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Dynamic photovoltaic greenhouse: Energy balance in completely clear sky condition during the hot period

Alvaro Marucci*, Andrea Cappuccini

DAFNE, University of Tuscia, Via San Camillo de Lellis s.n.c., 01100 Viterbo, Italy

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ABSTRACT

In this study, the energy balance for a prototype dynamic photovoltaic greenhouse was determined for days with completely clear skies during the summer. The rotation of photovoltaic panels along the longitudinal axis was the unique feature of the prototype. Inside the greenhouse, the degree of shading most suitable for the requirements of the crop, the cultivation period, the latitude of the site and the climatic conditions was selected by the rotation of the panels. To avoid energy losses from the reflection caused by unfavourably positioned photovoltaic panels, the panels were provided with highly reflective aluminium mirrors.

To evaluate the possibility of using the dynamic photovoltaic greenhouse prototype as a passive cooling system, the energy balance was determined. Based on the results, the use of photovoltaic elements offers an alternative perspective for both the shading of greenhouses and the production of electricity in periods of heat and in areas with a warm climate.

With planning that considers the type of crop, geographic coordinates, length of the cultivation period and local weather conditions, the use of this structure can reconcile agricultural production with the production of energy from renewable sources.

1. Introduction

In recent years, cultivation in greenhouses has expanded worldwide [1] because of the high level of production obtained in these structures compared with production in the field [2].

With control of the internal greenhouse environment, production increases because the greenhouse is almost independent of the external weather conditions. Additionally, the microclimate inside the structure can be programmed through simulation models to meet the cultivation requirements.

Models that predict the microclimate inside a greenhouse are a fundamental tool used by farmers to manage the production cycle of a crop and by designers to provide improvements in climatic control systems [3].

Inside the greenhouse, the microclimatic parameters of air temperature [4], relative humidity [5], level of light [6] and concentration of CO_2 [7] affect not only the quality and productivity of the cultivated crop [8,9] but are also critical factors that affect the spread of pathogens and diseases [10]. Furthermore, with the control of these parameters compared with external conditions, farmers can increase or decrease the cultivation time to increase the economic competitiveness of the farm.

In the first research to analyse the energy balance in greenhouses [11–13], the focus was on the thermal behaviour of the structure. Subsequently, many models of energy balance were developed to understand the relationships between internal microclimatic parameters and external climatic and some construction parameters (e.g., section shape and covering material, among others) [14–23].

Simulation models are widely used to predict greenhouse environments because these models are faster, cheaper and more flexible than the predictions based on experiments [3,24].

The characterization of the energy balance for a greenhouse in each bioclimatic zone of the world is fundamental to assess the feasibility of the system and to improve the control of the internal microclimate. Moreover, the construction characteristics of the structure and the mechanical systems for microclimatic control are significantly affected by geographical factors such as latitude.

In the countries of northern and central Europe, which are characterized by cold winters and low levels of solar radiation [1],

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* Corresponding author. Tel.: +39 (0)761 357365; fax: +39 (0)761 357453.
E-mail address: marucci@unitus.it (A. Marucci).

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Nomenclature

Alphabetic symbols

R	global solar radiation [W m^{-2}]
RT	heat transfer due to radiation [W m^{-2}]
T	heat transfer due to transmission [W m^{-2}]
E_V	heat transfer due to ventilation [W m^{-2}]
n	Julian day
K	thermal transmittance (W m^{-2} °C^{-1})
V	flow rate of ventilation (Kg Dry Air h^{-1})
H	enthalpy (KJ Kg Dry Air^{-1})
x	weight of water vapour in air (Kg water Kg Dry Air^{-1})
p	pressure (Pa)
f	view factor
h	hour days
A	altitude (km)
C_d	diffusivity coefficient of the cover
S	thickness of the cover
n	refractive index
k	absorption coefficient
r	surface reflectance

Subscripts

e	external
re	reflected external
i	internal
ri	reflected internal
b	direct
d	diffuse
c	cover
rg	reflected from the ground
ag	absorbed by the ground
ac	absorbed by the cover
g	ground
ia	internal air
atm	atmosphere
sky	vault of heaven

Greek letters

ω	solar hour angle (°)
δ	declination angle (°)
α	solar altitude angle (°)
θ_i	solar incidence angle (°)
θ_z	solar zenith angle (°)
ν	angle between the horizontal projection of the surface normal and the direction south (°)
φ	latitude of the location (°)
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})
ε_{12}	emissivity
τ	transmittance
ρ	cover reflectance
α_c	absorbance

Venlo greenhouses have been developed almost exclusively. In these countries, greenhouses must minimize the loss of heat through the use of glass and a favourable volume: surface ratio, in addition to exploiting most of the diffuse radiation with eaves high in the structures.

By contrast, the requirements of greenhouses for regions of the Mediterranean are the opposite; in these regions, the "Mediterranean greenhouse" is used, with a large spread of plastic for a covering material (providing cover for over 90% of the floor area). The energy used to create favourable microclimatic conditions is contributed primarily by solar energy. Externally supplied energy is used only during short cold periods (mostly at night) [25,26] and when the plants must be protected from excessive heat by lowering the temperature [27]. In some periods, lower temperatures are necessary because the intensity of solar radiation reaching the surface of the earth exceeds the requirements of crops and increases the internal air temperature to intolerable levels [28,29].

Although the protection of plants from intense solar radiation is relatively easy with shading [30], the protection from high air temperatures is difficult to achieve with only natural ventilation [31].

To prevent excessive internal air temperatures, ventilation with cooled air (e.g., evaporative filters, and others), use of water mist or complete opening of the cover (sky system) is required. However, for all these remedies to control high temperatures, external energy is required, with a significant increase in production costs.

Therefore, in this study, the energy balance of a prototype dynamic photovoltaic greenhouse with different degrees of shading during days in the summer with clear skies was evaluated. For the Mediterranean latitudes, these conditions are the most critical in the evaluation of a greenhouse.

The cover of the structure that faced south was covered with photovoltaic panels. The panels were rotated along the longitudinal axis to adjust the shading inside the greenhouse, and the different degrees of shading were caused by the projection of shade from the panels inside the greenhouse. With this arrangement, it may be possible to balance the production of photovoltaic energy with that of agriculture.

In studies of the photovoltaic greenhouse, a degree of shading that was fixed too high reduced the growth, development and productivity of the crops, whereas a degree of shading that was fixed too low substantially reduced the production of electrical energy. With the analysis of the energy balance, the possibility of using the dynamic photovoltaic greenhouse as a passive cooling system and simultaneously producing energy from renewable sources was assessed.

The following percentages of shading were analysed:

- 0%;
- 10%;
- 20%;
- 30%;
- 40%;
- 50%;
- 60%;
- 70%;
- 75%;
- 78%.

The zero percent shade referred to the shade caused by the thickness of the photovoltaic panels (3%). The maximum shading was 78% because of the spacing of the photovoltaic modules, which allowed 22% of the solar radiation to enter the greenhouse when the panels were parallel to the cover.

Furthermore, the shading was measured on each date at 12:00 p.m.; because the degree of shading changed continuously during