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Agri-voltaics near airport facilities. Reconciling the risk of solar glare with power generation

Ferdinando Salata *, Jacopo Dell'Olmo, Virgilio Ciancio

Sapienza University of Rome, Dept. of Astronautics, Electronic and Energy Engineering (DIAEE), Via Eudossiana 18, 00184 Roma, Italy

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ABSTRACT

The installation of photovoltaic systems on cultivated land enables both agricultural and green energy production simultaneously. The result is an efficient and inclusive use of land that promotes the rural economy, enables the recovery and maintenance of land and prevents its abandonment when it is considered not profitable. This intent is facilitated in semi-rural areas where there is already the presence of infrastructure connected to the national power grid, but at the same time is limited by other human activities. Runway approach and air traffic control operations impose very stringent constraints on the possibility that photovoltaic panels, reflecting solar radiation, may glare airport operators.

This article provides a methodology for verifying such phenomena (control function) and mitigating them by maximizing solar power generation (objective function). Through a case study located in central Italy, positioned near an airport, it was possible to investigate the design variables to protect the landing air routes and the airport control tower.

In this case study, with an azimuth angle of 47° and tilt angle of 25°, and thanks to a 5 m high tree screen placed on the edge of the land on which the agri-voltaic installation stands, it is possible to secure airport operations by eliminating all forms of solar glare. At the same time, 21.9 GWh of photovoltaic energy is produced annually, while avoiding the release of 8,773 tons of CO_2 into the atmosphere. Compared with the optimal, unconstrained case, photovoltaic panels arranged in this way decrease their annual energy production by only 6.8 %.

1. Introduction

Projections for the end of the current decade predict that the world will continue to increase its energy needs, even though with a lower growth in energy demand than in the previous decade [1] This is due to the crises of recent years, which are leading to a push on optimizing energy consumption [2]. On the other hand, climate change is also dictating that energy needs must increasingly be met in an eco-friendly manner. The challenge for societies from more advanced economies will be to be able to decouple emissions from growing energy demand as quickly as possible [3]. To do so a transition towards cleaner energy production appears inevitable. Within this general framework, G7 countries are committed to targets that aim at energy decarbonization in the coming decades, and there is an increasing demand for electricity generated from renewable sources.

Currently, 20 % of electricity generation is met through renewable sources, but this percentage needs to rise. Renewable energy will become the leading source of electricity worldwide in the long run globally, compared with just over 10 years ago, electricity generation from renewable sources has increased by more than 8 %, driven mainly by increases in solar photovoltaic and wind generation. Specifically, depending on the assumed global scenario, the share of electricity generated by photovoltaics compared to today will increase 4 to 7 times by 2030 and 12 to 27 times by 2050 [4].

In this context, solar photovoltaic power generation in the Italian scenario as of 2021 amounts to 39 % of that for the entire national renewable plant stock Specifically, 1,016,083 photovoltaic plants developing a total capacity of 22,594 MW are operational. Numerically, about 93 % of these plants have a capacity of less than 20 kW, while 35 % of the installed capacity is concentrated in plants between 200 kW and 1 MW. During the year 2021, solar electricity generation amounted to 25,039 GWh (or 21 % of the country's total renewable generation), with 61 % of the electricity generated by photovoltaic plants being produced by plants larger than 200 kW [5]. These data should also be considered taking into account what is reported in the report on land consumption

* Corresponding author.
E-mail addresses: ferdinando.salata@uniroma1.it (F. Salata), jacopo.dellolmo@uniroma1.it (J. Dell'Olmo), virgilio.ciancio@uniroma1.it (V. Ciancio).

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Nomenclature

Acronyms:

ARC	Anti Reflective Coating
ARP	Airport Reference Point
ATCT	Air Traffic Control Tower
FP	Flight Path
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
PV1	Photovoltaic Plant 1
PV2	Photovoltaic Plant 2
PVGIS	Photovoltaic Geographical Information System
SGHAT	Solar Glare Hazard Analysis Tool
WGS84	World Geodetic System 1984

Greek symbols:

δ	solar declination [°]
n	number corresponding to the day of the year [-]
φ	latitude [°]
ω	hour angle [°]
θ_z	zenith angle of the sun [°]
γ_s	azimuth angle of the sun [°]

in Italy provided by the National System for Environmental Protection. New artificial ground cover (reversible in nature) from 2006 to 2021 can be attributed to the installation of photovoltaic panels in a consistent part. 146 km^2 of land was consumed for the installation of PV panels, about 12.36 % of land consumption in Italy in those years [6]. Crossing all these data, it is understood that for the construction of large-scale photovoltaic installations useful for clean energy production, the transformation of agricultural land is taking place. This results in a decrease in land useful for food production. This can be avoided by the mixed-use (agricultural and energy) land plots through agri-voltaic power plants.

Within this complex framework, land for cultivation located near airport areas (which place severe constraints on urbanization and even other uses in their vicinity [7]) is often granted for photovoltaic production. In airport environs, the installation of photovoltaic systems is permitted, provided that it does not disrupt air traffic management and aircraft landing operations. To this end, in many countries, the Authorities grant permission to set up photovoltaic fields that are located in the surroundings of airports only with prior authorization related to the study of solar glare to air routes and the control tower. For example, in Italy (the site of this case study) such an area extends within a 6-km radius of the airport grounds [8].

1.1. Scientific background

The scientific community has been dealing with the problem of how to reconcile the possibility of harnessing solar radiation for photovoltaic power generation near airport facilities. In many cases, it is the airport operators themselves who resort to installing these facilities within airport boundaries to mitigate the fossil fuel consumption of airport activities and mitigate their climate-changing emissions. In this regard, analysing Amsterdam Schiphol Airport as a case study, Kılkış reports the possibility of generating up to 10 per cent of its needs in a sustainable manner [9]. This has led to a bibliography of case studies looking at how to optimize the problem in different contexts. On the one hand, there is the need to position photovoltaic panels as best as possible, optimizing the geometric parameters that characterize their arrangement, to maximize the capture of solar radiation annually. On the other hand, there is the need to preserve from the solar glare, from the specular reflections associated with the characteristics of the capturing surface of the panels, the operators (the personnel operating in the control tower and the flight crew). Sreenath and others have explored this topic in more scientific works. In their review work [10] they list the factors that influence the problem of solar glare dividing them into two categories: those not dependent on the design (such as the apparent path of the sun in the sky and cloud cover) and those dependent on the design (such as the position of the photovoltaic panels, their angle respect to the north axis, their angle respect to the horizontal, the texture and colour of the surface finish). Subsequently, they examine what the approaches for the analysis of solar glare can be by comparing methods, techniques and software that can be useful for this purpose, providing a review of the state of the art In one other paper [11] they evaluate the risks and impacts that the presence of solar photovoltaic in airport areas brings, evaluating the tolerability of the identified risks and suggesting corrective measures to reduce the risks. They also analyzed the economic and environmental convenience of photovoltaic energy production in airport areas [12] (Indianapolis Airport's solar power plant has an installed capacity of 25 MW as of 2020, Kuala Lumpur International Airport produces 18 284 MWh annually from PV in 2018, Cochin International Airport has 30 MW installed PV systems as of 2020), despite the need to implement solutions to mitigate solar glare phenomena. The know-how developed by these authors on the topic has found practical applications through case studies reported in various publications on different airport structures. Using Ahmedabad airport (Western India) as a case study [13], the authors show how to reconcile energy production from solar photovoltaic (With an installable capacity of up to 169 MW) and airport security by acting on the reflective properties of the surface finish of photovoltaic panels. In another case study, the authors focus on Senai International Airport (Malaysia) [14], determining the best positioning within the airport area to create a photovoltaic system that maximizes the energy produced (with an installable capacity of 12.50 MW e with an annual energy production of 30,941 MWh), minimizing solar glare. Finally, by analyzing the characteristics of the site where the Sultan Ahmad Shah International Airport (Malaysia) is located, they propose solutions by investigating the geometry of the photovoltaic system served [15] and analysing their energy performance [16] (with a potential energy output of 26.304 MWh annually. They also investigated the feasibility of using Solar Tracking PV Systems to produce renewable energy from land on airport grounds, determining the compatibility of these systems with airport operations and increasing energy production by 40 % compared to fixed ground-mounted PV systems [17].

Other authors have made contributions to the scientific bibliography in this field. Mostafa and others [18] assessed the risks and possible mitigation solutions for the use of solar PV in airports, concluding that there is a significant opportunity to exploit airport surroundings for power generation from photovoltaic systems. Zhu presented a method for evaluating glare from photovoltaic systems near airport facilities [19] based on the two-way reflection distribution function. Using analytical models, they were able to assess the potential risks of glare from specularly reflected sunlight. Kim and Song analysed the case study of Incheon International Airport (South Korea) [20] to evaluate the optimisation of the optimum tilt angle with respect to the north-sub axis of photovoltaic panels to maximise energy production while minimising glare (with an installed capacity of 7 MW). Sher et al. investigated the possibility of completely solar-powering Doncaster Sheffield Airport (UK) [21] verifying the possibility of containing solar glare and assessing the mitigation of climate-altering gas emissions (avoiding 11.643 tons of CO_2 emissions). Devita and Barrett carried out studies using the Tucson International Airport and the Newark Liberty International Airport as case studies to evaluate the performance of a computational model for predicting solar glare from photovoltaic systems built near airports [22]. Sedai et al. analysed the techno-economic feasibility of a photovoltaic system that could fully meet the 213 MWh/year energy needs of an airport in Nepal [23]. Kandt and Romero estimated a solar energy potential of 116.704 MW, exploiting sites near airports located in the U.S. [24].

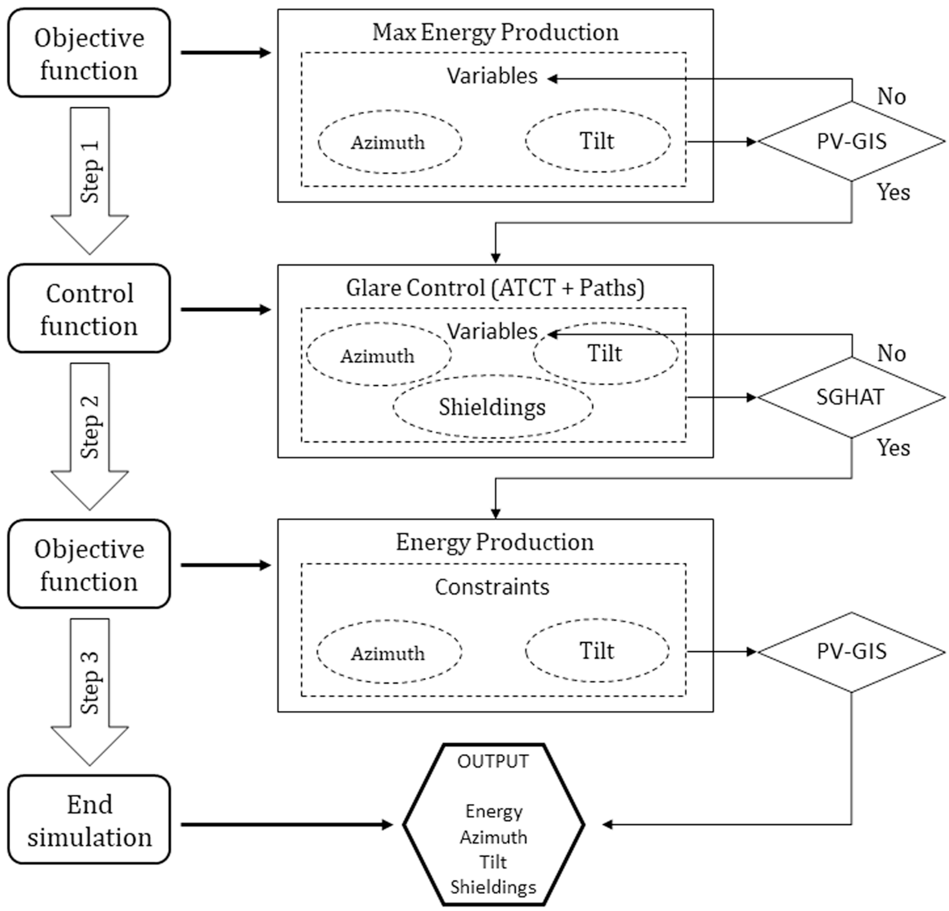

Fig. 1. Diagram of the analysis logic of the "objective function" (energy production) and the "control function" (solar glare).

1.2. *Purpose of the work*

A more sustainable use of arable land is currently the focus of interest of many governments that are looking to the possibility of reconciling agriculture and energy production as a way to promote the creation of shared value with the land and farming communities that can thus enhance the value of their properties and protect their industrious activity without depleting the agricultural sector in the mone of sustainable energy production. The scientific community has been engaged for years in the study of applications of photovoltaic technologies and their integration into the urban environment. Now the same research interests must also be directed towards man-made rural areas, where people are engaged in agricultural activities and where regulation and know-how on how to realise agri-voltaic farms that are respectful of the many needs that must be reconciled are needed.

In totally rural environments, these objectives are easier to implement, but interest in exploiting such land is often low due to difficulties in connecting photovoltaic installations to the national grid. For semi-rural environments, where infrastructure is already in place, there is greater interest in installing photovoltaic farms, but other human activities are already established (and strongly constraining), making it more complicated to reconcile. This makes plant design more complex (multi-objective and multi-parametric).

In particular, by analysing a case study where the most stringent constraints are posed by the presence on the territory of an airport facility operating in the vicinity of land intended for agri-voltaic use, this scientific work aims to:

- explore the opportunity to reconcile the two primary objectives, i.e. (i) the full utilisation of agricultural land, which must be able to fulfil its main purpose (cultivation); (ii) photovoltaic energy production from large-scale plants operating on the same land;
- investigate the possibility of maximising energy production from solar sources (objective function) while complying with particularly stringent environmental constraints (control function), such as the presence of an airport facility located adjacent to the agri-voltaic installation.
- provide a calculation methodology and working process that operates on the controlled design variables to satisfy the above points.

The authors of this paper believe that there is currently a need to expand what has been analysed so far by the international scientific community about glare at airport facilities due to the presence of power projection facilities from photovoltaic systems. There is a need to integrate these facilities with the needs of the agricultural production sector, bridging the knowledge gap that currently exists. Land should not be contested between growing food and the need for solar renewable energy supply. There is a contemporary possibility of exploiting large areas of land in semi-urbanized areas, but well connected to energy systems, taking advantage of the presence of major power facilities right next to airport areas (adequately distant from city cores). This work introduces, therefore, new elements to the scientific debate on this issue and indicates what are the multiple needs that must be considered and met, so that the productive sector can find viable solutions in the not simple integration between the world of energy production and the world of food production, while respecting the infrastructure present in semi-rural territories.

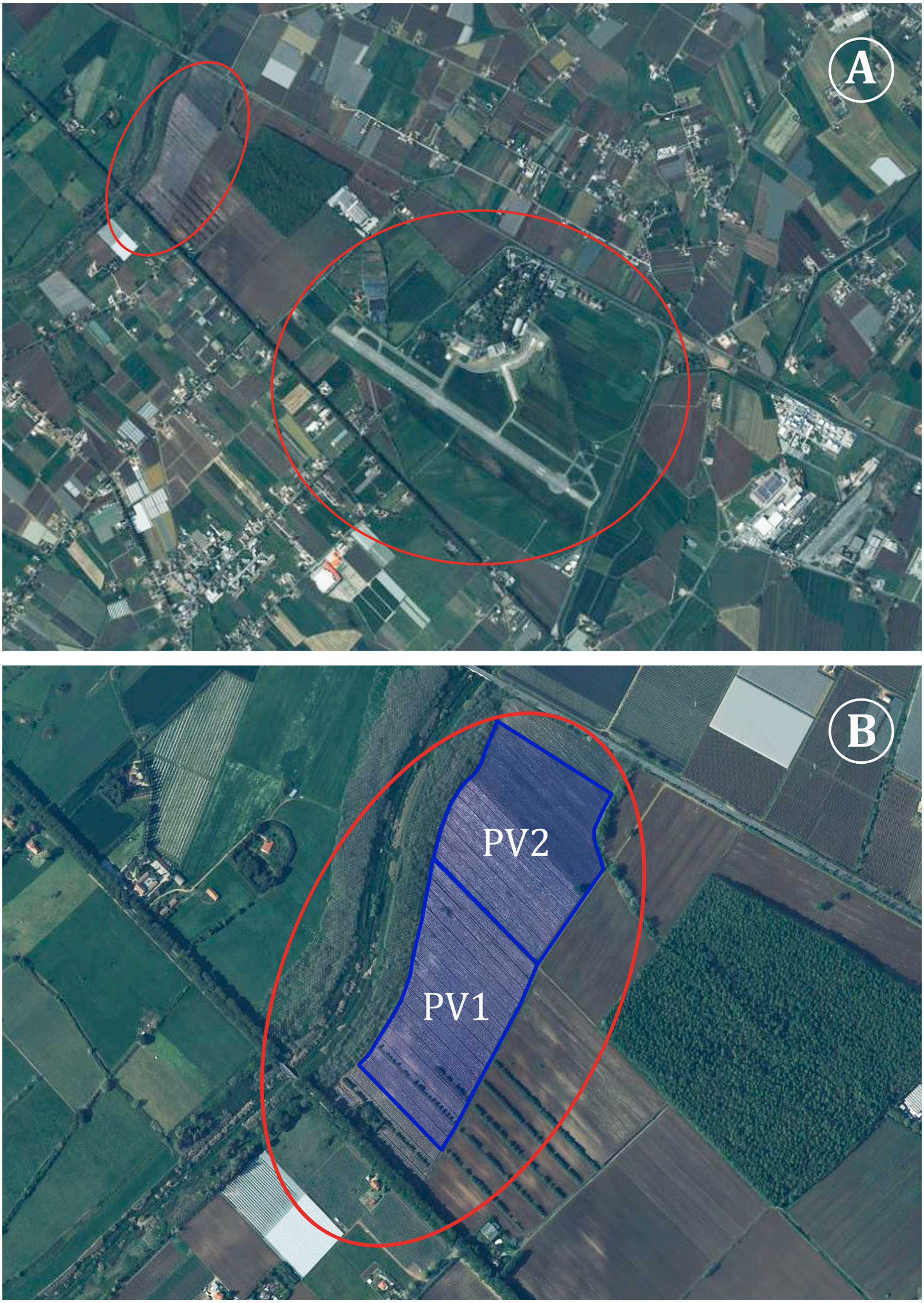

Fig. 2. Identification of the intervention area (PV1 and PV2) and airport facilities: a) zoom out; b) zoom in.

2. Methodology

According to the Guidelines for the "Verification of Potential Obstacles and Dangers to Air Navigation" provided by the Italian authorities in charge [8], photovoltaic installations are to be subjected to a compatibility assessment for authorization. They need to be analyzed as they are located near airports with instrumental procedures.

In particular, "special-hazardous constructions to air navigation" (in this case "photovoltaic installations-buildings/structures with potentially reflective construction features") that may give rise to reflection and/or glare for pilots must be checked [8]. Authorisation is therefore required for installations consisting of photovoltaic panels: i) located at a distance of less than 6 km from the ARP (Airport Reference Point); ii) consisting of a surface area greater than 500 m^2.

The verification of glare phenomena must be carried out in accordance with the guidelines defined by the Federal American Aviation (FAA) "Technical Guidance for Evaluating Selected Solar Technologies on Airports" (provided by the Airport Planning and Environmental Division) [25,26]which provides:

- the geographical characterisation of the site;
- identification of the observation points most exposed (pilots and operators in the control tower) to glare due to solar reflection;
- characterisation of the location and size of the photovoltaic field, as well as the characteristics of the materials of which the reflecting surface is composed;
- assessment of potential solar glare on structures due to the presence of photovoltaic panels.

This environmental compatibility must be seen as the "control function" of the study, but the "objective function" must always be taken into account. When building a photovoltaic system, the objective is the generation of electricity from a renewable source. The randomness of the solar source and its capture at different times of the day and year mean that an optimum must be sought in the annual energy production that is obtained by positioning the photovoltaic panels: (i) with an azimuth angle pointing south (for the northern hemisphere, and north for the southern hemisphere) from the meridian axis; (ii) with a tilt angle equal to the value of the latitude (and with a variation of 15°, less if you want to favour production during the summer months more during the winter months). The control function may determine the need to change the optimal values of these angles, reducing energy production in favour of environmental safety. These changes affect the calculations of the energy that can be obtained annually from the installation under analysis, determining the need to find an optimum that makes the installation energy sustainable [27].

Furthermore, unlike photovoltaic systems located in built-up areas or on land exclusively dedicated to solar energy production [28], Agrivoltaic installations must reconcile the needs of farmland cultivation, which today cannot be separated from the mechanisation of human activities. More specifically, it is necessary to guarantee the accessibility of agricultural vehicles and their manoeuvrability between the rows supporting the photovoltaic panels. Limits therefore arise on the exploitation of available space due to: i) the encumbrances of the power plant support structures at height (hence their spacing and azimuth angle); ii) the silhouette of the photovoltaic panels (hence their size and slope). All these are additional factors that limit design choices for energy production plants and pose "constraints" that create complications when optimising energy output. All these needs can be summarised in the diagram in Fig. 1, which shows the workflow for solving the problem of reconciling photovoltaic energy production with the use of land that can remain productive in agriculture.

2.1. Case study

In this work, in order to be able to explore all the difficulties that have to be resolved in order to be able to correctly evaluate photovoltaic production for an agri-voltaic system, a particular case study was selected that presented all the possible difficulties outlined so far. This was done in order to be able to discuss every aspect that can make the realisation of this type of system complicated, but also to find the right way to make the most of the possibilities that this system solution presents. The analysis carried out here concerns a plot of agricultural land located in the countryside of the Municipality of Latina in Lazio (Italy) that is to host two photovoltaic plants (named "PV1″ and "PV2″) with a maximum nominal power of about 8 MWp each (the power of the single plant is deliberately limited to below 10 MWp to avoid the complications of a connection to the high-voltage electricity grid, which is compulsory in Italy beyond that size), with a total production of about 24 GWh/year.

The plot of land integrates photovoltaic production with the activity of a farm, in order to give substance to an experiment on the sustainability of agri-voltaic installations. The area identified for the construction of the plants is located north of the urban centre of Latina, near the border with the municipality of Cisterna. The land is completely flat and is included in an area delimited in a quadrangle of geographical coordinates (lat/long WGS84) between:

- West Longitude = 12° 53′ 04.99″ E;
- Latitude North = 41° 33′ 41.35″ N;
- Longitude East = 12° 53′ 33.94″ E;
- Latitude South = 41° 33′ 08.60″ N.

The photovoltaic plant under analysis is located at a distance of less than 1,300 m from the Latina Military Airport (IATA Code: QLT, ICAO Code: LIRL). Both the area hosting the photovoltaic panels (Fig. 2a) and the areas adjacent to the airport structure (Fig. 2b) are substantially flat. The agricultural land presents a slight slope that ranges from 40 m a.s.l. in its northernmost part to 36 m a.s.l. in its southernmost part. The airport structure is located at an average height of 26 m above sea level.

The entire photovoltaic installation consists of a total of 30,100 photovoltaic modules. The panels are of the smooth glass type. The surface finish can be either "Light textured glass with AR coating" or "Deeply textured glass with AR coating" depending on the requirements that will be assessed during the glare analysis.

Solar panels are designed to absorb sunlight, as reflection is considered a loss in the energy conversion process. Since the absorption efficiency of solar panels depends strongly on the angle of incidence, solar panels have variable behaviour as the sun moves across the sky. By varying the angle of incidence, the potential for reflection and therefore glare can increase [29]. The first solution to this problem is to apply anti-reflection coatings on solar panels [30].

In this study, the surface physical characteristics of the chosen panels always concerned structured glass with AR-type coating. It is better to use these technologies a priori (with a loss of performance of the PV array about 4 %) [31] and only subsequently intervene in the orientation and arrangement of the solar panels to avoid glare, as this kind of intervention can significantly reduce the solar energy collection capacity of the panels [32]. The energy loss derived by choosing a sub-optimal orientation will be shown in detail in section 3, in particular in Fig. 6.

The panels must be positioned at a certain height above the ground, fixing them to the ground by means of steel support structures that allow their tilt angle to vary. The orientation of the azimuth angle of the plant with respect to the north–south geographical axis (in bioclimatic notation, this is defined as 0° to the south, 90° to the west, 180° to the north, 270° to the east), in addition to satisfying energy and glare constraints, must be such that the installation of the supports can allow the land to be cultivated with agricultural mechanical means and guarantee access to the main road leading to the farmland.

The entire photovoltaic installation is divided into two plants ("PV1″ located further south and "PV2″ located further north) with a capacity of 8 MW each, similar in terms of electrical characteristics. Each of them is

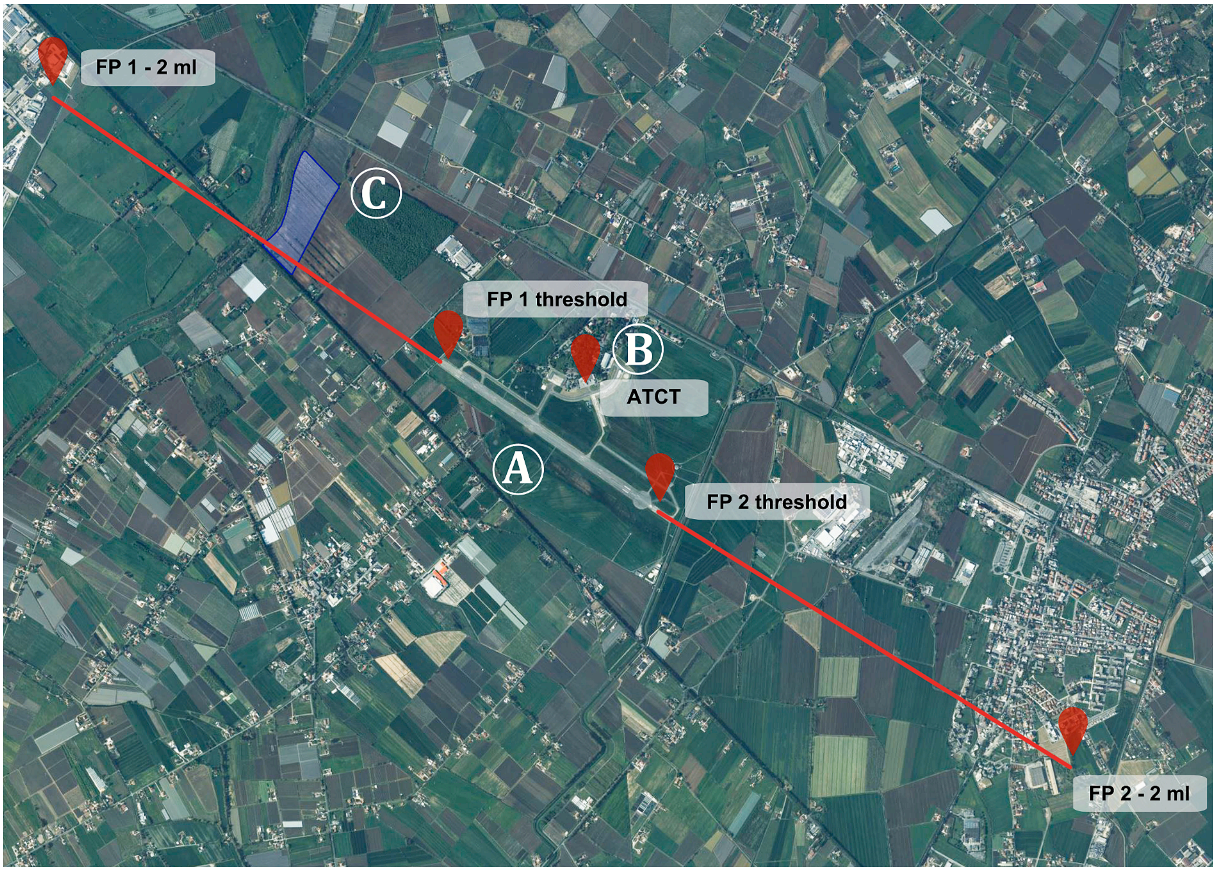

Fig. 3. A) airport configuration (runway fp1-fp2); b) detail of theairport's control tower (ATCT); c) Position of the photovoltaic panels (in blue) in relation to Flight Path 1 (FP1, magnetic heading at 12) and Flight Path 2 (FP2, magnetic heading at 30): landing manoeuvres, from 2 miles away to the threshold.

equipped with electrical substations containing the equipment (transformers, switchboards, etc.) arranged in a barycentric position, containing the switching, manoeuvring, conversion and transformation devices for the electrical energy produced by the photovoltaic modules; the inverters are arranged below the structures supporting the panels. The output voltage of the individual plant is 20 kV (medium voltage). The system is built on a suitable support surface in order to allow the photovoltaic modules to be anchored and to support their weight and wind, snow or earthquake loads, as required by the specific regulations in force in Italy.

The configuration of the airport structure affected by potential solar reflection phenomena (and thus glare for ground and flight personnel) is characterised by the presence of a single runway. The airport runways are marked with numbers indicating the direction in which the point of the runway. The indicated number is the result of dividing the magnetic orientation value by ten, rounded to the nearest unit. The runway of the analysed airport is therefore referred to as 12–30 and is depicted in the aerial photograph in Fig. 3a:

In this study, the analysis of glare phenomena was carried out:

- at the ATCT control tower (coordinates: 41°32′45.02″ N, 12°54′35.11″ E) with a tower office height of 25 m above ground level (Fig. 3b).
- for the landing trajectories parallel to the runway axis with a length of 2 miles (Fig. 3c) and relative to Flight Path 1 with magnetic heading at 12 (threshold with coordinates 41°32′47.13″ N, 12°54′2.68″ E) and Flight Path 2 with magnetic heading at 30 (threshold with coordinates 41°32′18.80″ N, 12°54′58.90″ E).

2.2. Informatic tools

The calculations for the "objective function", i.e. electricity production from photovoltaics, were carried out using the "PVGIS – Online Tool" software made available by the Joint Research Centre of the European Commission [33]. This software, using data on solar radiation (obtained from satellite images), ambient temperature and wind speed (from climatic analyses), allows the calculation of the electrical energy produced annually by a photovoltaic installation whose georeferenced location, geometric characteristics and technical and economic characteristics are known. For this study, version 5.2 of the software was used.

Parallel to the verification of the objective function, checks were carried out on the "control function", i.e. the solar glare attributable to the installed photovoltaic systems.

As the number of solar power generation facilities grows, glare from photovoltaic (PV) installations can become a hazard to pilots and air traffic control personnel. US government agencies have initiated the development of an interactive web-based computer tool that provides a quantitative assessment of:

- when and where glare will occur throughout the year for a photovoltaic solar power plant,
- the potential effects on the human eye at the locations where glare occurs,
- an estimate of the maximum annual energy production.

In cooperation with the US Department of Energy (DOE), the FAA made available the "Solar Glare Hazard Analysis Tool" (SGHAT)[34]. This computer tool is designed to determine whether the installation of a photovoltaic field for solar power generation may pose an eye-impact risk to airport personnel. The SGHAT is a validated instrument

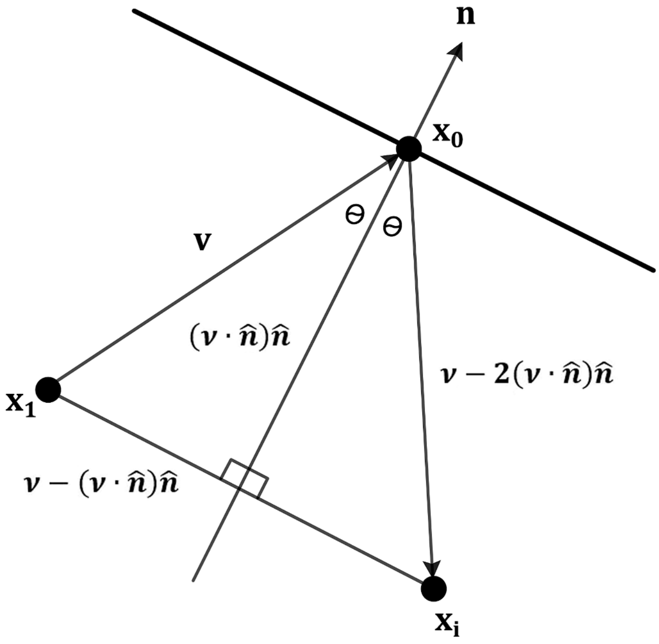

Fig. 4. Reflection of the solar radiation vector with respect to the normal of the solar panel surface.

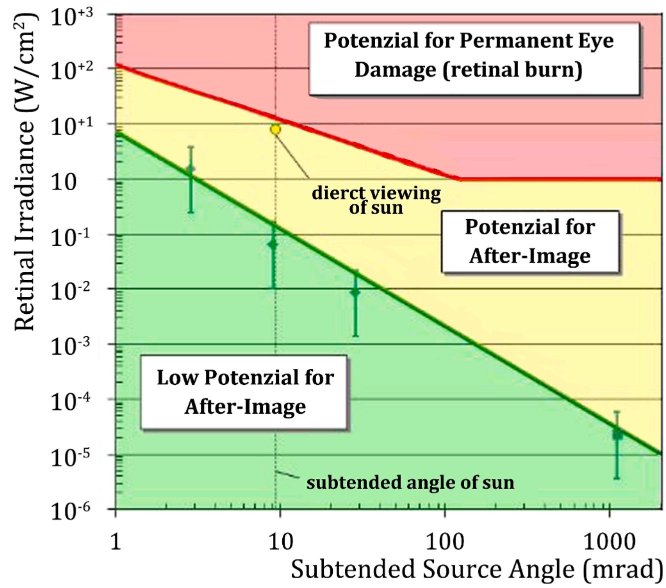

Fig. 5. Glare risk as a function of retinal irradiance and angle of the underlying Source [35].

specifically designed to measure reflections according to the Solar Glare Hazard Analysis Plot. The instrument calculates the irradiance on the retina and the angle subtended by the reflected light source. The SGHAT employs an interactive map, implemented in Google Maps, in which the user can locate the site under analysis, draw the outline of the installation area of the solar power system to be analysed, specify the positions of the observers (traffic control tower) and approach paths to the runway. Latitude, longitude and altitude are automatically recorded through the Google interface, providing the necessary information for the position of the sun and subsequent vectorial calculations.

The calculation of glare requires knowledge of the following:

- position of the sun;
- position of the observer;
- the tilt, orientation, position, extent, and optical properties of the solar panel modules.

The software implements an algorithm to calculate, at any time of the year, the angle value corresponding to the sun's zenith angle (θ_z) and the sun's azimuth angle (γ_s) [35], respectively:

$$\delta = 23.45 * sin\left(360 * \frac{284 + n}{365}\right) \quad (1)$$

$$\theta_z = cos^{-1}(cos\varphi * cos\delta * cos\omega + sin\varphi * sin\delta) \quad (2)$$

$$\gamma_s = sign(\omega)\left| cos^{-1}\left(\frac{cos\theta_z sin\varphi - sin\delta}{sin\theta_z cos\varphi}\right)\right| \quad (3)$$

where: "δ" is the solar declination, i.e. the angle formed by the direction of the sun's rays on the meridian under consideration with the earth's equatorial plane; "n" is the number corresponding to the day of the year (between 1 and 365); "φ" is the latitude; "ω" the hour angle calculated as the difference between solar time and solar noon (i.e. the highest position in the sky of the sun at the meridian of the place analysed).

Knowing the normal vector to the surface of the flat solar panels, and knowing the position of the sun, it is possible to derive the vector that is reflected by the panels according to the geometric diagram in Fig. 4.

$$x_i - x_0 = \nu - 2(\nu \bullet \hat{n})\hat{n} \quad (4)$$

Eq. (4) and Fig. 4 describe the law of reflection, where x_1 is the source of light, x_i is a hypothetical observer that by geometric construction is hit by the reflected ray, and x_0 is a point on a reflective surface with orientation n. It can be demonstrated that $x_i - x_0$ which represents the direction of the reflected ray as a function of the direction of the incident ray and the orientation of the reflective surface. This law allows to detect all the points that are hit by the reflected ray, which lay on the line passing through $x_i - x_0$ by using only the direction of the incident line and the orientation of the reflective surface and not the coordinates of the source of light.

Knowing the geometric parameters of solar panel installation, the reflection coefficients of the photovoltaic panel surface finishing material and ocular factors, the software allows the determination of retinal irradiance (i.e., the amount of energy hitting the observer's retina) as a function of the angle of the underlying source. These two parameters make it possible to identify the ocular risk and therefore the impact of glare for ground and flight personnel [35].

The ocular impact of glare can be classified into three levels (depending on the radiation on the retina and the angle subtended between the observer and the reflected light source) [36]: low potential for after-image (shown in green), potential for after-image (shown in yellow), potential for permanent eye damage (shown in red). The results of the glare analysis thus classified must be determined for the whole of a year [37].

On the basis of these requirements, the analysis shown in this study is carried out, where the "Green Glare" in Fig. 5 is compatible with the working conditions of the flight crew (on the ground and onboard). The "Yellow Glare" (glare conditions in the yellow zone), as well as the "Red Glare" (glare conditions in the red zone) imply the need for design corrections to the geometric parameters that characterise the configuration of the photovoltaic system [38].

3. Results and discussion

Proceed as schematically shown in Fig. 1.

3.1. Determination of the energy optimum

The geometric parameters influencing energy production are the azimuth and tilt angles of the photovoltaic panels. In the absence of constraints, for a fixed photovoltaic system resting on the ground and in

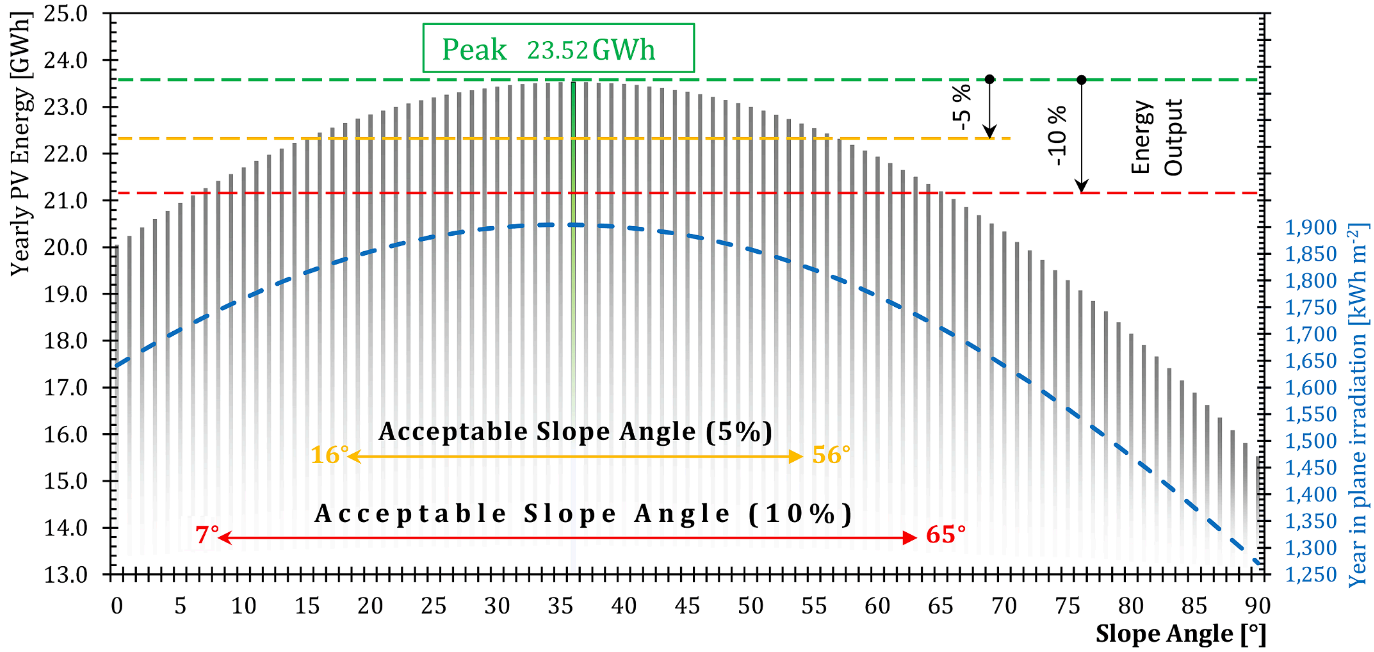

Fig. 6. Energy production with zero azimuth angle, depending on the assumed slope angle.

the absence of obstacles that could cast shadows on it, the best azimuth angle is θz = 0° (for the northern hemisphere). In order to maximise the energy output of the entire plant under study (PV1 and PV2), the best value of the tilt angle to be assumed for the photovoltaic panels is verified using PV-GIS, varying its value from 0° to 90°. Using PV-GIS, the results summarised in Fig. 6 emerged. On the left-hand y-axis is shown in black the annual electrical energy produced (GWh) and on the right-hand y-axis in blue the annual value of irradiation in the plane (kWh m^{-2}).

If a zero azimuth angle could be maintained (after glare verification), it is assumed that energy production would be maximum (so maximising the objective function) with respect to the achievable peak (equal to 23.53 GWh per year at a zero azimuth angle and a tilt angle of 36°). Then the tilt angle is changed to define two thresholds for the energy production till a decrease of i) 5 % (preferably); ii) 10 % (no more). Fig. 6 shows that tilt angles between 16° and 56° correspond to a a 5 % energy reduction and between 7° and 65 a 10 % energy reduction and be considered acceptable. In this way, the limits of the objective function can be defined while complying with the control function.

Thus, the optimal energy configuration of the solar panels constituting the photovoltaic installation on which the solar glare that could afflict the personnel working in the terminal was determined (Step 1 of Fig. 1). Subsequently, the energy output (objective function) for different geometric configurations due to the fulfilment of the control function (glare avoidance) will be compared with this.

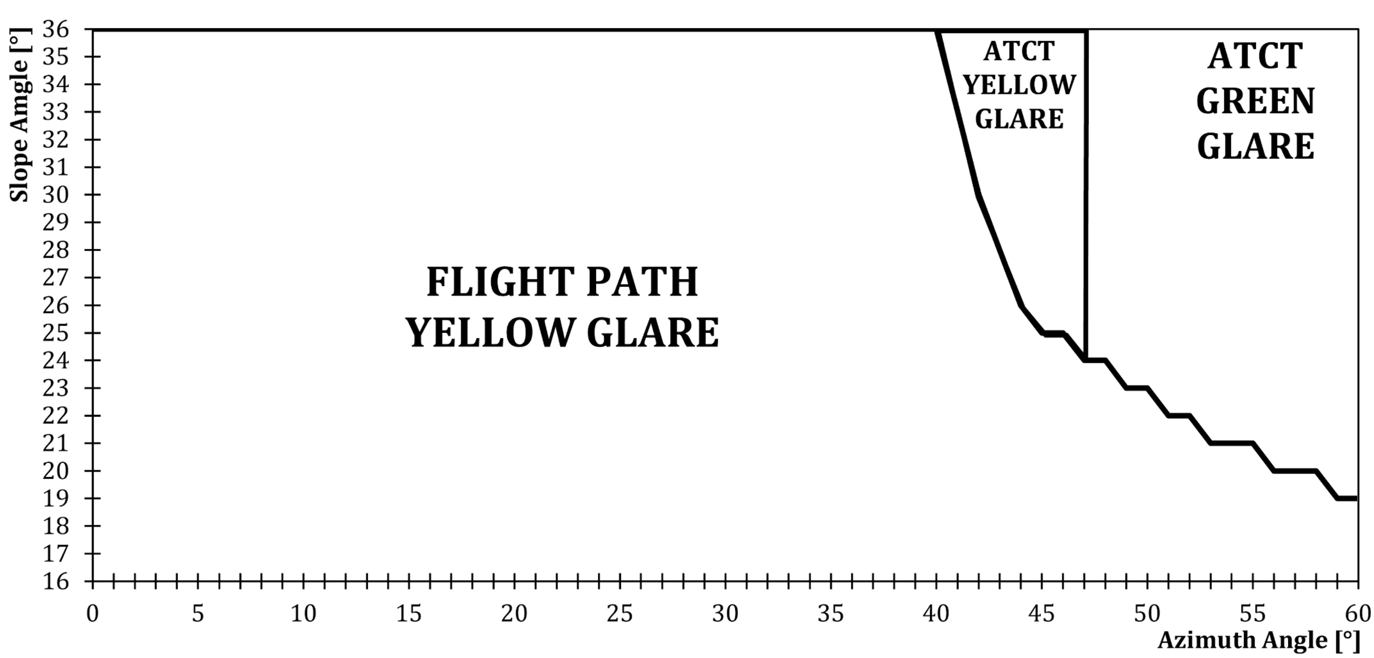

Fig. 7. Yellow glare conditions at Flight Path as a function of azimuth and tilt angle.

3.2. Solar glare verification

Taking into account the encumbrances, sun glare tests were carried out in the following order: i) at the flight paths relating to the landings at the two runway heads; ii) at the ATCT.

A check was first carried out on the possible glare of pilots landing on the two Flight Paths of the runway (depending on whether landing from header 12 or header 30), varying the azimuth and tilt angles. Initially, tilt angles between 16° (the value below which the annual solar energy capture falls below the threshold defined as acceptable) and 36° (the value where the peak of converted energy is obtained) were considered. If glare conditions occur, the azimuth angle is also varied from the null value, both east and west, along with the tilt angle.

It is also necessary to respect:

- the encumbrances previously described in Section 2.1 regarding the access of mechanical agricultural vehicles. Fig. 2b shows the layout of the agricultural property with respect to the road context that allows access and the rainwater channel that borders it to the west. In order to ensure easier access for motorised agricultural vehicles, the support pillars for the plant structures should be placed in a direction that follows the direction from northwest to southeast. Therefore, strings of photovoltaic panels should not be positioned at negative azimuth angles to the normal of their surface.
- in order to guarantee the work of tractors and their manoeuvring between rows of the photovoltaic system, it is necessary that the support poles are properly spaced and that the panels at the top are not placed too horizontally, as their bulk could collide with the cab of the bulkier agricultural vehicles that may be used in this agricultural context. High tilt angles lead to the profile of south-facing panels occluding downwards the passage area of taller agricultural vehicles. It becomes a problem of optimum because minimising the tilt angle also leads to a reduction in the electricity produced. The panel rows could be spaced further apart, but this would result in a smaller solar energy capture area. The supports of the photovoltaic modules are spaced to avoid mutual shading and to allow cultivation in a 2.65 m band, guaranteeing mechanised planting and harvesting of the crops. As a result, only positive azimuth angles will be analysed and the net area of the photovoltaic system is less than 50 per cent of the total area occupied on the ground.
- Possible glare phenomena at the control tower were also checked ("control function"). The regulations require the latter to be free of any kind of phenomenon. The case study (which, as we recall, was chosen for its peculiarities and for the possibility of investigating every possible problem that may arise in a study of this type) presents azimuth angles up to 46° yellow glare phenomena at the tower. Beyond this angle, green glare conditions, also unacceptable if less severe, remain [39]. These will be solved later by the use of green screens. With respect to all these alleys, the values of the azimuth and tilt angles were determined, useful to satisfy the control function, maximising, as far as possible, the objective function. Fig. 7 shows the results obtained in the search for the pair of these angles which do not produce unacceptable phenomena (of the "yellow" or "red" type) on any of the Flight Paths and which never lead to yellow glare phenomena at the control tower. The acceptable angles for fulfilling these needs assume the values included in the upper right part of Fig. 7. In particular, it will be necessary to place an azimuth angle as close as possible to the left boundary of that zone and as low a tilt angle as possible in order to preserve energy production ("objective function").

Following the verifications carried out on the agricultural machines' dimensions, the geometric configuration of the photovoltaic plant that complies with the Flight Path control function is characterised by: i) an azimuth angle of 47° (facing south-west), according to the bioclimatic notation; ii) a tilt angle of 25° with respect to the horizontal. In addition,

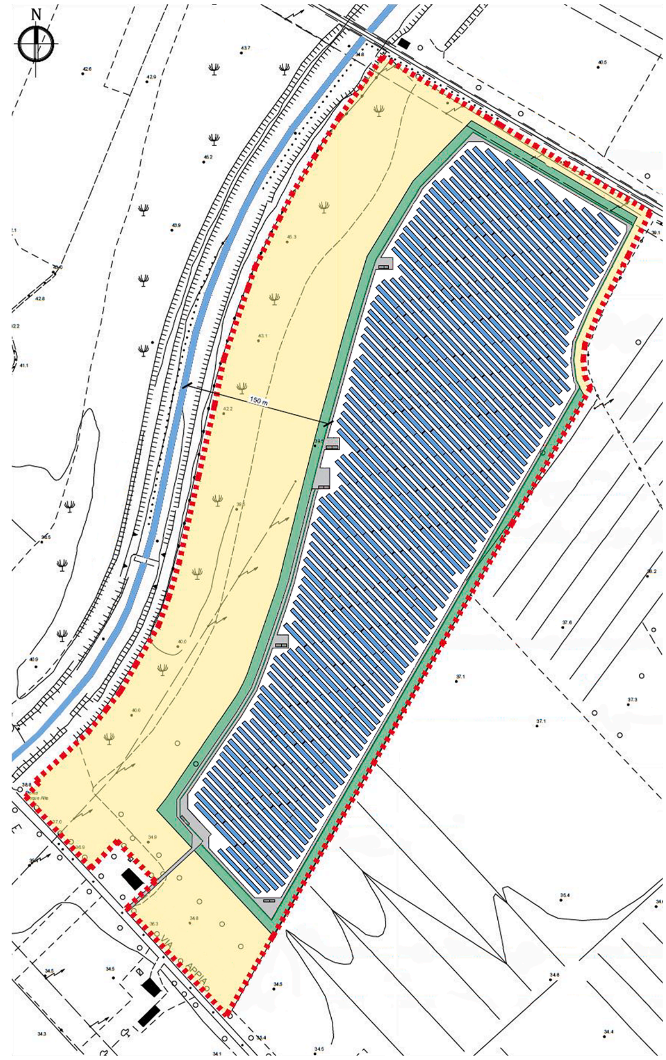

Fig. 8. Positioning and geometric configuration of the agri-voltaic installation.

the finishing surface can be of the type: "Light textured glass with AR coating" for the plant PV2 and "Deeply textured glass with AR coating" for the PV1 plant (which, due to its position in relation to the Flight Path, is more problematic in terms of glare phenomena).

The geometric configuration of the installation is summarised according to the layout in Fig. 8. This image shows the power plant scheme and its positioning with respect to the farmland analysed as a case study. It is possible to note:

- the buffer zone (in yellow) is left clear because of the necessary distances to be provided to the PV system from: i) the watercourse on the west and acting as a boundary to the land; ii) the road present to the south and providing access to the land.
- The positioning of the PV panels forming both PV1 and PV2 systems and their orientation with respect to the north–south axis.

For the geometric configuration of the systems represented in Fig. 8, more details are given (in Table 1) regarding the glare produced by the PV1 system (Fig. 9a) and the PV2 system (Fig. 9b) to the pilots of the aircraft flying over Flight Path 1 (runway 12 header) and Flight Path 2 (runway 30 header) when landing.

In particular, the hours at which glare phenomena occur are summarised as a function of the time of year, and the type of glare is determined on the graph described in Fig. 5. In the graphs shown on the left, the dots in orange (each tied to a time of year where there is a glare

Table 1
Annual hours of glare conditions produced by PV1 and PV2 photovoltaic systems on Flight Path.

PV1				PV2			
Flight Path 1		Flight Path 2		Flight Path 1		Flight Path 2	
Green	Yellow	Green	Yellow	Green	Yellow	Green	Yellow
94.872	0	5.106	0	9.053	0	0	0

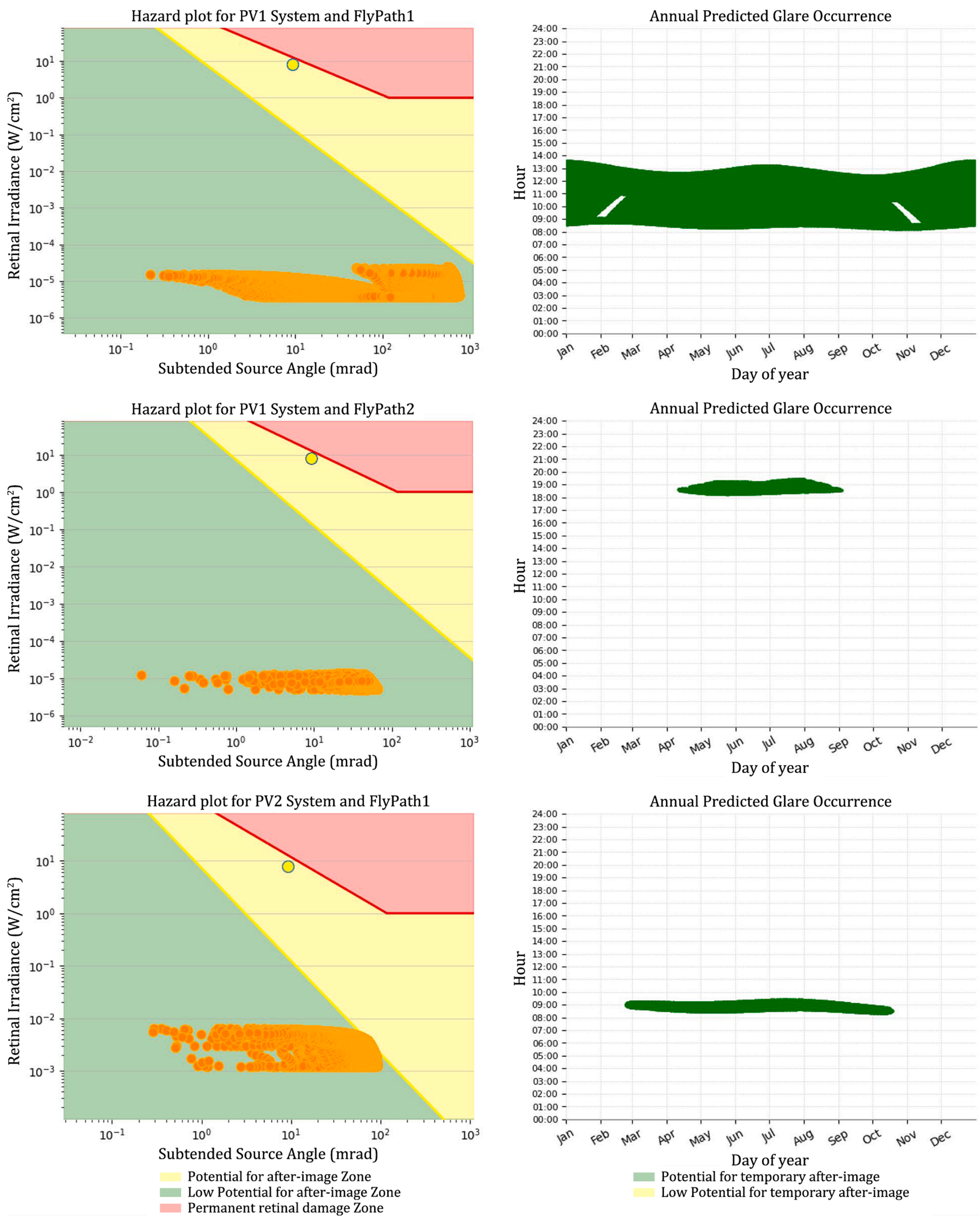

Fig. 9. Glare phenomena, before the positioning of the green barrier, at Flight Paths 1 and 2 due to the PV1 and PV2 system.

Table 2
Sensitive analysis of aircraft glide angle with respect to Yellow glare at Flight Path 1.

Aircraft glide angle	PV1	PV2
3°	100 %	100 %
4°	79 %	47 %
5°	62 %	14 %
6°	10 %	0 %

phenomenon) mark the area of the graph that determines the type of glare produced (due to the specified simulated PV system) to those driving an aircraft landing on the specified Flight Path. In the right-hand graphs, each point, tied to a specified time of year, indicates when there is potential glare and of what nature (as can be seen, only "Green Glare" phenomena, which are considered permissible, are present). The first line of the graph is related to the PV1 plant and Flight Path 1, the second line is related to the PV1 plant and Flight Path 2, and the third line is related to the PV2 plant and Flight Path 1. No glare is due to the PV2 plant compared to Flight Path 2.

In order to further investigate this study and to be able to discuss what was analysed in more detail in the conclusions, a further check was carried out concerning glare at Flight Paths. The regulations indicate to carry out the analysis of potential glare effects on landing flight paths using as input a standard glide path characterised by an angle of 3° with respect to the ground. However, at the airport in question, taking into account its intended use, the angle at which military aircraft (which are much more efficient and manoeuvrable than airliners) are able to land is between a minimum value of 3° and a maximum value of 6°. In this analysis, a check is carried out to determine the sensitivity of the results to the variation of this input parameter, by expressing as a percentage the results with respect to the standard case at 3°. This makes it possible to be certain that the standard angle is the one that renders the glare problem the most severe, and that if verified, always puts pilots in a safe position when landing. For PV1 and PV2, the Yellow type glare of Flight

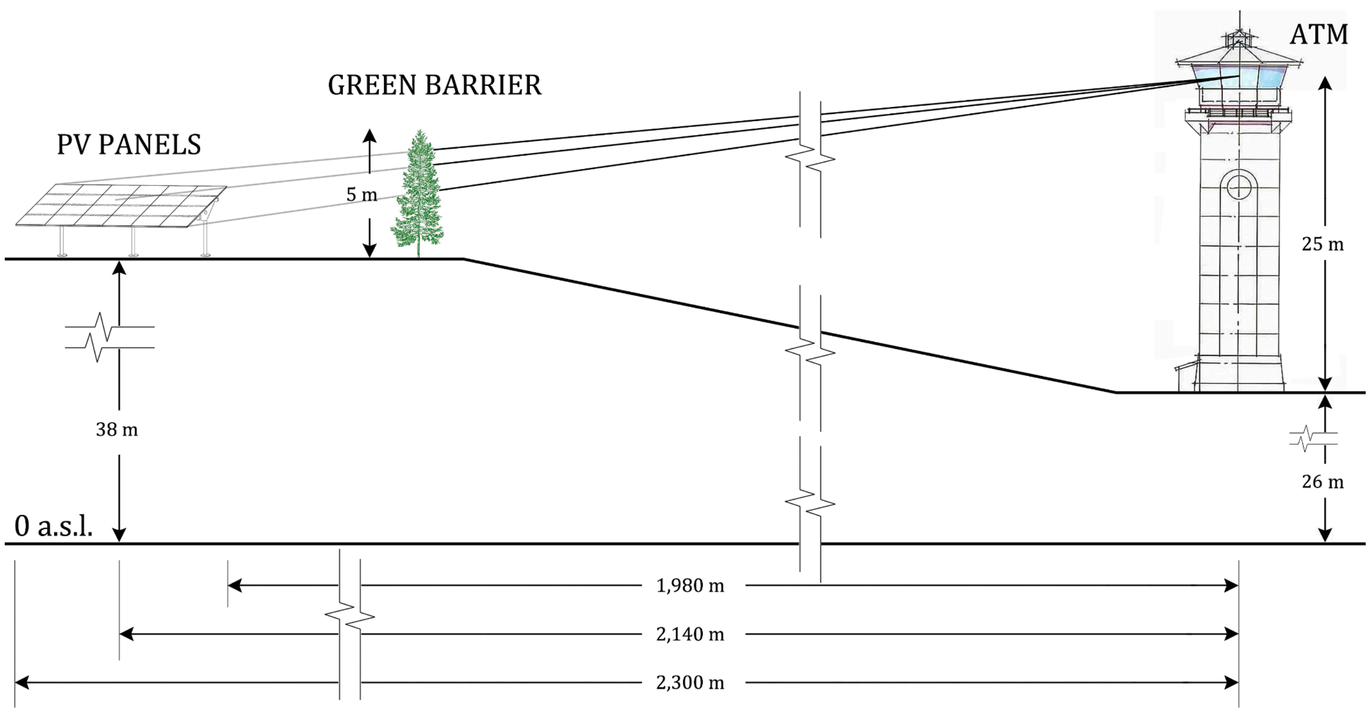

Fig. 10. Geometrical diagram for determining the minimum height of the tree barrier.

Fig. 11. Positioning (in orange colour) of the tree barrier on the agricultural background.

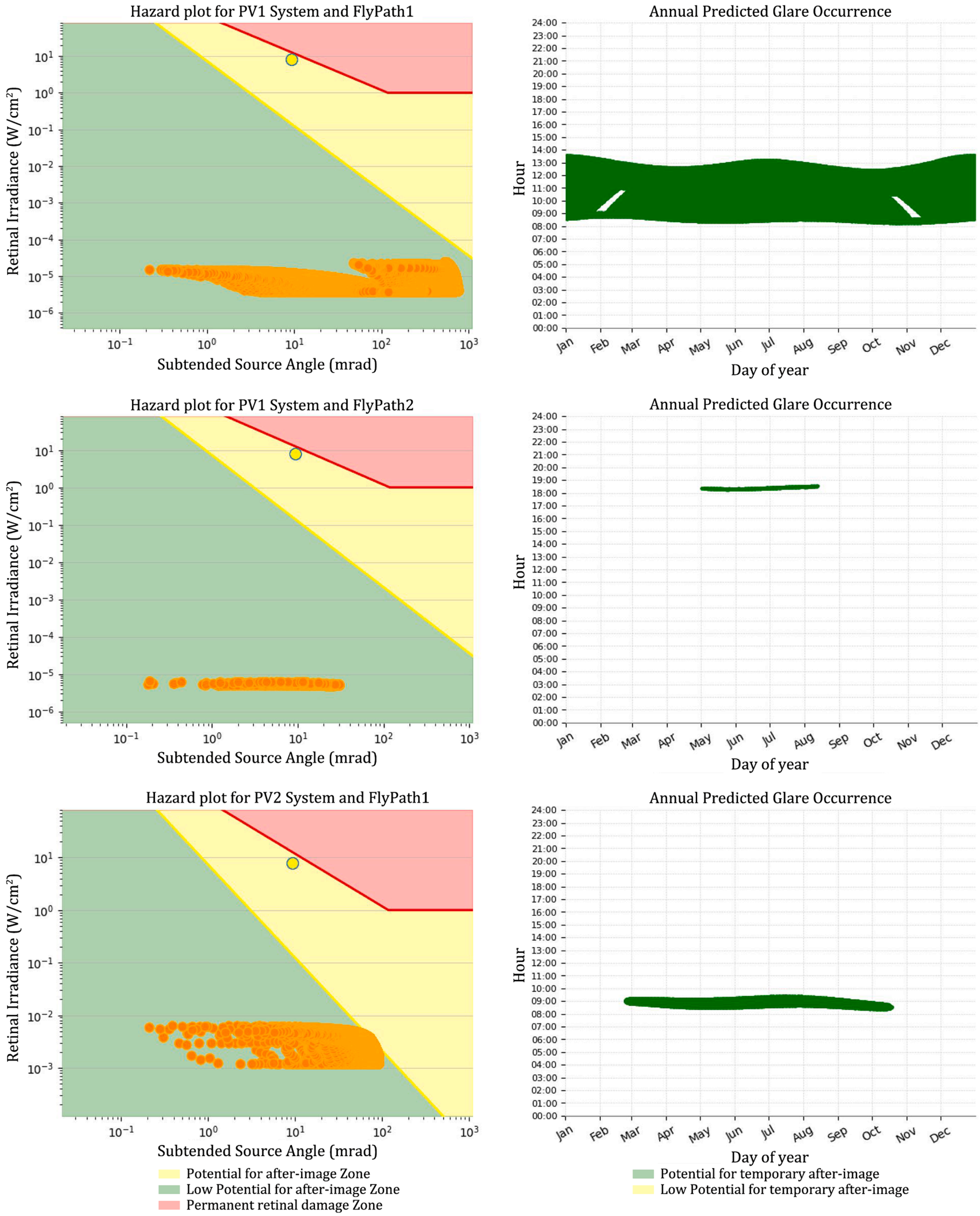

Fig. 12. Glare phenomena, after the positioning of the green barrier, at Flight Paths 1 and 2 due to the PV1 and PV2 system.

Path 1 (which was found to be the most problematic) was analysed for aircraft performing landing manoeuvres with a glide angle greater than 3°. The results are summarized in Table 2, the percentage used with respect to the starting case.

It must also be ensured that there is no glare at the control tower (ATCT). For this further analysis, the installation characterised by the geometric parameters obtained so far is considered. In order for the entire agri-voltaic installation to fully comply with regulatory requirements so as not to negatively impact nearby airport facilities and air traffic, "green" glare must also be avoided. The PV2 installation does

Table 3
Comparison of annual energy performance between the geometric configuration of the photovoltaic system that optimises the objective function and the chosen one that fulfils the control function.

	Optimal	Chosen	Δ	
Azimut	0	47	–	[°]
Tilt	36	25	–	[°]
Yearly PV energy	23.5	21.9	1.6	[GWh]
Year in plane Irradiation	1,904.4	1,781.2	123.1	[kWh m^{-2}]
Avoid CO_2	9.420	8.773	647	[t CO_2 $year^{-1}$]

not generate any problems towards the control tower, while there is glare from the PV1 installation. It was not possible to find any geometric configuration of azimuth and/or tilt angles that do not even generate green glare at the ATCT. The solution to solve the latter problem involves the construction of a tree-shaded screen along the western perimeter of the agricultural plot housing the PV1 plant.

In order to determine the minimum height of a tree screen to be interposed between the photovoltaic panels and the control tower, a geometric schematisation is carried out as shown in Fig. 10.

The shielding system, located on the eastern boundary of the farmland, must have a minimum height of 5 m above ground level in order to adequately shield the control tower from glare phenomena caused by the photovoltaic panels (Fig. 11). The presence of trees also brings advantages with respect to glare phenomena towards both Flight Paths (both for the PV1 system and, to a lesser extent, the PV2 system).

The extent and positioning of this tree line can be seen in Fig. 11 (in orange colour) showing the results in Fig. 12 (in a similar manner to Fig. 9, with the same notation for the figures).

This concluded the verification of glare from the agri-voltaic installation towards the airport facilities.

3.3. Evaluation of energy output after glare verification

After the necessary analyses to determine a configuration of the geometrical characteristics of the agri-voltaic plant under study capable of guaranteeing environmental compatibility and feasibility, it is necessary to evaluate the production of electrical energy for the plant thus defined.

To this end, Table 3 shows data on i) the total annual energy production of the two plants named "PV1″ and "PV2″. (ii) the values of the "year in plane irradiation" to better understand how the configuration that respects environmental constraints leads to a reduction of the energy irradiated on these surfaces and thus the usability of the solar resource; (iii) the variation of the amount of CO_2 avoided thanks to its realisation compared to the amount of carbon dioxide released into the atmosphere if that electricity had been taken for its final use from the national electricity grid (taking into account an emission factor of the latter equal to 400.4 gCO2 kWh-1 [40]). The data compares the agri-voltaic installation in its latest configuration ("Chosen") with the maximum achievable values ("Optimal", analysed in Section 3.1 with zero azimuth). The column marked "Δ" shows, where possible, the difference between the optimal value (reported in the first column and related to the "Objective Function" alone) and that related to the chosen configuration (due to the mitigation of the "Objective Function" with the "Control Function"), reported in the second column.

Finally, in Fig. 13, the monthly energy production trend is shown for the case of the optimal plant configuration (azimuth equal to 0°; tilt equal to 36°) and compared with the chosen configuration (azimuth equal to 47°; tilt equal to 25°), which meets the numerous requirements shown. The total amount of annual electrical energy produced is obviously greater in the former case (Table 3).

The gap in electricity production is especially related to better utilisation of the available solar resources during the months of September to April. The situation becomes the opposite during the months of May to August, but the summer surplus is not sufficient to repay the winter losses. There is a decrease in energy produced of about 1.6 GWh per year, or 6.8 %, compared to the optimum case. The photovoltaic panels used at this site could avoid up to 9,420 tonnes of carbon dioxide annually in their optimal installation. The constraints imposed to reduce this to 8,773 tonnes, a decrease of 647 tonnes annually.

The energy data thus determined make it possible to state that from an energy point of view, having to comply with the many alleys present does not penalise the site so severely that it cannot be considered for energy exploitation alongside agricultural exploitation.

4. Conclusions

In an international context that is increasingly sensitive to the environmental problems associated with energy production, a growing electrification of consumption appears to be the necessary path to follow in order to guarantee a massively compatible energy supply to meet the

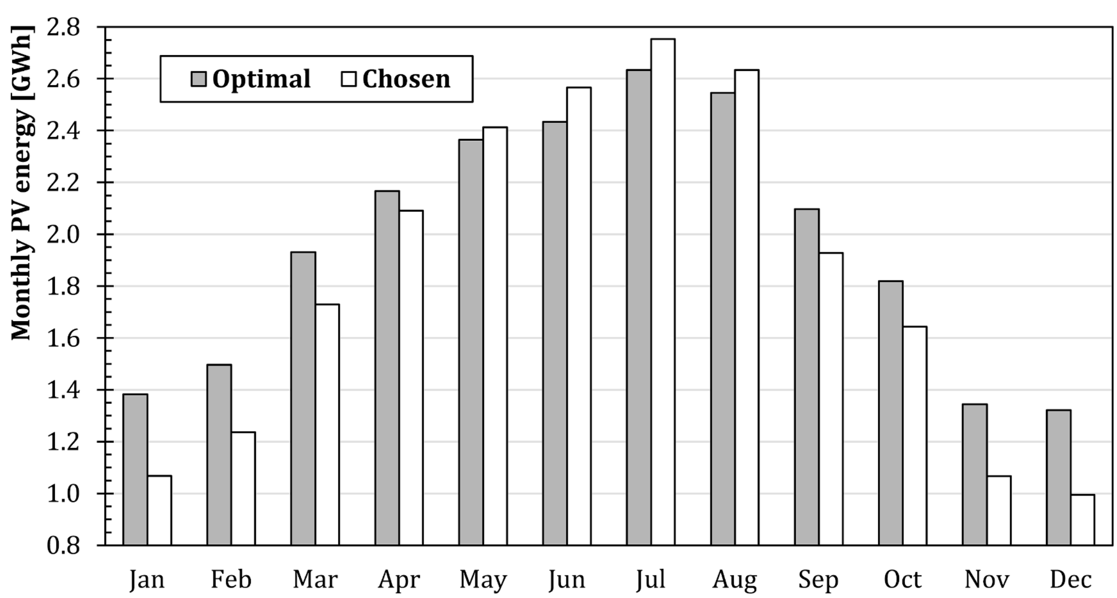

Fig. 13. Comparison of monthly energy production between the geometric configuration of the photovoltaic system that optimises the objective function and the chosen one that fulfils the control function.

environmental challenges of the coming decades. In order to break free from traditional sources responsible for the rise in greenhouse gas values in the atmosphere, the production of electricity from solar energy appears to be a technologically mature option to be massively deployed in all those countries with adequate annual solar irradiation. In order to meet the ambitious decarbonisation targets to be achieved in the coming decades by using photovoltaic installations, large areas of land will have to be massively exploited. In urban areas, this is not always easily compatible with the built environment. Turning attention to rural spaces already exploited for human uses will be increasingly necessary for the realisation of large-scale photovoltaic installations capable of lowering costs by exploiting the scale factor. The consumption of additional land is not desirable or sustainable. The best solution is to make agricultural production compatible with solar exploitation for energy purposes on the same land. For these purposes, agri-voltaic production assumes a function of considerable interest that will be greatly promoted in the future.

However, complete compatibility between the different needs that may arise in the implementation of agri-voltaic installations is often not easily achieved. This is especially true in man-made areas that provide other services. An example is the installation of photovoltaic panels in cultivated fields around airport areas. In this study, a particularly interesting and characterising case study was chosen to completely dissect the analysis of environmental compatibility in such cases, in order to determine a study methodology that could guarantee a complete analysis of the problems related to these plant installations, both in terms of environmental friendliness and the maximisation of the electrical energy produced (the objective of their installation).

The evaluations carried out here, following the proposed procedure, have made it possible to determine the geometric configuration of the agri-voltaic installation on the particular farmland chosen as a case study. The constraints posed vary in nature and all meet different overlapping requirements, making the analysis of the variables in play complex because it is directed towards several objectives.

The objectives are:

- keep the land fit for its intended purpose, safeguarding the production of agricultural products and the management of the land by mechanised means (the basis of modern fieldwork);
- enable photovoltaic production that is technically feasible and economically viable;
- meet environmental compatibility with highly constraining sites such as the presence of an airport facility in the vicinity of the land.

Environmental compatibility with the airport structure leads to the need to determine the angles that characterise the geometric configuration of the facility in such a way as to avoid glare to landing pilots and technicians working at the control tower.

In the case study analysed here, all these constraints are studied following the procedure proposed in this work. They were fulfilled by acting on the possible design variables. It was shown that, despite the many constraints imposed by the presence of the nearby airport (a particularly constraining site), it was possible to maintain the production of agricultural products, the environmental compatibility of the farmland with the structures in its surroundings, and adequate energy exploitation of the available surfaces.

- In characterizing the main design parameters of the proposed agri-voltaic plant (and thus, in particular, the characteristic azimuth and tilt angles of its constituent panels) in order to make it compatible with the airport infrastructure present in the immediate vicinity of the solar power plant, the following had to be taken into account simultaneously:
- the geographical location of the terrain relative to the airport facility, its control tower and the orientation of its runways (and associated landing routes),
- the orographic characteristics of the farmland,
- the presence of natural (particularly a watercourse), road and land access constraints,
- the needs related to the manoeuvrability of agricultural equipment to enable modern and profitable, hence, intensive farming,
- the constraints of regulatory nature, with respect to the subdivision of the plants into two separate voltaic fields so as not to exceed the power limits for connection to the power grid in the area,
- the need to analyze the location and geometric characteristics of a green barrier that would protect the control tower from glare,
- the maximization of the electricity produced annually.

In order to best assess the weight of compliance with the many constraints on the design of the agri-voltaic installation, a comparison was made with the same site exploited energetically in a totally free and independent manner (with the energy production of the installed photovoltaic panels maximised). The result was that the site chosen, although particularly constrictive, thanks to careful study still allows for its adequate energy exploitation while respecting its intended use and the built environment. As a result, land used in this way can be a source of double income (agricultural and energy) for their tenants. This is especially important in the vicinity of an airport facility, which has every interest that the land next to it is well maintained and not abandoned (to avoid problems such as potential fires due to dry brushwood, or the settlement of unwanted birds because they are dangerous to passing vehicles. Furthermore, the production of electricity from renewable sources with high power plants has zero climate-altering emissions during its operation; therefore, they are plants that help the decarbonisation of our economy in the coming decades.

It can be concluded that "the theorised optimum is the enemy of the realised good" and although having to respond to a series of design constraints that limit their possible energy production and diffusion across the territory, agri-voltaic installations can always be made compatible even in the presence of particularly complicated conditions for their realisation (such as an airport structure).

CRediT authorship contribution statement

Ferdinando Salata: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Jacopo Dell'Olmo:** Writing – review & editing, Writing – original draft, Validation, Software, Data curation. **Virgilio Ciancio:** Visualization, Validation, Supervision, Software, Investigation, Data curation, Conceptualization.

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.

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