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Research paper

Agrivoltaic: How much electricity could photovoltaic greenhouses supply?

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ABSTRACT

In regions where the land available is scarce it is of special interest to deploy agrivoltaic systems. The combined use of greenhouses to produce food and energy at the same time increases farmers' income, converting farming into a more attractive sector. The farming sector could benefit from agrivoltaic, since farmers could profit from a double source of incoming: vegetables and energy. The aim of this research is to establish how relevant agrivoltaic can be in terms of energy production at regional scale. For this purpose, a methodology is developed to: (i) identify greenhouses using cartographic information systems, (ii) estimate how much of these areas could be covered by solar photovoltaic panels without decreasing the crops production, thus, estimating the optimal photovoltaic cover ratio for different type of crops under different solar conditions by developing a novel set of equations and (iii) evaluate the corresponding photovoltaic power and production. This methodology has been applied to one regional practical case, the Canary Islands, and the results are surprising in terms of the potentiality of agrivoltaic, which could cover rates as high as 30% of the annual regional electricity demand depending on, among others, the transmittance value of the greenhouse material and the adequate determination of the cover ratio.

1. Introduction

Spain, aligned with the European Union, has set the objective of decarbonising the economy by 2050. The Government of the Canary Islands, eager to accelerate this process, has set the objective of covering 100% of the 2040 internal energy demand by renewable energies. This means moving towards a model entirely based on renewable energy to supply the electricity demand as well as the transport and heat demands. Thus, the Canary Islands must fully explore and exploit its great potential in renewable energies, particularly solar and wind energy. Currently, renewable energies account only for 20% of its electricity consumption and for 6% of its total primary energy demand, being the transport sector the sector with the highest energy consumption (Instituto Canario de Estadística, 2022).

One of the main constraints of developed/insular regions is their limited territory, so the deployment of renewable energies must be implemented, as far as possible, without using additional land. In a similar vein, land scarcity also poses agriculture challenges, and the food sovereignty is very often low in outermost regions and archipelagos, like the Canary Islands, where it is most needed due to the distance and food transportation challenges. These territorial constraints are common in regions with a high population density, being in general especially pressing on islands. Hence the need to evaluate the photovoltaic (PV) potential on greenhouses, which can contribute to solve both problems at the same time, food and energy production.

The concept of agrivoltaic is not new (Willockx et al., 2022; Cuce et al., 2016; Dinesh and Pearce, 2016; Fatnassi et al., 2015; Yano et al., 2010; Cossu et al., 2014, 2020). Some experiences have already been developed, which should help to define the optimal PV cover ratio, which is one of the key parameters to establish the potential of photovoltaic greenhouses (PVGs) (Touil et al., 2021; Jiang et al., 2022; Weselek et al., 2021). PV greenhouse makes it possible to combine food and energy production on the same land by integrating the PV systems on the greenhouse roof. One of their main advantages is the diversification of the farmers' income (Cossu et al., 2020). Nonetheless, agrivoltaic systems have raised some concerns regarding the agricultural sustainability in terms of crop development, due to the shading effect caused by PV panels (Cossu et al., 2020). Despite the advantages of PV greenhouses, some were built to maximise the PV energy production and incomes, regardless of the crop light requirements (Fatnassi et al., 2015; Cossu et al., 2014). In some European countries, such as Italy or France, regulations limited the installation of PV systems on agricultural land (Fatnassi et al., 2015; Delfanti

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et al., 2016; Colantoni et al., 2015). Under these circumstances, PV greenhouses were considered a solution to bypass those laws (Castellano, 2014; Marucci et al., 2018).

Proper development of PV greenhouses must be based on the optimal trade-off between energy and crop production, aiming to maximise the greenhouse crop productivity, based on the actual light requirements. On the other hand, the shading of the PV panels on the greenhouse area may positively affect yield, growth and development of the plants (Cuce et al., 2016; Dinesh and Pearce, 2016; Yano et al., 2010) and lead to the reduction of the water evaporation (Ali Abaker Omer et al., 2022).

This research shows how relevant agrivoltaic could be, especially in regions where land is scarce and, thus, a highly valuable resource. The combined use of greenhouses to produce food and energy at the same time increases farmers' income, diversifies their economy, converting farming in a more attractive sector. This is especially important in regions where farming has decreased over the last decades, favouring e.g., the tourism sector in opposition to the primary sector, and compromising food sovereignty in isolated regions, such as the Canary Islands. There is a slow movement back to the farming sector in isolated regions, especially after the COVID pandemic. This tendency could be accelerated by agrivoltaic, since farmers could profit from a double source of incoming: vegetables and energy. The economic feasibility of agrivoltaic has been already analysed for some cases (Agostini et al., 2021; Giri and Mohanty, 2022).

This research focuses on evaluating the PV potential on greenhouses at regional/island/local scale. To our best knowledge, this is the first time that such research has been developed. There are some articles that evaluate the potential of agrivoltaic at national scale (Dinesh and Pearce, 2016; Cossu et al., 2020; Fernández et al., 2022; Gonocruz et al., 2021; Coşgun, 2021; Trommsdorff et al., 2021; Malu et al., 2017) and others that review current developments in the area (Spaargaren, 2001; Gorjian et al., 2021; Lu et al., 2022; Mamun et al., 2022). Nonetheless, the methodology applied at national scale is not comparable to the one developed in this research at regional scale, where the site-specific requirements must be taken into account. In this research, a novel methodology has been developed to determine site-specific optimal PV cover ratios depending on the solar radiation conditions and the crop types. In addition, novel approach using geographical information systems were used to identify the greenhouses areas.

2. Methodology

The main objective of this research is to evaluate the available surface on greenhouses for the exploitation of photovoltaic solar energy, at the regional, island and municipality level.

The methodology used in this research step by step is described below.

- Step 1. Estimation of solar radiation.
- Step 2. Methodology to estimate the greenhouses' surface.
- Step 3. Analysis of the types of cultivation under greenhouses and their minimum light requirements.
- Step 4. Methodology for the determination of the usable area for photovoltaic solar installations on greenhouses depending on the cultivation type. Calculation of the PV cover ratio (PV_R).
- Step 5. Methodology to calculate the photovoltaic power that could be installed on greenhouses.
- Step 6. Methodology to calculate the annual and hourly photovoltaic production.
- Step 7. Estimation of the percentage of the annual insular demand that can be supplied with photovoltaic energy.

2.1. Estimation of solar radiation

2.1.1. Methodology

Global solar radiation can be measured using pyranometers. Pyranometer data can be used to develop solar irradiation maps by interpolation/extrapolation of these data. Nonetheless, errors may arise since these pyranometers are neither close nor uniformly distributed. Solar radiation can also be obtained using satellite images. Usually, the broad resolution of these images, in magnitudes of kilometres, and their variability in terms of cloud cover and microclimatic variables, can lead to high uncertainties.

Thus, the methodology selected for this research uses satellite data, as described below, together with the collection of solar data from available meteorological stations to, finally, calibrate the selected database with pyranometer measurements. The fundamentals of this methodology has been extensively described in Julieta et al. (2022).

2.1.2. Solar irradiation data

The satellite databases consulted showed a broad resolution of, at least, 1 × 1 km^2, except for the Solar Radiation Map of the Canary Islands, whose resolution is 50 × 50 m^2.

This solar map combines the GRASS software tool with spline interpolation techniques and digital terrain elevation maps, correlated with horizontal global radiation data from 97 meteorological stations located in the Canary Islands, resulting in maps with a resolution of 50 × 50 m^2 (Monedero et al., 2007). This solar map is the database selected for this research.

2.1.3. Collection of solar radiation data from pyranometers

63 pyranometers (from the State Meteorological Agency (AEMET), the Ministry of Agriculture and Fisheries, Food and Environment and private companies/promoters) were used to check the data from the selected solar map. The total area of the Canary Islands is 7493 km^2. Thus, an average of 1 pyranometer per 119 km^2 was used to check the solar radiation map data. The pyranometer data were also used to generate the hourly PV production data. Each island was sectorised into different zones according to their climate and one radiation series was estimated using the corresponding pyranometer data.

2.1.4. Calibration of the selected solar map using solar measurements

To calibrate the radiation map of the Canary Islands, this map was correlated with the annual averages of the pyranometer data. The differences were not consistent (sometimes downwards and others upwards) but, in most cases, they were not significant, except in the case of the island of Tenerife, where the data from the Solar Map consistently provided lower values than those provided by the pyranometers. Thus, this research has used the Solar Map data as solar radiation source for all islands except for Tenerife. For the island of Tenerife, the Solar Map data were weighted upwards using the deviation means calculated by comparing the Solar Map data and the meteorological stations.

2.2. Estimation of the greenhouse areas

The estimation of the area covered by greenhouses has been carried out using the *Element Capture Method*. The greenhouses' surfaces have been identified by using photo-interpretation techniques and cartographic elements and the Canary Islands Cultivation Map (Portal de Datos Abiertos del Sistema de Información Territorial de Canarias, 2019), published by the Regional Ministry of Agriculture, Livestock, Fishery and Water, and were generated using photo-interpretation techniques and field work. Fig. 1 shows an example of one greenhouse identified using this method.

Fig. 1. Example of the element "greenhouse". 1:400.

2.3. Analysis of the types of cultivation in greenhouses and their minimum light requirements

Photosynthetically Active Radiation (PAR) is the type of radiation that favours the process of photosynthesis in plants. Radiation greater than 700 nm does not favour photosynthesis, but it generates heat accumulation in greenhouses. The PAR represents between 45–50% of the total solar radiation received, and it represents the highest quality radiation for the growth and development of crops.

The light requirements of the crops are usually expressed as Daily Light Integral (DLI), that is the average light sum of the PAR received during one day (Faust, 2002; Torres and Lopez, 2002).

A first classification of the cultivation types can be done as function of their light requirements: high light demanding crops (such as tomato, cucumber, sweet pepper) with an optimal daily light integral (DLI) higher than 30 mol/m^2 d; medium light crops (such as asparagus) with an optimal DLI between 10 and 20 mol/m^2 d and low light crops (as some floricultural crops) with an optimal DLI between 5 and 10 mol/m^2 d (Spaargaren, 2001). Table 1 summarises the daily light requirements of different types of crops, classified as high, medium and low light demanding crops, as well as the optimal DLI and the minimum DLI required for each type of crop.

Calculation of the light requirements of different types of crops

The average outside daily PAR radiation sum (S_P) has to be calculated in the same unit of the DLI data. When the DLI data are available as mol m^{-2} d^{-1} Eq. (1) can be used to calculate the S_P.

$$S_p = I_0 \cdot f \cdot 0.0036 \cdot a \left(\frac{\text{mol}}{\text{m}^2\ \text{d}}\right) \tag{1}$$

where:

I_0 = annual average daily irradiation on the horizontal plane (Wh m^{-2} d^{-1})

$f = 0.48$ (fraction of the PAR radiation to the total radiation)

0.0036 Converts Wh m^{-2} to MJ m^{-2}

$a = 4.57$ (coefficient converting the PAR radiation from MJ m^{-2} to mol m^{-2})

In case that the DLI data are available as MJ/m^2 d, the average outside daily PAR radiation can be calculated as per Eq. (2).

$$S_p = I_0 \cdot f \cdot 0.0036 \left(\frac{\text{MJ}}{\text{m}^2\ \text{d}}\right) \tag{2}$$

The average daily PAR radiation sum inside a PV Greenhouse (S_{PC}) depends on the material used as greenhouse roof. The materials used for greenhouse roofs reflect a fraction of the light they receive from the sun, which generally ranges from 20 to 30% (Intagri, 2022).

The average daily PAR radiation sum inside a PV Greenhouse (S_{PC}) is calculated according to Eq. (3).

$$S_{PC} = S_P \cdot \tau_G \tag{3}$$

where:

τ_G = transmittance value of the greenhouse roof

According to Marucci et al. (2012) average transmittance values of the greenhouse roof are around 0.9 although they slightly vary depending on roof material. Marucci et al. (2012) studied the transmittance value for different materials such as Glass (4 mm), LDPE (low-density polyethylene), EVA (Ethylene vinyl acetate), ETFE (ethylene–tetrafluoroethylene copolymers). Table 2 summarises their transmittance values for solar radiation (SR) and for photosynthetically active radiation (PAR). Other authors, such as Cossu et al. (2020) and Intagri (2022), suggested transmittance values for commercial greenhouses between 0.7 and 0.8; although (Castellano, 2014) considered values up to 0.95 for glass greenhouses.

2.4. Calculation of the PV cover ratio

The PV cover ratio (PV$_R$) is the ratio of the projected area of PV panels on the ground and the total greenhouse area (Cossu et al., 2020). The calculation of the PV cover ratio in the case of greenhouses is complex due to several reasons: there are not many previous experiences neither worldwide nor in Europe nor in Spain, the different types of crops are affected differently by the shading, on each region/island/location the types of crops are different and, even if they are the same, the different global irradiation will lead to different utilisation factors. Thus, two of the main factors affecting the calculation of the PV cover ratio are the on-site solar radiation and the type of crop cultivated.

The cumulated global radiation inside PVGs decreases as a function of the increasing PV cover ratio (PV_R). This reduction was found to be equal to 0.8% for each 1% increase of the PV$_R$, as the average of the main commercial PVG types in Europe (Cossu et al., 2018). An acceptable compromise between horticultural crops and energy production is usually achieved when the PV$_R$ is low (around or lower than 20%), resulting in limited yield losses and negligible impact on the fruit quality (Ureña-Sánchez et al., 2012; Pérez-Alonso et al., 2012; Aroca-Delgado et al., 2019). As the PV cover ratio increases, the PV greenhouses microclimate changes mainly due to the reduced solar radiation, but also other parameters varied, such as a decrease of the air temperature and an increase of humidity when ventilation is not applied (Ezzaeri et al., 2018). Nonetheless, acceptable percentages of PV cover ratio heavily depend on the latitude (since the solar radiation is very different in North or South Europe or even in subtropical areas (like the Canary Islands) and the type of crop. Plants adopt species-specific physiological responses to shading that can include shade tolerance (Gommers et al., 2013). Most crops react by optimising their photosynthetic rate. However, while shade tolerant crops can adjust to lower light levels by optimising the radiation interception efficiency, the shade intolerant crops (such as tomato or sweet pepper) increase their vegetative growth rate and concentrate resources on stem and leaf growth instead of fruits, resulting in lower yields (Smith and Whitelam, 1997).

To estimate the affection of photovoltaic solar installations on greenhouses, an extensive literature review has been carried out. Table 3 shows some of the articles that have been considered most relevant for the purpose of this research as well as key

Table 1
Light requirements of different crops (Cossu et al., 2020).

Crop type: as High (H)/Medium (M)/Low (L) light demanding	DLI (mol/m^2 d)	
	Optimal DLI	Good/Enough DLI
Low light demanding		
Dracaena	>8	4–8
Kalanchoe	>8	4–8
Poinsettia	>10	6–19
Medium light demanding		
Ficus	>16	8–16
Asparagus	>16.7	6.5–16.7
Spinach	>17	8–17
Basil	>17.3	5.3–17.3
Strawberry	>19	12–19
Chrysanthemum	>20	10–20
Rose	>20	10–20
Lettuce	>20	12–20
High light demanding		
Cucumber	>30	12–30
Sweet pepper	>30	12–30
Tomato	>30	15–30

Table 2
Transmissivity coefficients of different greenhouse roof materials.
Source: Adapted from Marucci et al. (2012).

Transmissivity coefficients (%)	Glass 4 mm	LDPE 0.180 mm	EVA 0.180 mm	ETFE 0.100 mm
τ_{SR}	80.4	88.6	89.1	93.1
τ_{PAR}	87.5	91.0	89.7	92.4

Table 3
Experiences in PV greenhouses.

Crop type: as High (H)/Medium (M)/Low (L) light requirements	PV panel type	PV cover ratio (PV_R)	Potential yield reduction (%)	Country	Greenhouse type	Ref.
Lettuce (M)	Silicon rigid	20%		Greece	Cristal	Trypanagnostopoulos et al. (2017)
Tomato (H)	Silicon Flexible	9,8%		Almería	Canarian	Aroca-Delgado et al. (2019)
Tomato (H)	Silicon Flexible	40%		Agadir (Morocco)	Canarian	Ezzaeri et al. (2020)
Floricultural crops: Dracaena, Kalanchoe, Poinsettia (L)	Silicon rigid	60%	0%	Italy	Cristal	Cossu et al. (2020)
Dracaena, Kalanchoe (L)	Silicon rigid	100%	10%	Italy	Cristal	Cossu et al. (2020)
Poinsettia (L)	Silicon rigid	100%	20%	Italy	Cristal	Cossu et al. (2020)
Ficus (M)	Silicon rigid	25%	0%	Italy	Cristal	Cossu et al. (2020)
Ficus (M)	Silicon rigid	50%	10%	Italy	Cristal	Cossu et al. (2020)
Ficus (M)	Silicon rigid	60%	15%	Italy	Cristal	Cossu et al. (2020)
Ficus (M)	Silicon rigid	100%	35%	Italy	Cristal	Cossu et al. (2020)
Chrysanthemum, Rose (M)	Silicon rigid	25%	4%–6%	Italy	Cristal	Cossu et al. (2020)
Chrysanthemum, Rose (M)	Silicon rigid	50%	20%–30%	Italy	Cristal	Cossu et al. (2020)
Asparagus, Spinach, Basil (M)	Silicon rigid	25%	0%	Italy	Cristal	Cossu et al. (2020)
Asparagus, Spinach, Basil (M)	Silicon rigid	50%	20%	Italy	Cristal	Cossu et al. (2020)
Strawberry (M)	Silicon rigid	25%	2%	Italy	Cristal	Cossu et al. (2020)
Strawberry (M)	Silicon rigid	50%	25%	Italy	Cristal	Cossu et al. (2020)
Lettuce (M)	Silicon rigid	25%	6%	Italy	Cristal	Cossu et al. (2020)
Lettuce (M)	Silicon rigid	50%	22%	Italy	Cristal	Cossu et al. (2020)
Tomato, Cucumber (H)	Silicon rigid	25%	20%	Italy	Cristal	Cossu et al. (2020)
Tomato, Cucumber (H)	Silicon rigid	50%	40%	Italy	Cristal	Cossu et al. (2020)
Sweet pepper (H)	Silicon rigid	25%	25%	Italy	Cristal	Cossu et al. (2020)
Sweet pepper (H)	Silicon rigid	50%	48%	Italy	Cristal	Cossu et al. (2020)

parameters such as the PV cover ratio (PV_R) and the potential yield reduction compared to a control greenhouse.

Other possibilities of integrating photovoltaic solar energy in cultivation areas may be the use of open-air cultivation areas (without greenhouses) where photovoltaic structures could be installed on the cultivation area, creating partial shading.

It is worth highlighting the experiences with the so-called Canarian Greenhouses, named after the greenhouses traditionally installed in the Canary Islands, although they have been exported to other parts of the world. These experiences include the installation of PV on Canarian greenhouses used to grow a high demanding crop such as tomato in Almería where 9.8% of the roof area was covered with PV panels. Results did not show any yield reduction in the tomato production due to the shading of the PV panels (Ureña-Sánchez et al., 2012; Pérez-Alonso et al., 2012; Aroca-Delgado et al., 2019). Another similar experience took place in Agadir (Ezzaeri et al., 2020), where the climate is very similar to the one of the Canary Islands. In the case of Agadir, 40% of the greenhouse roof was covered with opaque (flexible) PV panels (Ezzaeri et al., 2020). Also in this case the tomato annual average production was not significantly affected. During the winter, the production worsened a bit compared to the control greenhouse, while in summer it improved since the temperature dropped a little with respect to the control greenhouse, being able to stay within the optimum growth temperature range for tomato (while in the control greenhouse this range was exceeded). In both cases, flexible panels were used, since they can be superimposed on the Canarian greenhouses without the need to modify or reinforce the structure. Fixed structure greenhouses allow easy integration of fixed (non-flexible) photovoltaic solar panels. In the Canary Islands, Canarian greenhouses are the predominant type. According to Cossu et al. (2020) a maximum yield reduction of 25% was assumed as acceptable for assessing the agricultural sustainability of PVGs for crop production.

Nonetheless, in his research, in order to do an accurate evaluation of the adequate PV cover ratio (PV_R) different aspects must be taken into account such as the type of crop, the onsite solar irradiation and the type of greenhouse among others. Eq. (4) is proposed to estimate the adequate PV cover ratio (PV_R) in the case of opaque PV panels (considering that no light is able to go through the panels).

$$S_{PC} \cdot (1 - PV_R) = DLI \tag{4}$$

where:

DLI: optimal daily light integral (expressed in mol/m^2 d or in MJ/m^2 d or equivalent units)

S_{PC}: yearly average daily PAR radiation sum inside the PV Greenhouse (expressed in the same units as the DLI)

Thus, the PV cover ratio (PV_R) can be estimated according to Eq. (5).

$$PV_R = \frac{(S_{PC} - DLI)}{S_{PC}} \tag{5}$$

Another factor that influences the PV cover ratio (PV_R) is the type of photovoltaic panel to be installed, which can be opaque (rigid or flexible), which produces higher shading, or translucent, which does not produce almost any shading. In the future, photovoltaic greenhouses may be based on transparent panels, since they allow the use of all the light and solar radiation at the same time. These new PV cells are less efficient than traditional ones, which absorb a greater range of wavelengths, but could enable energy harvesting on surfaces that could never otherwise be used to generate power. In October 2020, several investigations set a new efficiency record for colour-neutral transparent solar cells, achieving 8.1% efficiency and 43.3% transparency with an organic design, based on carbon instead of silicon. In comparison to conventional commercial silicon-based panels, whose efficiency is around 15% to 22%, the efficiency of transparent solar cells is still low but they will allow the integration of PV on greenhouses with almost no affection to the crops growth rate.

Design criteria for the next generation of PVGs may include the use of semi-transparent (Wang et al., 2021; Gorjian et al., 2022), bifacial PV panels (Katsikogiannis et al., 2022) or translucent PV panels such as Dye-Sensitised solar Cells (DSCs) (Katsikogiannis et al., 2022), organic PVs (OPVs) and semi-transparent PVs based on luminescent solar concentrators, where the incident light is filtered to share the spectrum between plant growth and electricity generation (Allardyce et al., 2017). Some authors have also suggested the use of the part of the PV energy production to power electrical appliances for microclimate control (Fatnassi et al., 2015; Yano et al., 2014, 2009; Bambara and Athienitis, 2019; Minuto et al., 2009; Emmott et al., 2015; Al-Shamiry et al., 2007). Some crops require moderate shading during their cycle and the semi-transparent PV panels can be used to provide it during periods of intense irradiation through dynamic PV systems, able to adjust the tilt of the PV modules according to the crop light needs (Moretti and Marucci, 2019a; Li et al., 2018; Marucci and Cappuccini, 2016). All these technical solutions are targeted to optimise the energy and the agricultural production by varying the shading of the PV panels at canopy level and the impact on the greenhouse farm in terms of energy consumption (Moretti and Marucci, 2019b).

Table 4
Transmittance values of semi-transparent PV panels (τ_{STPV}).
Source: Adapted from Bambara and Athienitis (2019).

STPV 10%	STPV 20%	STPV 30%	STPV 40%	STPV 50%
0.671	0.597	0.522	0.448	0.373

Crystalline silicon semi-transparent PV (STPV) modules consist of a frame, clear-glazed and PV cell portions (Bambara and Athienitis, 2019). The portion of PV-cell within the panel may vary depending on the selected semi-transparent PV panel, usually ranging from 10% to 50%. The transmittance of the semi-transparent PV modules varies depending on the portion of PV-cell within the panel, among others. The transmittance of the semi-transparent PV module can be calculated as per Eq. (6).

$$\tau_{STPV} = \alpha \cdot \tau_{glazing} + (1 - \alpha) \cdot \tau_{PV} \tag{6}$$

where:

τ_{STPV} = transmittance of the semi-transparent PV module
α = percentage of clear portion of STPV glazing
τ_{glazing} = transmittance of the clear portion of STPV glazing
τ_{PV} = transmittance of the PV cell portion of STPV glazing

The transmittance values are set according to (Bambara and Athienitis, 2019):

$$\tau_{\mathrm{glazing}} = 0.746$$
$$\tau_{\mathrm{PV}} = 0$$

Table 4 shows the transmittance values of semi-transparent PV panels depending on the portion of PV-cell within the panel, ranging from 50% to 10%.

If semi-transparent or translucent PV panels are used the set of equations (Eqs. (4) to (5)) are no longer valid. In this case, the following new set of equations to calculate the optimal $\mathrm{PV_R}$ are proposed.

$$S_{PC} \cdot (1 - PV_R) + S_P \cdot \tau_{STPV} \cdot PV_R = DLI \tag{7}$$

where:

DLI: optimal daily light integral (expressed in mol/m^2 d or in MJ/m^2 d or equivalent units)

S_{PC}: yearly average daily PAR radiation sum inside the PV Greenhouse (expressed in the same units as the DLI)

S_{P}: yearly average outside daily PAR radiation sum reaching the PV Greenhouse roof

τ_{STPV} = transmittance of the semi-transparent PV module

Thus, the PV cover ratio ($\mathrm{PV_R}$) for semi-transparent PV panels can be estimated according to Eq. (8).

$$PV_R = \frac{(S_{PC} - DLI)}{(S_{PC} - S_P \cdot \tau_{STPV})} \tag{8}$$

Regardless of the type of panel used (opaque or semi-transparent), each crop type on each site will result in a different PV cover ratio, using either Eq. (5) or Eq. (7). This will result in individual (and accurate) PV cover ratios for each site and crop type, which is adequate for local (not broad) studies. When higher areas are under study, a more general approach can be adopted where the type of crops can be classified as low, medium and high light requirement crop while, at the same time, an average solar radiation can be used for predetermined areas.

2.5. Methodology to calculate the photovoltaic power

This section describes the methodology used to calculate the photovoltaic power that can be installed on the greenhouses.

To find the installable power, the Surface/Power ratio is multiplied by the usable area. The usable area is the result of multiplying the available area by the corresponding PV cover ratio (PV_R).

Eq. (9) is used to determine photovoltaic power.

$$P\,(\mathrm{kW}) = PV_R \cdot S\left(\mathrm{m}^2\right) / \left(\frac{S}{P}\right) \tag{9}$$

where:

P (kW): Power (kW)
S: Available Surface (m^2)
S/P: Surface/Power ratio (m^2/kW)
$\mathrm{PV_R}$: PV cover ratio

To determine the efficiency and the Surface/Power ratio of the photovoltaic panel, several catalogues of the latest generation polycrystalline and monocrystalline silicon photovoltaic panels were consulted. The calculated Surface/Power ratio was between 4.42 and 4.94. In this study the selected panel was the SunForte PM096B00 Panel, whose main parameters are: power 330 W, efficiency 20.3% and Surface/Power ratio 4.94 m^2/kW.

Thus, one of the key factors to determine photovoltaic power is the estimation of the PV cover ratio. The PV cover ratio can be calculated for each single greenhouse, considering the crop cultivated and the onsite solar radiation. In order to do so, solar radiation data must be available for each greenhouse, as it is the case in this study, since each greenhouse is georeferenced and, at the same time, the crop type cultivated in each greenhouse must be known as well as their DLI requirement. This will result in one PV cover ratio value for nearly each greenhouse, which is, mathematically, very accurate, but may be difficult to implement in practical terms. One difficulty to implement this approach is that all the required data may not be available.

An alternative approach is to make ranges of solar radiation and classify the crop types cultivated as low, medium and high light demanding. This method will lead to a set of estimated PV cover ratio values that can be used at regional level. The number of PV cover ratio values will depend on how many ranges of solar radiation are proposed. In this research the solar radiation has been divided into 3 ranges (high, medium and low irradiation areas), thus a set of nine different PV cover ratio values will be applied.

Regardless of which of the proposed methods are used to determine the PV cover ratio value, once the PV cover ratio is set, the photovoltaic power is estimated using Eq. (9).

2.6. Methodology to calculate the annual and hourly PV production

This section describes the methodology used to calculate the annual photovoltaic production that could be installed on the identified areas. The photovoltaic solar production has been calculated as per Eq. (10).

$$P = \frac{365 \cdot IG_H \cdot \varepsilon \cdot PR \cdot S \cdot PV_R}{10^6} \tag{10}$$

where:

P: Production (MWh/a)
$\mathrm{IG_H}$: Solar radiation on horizontal surfaces ($\mathrm{Wh/m^2\ d}$)
ε: Panel efficiency
PR: Performance Ratio
S: Greenhouse area (m^2)
PV_R: PV cover ratio

Although the increase of the solar radiation on tilted areas (average tilt around 20% for the Canary Islands) with respect to the horizontal solar radiation is estimated in ca. 8%; in this study only horizontal panels have been considered since it is difficult to build an structure on top of Canarian Greenhouses due to their light structures. Whereas it is easier to implement them in glass greenhouses and even easier if the greenhouse roofs are already designed considering tilted roofs for PV purposes. The Performance Ratio (PR) considered was 0.8. The PV cover ratios for each type of greenhouse were estimated as specified in the previous section. The efficiency of the selected panel, SunForte PM096B00, is 20.3% as mentioned in the above section.

The hourly PV production has been estimated using different series of pyranometer data for each island. Each island has been sectorised in a series of zones with similar solar radiation. One pyranometer data series of several years has been assigned to each zone. The monthly PV productions have been calculated aggregating the hourly PV production data and, finally, the yearly production data has been calculated aggregating the monthly PV production data.

3. Results

3.1. Agriculture and greenhouses in the Canary Islands

The Canary Islands (Spain) is composed by eight islands located off the Western coast of Africa, parallel 28 N. The Archipelago is considered a touristic region. The service sector, dominated by tourism, represented 76.4% of the regional GDP in 2020 and has been increasing its contribution during the last decades (Confederación Canaria de Empresarios, 2020). The Islands are highly dependent on external energy sources and on food importation. The Canary Islands have no conventional energy sources, but plenty renewable energy sources, mainly wind and solar energy. Although most of the food is imported into the islands, nearly 40,000 hectares (ha) are devoted to agriculture (Instituto Canario de Estadística (ISTAC), 2009), from which 7284 ha are greenhouses (Ministerio de Agricultura P y A, 2020), corresponding to the so called Canarian Greenhouse. Most of the agriculture surface is devoted to exportation products such as the banana. Progressively, agriculture has lost weight in the Canarian economy, along with the loss of agriculture surface, losing more than 20% of the cultivated surfaces in the last 15 years (from 51,600 ha in 2007 to 39,500 ha in 2021). At the same time, agriculture has lost weight in the economy in terms of GDP, representing only 1,2% of the Canarian GDP in 2021. Thus, the Canary Islands cannot be considered an agricultural region but, nonetheless, it represents an important sector within the islands' economy and, even more importantly, in terms of food sovereignty. Nonetheless, a slow movement back to the farming sector can be observed, especially after the COVID pandemic. During 2020 a sharp decline in the GVA of the Islands of 21.4% in real terms (that is, eliminating the effect of the variation in prices) took place. This decrease more than doubles the decrease accounted for by the national GVA, which ended the year with a drop of 10.8%. Analysing the evolution of the different sectors that make up the productive activity of the Islands, it should be noted that except in the case of agriculture, all significantly reduced their activity in 2020 compared to the previous year. The primary sector (agriculture, livestock, forestry and fishing), that holds the least weight of those that make up the productive sectors of the Archipelago with a representation of 2.1% of the total regional production, managed to increase the value of its production by 2.2%. In terms of GVA the primary sector increased 3.2% in comparison to the previous year (Confederación Canaria de Empresarios, 2020). This tendency could be accelerated by agrivoltaic, since farmers could profit from a double source of incoming: vegetables and energy, while increasing, at the same time, energy and food sovereignty.

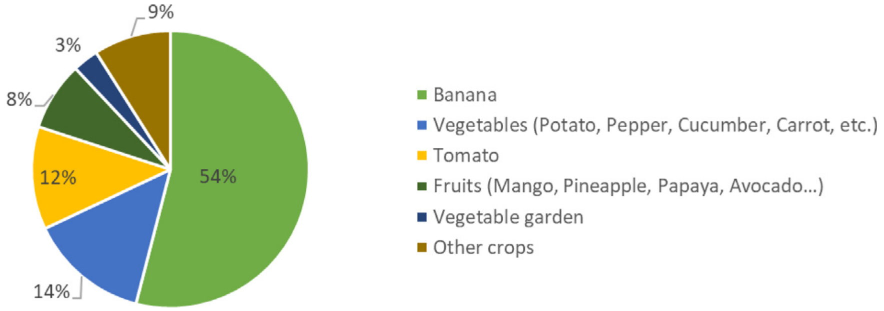

Fig. 2. Greenhouse surfaces in the Canary Islands.

The Cultivation Map (Portal de Datos Abiertos del Sistema de Información Territorial de Canarias, 2019), published by the Regional Ministry of Agriculture, Livestock, Fishery and Water, provides detailed information about the different cultivated crops on each island. In all islands, except for Fuerteventura, the main cultivated crop is the banana, accounting for more than 90% of the cultivated surface in La Gomera, El Hierro and La Palma. In Fuerteventura, where there is no banana cultivation, the main cultivated crop is the tomato. All in all, the greenhouse's surface in the Canary Islands is about 7284 hectares (ha) from which 6179 ha are being currently cultivated. Fig. 2 shows a summary of the agriculture surface and the main cultivated crops.

The crops cultivated in the Canary Islands have been classified as high, medium and low light demanding crops. Most of the cultivated crops are considered high demanding crops such as banana, tomato, most of the cultivated vegetables, most of the cultivated fruits. Thus more than 90% of the greenhouse's surface is devoted to high demanding crops, while less than 1% is devoted to low demanding crops (such as some flowers like strelitzia) and, thus, less than 10% is devoted to medium demanding crops, such as vegetables gardens (lettuce, spinach, etc.) in addition to some fruits such as strawberries. The non-cultivated agriculture surface, which refers to agricultural fields that are not currently under exploitation, accounts for 15% of the agriculture surface. It has been decided to consider these surfaces as surfaces for high demanding crops, to be on the conservative side.

Using the method described in Section 2.2, the number of greenhouses identified in all islands were 12,904. The average annual horizontal solar radiation on the identified greenhouses ranged from 5870 to 3578 Wh/m^2 d.

3.2. PV cover ratio

The PV panel used for this case study is the opaque PV panel, thus the equation used to calculate the PV cover ratio is Eq. (11):

$$PV_R = \frac{(S_{PC} - DLI)}{S_{PC}} \tag{11}$$

where S_{PC} is calculated using Eq. (3):

$$S_{PC} = S_P \cdot \tau_G \text{ with } \tau_G = 0.9$$

The transmittance value used for the Canarian greenhouse roof, according to Table 2, could be estimated in 0.9. The value for a glass greenhouse could be 0.8 or even lower. It is worth noticing that the PV cover ratio values are highly sensitive to the transmittance values, so it is key to accurately estimate the transmittance value.

Thus the PV_R value for each greenhouse depends on the type of crop cultivated, and its corresponding DLI, and the onsite solar radiation, and its corresponding S_{PC}. The PV_R can then be calculated using Eq. (5) for each greenhouse, resulting in one different PV_R per greenhouse. Since the area under study is a whole region, a more general approach that classifies the type of crops and the solar radiation will be used. The type of crops were classified as low, medium and high light requirement crops and the average annual solar radiation was also classified into three ranges. To classify the solar radiation areas as high, medium and low, the 12,904 greenhouses were split into three groups of the same number, resulting as follows: the highest solar radiation areas ranged from 5871 to 5229 Wh/m^2 d (average 5500 Wh/m^2 d), the medium solar radiation areas ranged from 5228 to 4557 Wh/m^2 d (average 4950 Wh/m^2 d) and low solar radiation areas ranged from 4556 to 3578 Wh/m^2 d (average 4235 Wh/m^2 d). Table 5 shows the PV cover ratio for the different types of crops as function of the average annual solar radiation for plastic greenhouses (PG) assuming $\tau_G = 0.9$ and for the sake of comparison values for glass greenhouses (GG), assuming $\tau_G = 0.8$ and $\tau_G = 0.7$ are also shown.

As it can be observed, the PV cover ratio of high light requirement crops are highly sensitive to the values of the annual solar radiation and also to the transmittance values, decreasing significantly when the transmittance value or the solar radiation decreases.

The medium light requirement crops are less sensitive to those changes and the low light requirement crops even less. In this last case, for the same transmittance value, the PV cover ratio decreases only a bit when the solar radiation decreases; conversely for decreasing transmittance value the PV cover ratio also decreases but the decrease is not significant.

In the Canary Islands, nearly 90% of the greenhouse cultivation crops are high light requirement crops, like banana, tomato, avocado, etc., thus, the PV cover ratio is highly dependent on the transmittance value and the solar conditions. Since the Canarian greenhouses are plastic ones, the PV cover ratio considered are the ones in Table 5. Since the vast majority of the cultivated crops are high light requirement ones, the suggested PV cover ratio will range from 23% to 0%, depending on the solar conditions.

3.3. Available area, power and annual electricity production on photovoltaic greenhouses

Fig. 3 shows the available areas on greenhouses in each island and Fig. 4, the resulting PV power and the annual PV production (calculated with the equations set described in the methodology section) considering transmittance values (τ_G) of 0.7, 0.8 and 0.9.

As shown in Fig. 4, agrivoltaic energy production is high in all cases (τ_G: 0.7 to 0.9) but it is profoundly affected by the transmittance values. Changes in the transmittance values of one decimal (from 0.8 to 0.9) nearly doubles the installable PV power and, thus, the energy production. The total power reaches figures as high as 1607 MW (τ_G: 0.8) or 2940 (τ_G: 0.9) and the annual energy production ranges from 2480 GWh/a (τ_G: 0.8) to 4497 GWh/a (τ_G:

Table 5
PV cover ratio values (Plastic greenhouses and glass greenhouses).

PV cover ratio (PV_R)	High average annual solar radiation (5500 Wh/m^2 d)			Medium average annual solar radiation (4950 Wh/m^2 d)			Low average annual solar radiation (4550 Wh/m^2 d)		
τ_G	0.9 (PG)	0.8 (GG)	0.7 (GG)	0.9 (PG)	0.8 (GG)	0.7 (GG)	0.9 (PG)	0.8 (GG)	0.7 (GG)
High light requirement crops (30 MJ/m^2 d)	23%	14%	1%	15%	4%	0%	0%	0%	0%
Medium light requirement crops (20 MJ/m^2 d)	49%	42%	34%	43%	36%	27%	33%	25%	15%
Low light requirement crops (10 MJ/m^2 d)	74%	71%	67%	71%	68%	63%	67%	62%	57%

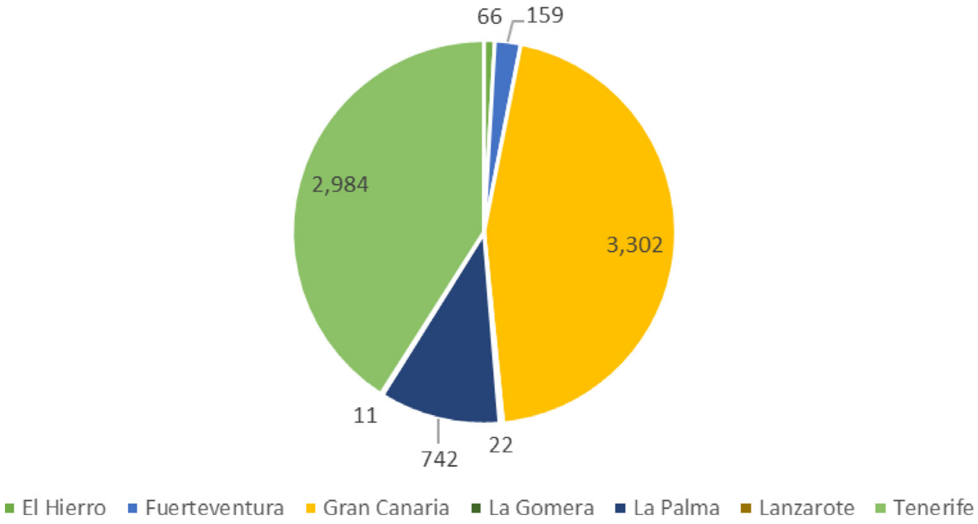

Fig. 3. PV greenhouses areas (ha) in the Canary Islands.

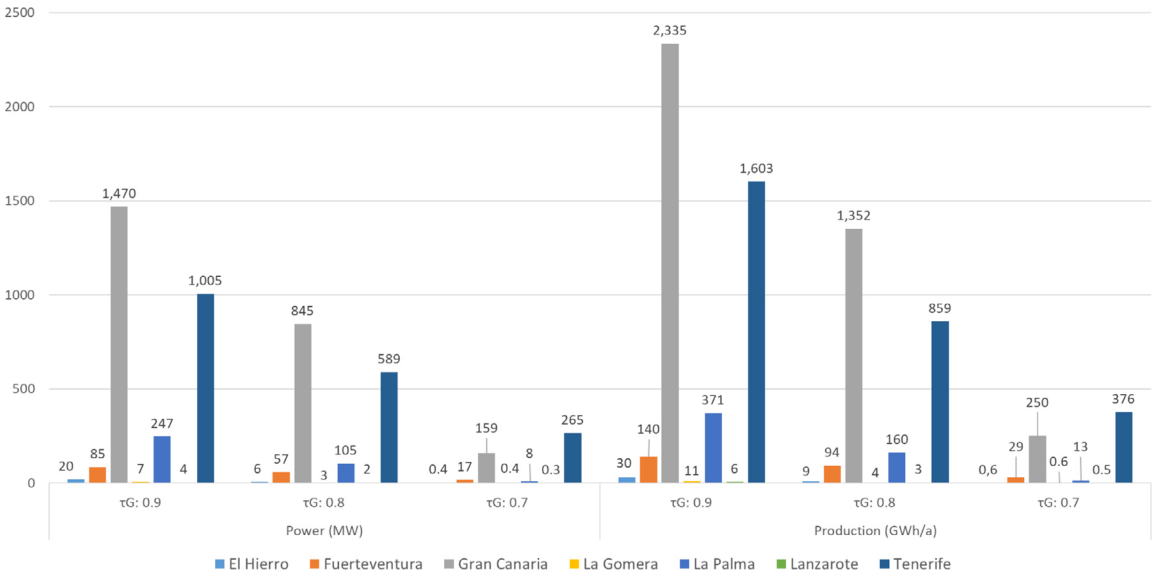

Fig. 4. PV greenhouses power and yearly energy productions.

0.9). The variation is even more dramatic when the one decimal change is from 0.7 to 0.8. In this case the installable PV power and, thus, the energy production is 350% higher. Thus, the total power reaches figures as high as 1607 MW (τ_G: 0.8) or as low as 451 (τ_G: 0.7) while the annual energy production ranges from 2480 GWh/a (τ_G: 0.8) to 669 GWh/a (τ_G: 0.7). These figures speak for themselves about the importance of appropriately selecting the greenhouse material.

At the island level, all islands present a very high potential for PV greenhouses, except for Lanzarote, due to the fact that the

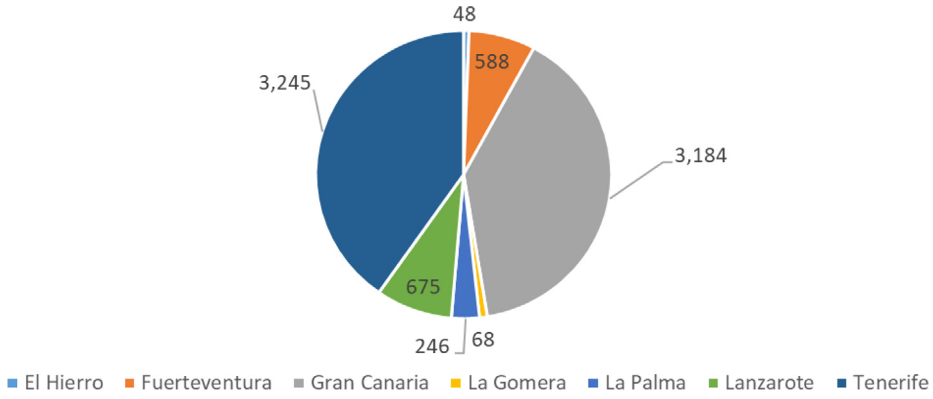

Fig. 5. Island's annual electricity demand (GWh) in 2021.

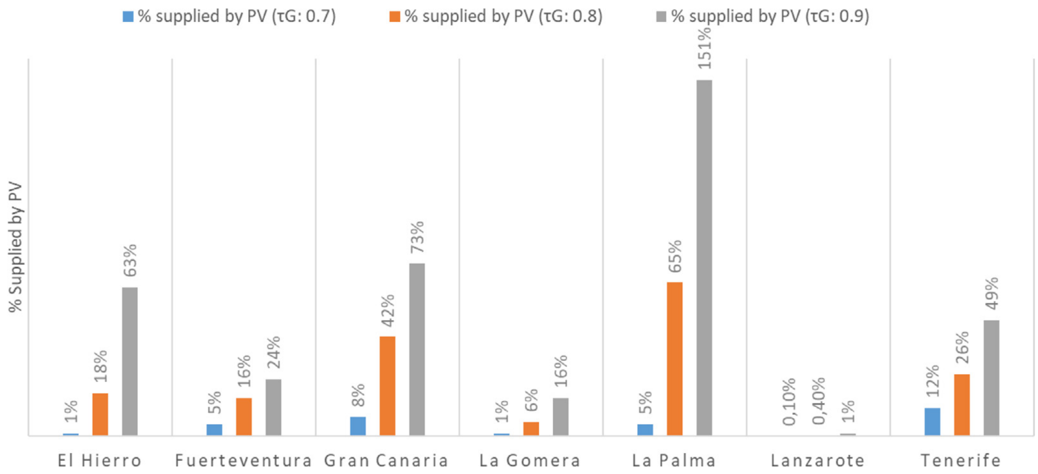

Fig. 6. Percentage of the electricity demand covered by PV greenhouses.

Lanzarote's greenhouse surface is very low in comparison to the other islands.

3.4. Annual electricity demand supplied by agrivoltaic

Fig. 5 Shows the island's annual electricity demand in 2021 and Fig. 6 the energy production of PV greenhouses compared to the electricity demand considering transmittance values (τ_G) of 0.7, 0.8 and 0.9.

Fig. 6 shows that the percentages of electricity demand that can be supplied by agrivoltaic vary significantly from island to island and heavily rely on the transmittance values (τ_G). Differences in the transmittance values from 0.8 to 0.9 can drastically change the results, at regional scale (from 31% to 56% PV supply) and, even more importantly, at the island level, e.g. in El Hierro island the PV supply can increase from 18% to 63% only by increasing the transmittance values from 0.8 to 0.9. The differences from island to island are even more important, considering the transmittance values of 0.8, agrivoltaic can supply rates as high as 65% of the total annual electricity demand as in La Palma or rates as low as less than 0.4% as in the case of Lanzarote. In the case of Lanzarote the coverage rate is so low reflecting the fact that the Lanzarote's greenhouse surface is very low in comparison to the other islands. These variations are even more dramatic if the transmittance values change from 0.8 to 0.7, since the percentages of electricity demand at regional scale decreases from 31% to 8%, nearly 4 times smaller, meaning a reduction of nearly 400%.

All in all, agrivoltaic can supply rates as high as 31% of the regional energy demand, considering transmittance values of 0.8, or even higher than 56% if transmittance values of 0.9 are considered. Even in the worst case scenario considered (transmittance values of 0.7) agrivoltaic could supply 8% of the regional electricity demand. These results show the annual average coverage of the demand considering that storage systems are available and the surplus of PV production can be stored to be use when the demand is higher than the production. The hourly analysis, next section, shows what is the actual coverage if storage systems are not available.

3.5. Hourly electricity PV production by agrivoltaic. Analysis of hourly series production data

The hourly PV productions for each island have been calculated and an analysis of the hourly series production data has been undertaken. This section will show the detailed analysis for the island of Gran Canaria.

Fig. 7 shows the results of the hourly photovoltaic production, for the three cases considered: transmittance values (τ_G) of 0.9, 0.8 and 0.7, in comparison to the hourly electricity demand for the island of Gran Canaria in the month of February. In the case of transmittance values (τ_G) of 0.7, the PV production is always lower than the demand; for transmittance values (τ_G) of 0.8, the PV production is usually lower than the demand but there are also some hours that show PV surplus; for transmittance values (τ_G) of 0.9, there are also many hours that show PV surplus, especially all hours around midday.

The analysis of the hourly PV production shows its importance to determine how much electricity could directly be used to supply the demand (while other restrictions apart from the demand

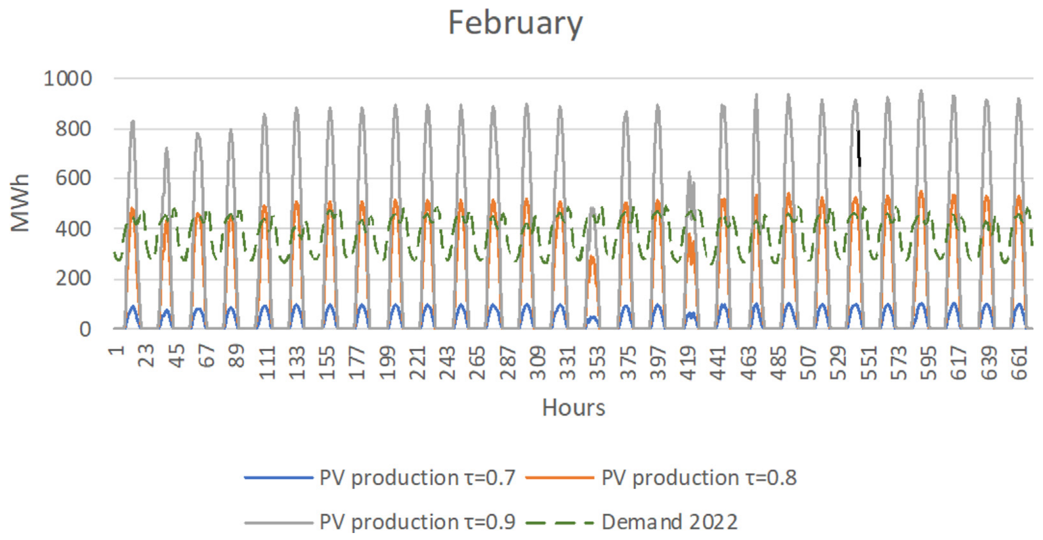

Fig. 7. Hourly PV production (transmittance values of 0.9, 0.8 and 0.7) versus electricity demand for the month of February (Gran Canaria).

level are not being considered under this study), while the surplus can either be stored or would be curtailed. An analysis of the hourly annual results shows that:

1. Transmittance values (τ_G) of 0.7: all the PV electricity production can be fed into the grid.
2. Transmittance values (τ_G) of 0.8: During 1214 h per year not all PV electricity production can be fed into the grid. The surplus of PV production accounts for 93,393 MWh per year (around 7% of its production). In the absence of storage systems, this means an average reduction of the annual PV coverage of around 4% (from 42% to 38%).
3. Transmittance values (τ_G) of 0.9: During 2639 h per year not all PV electricity production can be fed into the grid. The surplus of PV production accounts for 785,739 MWh per year (around 34% of its production). In the absence of storage systems, this means an average reduction of the annual PV coverage of around 25% (from 73% to 48%).

These results speak for the importance of estimating the hourly production and properly analyse the hourly production series data.

At the regional level, the hourly analysis demonstrate that using greenhouses with transmittance values (τ_G) of 0.7, all the PV production can be fed into the grid. The situation changes when higher transmittance values are used and no storage system is foreseen. Using transmittance values (τ_G) of 0.8, the PV production that can be fed into the grid can cover around 27% of the electricity demand. If the transmittance values (τ_G) is as high as 0.9, the PV production that can be fed into the grid can cover around 41% of the electricity demand.

4. Conclusions

This research shows how relevant agrivoltaic could be, especially in regions where land is scarce and, thus, a highly valuable resource. The combined use of greenhouses to produce food and energy at the same time increases farmers' income, diversifies their economy, converting farming into a more attractive sector. This is especially important in regions where farming has decreased over the last decades, favouring e.g. the tourism sector in opposition to the primary sector, compromising food sovereignty in isolated regions, such as the Canary Islands. There is a slow movement back to the farming sector in isolated regions, especially after the COVID pandemic. This tendency could be accelerated by agrivoltaic, since farmers could profit from a double source of incoming: vegetables and energy. The cornerstone of this symbiosis is the adequate estimation of the photovoltaic cover ratio (PV_R), which is the percentage of greenhouse area covered by PV panels, in a way that it does not reduce the crop production over the year while it optimises the energy production. Thus, the PV_R value for each greenhouse depends on the type of crop cultivated (characterised by its light requirement), the onsite solar radiation and the type of greenhouse (characterised by its transmittance value). The type of crops have been classified as low, medium and high light requirement crops and the average annual solar radiation has also been classified into three ranges. Results show that the optimal PV_R values range from 0% (for low average annual solar radiation sites and high light requirement crops) to 74% in the best case scenario. Furthermore, results also show that the PV cover ratio of high light requirement crops are highly sensitive to the average annual solar radiation and also to the transmittance values of the greenhouse materials, decreasing significantly when the transmittance value or the solar radiation decreases. Conversely, medium light requirement crops are less sensitive to those changes and low light requirement crops even less. In the Canary Islands, nearly 90% of the greenhouse cultivations are high light requirement crops, thus, the PV cover ratio is highly dependent on the transmittance value and the solar conditions. For high light requirement crops the PV cover ratio ranges from 23% (high solar radiation sites) to 0% (low solar radiation sites) considering transmittance values of 0.9; but the PV cover ratio ranges decrease to 14% (high solar radiation sites) if the transmittance values is 0.8 and even to 1% (high solar radiation sites) if the transmittance values go down to 0.7. Thus the importance of the greenhouse roof material is capital.

Accounting for a total greenhouse area of 7284 ha in the Canary Islands, and depending on the transmittance values (τ_G) of the greenhouse material, the total power reaches figures as high as 1607 MW (τ_G: 0.8) or 2940 (τ_G: 0.9) and the annual energy production ranges from 2480 GWh/a (τ_G: 0.8) to 4497 GWh/a (τ_G: 0.9). Thus, changes in the transmittance values of one decimal (from 0.8 to 0.9) nearly doubles the installable PV power and, thus, the energy production. The variation is even more dramatic when the one decimal change is from 0.7 to 0.8. In this case the installable PV power and, thus, the energy production is 350% higher. These figures speak for themselves about the importance of appropriately selecting the greenhouse material.

If storage systems are available, agrivoltaic could supply rates as high as 31% of the annual regional energy demand, considering transmittance values of 0.8, or even as high as 56% if transmittance values of 0.9 are considered. In the worst case scenario considered (transmittance values of 0.7), agrivoltaic could supply 8% of the regional electricity demand.

Moreover, the analysis of the hourly PV production shows its importance to determine how much electricity could directly be used to supply the demand (while other restrictions apart from the demand level are not being considered), while the surplus can either be stored or would be curtailed. At the regional level, the hourly analysis demonstrate that using greenhouses with transmittance values (τ_G) of 0.7, all the PV production could be used to satisfy the demand. Using transmittance values (τ_G) of 0.8, the PV production that could be fed into the grid could cover around 27% of the electricity demand. If the transmittance values (τ_G) is as high as 0.9, the PV production that can be fed into the grid can cover around 41% of the electricity demand. Thus, the hourly analysis shows the limitations due the demand level.

CRediT authorship contribution statement

Julieta Schallenberg-Rodriguez: Conceptualization, Methodology, Data processing (solar radiation), Writing – original draft, Research, Calculations (PV power and production), Supervision, Visualization, Project administration, Writing – review & editing. **José-Julio Rodrigo-Bello:** Software, Geographical Information System (GIS), Cartographic and topographic information, Identification of suitable areas. **B. Del Río-Gamero:** Statistical metrics, Literature review.

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

Data will be made available on request.

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