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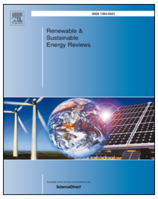

Assessment and comparison of the solar radiation distribution inside the main commercial photovoltaic greenhouse types in Europe

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ABSTRACT

The application of the photovoltaic (PV) energy to the European greenhouse industry has led to installations designed to maximise the energy production but detrimental for the greenhouse crops, due to the effect of shading of the PV panels on the roof. To assess these issues, the first step is to characterize the PV greenhouse microclimate, especially in terms of solar radiation at canopy level. After a comprehensive review of the current state-of-art of the PV greenhouse sector, four representative commercial PV greenhouse types are compared, with a percentage of the area covered with PV panels (PV cover ratio) ranging from 25% to 100%. The aim is to define the general relations between the main design parameters (PV cover ratio, greenhouse height and orientation, checkerboard pattern) and the available solar radiation, to provide original information on the design of next-generation PV greenhouses with improved agronomic sustainability. The yearly global radiation decreased averagely by 0.8% for each additional 1.0% PV cover ratio and increased by 3.8% for each further meter of gutter height. The N-S orientation increased the average cumulated global radiation on the greenhouse area by 24%, compared to the E-W orientation. Both the checkerboard pattern and the N-S orientation improved the uniformity of light distribution. All PV greenhouse types are provided with light distribution maps to evaluate the light variability on the greenhouse area. The light distribution is crucial to support adequate agronomic plans for both preexisting and new PV greenhouses, aiming to sustainable mixed systems for both energy and crop production.

1. Introduction

1.1. The troubled story of the photovoltaic greenhouse

The increasing energy demand for food production covered with fossil fuels causes both environmental and socioeconomic impacts which can be challenged with the application of the renewable energy sources in agriculture. Among these sources, the photovoltaic (PV) energy has been definitely the most successful one, due to the progress of the technology in the recent years, the durability, versatility, low carbon emissions and the relative low cost for maintenance in the long term [1–3]. The farmer is supposed to produce agricultural commodities, therefore the production of other goods or services, such as the electric energy, should be considered only a supplement to his income and a reduction of the production costs [4,5]. The application of the PV technology to protected agricultural systems led to the “PV greenhouse”, in which the PV panels cover partially or totally the roof area in different arrangements and designs. The principle of the PV greenhouse was to establish a particular mixed and balanced PV/crop system to meet the energy demand of the farm and support the competitiveness of the greenhouse company by producing income from both energy and crop production on the same land unit [6,7]. The PV array on the roof should produce enough energy to power on greenhouse electrical appliances and integrate the income, limiting the shading on the underneath crops to avoid yield losses and preserve the quality of the products.

The PV greenhouse has spread in Europe mostly due to the public European Union (EU) programmes for PV energy incentivisation. Italy has been the EU country with the widest and fastest diffusion of the PV greenhouse mainly due to the former national scheme for PV energy

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Nomenclature

OP	Observation point
CV	Coefficient of variation
R^2	Coefficient of Determination
I_d	Direct radiation ($W\,m^{-2}$)
I_f	Diffuse radiation ($W\,m^{-2}$)
G_{GR}	Cumulated global radiation on the PV greenhouse compared to conventional greenhouse (%)
I_{GR}	Cumulated global radiation on the OP ($W\,m^{-2}$)
I_G	Conventional greenhouse global radiation on horizontal plane ($W\,m^{-2}$)
m	Number of OP on the greenhouse area
τ	Greenhouse average transmissivity
G_{GRExt}	Cumulated global radiation on the PV greenhouse area compared to external radiation (%)
I_O	External global radiation ($W\,m^{-2}$)
I_R	Reflected radiation from the ground ($W\,m^{-2}$)
I_T	External global radiation on tilted plane ($W\,m^{-2}$)
E_{PV}	Yearly energy production of the photovoltaic system (kWh)
d	Day
p	Atmospheric transmissivity coefficient
N	Total number of photovoltaic modules
A	Photovoltaic active module area (m^2)
η	Conversion efficiency of the photovoltaic module
a	Albedo coefficient
α	Tilt angle of the photovoltaic modules (°)
BOS	Balance of System

production called "Conto Energia", in force from 2007 to 2014 through high tax-free feed-in tariffs, that led the country to the fifth place in the world for installed PV power (and the second in EU) with 19.2 GWp, among which 2.0 GWp are dedicated to agriculture [8,9]. Nowadays, the installation of PV systems on greenhouses is rapidly expanding in China (first country in the world for PV power) through similar public subsidy policies, due to the impressive amount of greenhouse area available and the need for reducing the competition of land use between PV energy and agricultural production [10–13].

Despite the mentioned principles that led to the concept of PV greenhouse, most structures were realised by multinational companies with an excessive proportion of the greenhouse area covered with PV panels (PV cover ratio), to maximise the profits generated by the incentives and the energy sold to the public power company. The agricultural land is usually cheap compared to other land-use destinations, pulling the investors to looking for agricultural lands for PV power plants and speculate on the public incentives [14]. However, since some EU countries have restricted the installation of PV systems on the ground in agricultural areas, the PV systems have been installed on new rural and agricultural buildings, among which the greenhouses were the cheapest solution. For this reason, nowadays PV greenhouses are often characterised by large-scale installations based on few typologies (PV greenhouse types), also occupying marginal and abandoned land once dedicated to conventional agriculture. This aspect posed the problems of the competition between land uses for energy towards food production. The same issue emerged also in the "agrivoltaic" systems, thus open fields with PV arrays installed above the crops, where the dual use of the land can be estimated using the Land Equivalent Ratios (LER), thus the land area required in different scenarios of integration of PV energy and crops on the mixed system [15–17].

The main problem of the PV greenhouse concerns the environmental and agricultural management. For example, in Italy there is a remarkable difficulty in mapping and managing such installations at national level [18]. The consequent lack of official statistical information on the magnitude of the PV greenhouse sector does not allow to set appropriate management plans, increase its agronomic sustainability at large-scale level and assess the land consumption and the environmental, economic and social impact on the territory. The actual PV greenhouse installations created the same environmental impact in terms of soil sealing, landscape deterioration and speculation peculiar of ground-based PV systems in rural landscapes [19–23]. The shading of the PV array on the roof penalizes the crop growth and productivity and the greenhouse agricultural management. Many installations are currently underutilized or empty: the PV greenhouse turned from a potential opportunity of relaunching disadvantaged agricultural territories and farms to speculative investments with a considerable environmental impact on agriculture. Given the lack of knowledge and agricultural experience, these new PV farms preferred to concentrate on the PV energy production and did not invest in the agricultural infrastructures for efficient greenhouse cultivation [24]. The competitiveness of the PV greenhouse is strictly dependent on the public incentives, that will decrease and expire in the next future. For this reason, the research in the PV greenhouse sector is focusing on identifying solutions to improve its agricultural sustainability and profitability without incentivisation, attempting to turn it into an efficient mixed system where agricultural and energy production combine together. These objectives can be pursued with the optimisation of the PV greenhouse design, new semi-transparent PV technologies specific for greenhouse installations, prototypes of next-generation PV greenhouses and identification of suitable crop species with low light requirements [25].

1.2. Photovoltaic technologies and design criteria of photovoltaic greenhouses

Previous studies already highlighted the tall greenhouse gutter height, the homogenous distribution of the PV panels on the roof (also using checkerboard patterns) and the vent design as important design parameters for new PV greenhouses and tunnels [7,26,27]. The radiometric and thermal properties of the greenhouse cladding material affect the spectral distribution of the solar radiation and the internal microclimate [28–30] and therefore, they should be considered in the design, also depending from the considered crops.

The semi-transparent PV technologies are considered strategic to increase the solar radiation inside the greenhouse, including both prototype and commercial PVs that can be adapted or specifically introduced in greenhouse systems, like the spherical solar silicon microcells, in which the spherical shape can use both the direct radiation and the reflected radiation from the greenhouse floor [31,32]. Other solutions for greenhouse integration are the organic PV cells, the CdTe (Cadmium telluride), the CIG (Copper indium gallium) and CGIS (Copper indium gallium diselenide) semiconductors, the flexible amorphous PV and thin films [14,33–36]. In addition, Fresnel lenses and parabolic concentrators were studied to concentrate the direct solar radiation on the PV cells (also using selective thin films), reducing the cooling load during summer time and letting the diffuse radiation enter the greenhouse [37–42]. The concentrating PV modules have been suggested for greenhouse systems to reducing the PV system size for the same power output, which decreases the capital cost and contribute to reduce or avoid the daylighting related problems such as the loss of color and smaller size of the fruits [7,43]. The PV energy produced in greenhouse systems has been studied to supply energy for climate control, i.e. heating, cooling and ventilation, in a sustainable way [6,44–48]. This is required also to manage the cooling effect of the shading and the thermal energy released by the PV modules, which dissipate about 50% of the incoming solar radiation into heat [49]. Some trials and prototypes of heat exchangers, hybrid PV/thermal (PV/

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