investigating the reduction of the solar radiation in a 50% PV covered area, deals with an agrivoltaic system installed 4 m above ground, where the reduction ranged between 48% and 68%, depending on the day of the year [39]. Rows 1 received the highest amount of solar energy, followed by rows 2 and 3, with a yearly reduction respectively of 18%, 43% and 77%, compared to the annual solar radiation potentially incident without the PV array (2684 MJ m^{-2}). The average reduction for the rows under the PV roof was 78%, 84% and 85%, respectively for rows 6, 5 and 4. The CV of the solar radiation between the rows was 76% on yearly basis. The highest reduction of solar radiation due to PV shading was observed in autumn (averagely 71%), followed by winter (69%), spring (66%) and summer (60%).

Two different trends of light distribution were observed throughout the seasons. The main trend, from March to October, similarly to the yearly trend, was characterized by a solar input statistically higher in the border rows (especially rows 1), decreasing towards the center of the span, with a CV of 71% between rows.

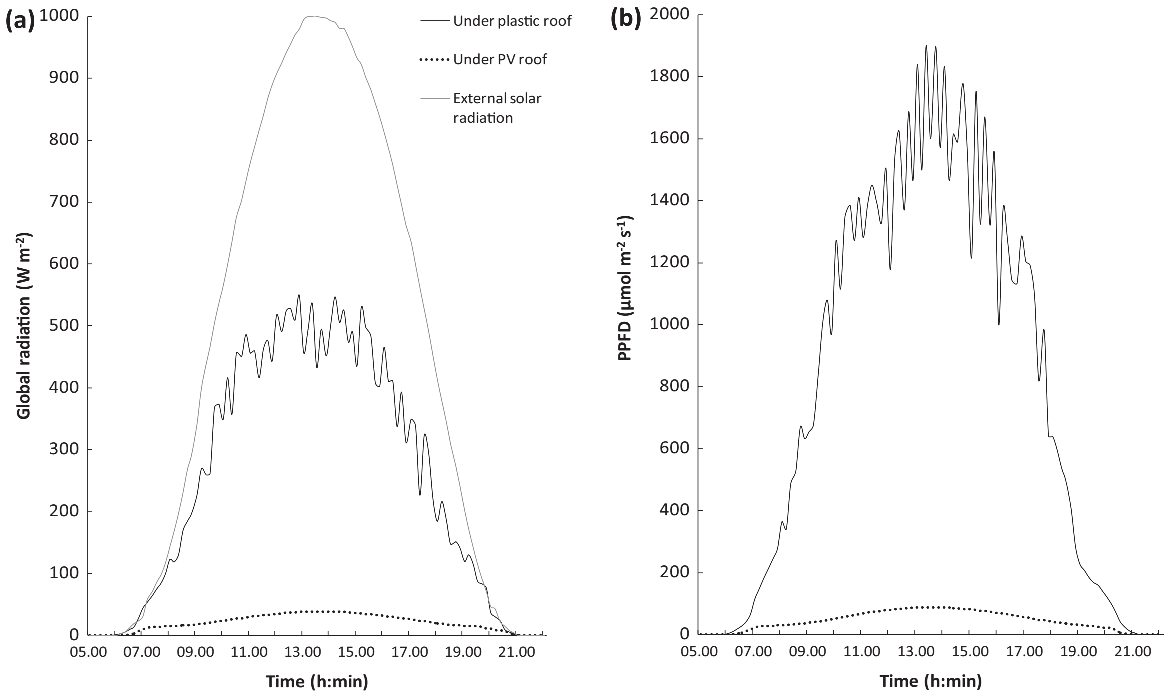

Fig. 3. Global radiation (a) and PPFD (b) distribution for a clear day (July 5th, 2012) measured under the PV cover, the plastic cover and outside.

Table 2
Daily average global radiation (MJ m^{-2}) of the four experimental areas, incident on the observation points during the months. The average reduction is calculated in relation to the potential solar energy input without PV array. The cumulated yearly global radiation is reported below with the standard deviation.

Months	Rows						Average reduction (%)
	Plastic cover			PV cover			
	1	2	3	4	5	6	
August 2011	7.04a	4.44b	2.22 cd	1.85e	1.99de	2.41c	61
September	5.37a	1.73b	1.27c	1.26c	1.36c	1.77b	72
October	1.46a	0.70b	0.72b	0.75b	0.83b	1.28a	77
November	0.59b	0.59b	0.60b	0.63b	0.69ab	0.89a	64
December	0.34b	0.35b	0.36b	0.38b	0.45b	1.03a	64
January	0.39b	0.39b	0.40b	0.43b	0.49b	0.97a	69
February	0.88b	0.73b	0.75b	0.77b	0.84b	1.16a	73
March	4.49a	1.26c	1.25c	1.27c	1.35c	1.68b	72
April	7.79a	4.79b	1.68 cd	1.38e	1.47de	1.85c	65
May	12.44a	9.63b	3.06c	1.49e	1.61e	2.18d	60
June	14.87a	12.46b	4.30c	1.51e	1.71e	2.24d	58
July	13.53a	10.79b	3.54c	1.43e	1.57e	2.18d	60
August 2012	10.60a	7.48b	2.39c	1.58d	1.69d	2.22c	63
Yearly sum	2201 ± 12	1535 ± 7	622 ± 7	397 ± 25	434 ± 52	599 ± 157	

Within the same month, mean data with the same letter shows no statistical difference for $P < 0.05$.

Rows 1 received averagely 68% more radiation than rows 6, and 55% more than the other rows under the plastic cover. No statistical difference was observed between the central rows under the PV cover (4 and 5), while it was significant between the central rows under the plastic cover (2 and 3), only from April to September.

Due to the much lower solar declination angles, a completely different trend was observed in winter (from November to February), where an inversion of the distribution was detected. During this season the shadow systematically casted also on the rows under the plastic roofs. Rows 6 received averagely 109% more solar radiation than rows from 1 to 5, which showed no statistical difference among them. A lower variability of the distribution was observed between the rows, with a CV equal to 40%.

No statistical difference was observed between the experimental areas of the same span, thus areas A–B and C–D. However, significant differences were observed between the spans: on yearly basis the areas in the north span (A and B) received averagely 7% less solar radiation than the S span areas (C and D). This difference was detected mainly on the rows placed under the PV roof of the S span, which received averagely 33% more solar radiation than the same rows placed under the PV roof of the north span, resulting in a higher standard deviation (averagely 78 MJ m^{-2}), compared to the one observed on the rows under the plastic roof (averagely 9 MJ m^{-2}).

3.3. Tomato production and relation with solar radiation

The tomato production amounted to 7.5 ± 1.2 kg m^{-2} on yearly basis, distributed in 3.3 ± 0.7 and 4.2 ± 0.6 kg m^{-2}, respectively for the first and second cycle. The marketable production accounted for 76% of the total yield, reaching average values respectively of 2.4 and 3.4 kg m^{-2} (Table 3). The overall linear relation between solar radiation including the supplementary light (S_t) and the total crop yield (C_t) was 0.3 kg m^{-2} for every 100 MJ m^{-2} PPFD, with a correlation of 81% ($C_t = 5.830 + 0.003S_t$).

Total and marketable yield were affected by the decrease of PPFD along to the north–south gradient and consequently significant differences have been observed among the rows.

On the yearly basis, the significantly highest yields were achieved in the rows 2 and 3, under the plastic roofs, and the lowest under the photovoltaic roofs (rows 4 and 5), accordingly to the PPFD cumulative values received. However, in the cycle 1 not significant differences between total and marketable yield of rows 3, 4 and 5 were found, while the 'Earliness Index' values were significantly higher in the rows under the plastic roofs compared to the rows under the PV roofs. The fruit dry matter content did not change significantly among the rows, reaching averagely 7.5%.

At the end of the first cycle, the cumulated PPFD in the greenhouse was averagely 72% lower than the potential value, calculated as no PV system was installed on the roof (410 MJ m^{-2}). The natural PPFD on the central rows (from 2 to 5) was averagely 0.52 MJ m^{-2} day^{-1}, which was below the minimum value of 2.60 MJ m^{-2} day^{-1}, necessary for a good tomato productivity [40,41]. The supplementary light provided an integration of 97%, compared to natural radiation inside the greenhouse from November to January, with the attempt to partly compensate the lack of natural light, with an additional PPFD of 39.44 MJ m^{-2} (0.45 MJ m^{-2} day^{-1}), but did not significantly affect the tomato production.

In the second cycle, the PPFD was 63% lower than the potential value (1112 MJ m^{-2}, averagely 6.57 MJ m^{-2} day^{-1}) and the differences between the rows were higher than those found in the first cycle. Even if the natural PPFD observed inside the greenhouse was similar to the optimal level commonly indicated for most horticultural crops (6.00 MJ m^{-2} day^{-1} [24,38]), the average production remained slightly below the most common cherry tomato yield in short cycle (5–10 kg m^{-2} [42,43]), probably due to the low irradiation during the first growth stages in January, February and March, where the average PPFD radiation on the central rows was respectively 0.27, 0.53 and 0.94 MJ m^{-2} day^{-1}. In fact, the average total yield amounted to 4.7 (rows 2 and 3) and 3.7 kg m^{-2} (rows 4 and 5), with significant differences between rows under the plastic and PV roofs. The 'Earliness Index' values showed a similar trend, while a lower marketable yield in the row 2 compared to the row 3 was observed, due to a high incidence of fruit affected by blossom end rot (BER) and fruit cracking recorded in the row 2 with respect to the other rows. The average fruit dry matter content of the crop was 8.8%, thus 15% higher than that observed in the first cycle, and significant differences along the north–south gradient were found. The integration with artificial light was 69% compared to the natural radiation received from January to April, with an additional PPFD of 36.69 MJ m^{-2} (0.40 MJ m^{-2} day^{-1}) and no effect on the yields was observed.

On the whole, the economic value of fruit production decreased significantly along the rows 2–5, accordingly to the differences in the marketable yield on the yearly basis, the trend of the 'Earliness Index' values in both cycles, and the trend of sale prices in the cycle 1 (Fig. 4, Table 4). In fact, nevertheless were observed in both cycles significant differences between rows in terms of EI, the rows under the PV roof were penalized mainly in the cycle 1 due to the lowest earliness index and a price trend more favorable in the middle part of the harvest period. The significantly higher value was achieved in row 2 (€ 5942 per 1000 m^2) with respect to the rows under the PV roofs (average value € 4498), with greater differences among the rows in cycle 1 compared to cycle 2.

Table 3
Cumulated PPFD, yield and fruit characteristic in response to row positions.

	Row 2	Row 3	Row 4	Row 5
Cycle 1				
Total PPFD (MJ m^{-2})	102a	76bc	75c	85b
Total yield (kg m^{-2})	4.2a	3.2b	2.8b	2.9b
Marketable yield (kg m^{-2})	3.0a	2.3b	2.0b	2.1b
Earliness index	38.9a	35.8b	31.4c	31.5c
Fruit dry weight (%)	7.50	7.30	7.60	7.80
Cycle 2				
Total PPFD (MJ m^{-2})	713a	263b	142c	156c
Total yield (kg m^{-2})	4.7a	4.8a	4.1b	3.3c
Marketable yield (kg m^{-2})	3.4a	3.8a	3.4b	2.9c
Earliness index	37.5a	31.8b	29.8c	30.8bc
Fruit dry weight (%)	10.7a	9.0b	8.2c	7.6d
Cycle (1 + 2)				
Total yield (kg m^{-2})	8.9a	7.9b	6.9c	6.2c
Marketable yield (kg m^{-2})	6.4a	6.1a	5.4b	4.9c

Means followed by the same letters did not differed per $P \leqslant 0.05$.

3.4. Energy production of the photovoltaic system and lighting consumption

The annual electricity production was 107,885 kWh, equivalent to 1563 kWh kWp^{-1} and 112 kWh m^{-2} greenhouse area. The peak production was reached in June, with 12,080 kWh and averagely 15 h solar irradiation per day. The lowest was found in December, with 4676 kWh and 10 h daily solar irradiation (Fig. 5).

The cumulated yearly solar radiation on the PV system area was 942,541 kWh. The overall conversion efficiency of the PV system (η_g) was 11.4% (Fig. 6a). This value changed throughout the year, due to the different module temperatures, with an estimated decrease of 0.8% °C^{-1} above 25 °C (Fig. 6b). The highest monthly efficiency was observed in December (12.2%), while the lowest in July (11.0%). The reduction of the conversion efficiency can be expected also using other semiconductors potentially suitable for greenhouse applications, such as the amorphous silicon, the cadmium telluride or the copper indium diselenide (CIS) [15].

The difference between the PV module temperature and the ambient temperature (ΔT_{mo}) was averagely 18 °C during the year, while the difference between the PV module and the internal greenhouse temperature (ΔT_{mg}) was averagely 15 °C (Table 5). The two differences diverged more in winter, due to the greenhouse heating sessions. The thermal energy released from the back cover of the PV modules was averagely only 8% of the external global radiation and 25% of the internal global radiation, with the highest average value of 47 MJ m^{-2} reached in June and the lowest of 14 MJ m^{-2} released in winter. The module temperature reached the highest daily average temperature of 52 °C and 53 °C, respectively in July and August, where the peak temperature was also observed (76 °C), and minimum values of 25 °C in December and January. The extreme working temperatures observed in summer have already been reported

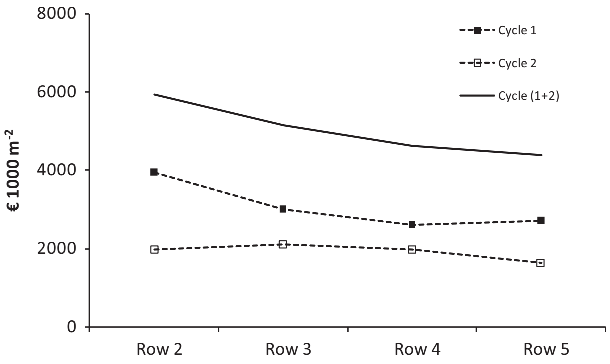

Fig. 4. Economic marketable yield value on yearly basis and in the two tomato cycles.

Table 4
Estimated economic yield value.

Harvesting date	Weekly price	Row 2	Row 3	Row 4	Row 5
	€ kg^{-1}	€ 1000 m^{-2}			
Cycle 1					
10-nov	1.06	70	38	88	29
17-nov	1.06	172	100	88	66
23-nov	1.06	235	244	89	219
30-nov	1.06	394	226	157	164
07-dic	1.46	258	146	190	165
14-dic	1.46	499	483	234	279
21-dic	1.46	583	231	232	265
28-dic	1.46	161	149	182	159
04-gen	1.34	97	119	80	77
11-gen	1.34	353	187	76	160
18-gen	1.34	493	501	473	386
25-gen	1.34	643	604	736	759
Total (€ 1000 m^{-2})		3960a	3027b	2625b	2728b
Cycle 2					
07-giu	0.53	200	16	13	19
14-giu	0.53	229	389	190	81
21-giu	0.53	254	190	355	442
28-giu	0.53	636	655	564	454
05-lug	0.53	519	540	552	407
12-lug	0.53	144	322	316	248
Total (€ 1000 m^{-2})		1982a	2113a	1990a	1652b
Cycle (1 + 2) yield value (€ 1000 m^{-2})		5942a	5140ab	4615b	4380c

Means followed by the same letters did not differed per $P \leqslant 0.05$.

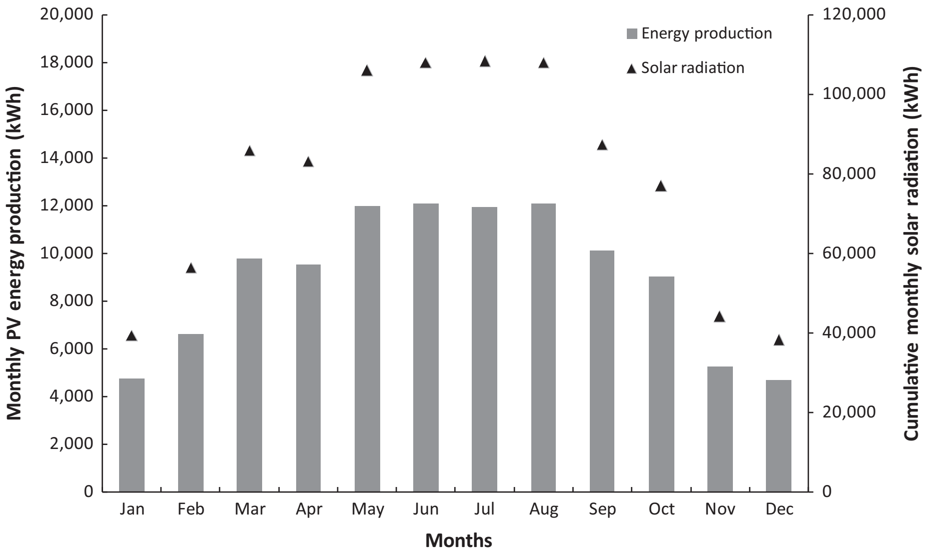

Fig. 5. Monthly energy production from the PV system and cumulated global radiation on the PV area. Data of August is the sum of the days in August 2011 and 2012.

by Chow [44], indicating that more than 50% of the incident solar radiation is converted as heat, leading to cell temperatures as much as 50 °C above the ambient temperature.

The annual incentive income, derived from the feed-in tariff system (0.422 € kWh^{-1}), accounted for 45,527 € for all the PV energy produced, regardless of the final use of the electricity (consumption or sale). The feed-in tariff has been adopted in many european countries, contributing to shorten the payback time of the PV systems [45–49]. Public subsidies have consistently decreased nowadays, but they are also constant and secured for 20 years once assigned. The PV system generated also an additional revenue, deriving from selling or consuming the energy instead of purchasing it (indirect income), estimated around 19,419 € (average electricity price: 0.18 € kWh^{-1}). Consequently, the potential income of the PV array could reach up to 0.60 € kWh^{-1}, thus about 67.2 € m^{-2} for this specific greenhouse.

The power consumption due to supplementary lighting amounted to 50 kWh m^{-2} of the greenhouse area (total consumption 10,310 kWh), while the energy production of the PV system in the same period was 41 kWh m^{-2} (total production 39,360 kWh). The cost due to the energy consumption of the lamps was 9 € m^{-2}.

4. Discussion

4.1. Internal climate conditions

Temperature and humidity were uniform in the greenhouse area, given the low variability observed between experimental areas. The low percentage of thermal energy released from the back cover of the PV panels, compared to the incident global radiation (averagely 8%), negatively contributed to the overall energy

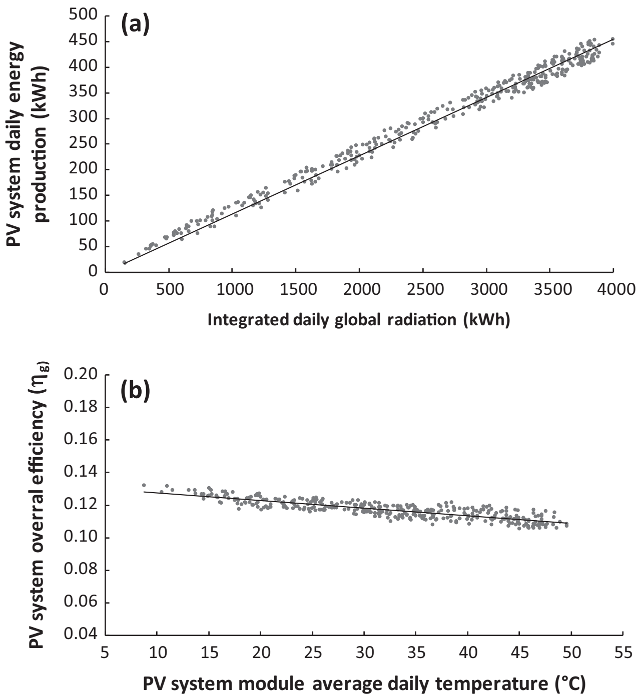

Fig. 6. Relation between global radiation and PV energy production (a, $R^2 = 0.986$); relation between PV system overall efficiency and module temperature (b, $R^2 = 0.709$).

balance of the whole greenhouse. The reduced solar energy input suggests that the PV array carried out a cooling effect on the internal environment, also considering that the transmitted solar radiation falling on the transparent north-oriented covers does not contribute to the thermal heating of the greenhouse [50]. The impact of the PV panels on the heat flux through the roof is well known and used for reducing the cooling load inside buildings [51–53], but it could have a negative effect during winter, increasing the energy consumption for heating.

The use of polycarbonate as material for cover, instead of PVC, may help to better conserve thermal energy inside the greenhouse in winter, resulting in up to 30% energy saving without reducing the solar light availability [54]. Furthermore, the double glazing or thermal screen scan reduce the energy demand up to 60% [55]. However, the use of these cover materials leads also to an increase of the costs for the PV greenhouse construction or modification, which may not be convenient.

4.1.1. Solar radiation

The overall greenhouse transmissivity was lower than the declared value for the PVC, due to factors such as the shading of the structural elements of the roof, the dust and the angle of incidence of the sunrays, which is always different from the perpendicular rays used by manufacturers to test the transmissivity of their materials [56,57]. The E–W orientation allowed to succeed a higher transmissivity in winter (66%), when the solar radiation is a limiting factor, showing to be the best orientation for year round greenhouse cultivations, as already observed by Panwar et al. [58] and Sethi [59].

The dynamic shadow movement during the year showed that the solar radiation was distributed on a N–S gradient, since the sunrays come from S. The rows under the plastic cover always received a higher amount of solar radiation compared to those under the PV cover, with more light incident in the side walls (especially rows 1) and decreasing towards the center of the spans. This distribution can be observed during most part of the year, especially in summer, where more natural light was available, together with a high variability between the rows. In fact, due to high angles of solar declination in summer, the shadow of the PV panels mainly casted over the rows under the PV roof, resulting in a consistent reduction on rows from 4 to 6. The movement of the shadow above these rows caused the solar radiation input to be more fluctuating within the single day, as shown by the higher standard deviation of the yearly global radiation, compared to the ones observed on the rows under the plastic cover.

However, only in winter the lower declination angles caused the shadow to cast also on the rows under the plastic roof, reducing the variability between the rows, with no statistical differences, except for rows 6, close to the S side wall of the span and with the highest energy input. For the same reason the N span, where areas A and B were located, suffered in winter the shading coming from both PV roofs, thus receiving less solar radiation than the S span.

4.2. Test crop performance and effects of supplementary light

The production of cherry tomato type achieved in conventional greenhouse in Southern Europe usually ranges between 5 and 10 kg m^{-2} [42,43], depending on the cycle duration. In our study a reduction of the crop productivity was observed on cherry tomato, confirming the trend of the solar radiation distribution and showing a total and marketable production higher in the rows under the plastic roof. This is in agreement with the direct relation between the incident solar radiation on the crop and the cumulated yield [60,61]. Accordingly to Kläring and Krumbe [62], the reduction in photosynthesis due to constraints in PPFD resulted in significant decreases in yield of the shaded tomato crop, compared to the non-shaded one. Moreover, Tinyane et al. [63] in their study aimed to verify the influence of photo-selective nettings on fruit quality and nutritional properties of tomato, found that the three compared cultivars showed lower production of marketable fruits when grown under a commercially used black net (25%

Table 5
Average daily thermal energy released from the back cover of the PV module (E_c). The daily hours of irradiation (h), the average temperature of the module (T_m) and the average global radiation (G_r) are reported, together with the monthly temperature differences between: the module and outside (ΔT_{ma}); the module and the greenhouse (ΔT_{mg}).

Months	Hours of irradiation (h)	T_m (°C)	DT_{ma} (°C)	DT_{mg} (°C)	Global radiation, G_r (MJ m^{-2})	Thermal energy from the back cover, E_c (MJ m^{-2})	E_c/G_r (%)
January	10	25	12	8	237	15	6
February	11	30	20	11	343	22	7
March	13	37	21	15	372	31	8
April	13	36	18	15	343	32	9
May	15	42	19	17	405	36	9
June	15	49	21	21	374	47	12
July	15	52	21	20	396	44	11
August	14	53	20	19	400	41	10
September	13	46	18	17	376	36	10
October	12	39	17	16	348	35	10
November	10	32	13	10	268	20	8
December	10	25	11	8	210	14	7

shading). On the contrary, in studies carried out at low latitude sites (Granada, Spain) and when solar radiation was reduced by more than 40 compared to outside, total and commercial tomato yield reached the highest values. In this latter study, the yield reduction due to shading probably appeared to have been offset by combined application with cooling (fogging) [64]. Similar results were found in another study on the effects of shading with netting (0%, 35%, 51% or 63% shade) in Egypt [65], which showed that greater shading of the tomato crop boosted total production by 50%.

As regard the supplementary lighting system, nevertheless it was designed with a limited power and used only in winter, the energy consumption of the lamps was slightly higher than the energy produced in the same period by the PV panels above the supplied experimental areas. The cost of the energy consumed was considerably higher than the entire income of the marketable production achieved. In addition, the artificial light did not positively affect the low crop productivity, even with an integration close to 100%, supplied during the first cycle. The yields were lower than the average yearly values of 13 kg m^{-2} obtained on cherry tomato using HPS lamps [66], thus with an increase up to 3 kg m^{-2}, compared to the yield with natural light (5–10 kg m^{-2}). This was probably due to the insufficient hours of additional irradiation supplied. In fact, by using the correlation between yield and PPFD, the effect of the supplementary lighting can be estimated in 0.12 kg m^{-2} and 0.11 kg m^{-2}, respectively after the first and second cycle. These values were considerably lower than the standard deviation observed on the resulting crop yield of both cycles (0.7 and 0.6 kg m^{-2}), resulting in a negligible statistical difference, compared to the experimental areas without additional PPFD. Therefore the supplementary light in PV greenhouses is not profitable both under an agronomic and economic point of view, because the energy cost can hardly be covered by an adequate increase of crop productivity and the energy consumed is not available for powering other users. Improving the light conditions inside PV greenhouses by using an artificial light source may have effects only increasing power and hours of irradiation, thus consuming more energy than that produced by the PV array.

4.3. Considerations on the agronomic sustainability of the photovoltaic greenhouse

The advantage of greenhouses with 50% of the roof area covered with PV modules is mainly related to the huge amount of PV electricity produced. This study demonstrated that the income deriving from the energy production is considerably higher than that resulting from the crops, whose yields are strongly penalized by the modules shading. In fact, the income from PV electricity was estimated up to 67.2 € m^{-2}, while the income from tomato production reached 5.9 € m^{-2}, only in the measured plant rows receiving the highest amount of solar radiation (rows 2). The total cost for heating (2.12 € m^{-2}; oil price 1.06 € L^{-1}) and supplementary lighting amounted to 11.12 € m^{-2}, thus higher than the income from crop production. Consequently, until now the minor role of crop cultivation has led the greenhouse roof to be covered with PV panels as much as possible. However, the local laws compel the grower to succeed and prove income from agricultural activity, hence the need for solutions able to improve the agronomic sustainability of such PV greenhouses, influenced by the reduction of solar radiation and thermal load. The limitation to new PV greenhouse construction was due to their high land use impact (LUI) in agricultural areas, since single installations can involve several hectares. The LUI can be estimated using the total area required, the time of occupation of land and the change in the quality of land for a specific activity [67]. This means that it can be considered negligible when the PV systems are integrated in preexisting greenhouses.

A decrease of the PV power installed on the roof of these PV greenhouses would be a simple answer to the poor crop yield and quality, but it can also increase or compromise the pay-back time of the investment. In fact, the few PV greenhouses reported in literature have been designed with the specific attempt to improve their compatibility with the common greenhouse crops, by covering only a small portion of the roof area, ranging between 8.9% and 12.9%, with yields similar to those achieved in conventional greenhouses [10,11,68,69]. These structures may affect the quality of the marketable production, but they already represent a good compromise between energy generation and crop cultivation. Therefore, these coverage levels should be carefully considered even when adapting preexisting structures.

The increase of the gutter height, the introduction of different installation patterns of the PV panels on the roof, such as the checkerboard scheme, or the installation of PV panels also on north-facing roofs, may contribute to a better distribution of the shading on the canopy without reducing the installed PV power [27,69,70].

Furthermore, some promising PV technologies, such as the flexible PV and thin films, the semi-transparent PV panels, the spherical micro-cells, the CIS and CIGS (copper, indium and gallium diselenide) semiconductors, can increase the amount of solar light entering the greenhouse [71–74]. Other solutions include the application of selective plastic films on the greenhouse cover, reflecting the near infrared radiation (NIR) and transmitting the PPFD inside. The roof acts as a solar concentrator, which reflects the NIR radiation on a focal line where the PV cells are placed [75,76]. Although most of these technologies have been specifically developed for greenhouse applications, they are often expensive and still require further investigation for testing the performance on the field and the impact on the crops.

In the already existing greenhouses with 50% PV coverage, the only way to increase the internal irradiation seems to be either the partial removal of PV panels or their allocation on N and S roofs. Both solutions, which require additional investments, reduce the electricity production, but allow a better shade distribution, thus reducing the impact on the crop growth and development. In this study, the solar radiation distribution showed that the greenhouse areas with less light reductions were those under the plastic covers, mainly the portions close to the side walls, as expected. In multi-span greenhouses, the span facing S always receives a slightly higher irradiation and may contribute to a higher crop productivity, compared to average greenhouse crop yields. As for the cultivation period, the best lighting conditions of the year can be found in summer under the transparent covers, while the performance of a crop in winter could be compromised by the lack of natural light. This consideration implies that the seasonality heavily affects the productivity of the crop, depending on the position of the plant inside the PV greenhouse [10]. Furthermore, the variability of the microclimate in PV greenhouses in terms of solar radiation may cause a heterogeneous crop water demand on the cultivation area, deriving from different transpiration rates. This aspect requires a specific crop management, such as a different distribution rate of mineral solution among the plant rows.

5. Conclusions

Nevertheless high persistent shading levels should be avoided in protected cultivation, PV greenhouses with 50% coverage already represent a considerable part of the PV greenhouse area in southern Europe. This study quantified their occurring reduction of solar radiation, which was averagely 64% on yearly basis, up to 82% for the areas under the PV covers, and 46% under the transparent covers. This condition decreased the yield of tomato if compared to conventional greenhouses, but generated a huge income from PV energy. The performed characterization of the solar radiation distribution provides the decision support information for choosing the most suitable crops to cultivate when 50% of the roof area is covered with PV panels. Some solutions for designing new PV greenhouses or adapting existing structures are suggested, considering the plant physiology and the economic convenience of the investment. The variability of the microclimate in PV greenhouses may cause different crop water demand, thus requiring a specific crop management, which can include a different distribution of mineral solution between the plant rows. Furthermore, the high humidity rates and the agrochemicals could affect the long-term life of the PV arrays integrated on the greenhouse roofs. All these aspects can help to improve the information for supporting the grower, thus contributing to make the PV greenhouse capable of producing income from both electric power and agricultural activity.

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