Analysis of internal shading degree to a prototype of dynamics photovoltaic greenhouse through simulation software

Alvaro Marucci, Danilo Monarca, Massimo Cecchini, Andrea Colantoni, Andrea Cappuccini

Department of Agriculture, Forests, Nature and Energy, University of Tuscia, Viterbo, Italy

Abstract

In recent years the use of photovoltaic panels as cover materials for greenhouses developed a great interest due to the state's incentives obtainable by such applications. Shading caused by these elements inside the structure appears to be often too much for the normal development of agricultural activity. In this study it was analyzed the behaviour of shading caused by the photovoltaic panels inside a prototype of dynamic photovoltaic greenhouse whose particularity lies in the possibility of rotation of the panels along the longitudinal axis. The panels' rotation allows varying shading degree in function of some parameters such as latitude and the different solar angles. In order to avoid any reflection losses due to imperfect inclination of the photovoltaic panels, 24 highly reflective aluminium mirrors were prepared with the objective of recovering the portion of solar radiation otherwise lost by reflection. For the study it was used the simulation software Autodesk® Ecotect® Analysis which allows to analyse the path of the shadows during the day and throughout the year for any latitude considered. For this study it was analyzed shading with the panels in a horizontal position. It was also analyzed the evolution of the percentage of shading simulating different latitudes. The results obtained show a great variation of the shading degree inside the structure during a single day and during the year. We can conclude that integrating this analysis with the energy balance it is possible to study the behaviour of photovoltaic greenhouses in order to integrate the energy production from renewable energy sources and agricultural production.

Correspondence: Alvaro Marucci, Department of Agriculture, Forests, Nature and Energy (D.A.F.N.E.), University of Tuscia, via S. Camillo de Lellis, snc 01100, Viterbo, Italy.
Tel.: +39.0761.357365 - Fax: +39.0761.357453.
E-mail: marucci@unitus.it

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Introduction

The greenhouses for crop production, widely diffused in the Mediterranean agricultural scenery, are structures that ensure continuity of the crops' production for the entire year regardless of external climatic variations. These structures exploit the greenhouse effect created inside them to reach and maintain the values of the different climatic parameters on the appropriate levels for the needs of plants. Environmental control in terms of light (Ioslovich, 2009), water (Katsoulas *et al*., 2006), air temperature (Sethi and Sharma, 2008), relative humidity (Kim *et al*., 2008), CO_2 concentration (Korner *et al*., 2007) and ventilation (Bartzanas *et al*., 2004; Fatnassi *et al*., 2004) is regulated in greenhouses to improve yield and quality of crops (Yano *et al*., 2010).

These agricultural structures are used in the areas of central and northern Europe, where the open field cultivation of horticultural species, for much of the year, is difficult because of the unfavourable climate (Sonneveld *et al*., 2010a), and in the regions of southern Europe, where it is necessary to protect plants by drops in temperature (Stanghellini, 1987) that occur occasionally in the cold season (mostly at night).

During the coldest months in Mediterranean areas, the greenhouses face overheating problems during the day and excessive cold at night. Greenhouse heating is one of the most important and essential requirements for better growth during coldest period and especially during cold nights (Attar *et al*., 2013; Attar *et al*., 2014).

The agronomic research, the construction technology of the greenhouses and the selection of transparent cover materials are now oriented to try to reduce the use of energy artificial both to contain the production costs and to reduce the environmental impact (Campiglia *et al*., 2007; Marucci *et al*., 2011; Marucci and Pagniello, 2011).

In the Mediterranean areas the intensity of solar radiation reaching the Earth's surface at certain times of the year is often excessive in relation to the plants' needs so as to cause increment in internal air temperature to levels not tolerated by crops (Jolliet and Bailey, 1992; Medrano *et al*., 2005b) and by those who must operate (Marucci *et al*., 2012b; Marucci, 2013).

To ensure protection against thermal and energy excesses are used shading screens (Lorenzo *et al*., 2003; Medrano *et al*., 2005a) placed on the roofs of greenhouses, cooling systems of the type fog cooling (Katsoulas *et al*., 2009; Villarreal-Guerrero *et al*., 2012b; Sánchez-Hermosilla *et al*., 2013) or, more simply, an increase in natural ventilation (Ganguly and Ghosh, 2009; Villarreal-Guerrero *et al*., 2012a, 2012b) through large openings or resorting to mechanical ventilation with electric fans (Bournet and Boulard, 2010; Coomans *et al*., 2013). All these solutions entail a considerable increase of the construction and operation costs.

Systems for the control and management of air-conditioning and irrigation, as well as systems for handling of pallets and for the ventilation openings, use large amounts of electricity. Summing also that used in areas dedicated to post-harvest management, all the energy consumption of farms appears significant (Banaeian *et al*., 2011; Banos *et al*., 2011; Omid *et al*., 2011; Joudi and Farhan, 2015).

Consequently a sustainable plant production in the greenhouse should minimize the consumption of energy and compensate for the energy consumed with renewable energy (Bot *et al*., 2005; Yano *et al*., 2009; Yano *et al*., 2010). So the biggest problem in Mediterranean areas is to try to reduce significantly the solar radiation penetrating into the greenhouse in warm periods. This reduction can reach values also very high (more than 80%) but it is conditioned by the needs of the cultivated plants that, for their biological activity, always need to well identified quantitative and qualitative levels of light (Hurd, 1983; Kittas and Bailie, 1998; Kittas *et al*., 1999; Lamnatou and Chemisana, 2013).

Solar radiation rejected by passive means of protection could be more conveniently used for other purposes having available appropriate means of collection and processing. Among these means particular interest are photovoltaic panels (PV) for converting a rate of solar energy into electricity.

In recent years, many researchers have studied the use of photovoltaic panels to provide electricity for the air conditioning of the greenhouse (Al-Ibrahim *et al*., 2006; Rocamora and Tripanagnostopoulos, 2006; Al-Shamiry *et al*., 2007; Campiotti *et al*., 2008; Sonneveld *et al*., 2008; Nayak and Tiwari, 2009; Yano *et al*., 2009; Ganguly *et al*., 2010; Sonneveld *et al*., 2010a, 2010b; Yano *et al*., 2010; Sonneveld *et al*., 2011; Lopez-Marin *et al*., 2012; Kadowaki *et al*., 2012). The results obtained are often favourable to the production of energy from photovoltaic elements but the shade created by them inside the structure appears to be excessive for a normal development of agriculture.

The search of other materials for the production of photovoltaic energy in substitution of silicon (Hailin *et al*., 2009; Shin *et al*., 2010; Marucci *et al*., 2012a; Marucci *et al*., 2013a, 2013b) and that are partially transparent to solar radiation shows the possibility of applying such PV materials on the roofs of the greenhouses, achieving the dual positive effect of reducing the radiation inside the greenhouse during periods of thermal excess and of using the surplus to produce electricity (Marucci *et al*., 2012a; Marucci *et al*., 2013b).

The goal of this research is to evaluate by simulation the possibility of using a prototype of dynamic photovoltaic greenhouse as a passive cooling system through the study of the variation of the shading degree inside the structure with PV panels in horizontal position.

Materials and methods

For the simulation it was used the prototype of dynamic photovoltaic greenhouse located at the experimental farm *N. Lupori* of the University of Tuscia in Viterbo (Lazio, Italy, 42° 25' 38'' N, 12° 04' 51'' E, 306 m above sea level). The prototype was made of iron and glass with polycarbonate end caps and has an EW orientation with photovoltaic surface south facing. The orientation is a fundamental parameter for the production of photovoltaic energy and in the northern hemisphere the optimum is south (Hartner *et al*., 2015).

The shape of the cross section is asymmetrical in order to ensure a greater surface to the photovoltaic elements (no. 24) (Figure 1).

The dimensions of the prototype are:

- Length: 3.79 m
- Width: 2.41 m
- Ridge height: 2.05 m
- Eaves height (south wall): 0.94 m
- Eaves height (north wall): 1.36 m
- Photovoltaic surface: 8.15 m^2
- Photovoltaic pitch slope (south): 33°
- Not photovoltaic pitch slope (north): 51°
- Glass thickness: 3 mm.

The prototype's particularity is the possibility of rotation of the photovoltaic panels along the longitudinal axis. The panels' rotation allows you to vary the degree of shading inside the structure due to the panels according to the weather conditions and the needs of the crop. You can then take into account the period of cultivation, the crop type and the parameters that influence the solar radiation: time of day, day of the year, latitude, altitude and degree of cloud cover. In order to avoid eventual reflection losses due to imperfect inclination of the photovoltaic panels, 24 highly reflective aluminium mirrors were provided with the objective of recovering the portion of solar radiation otherwise lost by reflection. The mirrors are always oriented according to the sun's trajectory in order to minimize the shading caused by them both inside the structure that on the photovoltaic panel.

A principle of the sustainable building design, which is based on the concept of geometry solar (Szokolay, 2007), provides that the dimensioning of any external arcades must be realized in such a way that during summer periods will prevent the entrance of solar rays inside the structure avoiding the increase in internal temperature and during the coldest periods instead will allow the entry of the rays so that it exploits the heat of the sun as partial heating.

On the basis of this principle it was thought to analyse the behaviour of internal shading to the prototype in the case wherein the panels were horizontal.

For this purpose it was used the simulation software Autodesk® Ecotect® Analysis. This software for sustainable architectural design is a complete analysis tool and can provide a wide range of capabilities for simulation and energy analysis aimed at improving the energy performance of existing buildings and new construction. It allows studying the positioning of the shadows of a given structure by displaying position and path of the sun for any date, time and latitude (Figure 2).

For this purpose, the variations in the internal shading degree were

Figure 1. Prototype of dynamic photovoltaic greenhouse.

examined during the fifteenth day of each month of the year at 12:00 when the angle of solar elevation is maximum in the day.

Subsequently it was simulated the variation of the shading degree during the year obtained with the panels in a horizontal position, as done previously, varying the latitude of the site. In this regard we simulated three different case studies that represent areas with latitude of about 42° N (Viterbo), 52° N and 62° N.

Results and discussion

Figures 3 and 4 show simulations performed to analyse the variation of the shading's degree inside the prototype during the year by examining the fifteenth day of each month at 12:00 when during the day the sun elevation angle is at the peak. In order to do this it was taken into account only the part of light entering from the cover thus excluding the light part that penetrates from the sidewalls and from polycarbonate walls.

Figure 5 shows the shading percentages obtained from simulations comparing the area shaded by photovoltaic panels inside the structure with the total projection of the roof. By the results obtained and shown in Figure 5 it can be seen how the behaviour of shading follows the principle of sustainable building previously mentioned. During the coldest months (January, February, November and December) the shading percentage obtained with the panels in a horizontal position is lower or at least approaching 40%, allowing a greater introduction of solar radiation and at the same time a rise in internal air temperature during periods of increased need for heat.

During the spring and autumn the shading percentage obtained was variable between 55% and 65%.

During the summer, instead, shading obtained was always greater than 70% up to a maximum of 79% (June) allowing also a probable lowering of the internal air temperature.

From these results it is possible to envisage the use of this structure as a protection system able to improve the internal microclimate, not just with a significant energy saving, but also with the possibility of producing energy from renewable sources to power any electrical systems present.

Subsequently, was simulated the effect of panels' rotation on the shading degree, by rotating them at 10° intervals. For this simulation were considered 12:00 of days related to the summer and winter solstices and the spring and autumn equinoxes.

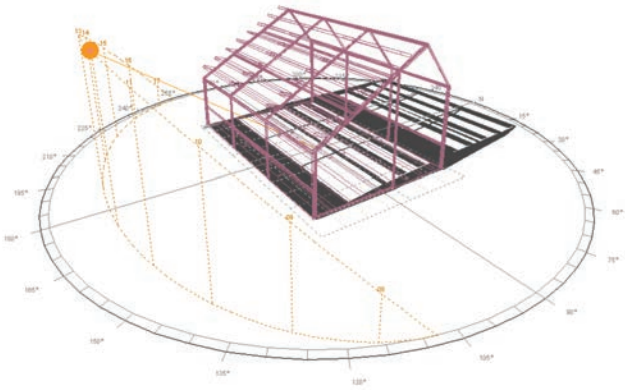

Figure 2. Example of the shadows analysis by means Autodesk® Ecotect® Analysis.

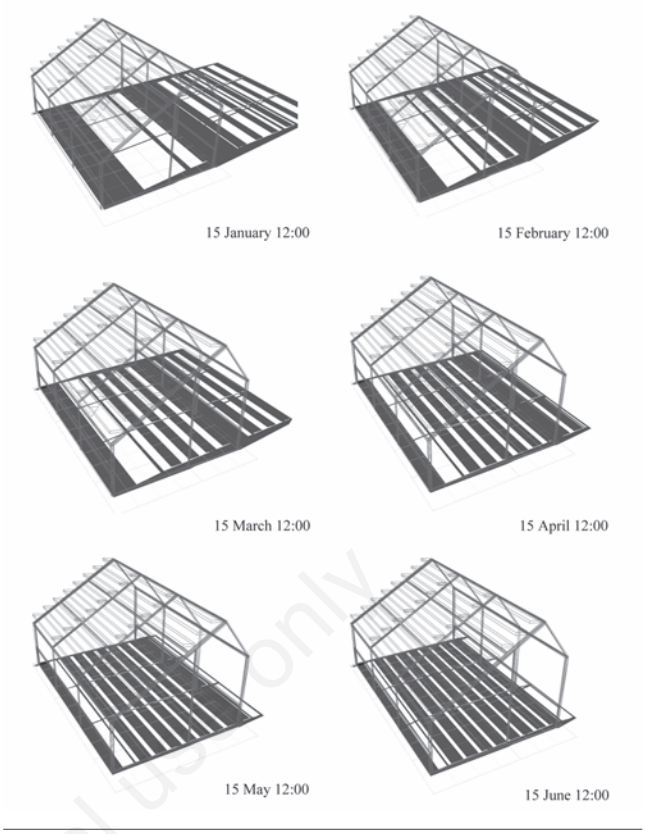

Figure 3. Elaborations by means Autodesk® Ecotect® Analysis of developments in the shadows during 6 months (January-June).

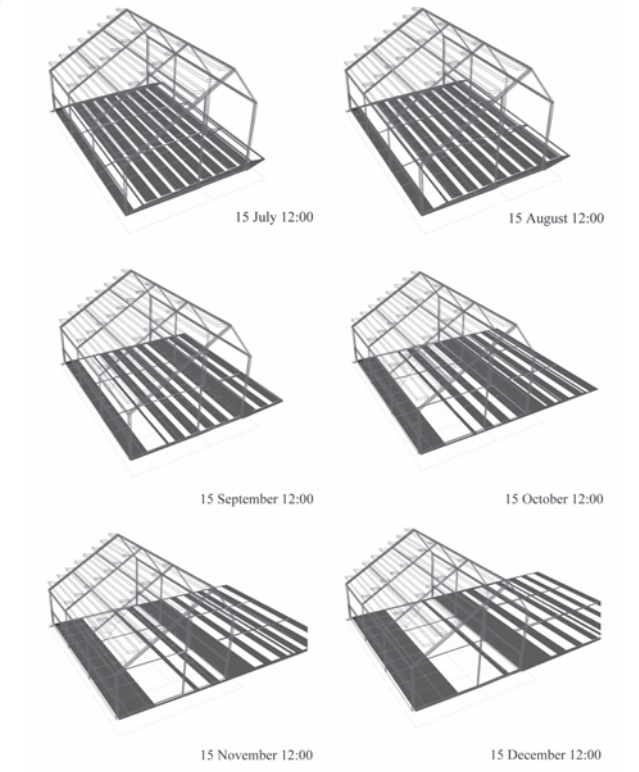

Figure 4. Elaborations by means Autodesk® Ecotect® Analysis of developments in the shadows during 6 months (July-December).

During June, increasing the angle of inclination of the panels from a horizontal position (30°) in steps of 10° was obtained a steady decrease in shading degree of about 8% for each 10° of rotation. Conversely, by rotating the panel towards the flap, the shading percentage increases by 2% every 10° of rotation. During the equinoxes increasing the angle of inclination of the photovoltaic panels at 10° intervals, was obtained a decrease of the shading degree of 12%. By decreasing the inclination, the shading percentage increases of 8-9% for every 10° of variation. During the winter solstice increasing the angle of inclination of the panels at 10° intervals was obtained a steady decrease in the shading percentage of about 16% for every 10° of rotation. By turning the panel towards the flap, the shading percentage increases of 12% every 10° of rotation.

In Table 1 are reported the hourly percentage values of the shading degree obtained with panels in horizontal position at 42° N latitude relative to the fifteenth day of each month of the year.

The variation in the degree of shading is rather significant considering different times of day along the same month, but even more so when one considers the monthly variations.

At this latitude, in the coldest months, the daily differences between

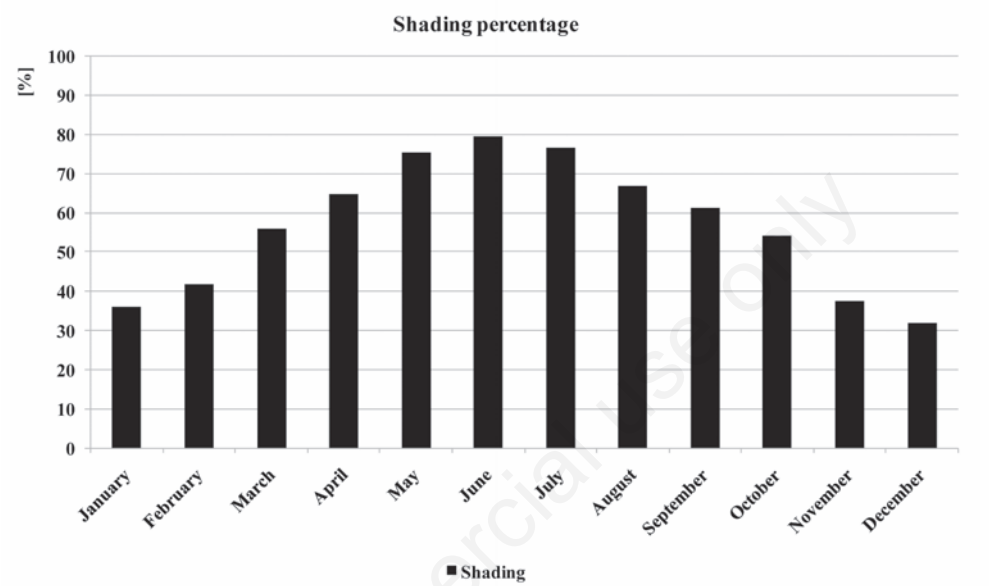

Figure 5. Shading percentages obtained from processing.

Table 1. Annual trend in the shading percentage at latitude 42°.

	42° latitude											
h	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
3												
4												
5					7	13	11					
6				15	25	30	28	20	4			
7		3	19	31	39	42	40	35	25	10		
8	12	23	34	43	49	51	50	46	38	27	15	8
9	26	34	43	52	57	59	58	54	47	38	28	23
10	34	42	50	58	64	66	65	61	54	45	36	32
11	39	46	54	63	69	72	70	66	58	49	41	36
12	40	48	56	64	71	74	73	67	59	51	42	38
13	39	46	54	63	69	72	70	66	58	49	41	36
14	34	42	50	58	64	66	65	61	54	45	36	32
15	26	34	43	52	57	59	58	54	47	38	28	23
16	12	23	34	43	49	51	50	46	38	27	15	8
17		3	19	31	39	42	40	35	25	10		
18				15	25	30	28	20	4			
19					7	13	11					
20												
21												

minimum and maximum values vary between 28% and 45%, while in spring and summer this difference results to be between 50% and 65%.

Considering the shading degree achieved at 12:00 of each month, when the sun elevation angle is the greatest in the day, you can see the variation in this parameter. It varies from 38% achieved in the month of December to 74% in June.

Increasing the latitude of 10° the trend remains the same but the difference between the maximum and minimum percentages along the same month is reduced (Table 2).

The shading hourly average percentage variations along each month are more or less extensive depending on the season under review. For example in autumn-winter the difference in shading percentage varies

Table 2. Annual trend in the percentage of shading at latitude 52°.

	52° latitude											
h	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
3												
4						4						
5					13	20	17	5				
6				16	28	32	31	22	4			
7			16	31	39	42	41	35	23	4		
8		16	30	41	48	50	49	44	35	21	5	
9	16	28	39	49	55	57	56	52	43	32	20	13
10	25	35	45	54	60	63	62	57	49	39	28	22
11	30	39	48	58	64	67	66	61	52	43	32	27
12	31	40	50	59	65	69	67	62	54	44	34	29
13	30	39	48	58	64	67	66	61	52	43	32	27
14	25	35	45	54	60	63	62	57	49	39	28	22
15	16	28	39	49	55	57	56	52	43	32	20	13
16		16	30	41	48	50	49	44	35	21	5	
17			16	31	39	42	41	35	23	4		
18				16	28	32	31	22	4			
19					13	20	17	5				
20						4						
21												

Table 3. Annual trend in the percentage of shading at latitude 62°.

	62° latitude											
h	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
3						6	2					
4					9	17	14					
5				4	21	27	24	12				
6				18	30	35	33	24	5			
7			11	29	39	43	41	34	19			
8		4	23	37	45	49	47	41	29	11		
9		16	31	43	51	54	53	47	36	22	4	
10	8	23	36	48	55	58	57	51	41	28	13	4
11	14	27	39	50	57	60	59	54	44	32	18	9
12	15	28	40	51	58	61	60	55	45	33	19	11
13	14	27	39	50	57	60	59	54	44	32	18	9
14	8	23	36	48	55	58	57	51	41	28	13	4
15		16	31	43	51	54	53	47	36	22	4	
16		4	23	37	45	49	47	41	29	11		
17			11	29	39	43	41	34	19			
18				18	30	35	33	24	5			
19				4	21	27	24	12				
20					9	17	14					
21						6	2					

between 15% and 40% while in spring-summer seasons this difference increases and it is between 40% and 65% with the maximum value obtained in June (65%). At 12:00, the maximum shading degree was obtained in June (69%) and the minimum in December (29%).

In winter, at a latitude of 62° N (Table 3), the hourly average difference of the shading degree undergoes a sharp reduction (7-30%) also due to the duration of the daylight during this period. Conversely, during summer season, when the days present even 20 h of light, the shading percentage variations varies between 40 and 60%.

At 12:00 the maximum shading degree was obtained in June (61%) and the minimum in December (11%).

Conclusions

Through this analysis, it is possible to study the behaviour of photovoltaic greenhouses to any latitude and then to reconcile the agricultural activity and the production of energy from renewable sources in all seasons and in any place but taking into account that the optimum tilt angle of the photovoltaic panels is related to crop needs and energy production and varies depending to the latitude.

The horizontal position of the panels can be a great advantage especially in Mediterranean areas where, because of the high levels of solar radiation it is necessary to protect crops against energy and thermal excess. Conversely, in the regions with greater latitude where the problem of greenhouses is to perceive a greater quantity of solar radiation, the presence of photovoltaic panels turns out to be a great disadvantage because of their shading action.

By relating the optimum tilt angle for photovoltaic production with various solar angles and energy needs of the crops in production, it is possible to study the optimum position of the panels in order to reconcile the production of energy with agricultural production, bearing in mind that the main goal of these structures is the agricultural production. Further studies will be addressed by integrating this simulation with the energy balance of this structure in the presence of various crops more or less demanding in terms of light and energy and correlating the results obtained from the simulations with the values obtained from the prototype.

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