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INNOVATIVE SIMULATION TOOLS FOR AN EXHAUSTIVE AND SYNTHETIC CHARACTERIZATION OF THE SOLAR GLARE OCCURRENCES FOR THE DESIGN AND THE ADMINISTRATIVE INSTRUCTION OF LARGE-SCALE PHOTOVOLTAIC PLANTS

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ABSTRACT: Photovoltaic (PV) is challenged to play a major role in the energy transition that must be conducted in the coming decade, through the development of large-scale PV plants. This emergence generates potential disturbances with the local environment starting with solar glare, i.e. the sun reflection on PV panels, which may jeopardize transportation safety. Some rare aviation administration already established restrictive policies for the construction of PV systems close to airports, such as the FAA in the United-States and the DGAC in France, but nothing yet for railways and motorways. These works, presented through a case study, aim at proposing to PV actors some innovative and generic simulation tools in order to address the glare problematic as part of their project development. The analysis of the glare is carried out in order to characterize the identified glare occurrences through an exhaustive set of physical quantities: occurring day and hour throughout the year, angle between reflected ray and user's field of view, etc. The overall analysis allows concluding on both the severity of the impact and the project compliance with the applicable requirements (e.g. aviation administration) while locating, within the finely-meshed PV plant, the impacting areas for which remediation must be considered.

Keywords: photovoltaic, glare, safety, simulation, characterization

1 INTRODUCTION

Photovoltaic (PV) is challenged to play a major role in the energy transition that must be conducted in the coming decade, through the development of large-scale PV plants, mostly ground-mounted, whose individual power now reaches hundreds of megawatt peak (MWp). As an illustration, Fig. 1 issued from PVresources.com, depicts the ranking of the 121 PV plants commissioned between 2010 and 2015 around the world, with an individual capacity exceeding 50 MWp. In 2010, only 6 plants were commissioned, with an average power of 73 MWp and a maximum of 97 MWp; their number reached 35 in 2015 with an average power of 151 MWp and a maximum of 575 MWp in California. On that period, Europe recorded 25 power plants with a maximum of 300 MWp in France.



Figure 1: Breakdown of the 121 PV plants commissioned between 2010 and 2015 around the world, with an individual capacity exceeding 50 MWp.

The emergence of large-scale PV plants inevitably generates disturbances with the local environment, among which the sun reflection on the PV panels, also known as solar glare, whose consequences may vary from loss of visual comfort (e.g. residents) to the endangering of people in the case of transportation (e.g. airplanes, trains, cars). Besides maintaining good neighborly relations on the long term and preventing any

legal action, PV developers shall consider the glare problematics early in the development process in order to successfully pass the administrative instruction, i.e. the building permit issuing process. Some high-level guidelines are already applicable depending on the country or the state. As an example, in Belmont, Massachusetts, a section of the law states that rooftop PV panels shall be placed and arranged such that glare shall not be directed onto adjacent buildings or properties [1]; other national laws indicate, for the same rooftop PV panels, a maximum time of exposure per day and per year. On the opposite side, complex policies were established by some aviation administrations for the construction of PV systems close to airports: the Federal Aviation Administration (FAA) in the United States or the Direction Générale de l'Aviation Civile (DGAC) in France, as detailed hereafter.

The FAA's opinion regarding the building of a specific PV generator is based on the assessment of the potential ocular hazard analyzed over the entire calendar year and defined as a function of the retinal irradiance and the subtended angle (size/distance) of the glare source [2]. Fig. 2 below defines three regions for the impact characterization: potential for permanent eye damage (retinal burn), potential for temporary after-image (flash blindness), and low potential for temporary after-image [3]. All potentials for glare in the airport traffic control tower (ATCT) cab is prohibited while only the low potentials for after-image are accepted regarding the final approach paths.

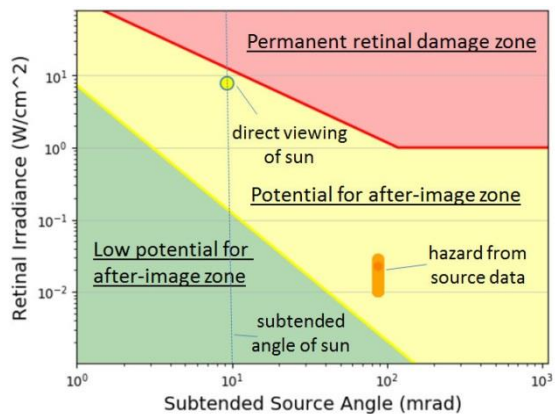


Figure 2: Impact of different retinal irradiances as a function of subtended source angle for short-term exposures.

In 2010, the French DGAC issued some rules for the impact characterization over control tower, the final approach path and the rolling of each runway, mostly based on the angle of view, i.e. the angle between the trajectory and the potential reflected ray, and the associated luminance ([4], [5]). The latter, expressed in candela per square meter (cd.m^{-2}), measures the luminous intensity per unit area of light travelling in a given direction; solar disk is about $16.10^8 \text{ cd.m}^{-2}$ at noon and 6.10^5 cd.m^{-2} at sunrise [6]. Impacts over control tower are acceptable only when they are in the back of the air controller, whatever luminance is. Regarding the final approach and the rolling, Fig. 3 below describes three protection areas defined for each approach, namely A (around airport), B (around touchdown) and C (around runway): depending on the location of the PV project with respect to these three zones, the acceptance thresholds for the angle of view and the luminance vary (respectively $\pm 30^\circ$ or $\pm 90^\circ$ and 10^4 or 2.10^4 cd.m^{-2}).

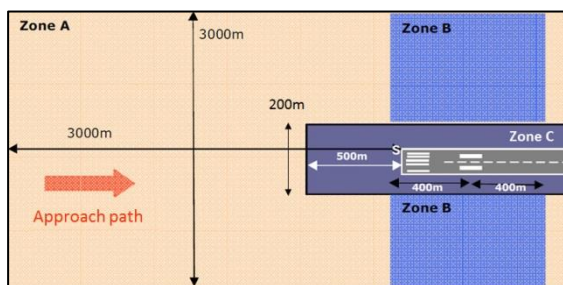


Figure 3: Definition of the three geographical zones A, B and C as per DGAC's requirements depending on the airport threshold (beginning/end of runway) and the touchdown point. The distances are different for a helicopter final approach and take off area (FATO) but the definition remains the same.

Finally, the DGAC systematically delivers a positive opinion to any project that implements glare-free PV panels, i.e. PV panels certifying a maximum luminance level of 10^4 cd.m^{-2} for PV project in zone A or 2.10^4 cd.m^{-2} for zone B.

Though quite different in the impact characterization, both the FAA and DGAC requirements are relevant references for the aviation administration outside the United States and France, but also for other administrative authorities that newly face PV projects close to sensible areas: networks of railways and

motorways regarding security issues but also municipalities regarding urban constraints (e.g. co-visibility with historic monuments or neighbors). Considering the wide range of applications and targeted audience, the recent works carried out by SOLAÏS aim at proposing some innovative and generic simulation tools in order to address the glare problematic as part of the PV project development. The results are presented in this paper through a case study of a 1-axis tracking PV project close to a French airport, thus subject to the DGAC's requirements. Section 2 introduces the case study then presents the proposed modelling of the glare source (i.e. the PV panels) and the critical elements (e.g. final approach). Section 3 finally presents the identification and characterization of the glare impacts through a synthetic and visual approach for a better understanding of the results.

2 PROPOSED MODELLING

2.1 Introducing the case study

The case study considered in this paper was carried out by SOLAÏS in 2016 and consists in a ground-mounted PV plant using 1-axis tracking solution. It is located in Bretagne Region, south-west part of France, on the lands of the Bretagne Atlantique airport (also called Guiscriff - Scaër) whose main information is presented in Table I.

Table I: Information about Bretagne Atlantique airport

ICAO code	LFES
Latitude	$48^\circ 3'4.96'' \text{ N}$
Longitude	$3^\circ 39'55.74'' \text{ W}$
Landing strip	Paved, 1500 x 30 m
1 st magnitude orientation	24° (QFU 02)
2 nd magnitude orientation	204° (QFU 20)

The 55-hectare footprint corresponds to the targeted cadastral parcels; it is divided into two areas, respectively 17 and 28 ha, located on both sides of the runway, as depicted in Fig. 4.



Figure 4: Superimposing the footprint of the ground-based PV plant (yellow) with the satellite image; thresholds (THR) and touchdowns are highlighted.

Considering the surface and the current state of PV panel efficiency, more than 40 MWp could be theoretically installed. A glare study must be conducted for the building permit examination in order to prove that the PV plant fulfils the DGAC's requirements.

2.2 PV plant mesh

A first challenge consists in defining a fine mesh of the PV plant in order to identify accurately the critical zones of the layout for which remediation should be potentially considered. For that purpose, the layout is firstly delimited by Jordan polygons, either concave or convex, which are defined as closed and simple, i.e. without intersection except the first and last points. An iterative process is then run in order to split each Jordan polygon into triangular facets whose maximum side length (L_{MAX}) can be changed down to ten meters. Fig. 5 below depicts the meshing for the case study using only two Jordan polygons (one per PV area), depending on L_{MAX} value.

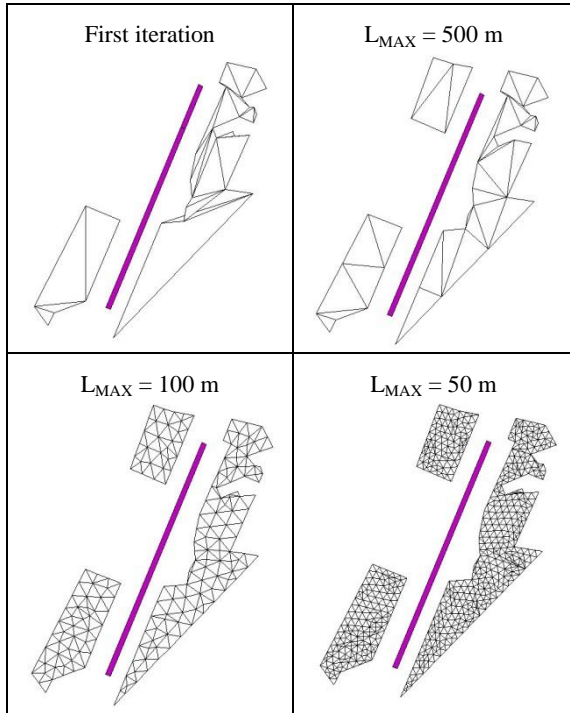


Figure 5: Meshing of the PV plant using two Jordan polygons depending on the maximum side length (L_{MAX}) of the triangular facets; runway is highlighted in purple.

It has to be noted that the size of the mesh, through L_{MAX} , doesn't have any influence on the overall results of the analysis because the latter only considers the intersection between a trajectory and a reflected ray for a given triangular facet as presented later in section 3. However, decreasing the mesh size allows refining the location of prohibited areas while increasing the computation time. This is all the more important when the PV plant layout intersects the protection areas defined by the French DGAC, cf. Fig. 6 for the QFU 20 approach.

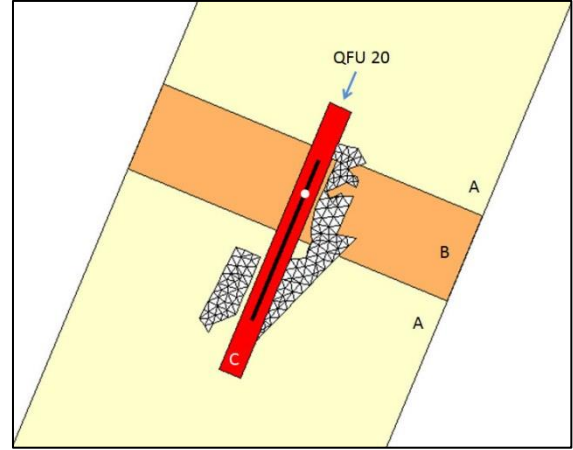


Figure 6: Location of the PV plant within the protection areas (A, B and C) as defined by the French DGAC.

2.3 PV panel modelling

The baseline considered in this study consists in classical crystalline PV cells encapsulated into a glass layer that protects them from the environment while allowing light energy to pass through. The disadvantage of this rigid outer layer is that part of the sun rays are reflected, thus generating glare, depending on the angle of incidence (AOI), i.e. the angle between the sun direction and the normal of the PV panel. The simplest approach to estimate the loss was developed in [7] and later adopted by the American Society of Heating, Refrigeration and Air Conditioning (ASHRAE, [8]) through the incident angle modifier (IAM) and the ASHRAE modelling defined by Eq. 1 and illustrated in Fig. 7. These profiles highlight the fact that PV panels behave as simple mirror for low incidences.

$$(Eq. 1) \quad IAM = 1 - b_0 \left(\frac{1}{\cos(AOI)} - 1 \right)$$

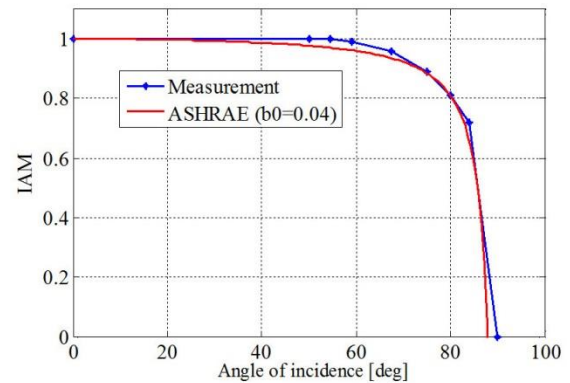


Figure 7: IAM profile of glass-protected PV panels based on ASHRAE modelling ($b_0=0.04$) and measurements of a specific PV panel performed by Sandia National Laboratories.

In the present study case, the PV panels are mounted on a one-axis tracking system whose kinematic profile aims at maximizing the incident energy throughout the day. The rotation axis is horizontal and oriented north-south. A backtracking algorithm is implemented so as to remove the mutual shading, from one row to another one, at the sunrise and sunset. The tool allows processing the kinematic provided by any tracker manufacturer. However, in the early stage of a PV project development where manufacturer hasn't been selected yet, SOLAÏS

proposes a generic tracking model depending on the “dihedral solar angle” defined as the dihedral angle between:

- The PV panel plane when the rotation angle is null;
- The plane containing the rotation axis and the sun direction.

Working with the dihedral solar angle allows working on a single profile, whatever the day is. Three different modes can then be considered, as depicted in Fig. 8:

- 1 Backtracking mode at sunrise and sunset to minimize the mutual shading;
- 2 Underperforming tracking due to the constraint on rotation angle;
- 3 Perfect 1-axis tracking around solar noon.

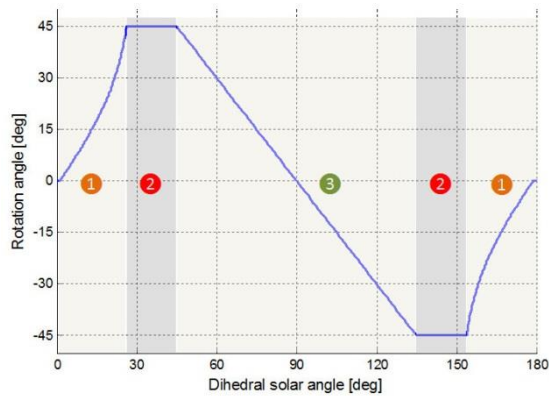


Figure 8: Daily kinematic profile of the 1-axis trackers depending on the dihedral solar angle, highlighting three different modes: backtracking (1), maximum rotation angle (2) and perfect 1-axis tracking (3); applicable whatever the day in the year.

Table II below presents the input parameters considered in the model where the PV panel thickness is used to slightly delay the rotation of the PV panels at the sunrise (symmetric for the sunset).

Table II: Input parameters for the tracking system of the case study

Distance between axes	4.5 m
Width of PV arrays	2.2 m
PV panel thickness	0.05 m
Azimuth of the axis	180° (north/south)
Inclination of the axis	0° (horizontal)
Maximum rotation angle	45°

3 CHARACTERIZING THE GLARE

A glare impact occurs when an incident sun ray, reflected on the surface of the PV panel, enters a user’s visual field. A user can be either static (e.g. air controller, residents) or dynamic (e.g. pilot, train driver) and its localization is defined in the tool by using at least one segment; curved trajectories are then approximated using many segments. The impact identification consists in determining for each triplet {triangular facet, segment, sun position} the potential intersection between the segment and the infinite triangular prism derived from the reflection of the incident sun ray on the PV panels located in the triangular facet, as depicted in Fig.9.

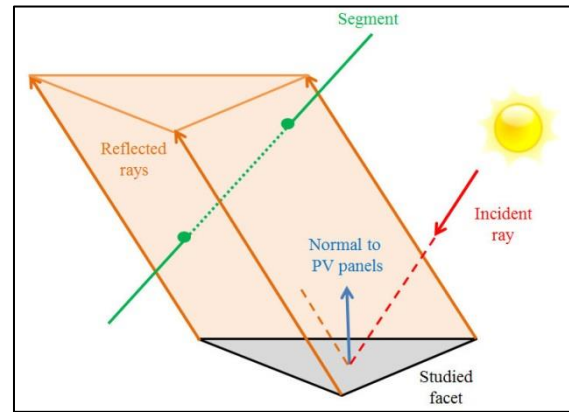


Figure 9: Intersection between a segment and the infinite triangular prism derived from the reflection of the incident sun ray on the PV panels located in the triangular facet.

The results for the specific case of the final approach coming from the north (i.e. QFU 20) are presented in two synthetic views. Fig. 10 first presents the geographical identification of the critical facets (in orange) for which at least one glare impact has been found. This 2D view provides useful information about the location of the critical areas for which glare has been identified (about 30 % of the total area). Regarding the development process, it allows PV developer balancing different trade-offs: abandoning the critical areas versus accepting another PV panel configuration with lower performance.

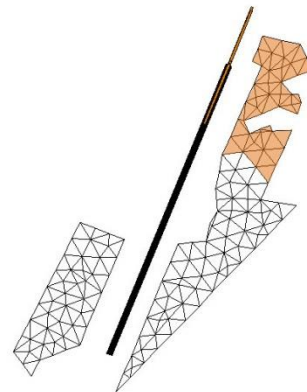


Figure 10: Geographical identification of the critical facets.

Then, a second chart characterizes the identified impacts throughout the year using true solar time (TST) on x-axis and day in the year on y-axis (Fig. 11); symmetric black curves corresponds with sunrise/sunset while topography may appear if present. The available physical quantities are the angle between the reflected ray and the user’s visual field, the luminance of the reflected ray, the sun elevation, the angle between the reflected ray and the sun, the distance between the user (e.g. the pilot) and some critical locations (e.g. touchdown, railway crossing), etc. For this specific simulation, Fig. 11 show that a pilot approaching on QFU 20 is impacted by glare early in the morning (precise hour are available), during 2 to 34 minutes, between end of October and mid-February (accurate date are available), with an angle between user’s field of view and reflected ray higher than 68°.

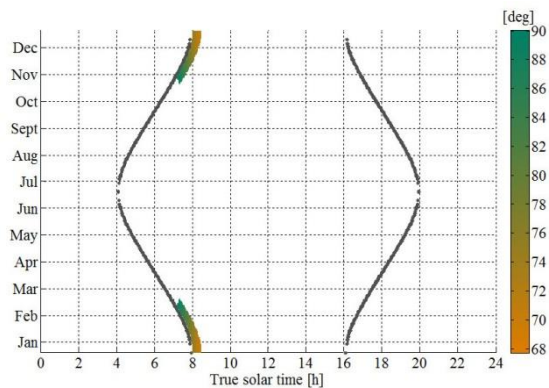


Figure 11: Characterization of the identified impacts through available physical quantities, here the angle between the reflected ray and the user's visual field is analyzed.

Finally, because the glare analysis is issued for people who may not have the adequate technical background (e.g. municipal councilor, administrative authority), another effort was made on the visual synthesis through the 3D envelop of the reflected rays embedded into Google Earth, as depicted in Fig. 12. This envelop, only applicable to fix structures, is defined by the direction of the reflected rays throughout the day for both summer and winter solstices; any trajectory that intersects this envelop is geometrically impacted by glare.

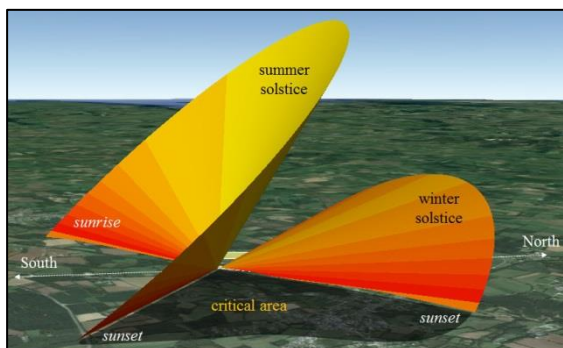


Figure 12: 3D envelop of the reflected rays embedded into Google Earth; applicable to fix structures only.

4 CONCLUSION

The tools proposed in these works are based on SOLAÏS' large experience regarding the glare studies requested since 2010 by the French aviation administration (DGAC) to the PV project developer. The latter now benefits from visual and synthetic results which are valuable for both the design and the administrative instruction of the project (building permit issuing process) and which ease the reading and the understanding of such a complex topic. The latest version of the tools finally intends to be as generic and adaptive as possible in order to address other national policies and other risk assessment (e.g. PV plants close to railways and motorways) while minimizing the study costs for the developers.

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