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A combination of agricultural and energy purposes: Evaluation of a prototype of photovoltaic greenhouse tunnel

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A B S T R A C T

The recent increasing attention in energy production from renewable energy sources has led to photovoltaic (PV) elements, being located on greenhouse roofs. However, their assessment is almost underdeveloped in Italy. The present paper investigated the lack of a spatial database of PV greenhouses in Italy. The first aim is to detect the evolution of PV panels on the roof of greenhouses during several Energy counts (E.C.).

The succeeding goal instead aims to examine the shading of PV panels of a prototype greenhouse that enables an environmentally adapting to the intrinsic characteristics. The shading on crops is one of the major limits for the PV installation on the roofs of greenhouses because it causes problems regarding the usual sequence of agricultural activity. Until now many studies applied PV panels as covering material of greenhouses concentrated on flat structures. The present study investigates tunnel greenhouses which, due to their curved shape, do not lend themselves to accommodate easily PV panels on their coverage.

The shading variation was analysed inside our prototype greenhouse, by installing PV panels in a checkerboard arrangement. The transparent flexible PV panels, with dimensions of 1.116 m × 0.165 m, are manufactured using mono-crystalline silicon cells, with an efficiency of 18%, incorporated into polymers with high resistance. The difference and distribution of the shading percentage were examined regarding the surface area affected by the PV roof, the total area and the section of the greenhouse. Particularly, variations in the percentage of shading and the size of the shaded area have been observed on the twenty-first day of each month of the year.

Results exposed some consistency in the shading percentage, primarily because of the curvilinear shape of the section of the greenhouse. From mid-March to mid-September, the shading was practically and constantly inside the greenhouse during the daytime; while it was partly inside and partly outside the tunnel greenhouse during the remaining months. The percentage of shading with the PV arrangement adopted never exceeds 40% during the year.

1. Introduction

Agricultural land loss and abandonment, excessive rate of land consumption and sealing soil represent some of the recent challenges in Europe [10,32,73]. For this reason, the European Union introduced policies and strategies for evolving a greater awareness towards sustainable attitudes and therefore by taking renewable energies the main role both in the primary and energy sector [27]. An example can refer to the evolution of the photovoltaic (PV) industry: the latter has rapidly spread in recent years thanks to the European energy policies but above all to favourable subsidy policies for their installation [12,17,5,70,74]. Given their strong diffusion, PV plants constitute an element of the modern Mediterranean landscape in Europe [29]. Many studies have focused on PV systems in Italy, as they allow substantial energy saving, rural multi-functionality and diversification of farmers' income [47,77,78] and guarantee a suitable economic perspective under the new Italian regulatory framework [44]. On the other hand, the installation of ground-based PV systems has involved the use of rural land for energy purpose, resulting into an increase of soil sealing, landscape deterioration, speculative activities and other negative environmental and biodiversity effects in rural landscapes [11,25,29,39,47,75]. So, since 2013 they have been banned on agricultural soils, promoting their mounting only on existing structures, such as urban buildings [23] or rural greenhouses [22,37].

Based on these premises, the present paper firstly aimed to combine agricultural and energy purposes into a unique built-up structure. PV panels installed on greenhouses can represent an original chance for agriculture and the energy sector regarding renewable energies

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[63,77,78]. This opportunity has interested several areas around the world (e.g. [4,38,41,62,72]) such as Italy (e.g. [20,22,27,28,70]).

Greenhouse structures, even if they are required to minimize potential drastic temperature changes [51], define important activities to the primary sector, also permitted by favourable geographical and climatic conditions and highly-quality production and technology [24,33,68,69]. Literature is rich in studies due to a wide availability of surfaces designated to greenhouse activities in Italy [67]. Only over the past few years, greenhouses have been used for sustainable purposes, such as integrating them into systems to produce renewable energies [48,50]. One of these is to use solar radiation to produce energy and heat [33]. PV plants can be placed on the roofs of greenhouse structures, leading to a new and diversified sustainable profile for agriculture [20,4,52,54–57,70,77,78]. Given the versatility of such technology and the ability to integrate PV panels on the roofs and facades of already existing buildings [15], several benefits can be achieved [34]. Nevertheless, national and regional administrations have deliberated limitations to avoid possible speculative occurrences concerning PV mounted on greenhouses. For example, the incidence of the rural income should be equivalent (or higher) than the income originating from energy production, when the PV power exceeds 200 kWp (or the percentage of PV coverage), whose ground projection must not be greater than 50% of the total greenhouse area [36].

The transformation of the solar radiation into electrical energy has a twofold advantage: (i) recovery of the excess solar radiation in the greenhouse and (ii) production of electricity from renewable sources without negative environmental effects [49,51]. In some the hottest periods of the year, Italy is characterised by an excess of solar radiation if compared with the real requirements, reaching 50% of the incident radiation under the best conditions [48]. Despite the couple formed by photovoltaic energy and greenhouse structures presents many benefits, research is moving to design new systems that optimizes both energy and rural production [26,53,82]. In fact, several issues emerge associated to the effect of shading and the coverage of fertile soils in greenhouses [35]. The spatial distribution of shades is an essential parameter for choosing the best combination of PV panels and crops [14,3,31,38,46,72,79].

Furthermore, one of the biggest problems encountered on these latest innovations, enabling multi-functionality, is the difficulty to manage and locate, at the national level, greenhouses on which PV plants are installed. Greenhouses and PV systems have not yet been mapped in a suitable database in Italy [82]. Additionally, research studies have been limited to study contexts only at local scale (e.g. [71,27,62,77,78,50,70]), without ever considering a larger scope. According Zambon et al. [82], currently an overall spatial database for predicting and monitoring the evolution process of the greenhouses, photovoltaic and their integration does not exist in Italy. The first purpose of our article is to define the evolution of the PV mounted on greenhouse roofs, according to Energy count (E.C.). The latter allowed to place Italy, in 2009, to occupy the second position in the world rankings for the newly installed photovoltaic power. In fact, the advent of E.C. has guaranteed the affirmation of PV technology in Italy through a highly profitable and innovative incentive mechanism [34].

The second goal of this paper was to examine the shading of PV panels of a prototype greenhouse, placed in Viterbo (in Central Italy) that enables an environmentally adapting to the intrinsic characteristics. The shading on crops is one of the major limits for the PV installation on the roofs of greenhouses because it causes problems regarding the usual sequence of agricultural activity [62,77,78]. Until now, many research activities applied PV panels as covering material of greenhouses concentrated on flat structures (e.g. [8,64,53]). The present study investigated tunnel greenhouses which, due to their curved shape, do not lend themselves to accommodate easily PV panels on their coverage. The shading variation was analysed inside our prototype greenhouse, by installing PV panels in a checkerboard arrangement. The transparent flexible PV panels are manufactured using monocrystalline silicon cells, with an efficiency of 18%, incorporated into polymers with high resistance. The difference and distribution of the shading percentage will be examined regarding the surface area affected by the PV roof, the total area and the section of the greenhouse. Particularly, variations in the percentage of shading and the size of the shaded area will be observed on the twenty-first day of each month of the year, in order to observe the percentage of shading with the PV arrangement adopted during the year.

2. Materials and methods

2.1. Case study

Viterbo is a central Italian city of about 70,000 inhabitants in the Latium region. Its province is also known by the name of Tuscia [30]. It is bordered to the north-west by Tuscany (provinces of Grosseto and Siena), by Umbria on north-east (Terni province), by the province of Rieti on the east, by the capital city of Rome on the south and by the Tyrrhenian Sea on the west. The city is located at 326 m above sea level, with an area of 406.23 km^2. The slight slope, on which stands the city centre, extends west to the Maremma plain.

Depending on its weather and solar radiation, Viterbo belongs to the zone D according the climate classification (on average 1501 kW/h a year). The latter catalogued zones the Italian municipalities according to the climatic classification, introduced by the Decree of the President of the Republic no. 412 of August 26, 1993, concerning the Rules for Designing, Installing, Operating and Maintaining the Thermal Installations of Buildings for Containment of Energy Consumption, in implementation of art. 4, paragraph 4, of the Law of 9 January 1991, no. 10. The weather in Viterbo is closely related to that of the neighbouring areas of southern Tuscany, clearly differentiated from the southern part of the Latium region [13]. The climate is temperate and affects the influence of the sea. The summers are hot and the winters are usually quite mild. Rainfall is largely concentrated in the fall and spring months with an average annual precipitation of about 800 mm, while the average annual temperature is 14.4 °C. Despite some episodes of dispersive urbanisation processes, Tuscia has maintained intact its agricultural landscape throughout time, which is still the driving force of its economy [83].

2.2. Statistical and spatial data

As a first point, the issue of the situation of PV plants on greenhouse structures in Italy was addressed and discussed. Thanks to its favourable geographical position and climatic features, greenhouse structures and PV fields have been widely dispersed in Italy, identifying a relevant production quality and technology progress [50]. The study area considered has a significant presence of greenhouses dedicated to the cultivation of vegetables: if compared with the national context, the Latium region records approximately 20% of the surface (both total and in production) and of the total production (ISTAT census).

Available statistical databases are disposed by the National Institute of Statistics (ISTAT) and the Italian Energy Services Manager (GSE), with annual report. At regional level, GSE provides an Italian census regarding the number and the power installed (in kW) of PV plants on greenhouses for each E.C. during the last years. However, PV greenhouse plants have never been used as a landmark for the spatial analysis at the national scale [82]. Despite the statistics of ISTAT and GSE, currently geo-referenced elements of greenhouse and PV structures do not exist for the whole Italy. The lack of large-scale spatial information restricts research fields for analyzing the national territory in terms of landscape impact, economy, energy and land consumption. Existing available spatial data concerning PV greenhouses are limited to local-scale study contexts (e.g. [77,78,27,70,62,71]); or furthermore, last research activities about greenhouses did not consider their spatial distribution, focusing for example on the spatial illustration of the