Applied Energy 365 (2024) 123232

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Estimation of maximum photovoltaic cover ratios in greenhouses based on global irradiance data

Natalie Hanrieder [a,*], Anna Kujawa [a], Ana Bendejacq Seychelles [b], Manuel Blanco [a], José Carballo [c], Stefan Wilbert [a]

[a] German Aerospace Center (DLR), Institute of Solar Research, Calle Doctor Carracido N°42, 04005 Almería, Spain
[b] Agroécologie, INRAE, Institut Agro, Univ. Bourgogne Franche-Comté, 21000 Dijon, France
[c] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Plataforma Solar de Almería, Ctra. de Senes s/n, 0 4200, Tabernas, Almería, Spain

HIGHLIGHTS

- Method to estimate the maximum photovoltaic cover ratios for plastic greenhouses.
- Analysis of CAMS global radiation data to estimate the DLI inside greenhouses.
- Derivation of maximum PV cover ratio for different minimal DLI thresholds.
- Comparison with experimental results for plastic greenhouses from literature.

ARTICLE INFO

Keywords:
Agrivoltaics
Photovoltaic
Horticulture
Mediterranean region
DLI data series

ABSTRACT

In this study, a method for estimating the maximum PV (photovoltaic) cover ratio for plastic greenhouses based on various years of global horizontal irradiance (GHI) data is presented and illustrated with an exemplary site in southeastern Spain. CAMS (Copernicus Atmosphere Monitoring Service) GHI data from 2005 to 2023 were analyzed to estimate the DLI (daily light integral) inside the greenhouses for various PV coverage ratios with East-West or North-South orientation. The conversion from GHI to photosynthetically active radiation is performed with the usage of a regression model from literature based on satellite and measurement data. The shading effect of the PV cover is estimated with a regression model from literature based on radiation distribution simulations in different greenhouse types. The maximum PV cover ratio was derived for different minimal DLI thresholds, corresponding to different crops. The proposed methodology has been tested for the Almería region in southeastern Spain which is characterized by high solar irradiance and can be applied also to other regions with similar climatic conditions. With a required DLI of at least 12 mol/m^2/day, a theoretical maximum PV coverage of about 44% is acceptable even in December at the studied site for East-West orientation, while it reaches up to 100% (June) during the year. Further, the maximum PV cover ratios for a DLI threshold range have been calculated and compared with experimental results for plastic greenhouses from literature. In 87.2% of the case studies analyzed from literature, the proposed method showed an agreement in the estimation of the effect of PV shading ratios on marketable crop yields. The study indicates that significant PV cover ratios are theoretically possible even for light demanding crops considering DLI thresholds only and can help to select a useful PV cover ratio in PV greenhouses.

1. Introduction

Combined land use for agriculture and electricity production with photovoltaic (PV) modules is a promising way to meet the increasing demand for food and energy. This is especially true in regions with low land availability or high solar radiation. Horticulture of fruit and vegetables accounted for around 14% of the total value of agricultural production in the EU in 2018. This sector is of fundamental importance for many EU countries, especially in the Mediterranean region and in northern and eastern European countries. Horticulture and fruit farms accounted for around 7% of the 10.5 million agricultural holdings in the

---

* Corresponding author.
E-mail address: nataliehanrieder@dlr.de (N. Hanrieder).

https://doi.org/10.1016/j.apenergy.2024.123232
Received 19 September 2023; Received in revised form 10 February 2024; Accepted 12 April 2024

Nomenclature

CAMS	Copernicus Atmosphere Monitoring Service
CR_i	PV cover ratio of experiment *i*
$CR_{scaled, i}$	Scaled PV cover ratio of experiment *i*
DLI	Daily light integral
E-W	East-West
G_A	GHI sum at the studied El Ejido site
GHI	Global horizontal irradiance
G_i	GHI sum of test sites
N-S	North-South
PAR	Photosynthetic Active Radiation
PSA	Plataforma Solar de Almería
PV	Photovoltaic

EU in 2016 [1]. Direct payments under the Common Agricultural Policy (CAP) are the main form of EU-funded support for the agricultural sector and they are paid as aid per hectare (according to economic, environmental and administrative criteria). Fruit and vegetable producers cultivate comparatively small areas of land intensively, therefore, this type of support is less critical for horticultural enterprises in comparison to open-field cultivation. Combining horticulture and PV in “PV greenhouses” can therefore diversify farmers income and reduce dependence on the highly volatile market for horticultural products. It can also reduce dependence on rising energy prices through PV production and self-consumption of electricity and heat [2].

The here presented study outlines a methodology for estimating the maximum PV cover ratio of PV greenhouses, which can be also applied in different parts of the world to develop localized studies. This would be particularly valuable for regions facing similar challenges related to sustainable agriculture and energy-efficient greenhouse practices. The aim of this study is to present the theoretical method with the help of one exemplary case study.

In this manuscript, a site in the region of Almería (Southern Spain) is used as an example to illustrate the application of the method. The province of Almería in Southern Spain is known for an intensive implementation of plastic greenhouses which makes horticulture one of the most important industrial sectors of the region (about 33 kha). 99% of the installed greenhouses in Almeria use flexible plastic sheets to cover the greenhouse (see Fig. 1) [3]. In Almería, irradiation levels surpass the optimum levels for the cultivated crops during some periods throughout the year that they have to be actively reduced e.g. by so-called “whitewashing” during parts of the crop cycles to avoid harm to the plants. When whitewashing, the greenhouse roof is usually painted with white paint. 99% of farmers in Almería increase the solar reflection coefficient of the greenhouse cover by whitewashing [3]. The whitewashing aims to reduce the radiation and the temperature in the greenhouse by adjusting the transmittance of the greenhouse cover according to the crop needs. Farmers decide individually when and how often whitewashing is necessary. The decision is based on personal experience, observation of plant development and the age and light transmission of the plastic cover. For this purpose, in most cases, micronized calcium carbonate is used. To adjust the transmittance of the greenhouse cover, the concentration of calcium carbonate in the water is adjusted. Usually, whitewashing is done at the beginning of each crop cycle (e.g. one in August and another one between February and April). When the global radiation decreases at the end of autumn or beginning of winter, the farmers clean the greenhouse cover [3].

In the literature, the effects of artificial shading by PV modules on greenhouses for horticulture have been studied [e.g. 4, 5, 6, 7, 8]. For example, [4] summarized recent studies at different locations on the effects of PV shading on crop production to establish a relationship between growth indicators, crop quality, and the degree of PV shading. The main findings in [4] were that solar radiation reduction is the most important influencing factor and that agrivoltaic systems (PV greenhouse or ground) with 25% or less coverage have no significant effect on plant growth and quality. At coverage levels of 50% to 100%, growth-inhibiting effects on plants were observed, with the exception of strawberries and spinach. Although these results are highly correlated with the radiation conditions at each site. According to [5], further crop-specific studies are needed to determine the optimal shading ratio of PV modules that will not affect agricultural production. Microclimatic changes under the PV modules are expected to become critical at high shading ratios. In [8], the crop growth model TOMGRO has been coupled with a climate model to estimate the effect of PV shading on tomato crop yields in two different greenhouse types. The authors of [6] summarized a comprehensive review on opportunities for the implementation of solar energy technologies in agricultural greenhouses. In the publications [10–22], several experimental studies on artificial shading in greenhouses and the according effect on crop growth are described. The results of these studies will be discussed in detail in Section 3.2. In [7], the progress and challenges of integrating semi-transparent PV technologies were reviewed in open (farmland) and closed (greenhouse) agricultural photovoltaic systems. Crystalline silicon, thin-film photovoltaics, organic PV, dye-sensitized solar cells, concentrating PV, and luminescent solar concentrators were considered. In their study, Gorjian et al. [7] emphasized the critical importance of finding optimal locations for agrivoltaic systems, as well as the design of PV systems to maximize power generation and ensure ideal irradiation

Fig. 1. Horticultural region “Campo de Dalías” in the province of Almería, Spain. Source: AdobeStock 254,499,538 and 438,584,983.

conditions. These factors are key considerations for the successful integration of photovoltaic systems in agriculture.

To assess these issues, the microclimate in the PV greenhouse must first be characterized, especially with respect to solar radiation at the height of the canopy. To evaluate the solar distribution in PV greenhouses, [9] compared different commercial greenhouse types (monopitched roof, Venlo type, and gable roof) for both east-west (*E*-W) and north-south (N-S) orientations and performed numerical simulations for PV cover ratios between 25% and 100% to derive a linear correlation between the cumulated global radiation in the greenhouse and the PV cover ratio.

Several experimental studies on horticultural crops have been carried out to measure or estimate crop productivity in PV greenhouses, which also depends on the climatic conditions of the site. For example, at the exemplary site for this study, the Almería region in southern Spain, [10,11] analyzed the effects of flexible PV modules mounted in two different patterns on an "Almería-type" greenhouse (so-called "raspa y amagado" greenhouse). [12] studied the effects of PV modules on microclimate and tomato yield in a Canarian greenhouse in Agadir (Morocco). In [13], different levels of shading and their effects on tomato yield and fruit quality were tested.

Although these studies already show important initial investigations of Agrivoltaics, further studies are needed to assess the full potential of implementing Agrivoltaics in this intensively horticultural region to complement the single case studies already available in literature. Moreover, it is particularly interesting to look at different crops and also several years of data in order to consider possible variations from year to year. In this study, the theoretical maximum PV cover ratio for PV greenhouse designs for the province of Almería is discussed based on Daily Light Integral (DLI) evaluations estimated from a satellite-based irradiance database for the last 18 years. Analysis of multiple years of data allows for an examination of year-to-year variability for a site. Such an analysis has not previously been found in the literature. In Section 2, the methodology is described and the analyzed data as well as the considered greenhouse configuration is presented. Section 3 discusses the results for the region of Almería as well as a comparison with experimental results found in the literature. Section 4 gives a summary and an outlook. The paper focuses on the interplay between solar radiation, greenhouse technologies, and crop productivity and these findings can be adapted to regions with comparable environmental characteristics in terms of solar radiation levels.

2. Methodology and data processing

In this section, the methodology of the proposed method is explained. An overview of the separate steps can be seen in Fig. 2 and they are described in details in Sections 2.1–2.5.

2.1. Satellite data source CAMS

For the development of the methodology, solar radiation time series from the Copernicus Atmosphere Monitoring Service (CAMS) Radiation Service version 4.5 database [23–26] have been analyzed for the test site of the Almería region. CAMS Radiation Service provides time series of global radiation on the horizontal surface (among other parameters). It covers −66° to 66° in both latitude and longitude which is the field of view of the Meteosat satellites. Data is available operationally starting in February 2004 and until 2 days before the current day with a temporal resolution of 1 min and a horizontal resolution of 3 km at nadir. Data is interpolated to the chosen coordinates. The CAMS products are quarterly benchmarked against ground stations to monitor the consistency and detect possible trends. Details on the quality control in the operational processing chain of the CAMS products can be found in [25]. One of the regular benchmarking sites is CIEMATs' Plataforma Solar de Almería (PSA), which lies around 50 km of the exemplary site of interest in this study.

For this study, the global irradiation on the horizontal plane at ground level from CAMS for the site of El Ejido, Spain (latitude 36.74043°N, longitude 2.74968°W) from January 2005 and January 2023 have been extracted, interpolated and analyzed. To apply the here proposed methodology for other sites, CAMS data can be utilized according to the data availability within the Meteosat satellites' field of view. For regions outside this field of view, any other data source for the horizontal global solar radiation can be chosen.

2.2. Derivation of DLI from global horizontal irradiance satellite data

To estimate the Photosynthetically Active Radiation (PAR) outside the greenhouse from the broadband Global Horizontal Irradiance (GHI), the regression model according to [27] has been used. This model has been developed using satellite-derived broadband GHI and PAR estimations for mainland Spain and has been validated against ground measurements. For the validation site of CIEMATs' PSA, a correlation coefficient higher than 0.99 has been found by [27] as well as a mean bias error of −2.36% and a root mean square error of 2.8 W/m^2. The regression model of [27] enables an estimation of PAR in W/m^2 from GHI in W/m^2 using eq. 1:

$$PAR = a^{*}GHI + b \tag{1}$$

The coefficients *a* and *b* are given in [27] and are dependent on the region for which the regression model is used. For this study and the region of Southern Spain, the coefficients of [27] in Table 1 are applied.

The regression model of [27] has been validated for two other sites within Spain with daily ground measurements for two years. One validation site in Northern Spain showed an average underestimation (mean bias error) of PAR by about −2.36%. This underestimation is partly explained in [27] by the error of the satellite-derived GHI. The

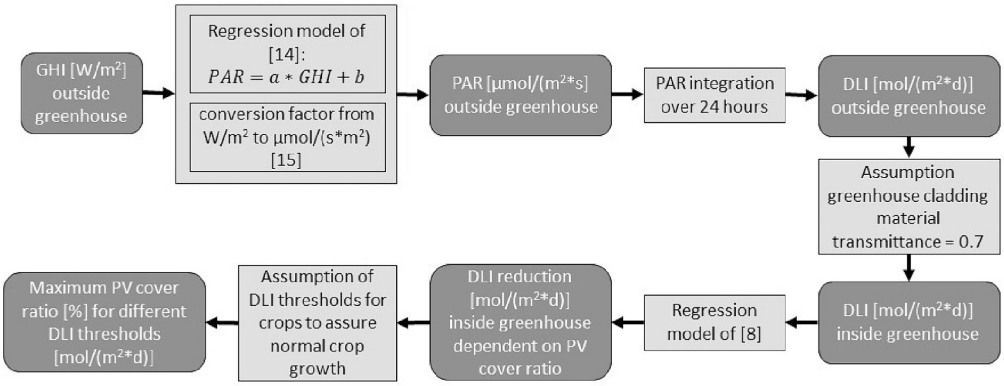


Fig. 2. Flow chart to describe proposed method to derive maximum PV cover ratios for different DLI thresholds from GHI data.

Table 1
Values of slope and intercept coefficients a and b of regression model of [27].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
a	0.42	0.42	0.41	0.41	0.38	0.39	0.36	0.39	0.39	0.41	0.41	0.41
b	0.35	0.49	1.37	2.15	10.94	9.37	18.05	8.63	7.12	2.25	1.45	1.25

conversion factor from broadband GHI to PAR highly depends on the temporal and 3-dimensional distribution of e.g. aerosol particles or water vapor in the atmosphere and therefore the radiation spectrum. A regression model can only supply an estimation of temporal and horizontal averaged GHI to PAR conversion factors. For the site of interest in this study, the correlation coefficient of the model is above 0.99 and the above-mentioned low bias and root mean square error were found. But it has to be noted that the performance of the model might differ for other sites where the regression model has not been validated so far. This has to be considered applying the proposed method in other regions. Alternatively, direct PAR measurements, satellite derived PAR data (like e.g. the Surface Radiation Data Set - Heliosat (SARAH-3) [28]) or other GHI to PAR conversion factors or models can be considered.

To convert from W/m^2 to PAR in μmol/(s*m^2), the conversion factor 4.6 μmol/J of [29] has been used. From the derived PAR, the DLI is calculated. DLI is defined as the number of photons in the PAR spectrum from 400 to 700 nm per m^2 and 24 h [30]. Thereafter, monthly DLI averages are calculated for each year, i.e. also for the entire period analyzed. The simplification of the analysis of monthly mean values instead of daily values could lead to neglecting effects on plant growth. To compensate for these introduced uncertainties in the study, conservative assumptions are made at various points, such as the assumption of transmittance explained below.

In the next step the effect of the plastic cover is estimated. According to [3], most greenhouses in the province of Almería are covered by different materials of flexible plastic films. These materials have transmittances in the visible radiation spectrum between 0.7 and 0.95 [3,9,31–34]. These values generally refer to new and clean plastic films. Aging as well as soiling effects (natural soiling also in connection with white paint residues), which usually lead to lower transmittance values, are not considered explicitly in these studies. For a preliminary assessment within this study of PV greenhouses and considering the uncertainties created by not accounting for aging or soiling effects of the plastic films, we assume a conservative overall transmittance of 0.7 based on [14]. Further, we analyze monthly rather than daily DLI averages. To use the here proposed methodology for other areas, this value has to be adapted according to the predominant materials used at the site of interest. The assumed transmittance reduction due to the PV modules is described in Section 2.5.

2.3. Typical optimal DLI values for different crops

The DLI values which are demanded by each crop for optimal crop growth are given in literature, and have to be selected for the estimation of the maximum PV cover ratio. The growth of plants and thus the reaction of yields to changing radiation conditions are influenced by the amount of radiation such as the radiation integral, the radiation intensity per radiation period and the number of photons absorbed per area and time unit. The amount of radiation also depends on the length of the day, the angle of the sun, the radiation spectrum, the plant density and the structure of the tree canopy [35]. A simple derivation of the crop yield from the irradiation conditions is therefore not straight forward.

In the province of Almería, mainly high light demanding crops, like tomato, cucumber, sweet pepper, eggplant or melon, are cultivated [36]. According to [37,38], varying ranges for optimal DLI values are given for high light demanding crops. Surpassing the according thresholds, reduce e.g. fruit set or flowering quality. Cossu et al. [14] states that the optimal DLI value for high light demanding crops is around 30 mol/m^2/day and the sufficient DLI values lie around 12 mol/m^2/day. On the other hand, e.g. [37] or [38] state that the minimum sufficient DLI level e.g. for tomatoes lies above 8 mol/m^2/day while the maximum DLI level should not exceed 50 mol/m^2/day. During the growing cycle, crops usually demand different DLI levels e.g. for flowering or bud development. Seedling production usually has lower DLI requirements than as the plants develop [35]. For simplification in this study, the demanded DLI levels are assumed constant during the crop cycle.

Therefore, we assume that DLI levels of 12 mol/m^2/day are sufficient for high light demanding crops and 30 mol/m^2/day are optimal as given in [14]. Further, we look at a DLI threshold range between 8 and 50 mol/m^2/day in Section 3.2 to estimate the theoretical PV cover ratio which would not cause the DLI dropping below the given thresholds from [37,38]. In other regions, different crops types might be mainly cultivated which has to be considered accordingly applying the here presented methodology.

2.4. Greenhouse characteristics

To obtain good light availability for the crops and sufficient ventilation and stability of the structure considering wind loads, the greenhouse orientation is usually chosen wisely by the agronomists when designing the greenhouse. In the mid-latitudes, the radiation and length of the days are lowest during winter season. For greenhouses with high roof slopes, an *E*-W orientation of the greenhouse would therefore benefit from a greater solar radiation transmittance in comparison to a N-S orientation in this region [3]. But as the typical “Almería type” greenhouse has an average slope of around 7.2° [3], the differences in transmittance for an E-W or N-S oriented greenhouse are minor. In the province of Almería, usually only passive ventilation windows are installed in the greenhouses. The ventilation would therefore be better if the greenhouse would be perpendicular to the prevailing wind directions, especially during spring and summer when high radiation levels require ventilation of the greenhouse to cool down interior temperatures. Therefore, it is common in the region to orient the axis of the ridge of the greenhouse in N-S direction if the plot allows this orientation [3]. In this study, we analyze the proposed method both for *E*-W as well as N-S oriented greenhouses for the sake of completeness. If the proposed method is to be applied to other regions of the world, the prevailing greenhouse orientation for the region and the roof slope angle must be considered accordingly.

2.5. Estimation of DLI reduction due to PV cover ratio and maximum PV cover ratio

The DLI reduction for a given PV cover ratio can be estimated based on a regression model of [9] which considers transmittance through the roof and the walls based on experimental data and numerical calculations. Using the regression model, the sufficient DLI inside the greenhouse and the DLI outside the greenhouse can be used to estimate a maximum PV cover ratio.

Cossu et al. [9] investigated the relation between PV cover ratios and the actual yearly radiation reduction inside gable roof and Venlo greenhouses at two different heights (0.5 and 1.5 m) above the ground at the site of Decimomannu, Sardinia, Italy (39.33°N, 9°E). The authors present a regression model for this relation which aims to be applicable at locations with similar latitudes which is the case for the site of interest for this study (El Ejido, latitude 36.740430°N).

It has been shown e.g. by [14] that the checkerboard pattern and the N-S orientation improve the uniformity of light distribution within typical greenhouses like gable roof greenhouses or Venlo greenhouses in the Mediterranean region. A 30% PV cover ratio with the checkerboard pattern can result in about 10% higher light homogeneity than an according straight light pattern [39]. Cossu et al. [9] simulated different greenhouse designs as well as PV panel distribution pattern and derived a global regression model for those simulations. In this study, we did not consider different PV pattern, but applied the regression model of [9] for simplicity.

For the purpose of this study, this regression model for the height of 1.5 m above ground has been applied as typically plastic greenhouses in the province of Almería have a lower overall height than gable roof or Venlo greenhouses. Therefore, the estimations for a height closer to the roof might be more representative.

The regression model states, that global radiation inside the greenhouse does not decrease with an inverse quadratic linear proportion to the PV cover ratio, mainly due to the diffuse radiation and the solar radiation entering from the gable and side walls, which is not dependent from the covered roof area [9]. The following equations of [9] to estimate the global radiation (G, in percent) reduction within the greenhouse dependent on the PV cover ratio (CR, in percent) have been adapted for this study and applied to derive the relative DLI reduction (in percent) for E-W- oriented greenhouses:

$$\Delta DLI = -0.0079^{*}CR + 1 \tag{2}$$

and for N-S oriented greenhouses:

$$\Delta DLI = -0.006^{*}CR + 1 \tag{3}$$

For an E-W oriented greenhouse, a DLI reduction of 0.8% per each 1% of PV cover ratio (Eq. 2) and for a N-S oriented greenhouse a DLI reduction of around 0.6% per each 1% of PV cover ratio (Eq. 3) is assumed. In the following, we investigate both E-W and N-S oriented greenhouses to estimate the relationship between PV cover ratios and the yearly radiation reduction.

One disadvantage of the usage of this model for the purposes of this analysis is, that this regression model has not been developed on the basis of radiation data within a plastic greenhouse typical for the province of Almería. But for a first conservative estimate, we assume in this study that such a model can be used to derive the maximum PV ratio which would still guarantee that the DLI thresholds which are considered as sufficient for the different crop types are not surpassed. The here presented methodologies and findings can therefore be further adapted and applied to other areas with similar climate characteristics. The usage of the regression model of [9] for different climates should be done with precaution and it is recommended to perform an on-site validation of the model.

To derive the maximum PV cover ratio for a given site, the long-term monthly averages of the DLI outside the greenhouse are compared to the sufficient DLI to derive the maximum relative DLI reduction for each month. Eqs. 2 or 3 can then be used to derive the maximum PV cover ratio for each month. The month with the smallest resulting maximum PV cover ratio defines the overall maximum PV cover ratio.

3. Results for the exemplary site in El Ejido, Almería, Spain

3.1. Monthly DLI averages, DLI reduction averages and corresponding PV cover ratios

Fig. 3 shows the monthly averages of DLI for the time period January 2005 to January 2023 next to the monthly averages for each month and year. Considering a mean transmittance of 0.7, the estimation of monthly averaged DLI inside a plastic greenhouse in El Ejido is also shown in grey. Further, the DLI thresholds (sufficient, optimal and maximum) for high light demanding crops (according to [14,37,38], see also Section 2.3) are marked in red. It can be seen that between October and February/March the DLI values lie well within the DLI thresholds for high light demanding crops. During the summer months, the mean daily DLI values surpass the light demand. This result fits well to the fact that growers usually additionally decrease the transmittance of the greenhouse roofs during summer months by whitewashing to reduce the incoming radiation.

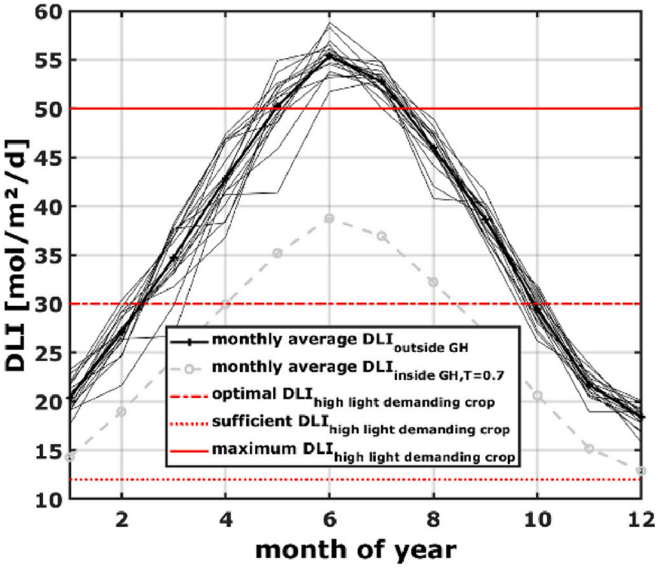


Fig. 3. Monthly averaged DLI for all years (fat black line) and for each year (fine black lines), monthly averaged DLI inside a plastic greenhouse (broken grey line) and the DLI thresholds (optimal, sufficient and maximum) according to [9] (dotted red lines). All results are for the time between January 2005 and January 2023 for the site of El Ejido, Spain. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In Fig. 4, the DLI threshold of 12 mol/m^2/day, which is considered to be sufficient for normal plant growth of high light demanding crops, has been used for the example. The monthly mean of the maximum absolute reduction of DLI is shown for all analyzed years (fat black line) and each individual year (broken black lines). The resulting maximum PV cover

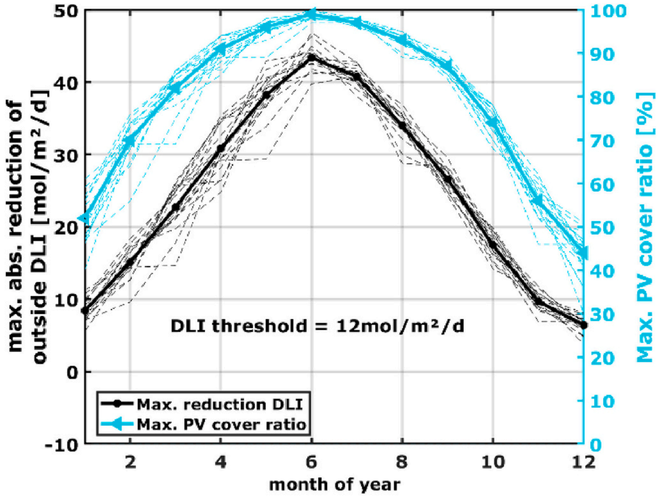


Fig. 4. Monthly maximum absolute DLI reduction for average of all years (thick black curve) and for each year (black broken curves) and corresponding monthly maximum PV cover ratios (average: thick cyan curve; for each year: cyan broken curves) for an E-W greenhouse orientation and for a DLI threshold of 12 mol/m^2/day. All results are for the time between January 2005 and January 2023 for the site of El Ejido, Spain. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ratio according to the regression model of [9] for *E*-W oriented greenhouses is also displayed for each year (broken cyan line) and the average for all years (fat cyan line).

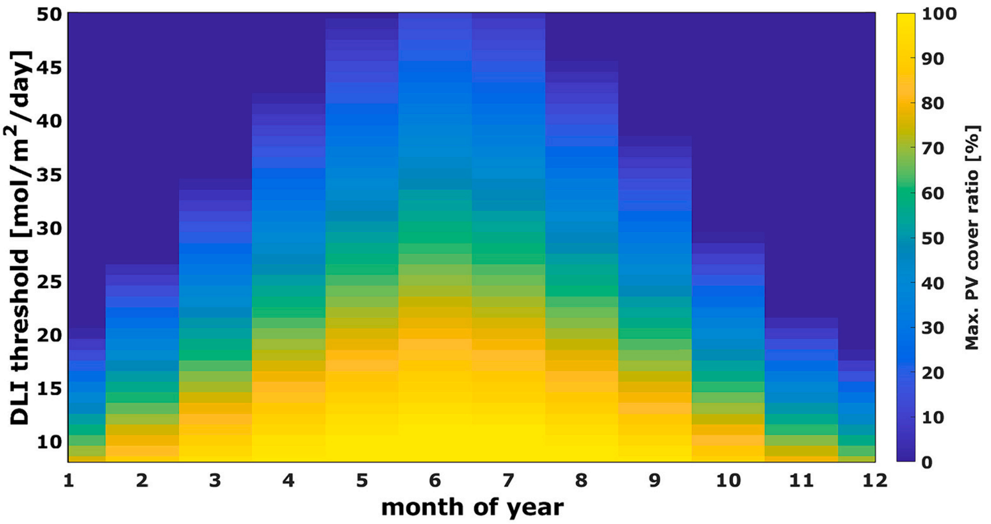
Fig. 5 shows the maximum PV cover ratio for the months of the year and for different DLI thresholds. The E-W oriented greenhouse is shown in the upper, the N-S orientation scenario in the lower plot. In the N-S orientation scenario, higher PV cover ratios are acceptable during more months of the year without causing the DLI values to drop below a certain threshold between 8 and 50 mol/m^2/day. For example, maximum PV cover ratios of 100% might be acceptable for DLI thresholds of 10 mol/m^2/day almost throughout the whole year.

We consider here average monthly values of DLI. However, if the DLI falls below a certain threshold on several days within a month and then rises above the threshold again for several days, this could have an effect on plant growth. For simplification, these possible effects are neglected here. The assumed conservative low plastic cover transmittance compensates for such possible uncertainties. A more detailed study of these effects is planned for the future.

Further, reduced radiation levels have an effect on the microclimate within the greenhouse in terms of e.g. ambient temperature. Shading from PV panels can lead to lower daytime (and potentially also to nighttime) temperatures. These fluctuations can affect plant growth. Changes in temperature also alter the relative humidity within the greenhouse which can have a significant effect on crop development and health and therefore also crop yield quality. For optimal crop growth and development, crops require a specific radiation spectrum. The radiation spectrum under a PV cover may also be altered as the PV panels may absorb or filter out specific wavelength of the radiation. This can affect the quality of the light which is available for the crops. For the sake of simplicity in this study, the effect of PV shading on the microclimate within the greenhouse and the consequences of the changed microclimate on crop yields and quality are neglected.

3.2. *Comparison to results from literature*

In Fig. 6, the overall maximum PV cover ratio calculated assuming the regression model of [9] between January 2005 and January 2023 for the site of El Ejido is shown. This overall maximum PV cover ratio is the lowest monthly averaged maximum PV cover ratio of Section 3.1 throughout the complete year. This analysis has been performed both for the E-W and the N-S greenhouse orientation scenarios and can also be derived from Fig. 5. It can be seen for example, that in an E-W orientation scenario at the site of interest and for a crop which demands at least DLI values of 12 mol/m^2/day for normal crop growth, the maximum constant PV cover ratio throughout the year should not exceed 44%.



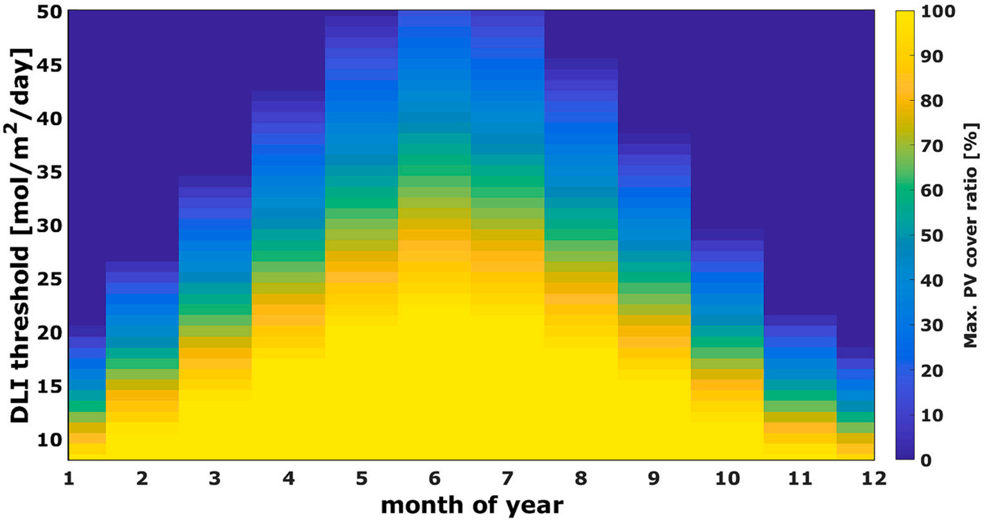


Fig. 5. Monthly maximum PV cover ratios for a DLI threshold range between 8 and 50 mol/m^2/day for the average of all years between January 2005 and January 2023 and the site of El Ejido, Spain. Upper plot: *E*-W oriented greenhouses. Lower plot: N-S oriented greenhouses.

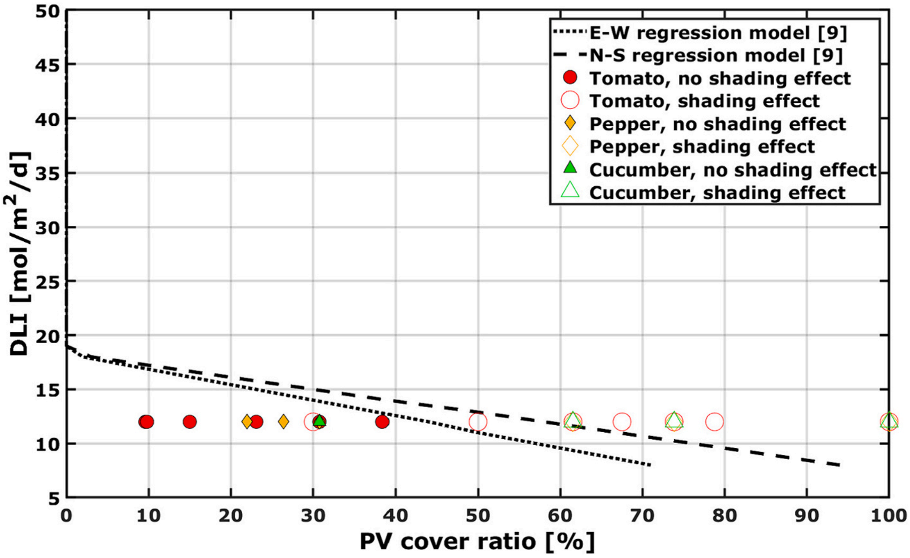


Fig. 6. Dotted and broken line: Maximum PV cover ratio for the corresponding DLI inside a plastic greenhouse between January 2005 and January 2023 for the site of El Ejido, Spain. Circles, diamonds and triangles $CR_{scaled,i}$ according to G_i from the experimental sites for tomatoes, peppers and cucumber. Filled symbols display experiments in which no yield or fruit quality reduction has been observed, non-filled symbols show experimental results where a reduction has been measured.

It is clear from the literature that the optimal DLI level can vary greatly per crop and also during crop development because plant growth depends on several different parameters and therefore no fixed threshold can be clearly defined. In the next thought experiment, we therefore again assume a fixed DLI threshold of 12 mol/m^2/day for tomatoes, peppers and cucumbers as a test. Experimental results from [10–22] for tomatoes, peppers and cucumbers (circles, diamonds and triangles, respectively) for different PV cover ratios have been summarized in [4] and are considered for the following thought experiment. For each site of the experiments, the annual GHI sums have been taken from the Solar World Atlas (https://globalsolaratlas.info). The according data can be found in Table 2.

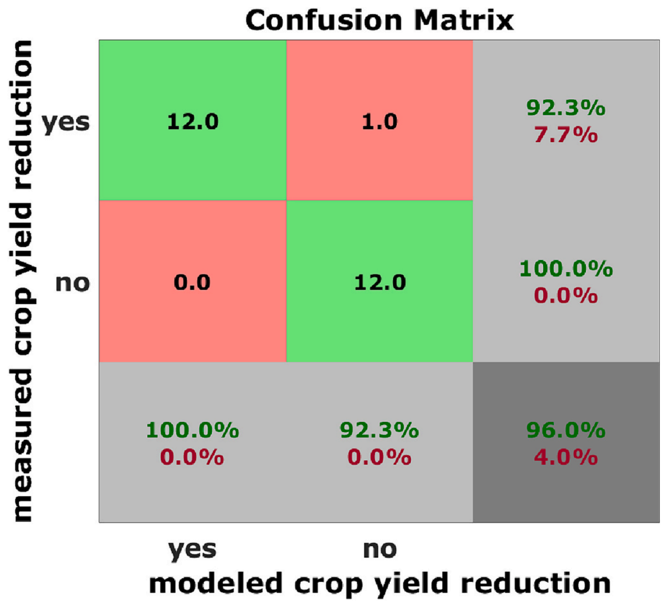
From 2005 to 2022, the average annual GHI sum (G_A) at the in this study exemplary site El Ejido is 1920 kWh/m^2/y according to the CAMS dataset analyzed. In Fig. 6, we scale the PV cover ratio (CR_i) of experiment *i* with the ratio of G_A and the GHI sum of the test sites (G_i) from the experiments found in literature as follows:

$$CR_{scaled,i} = CR_i^{*} \, G_A / G_i \tag{1}$$

Resulting $CR_{scaled,i}$ larger 100% have been set to 100%. The scaling allows the comparison to studies from literature from different sites around the world with the case study presented in this work. Filled symbols in Fig. 6 display experiments in which no yield or fruit quality reduction has been observed, non-filled symbols show experimental results where a reduction in yield or quality has been measured and reported in the according literature. It can be seen that most of the experimental results where no shading effect has been observed are located below the regression model curves of [9], while experiments with observed shading effects are above the regression curves.

Table 2
Experiments analyzed in Fig. 6.

Location	Source	Crop type	PV cover ratio tested [5]	G_I [W/m^2]
Almería (Spain)	[10,11,15]	tomato	9.8	1920
Almería (Spain)	[13]	tomato	15,30,50	1920
Sardinia (Italy)	[16]	tomato	64	1560
Sardinia (Italy)	[14]	tomato, pepper, cucumber	10,25,50,60,100	1560
Merlino (Italy)	[17]	tomato	50	1422
Kumming (China)	[18]	tomato	20	1663
Agadir (Morocco)	[12,19]	tomato	10, 40	2000
Thessaloniki (Greece)	[20]	pepper	22	1600
Southwest Greece	[21,22]	pepper	20	1750



	yes	no	
yes	12.0	1.0	92.3% 7.7%
no	0.0	12.0	100.0% 0.0%
	100.0% 0.0%	92.3% 0.0%	96.0% 4.0%

Fig. 7. Confusion matrix for 25 experimental cases from literature listed in Table 2 for the question: Is there an effect of PV shading on the marketable crop yield? Upper two rows: is there an effect measured in the considered experiments from literature? First two columns from the left: Does the here proposed method with the usage of the regression model of [9] for E-W oriented greenhouses estimate an effect or not for each case from literature? Light grey boxes: In green color percentage for true-positive and false-negative cases. In red color percentage for true-negative and false-positive cases. Dark grey box in lower right corner: Overall performance of model in comparison to measurement results from literature. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

This result is also displayed assuming *E*-W oriented greenhouses in the proposed method in a confusion matrix shown in Fig. 7. From the 25 experimental case studies found in literature and also listed in Table 2, it has been analyzed if for a given maximum PV cover threshold of 44% and a DLI threshold of 12 mol/m^2/day, the here proposed method would estimate a marketable crop yield reduction. In 12 cases, the experiments as well as the proposed method showed a yield reduction. Further, in 12 cases no yield reduction has been found within the experiments neither a yield reduction has been estimated by the proposed method. In totally 96% of the experimental cases, the method estimated the same result (reduction in marketable crop yield/no reduction in marketable crop yield) as found in the experiments. In 4% (1 case study from [13]), the proposed method did not match the results from literature. In the following, some experiments conducted at sites with similar radiation levels are looked at in detail.

In [10,11] and [15], the effect of flexible PV modules mounted in two different patterns on an "Almería type" greenhouse was studied. The PV shading ratio of the experiment was 9.8% and tomatoes were grown in the greenhouse. The main result of the experiment was that the total and marketable tomato production was the same as in the reference zone without PV shading. This result agrees well with the estimates in this study. With a PV shading ratio of about 10%, crops requiring a DLI of up to about 17 mol/m^2/day are not assumed to suffer from the corresponding shading.

In [12], the measurements of an experiment in an *E*-W oriented typical Canarian greenhouse in Agadir (Morocco) were analyzed. A PV cover ratio of about 10% was tested in a checkerboard pattern with the cultivation of tomatoes. Again, no significant effects on microclimate and tomato yield were found in this experiment.

In [13], the effect of different levels of artificial shading (15, 30, and 50% roof cover) was tested in Almería growing tomatoes in a N-S oriented greenhouse. The shading panels have been placed in a linear pattern on the greenhouse roof. It was found that a roof cover ratio higher than 30% decreased fruit quality and color and increased tomato firmness significantly, while fruit pH was not affected by artificial shading. Additionally, early yields have been reduced and the production has been shifted towards the end of the cropping season. For 30% shading, a relevant shading effect concerning fruit color has been observed. In this study, it was found that the given geometry of artificial roof cover reduced the average measured PAR in the greenhouse by about 1.6% for every 1% of artificial cover. Therefore, the corresponding curve in Fig. 6 would have a much steeper slope than the black dashed curve for the DLI reduction model based on the regression model of [9], and the DLI threshold would be exceeded at lower PV cover ratios. In the confusion matrix in Fig. 7, it can be seen that the particular case for a 30% shading ratio is the only true-negative case detected in comparison to the proposed method. According to [39], around 10% less light homogeneity is achieved by a linear shading pattern in comparison to a checkerboard pattern for 30% shading ratios which is considered in the proposed method. Therefore, the discrepancy could be caused by considering different shading pattern.

4. Summary and outlook

In this study, a method to estimate the maximum PV cover ratios for plastic greenhouses has been presented and illustrated with a site in Southeastern Spain. This has been done by analyzing CAMS radiation data from 2005 until 2023. To estimate the according PV cover ratio for an *E*-W or N-S oriented greenhouse from the maximum possible DLI reduction, the regression model of [9] has been used. The here method is illustrated with data for the Almería region and the methodology can be applied to other areas. The findings for the specific site can also indicate the maximum greenhouse PV cover ratio at sites with similar climate. It has been found that e.g. considering a DLI threshold of 12 mol/m^2/day, an E-W greenhouse orientation and the average radiation level for the analyzed period, a theoretical maximum PV cover ratio of around 44% is acceptable also during December at the investigated site while it fluctuates throughout the year up to 100% (June). In one of the investigated years, only 30% PV cover ratio would have been acceptable in December. Interannual fluctuations should be therefore considered. A theoretical investigation of maximum PV cover ratios for a range of DLI thresholds between 8 and 50 mol/m^2/day has been performed. The results of the method have been compared to experimental results for plastic greenhouses in Southern Spain as well as other experiments with similar boundary conditions which can be found in literature. The study indicates that significant PV cover ratios are possible even for light demanding crops and can help to select a useful PV cover ratio in PV greenhouses. The PV greenhouses concept is a growing trend globally. To enhance food security and sustainability while reducing carbon footprints, the here presented results could help other countries implement PV greenhouse systems effectively.

In the future, it is planned to examine these theoretical results with detailed radiation distribution simulations for plastic greenhouses and according further real scale experiments in the province of Almería. A detailed PV greenhouse model is currently being developed that aims to reduce the uncertainties introduced by the estimates in this preliminary study, such as the corresponding reduction in indoor temperature due to higher PV cover ratios, or simplification by considering monthly average DLI values. Also, the shading effect on the microclimate, especially the indoor temperature has to be considered in the future. Especially during winter months, the limiting factor for optimal plant growth might be the indoor temperature instead of the radiation conditions. Further, the importance of tracking strategies and its benefit for optimal crop development, ventilation and the replacement of the whitewashing practice or a combination with it will be also examined.

CRediT authorship contribution statement

Natalie Hanrieder: Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft. **Anna Kujawa:** Investigation, Writing – review & editing. **Ana Bendejacq Seychelles:** Investigation, Writing – review & editing. **Manuel Blanco:** Project administration. **José Carballo:** Writing – review & editing. **Stefan Wilbert:** Funding acquisition, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The analyzed solar radiation time series from the Copernicus Atmosphere Monitoring Service (CAMS) version 4.5 database can be accessed online via the CAMS website https://www.soda-pro.com/web-services/radiation/cams-radiation-service.

References

[1] Rossi Rachele. EPRS | European parliamentary research service. Memb Res Serv PE March 2019;635(563).

[2] Kujawa A, Hanrieder N, Wilbert S, Wolfertstetter F, Carballo J, Osterthun N, et al. Economic study of agrivoltaic greenhouses in Spain and the Netherlands. In: Poster at Agrivoltaics Conference 2022, Piacenza, Italy; 2022.

[3] Valera D, Belmonte L, Molino F, López A. Greenhouse agriculture in Almería. A comprehensive techno-economic analysis. Cajamar Caja Rural 2016. ISBN-13: 978-84-95531-75-9.

[4] Touil S, Richa A, Fizir M, Bingwa B. (2021), "shading effect of photovoltaic panels on horticulture crops production: a mini review". Rev Environ Sci Biotechnol 2021; 20:281–96. https://doi.org/10.1007/s11157-021-09572-2.

[5] Aroca-Delgado R, Pérez-Alonso J, Callejón-Ferre A, Velázquez-Martí B. (2018), "compatibility between crops and solar panels: an overview from shading systems". Sustainability 2018;10:743.

[6] Gorjian S, Calise F, Kant K, Ahamed MS, Copertaro B, Najafi G, et al. A review on opportunities for implementation of solar energy technologies in agricultural greenhouses. J Clean Prod 2021;285:124807.

[7] Gorjian S, Bousi E, Özdemir Ö, Trommsdorff M, Kumar N, Anand A, et al. Progress and challenges of crop production and electricity generation in agrivoltaic systems using semi-transparent photovoltaic technology. Renew Sustain Energy Rev 2022; 158(2022):112126.

[8] Bertin N, Fatnassi H, Vercambre G, Poncet C. Simulation of tomato production under photovoltaic greenhouses. Acta Hortic 2017;1170. https://doi.org/10.17660/ActaHortic.2017.1170.52. ISHS 2017.

[9] Cossu M, Cossu A, Deligios PA, Ledda L, Li Z, Fatnassi H, et al. Assessment and comparison of the solar radiation distribution inside the main commercial photovoltaic greenhouse types in Europe. Renew Sustain Energy Rev 2018;94 (2018):822–34. https://doi.org/10.1016/j.rser.2018.06.001.

[10] Ureña-Sánchez R, Callejón-Ferre A, Pérez-Alonso J, Carreño-Ortega A. Greenhouse tomato production with electricity generation by roof-mounted flexible solar panels. Sci Agric 2012;69(4):233–9. July/August 2012.

[11] Aroca-Delgado R, Pérez-Alonso J, Callejón-Ferre A, Díaz-Pérez M. Morphology, yield and quality of greenhouse tomato cultivation with flexible photovoltaic rooftop panels (Almería-Spain). Sci Hortic 2019;257(2019):108768. https://doi.org/10.1016/j.scienta.2019.108768.

[12] Ezzaeri K, Fatnassi H, Bouharroud R, Gourdo L, Bazgaou A, Wifaya A, et al. The effect of photovoltaic panels on the microclimate and on the tomato production under photovoltaic canarian greenhouses. Solar Energy 2018;173(2018):1126–34.

[13] López-Díaz G, Carreño-Ortega A, Fatnassi H, Poncet C, Díaz-Pérez M. The effect of different levels of shading in a photovoltaic greenhouse with a North–South orientation. Appl Sci 2020;10:882. https://doi.org/10.3390/app10030882.

[14] Cossu M, Yano A, Solinas S, Deligios P, Tiloca M, Cossu A, et al. Agricultural sustainability estimation of the European photovoltaic greenhouses. Eu J Agr 2020; 118:126074. https://doi.org/10.1016/j.eja.2020.126074.

[15] Pérez-Alonso J, Pérez-García M, Pasamontes-Romera M, Callejón-Ferre AJ. Performance analysis and neural modelling of a greenhouse integrated photovoltaic system. Renew Sustain Energy Rev 2012;16(7):4675–85.

[16] Cossu M, Murgia L, Ledda L, Deligios PA, Sirigu A, Chessa F, et al. Solar radiation distribution inside a greenhouse with south-oriented photovoltaic roofs and effects on crop productivity. Appl Energy 2014;133:89–100.

[17] Bulgari R, Cola G, Ferrante A, Franzoni G, Mariani L, Martinetti L. Micrometeorological environment in traditional and photovoltaic greenhouses and effects on growth and quality of tomato (*Solanum lycopersicum* L.). Ital J Agrometeorol 2015;20:27–38.

[18] Hassanien RHE, Li M, Yin F. The integration of semitransparent photovoltaics on greenhouse roof for energy and plant production. Renew Energy 2018;121:377–88.

[19] Ezzaeri K, Fatnassi H, Wifaya A, Bazgaou A, Aharoune A, Poncet C, et al. Performance of photovoltaic Canarian greenhouse: a comparison study between summer and winter seasons. Sol Energy 2020;198:275–82. https://doi.org/10.1016/j.solener.2018.08.043.

[20] Zisis C, Pechlivani E, Tsimikli S, Mekeridis E, Laskarakis A, Logothetidis S. Organic photovoltaics on greenhouse rooftops: effects on plant growth. Mater Today Proc 2019;19:65–72.

[21] Kavga A, Trypanagnostopoulos G, Zervoudakis G, Tripanagnostopoulos Y. Growth and physiological characteristics of lettuce (*Lactuca sativa* L.) and rocket (*Eruca sativa* Mill.) plants cultivated under photovoltaic panels. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 2018;46:206–12.

[22] Trypanagnostopoulos G, Kavga A, Souliotis M, Tripanagnostopoulos Y. Greenhouse performance results for roof installed photovoltaics. Renew Energy 2017;111 (2017):724e731.

[23] Qu Z, Oumbe A, Blanc P, Espinar B, Gesell G, Gschwind B, et al. Fast radiative transfer parameterisation for assessing the surface solar irradiance: the Heliosat-4 method. Meteorol Z 2017;26:33–57.

[24] https://www.soda-pro.com/web-services/radiation/cams-radiation-service.

[25] Schroedter-Homscheidt M, et al. User guide to the CAMS radiation service (CRS). In: Copernicus Atmosphere Monitoring Service; 2022. CAMS2_73_2021SC1_D3.2.1-2022_UserGuide_v1.

[26] Schroedter-Homscheidt M, Azam F, Betcke J, Hanrieder N, Lefèvre M, Saboret L, et al. Surface solar irradiation retrieval from MSG/SEVIRI based on APOLLO next generation and HELIOSAT-4 methods. Contrib Atm Sci/Meteorol Z 2022. https://doi.org/10.1127/metz/2022/1132.

[27] Vindel JM, Valenzuela R, Navarro A, Zarzalejo L, Paz-Gallardo A, Souto J, et al. Modeling photosynthetically active radiation from satellite-derived estimations over mainland Spain. Remote Sens (Basel) 2018;2018(10):849. https://doi.org/10.3390/rs10060849.

[28] Pfeifroth Uwe, Kothe Steffen, Drücke Jaqueline, Trentmann Jörg, Schröder Marc, Selbach Nathalie, et al. Surface radiation data set - Heliosat (SARAH) - edition 3. Satellite Appl Fac Clim Monitor 2023. https://doi.org/10.5676/EUM_SAF_CM/SARAH/V003.

[29] McCree KJ. Photosynthetically active radiation. In: Lange OL, Nobel PS, Osmond CB, Ziegler H, editors. Physiological plant ecology I. Encyclopedia of plant physiology. vol. 12 / A. Berlin, Heidelberg: Springer; 1981.

[30] Faust J. FIRST research report. Light Management in Greenhouses. I. Daily light integral: A useful tool for the U.S. Floriculture Industry; 2002.

[31] Papadakis G, Briassoulis D, Mugnozza GS, Vox G, Feuilloley P, Stoffers JA. Radiometric and thermal properties of and testing methods for greenhouse covering materials. J Agric Eng Res 2000;77(1):7–38.

[32] Emekli NY, Büyüktaş K, Başçetinçelik A. Changes of the light transmittance of the ldpe films during the service life for greenhouse application. J Build Eng 2016;6: 126–32. https://doi.org/10.1016/j.jobe.2016.02.013.

[33] Baytorun NA, Başçetinçelik A. Plastic covering materials used in greenhouses. Antalya: Panel on Plastic Use in Agriculture; 1993.

[34] Geoola F, Kashti Y, Levi A, Brickman R. Quality evaluation of anti-drop properties of greenhouse cladding materials. Polymer Test 2004;23(7):755–61.

[35] Dorais M. The use of supplemental lighting for vegetable crop production: light intensity, crop response, nutrition, crop management, cultural practices. In: Canadian Greenhouse Conference, Oct. 9th, 2003; 2003.

[36] http://www.fao.org/faostat.

[37] Soussi M, Thameur Chaibi M, Buchholz M, Saghrouni Z. Comprehensive review on climate control and cooling systems in greenhouses under hot and arid conditions. Agronomy 2022;12:626. https://doi.org/10.3390/agronomy 12030626.

[38] Torres AP, Lopez RG. Measuring daily light integral in a greenhouse commercial greenhouse production purdue extension HO-238-W. 2012. Available online, https://www.extension.purdue.edu/extmedia/ho/ho-238-w.pdf.

[39] Özdemir Ö, Berwind M. An assessment of light availability and distribution inside a photovoltaic greenhouse. In: Poster at Agrivoltaics Conference 2022, Piacenza, Italy; 2022.