The Potential Hazard Analysis Method of Glare for Photovoltaic near airports or within

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Abstract: With growing numbers of solar energy installations near airports or within, solar glare is becoming an increasing concern. The glare impact which is the potential hazard for pilots and air-traffic control personnel can range from discomfort to disability. First, a review of metrics used to determine safe retinal irradiances was presented. Metrics for both permanent eye damage and temporary after-image effects were included. A summary of safety standards is compiled from the literature to evaluate the potential hazards of calculated irradiances from glare. The impact factors of glare for photovoltaic near airports or within are analyzed. It has presented a new evaluation method based on bidirectional reflection distribution function (BRDF) to evaluate potential glint and glare hazards from specular reflected sunlight for solar Photovoltaic in this paper. The analytical models were then derived to calculate irradiances. Finally, a sample is provided for glare in the airport.

1. Introduction
Solar energy has been evolving as a mainstream form of renewable energy generation since the early 1990’s. This is because of the availability of ample space and huge demand of power by the airports themselves has led to the huge interest of the power sector towards airports. Airport managers also believe that the use of new energy can both long-term cost savings and reduce greenhouse gas emissions. In addition, the government is guiding the enterprises to use the clean energy for achieving the greenhouse gas emission reduction targets. Among the world that solar arrays have been installed at or near airports all over the world. Such as Singapore’s Changi Airport, London’s Gatwick Airport, California’s San Jose Airport, Germany’s Dusseldorf Airport, Australia’s Newman Airport, the US’s Denver International Airport, Nellis Air Force Base in Nevada, and Ontario’s Thunder Bay Airport [1, 2].

Whether it is from photovoltaic (PV) or concentrated solar power generation devices are likely to cause glare. With growing numbers of solar energy installations around the world, solar glare is becoming an increasing concern. In 2012, CNN and local media reported that modules in a $3.5 million PV array on a parking garage at the Manchester-Boston Regional Airport had to be covered to alleviate glare to air-traffic controllers in the nearby control tower [3]. The Federal Aviation Administration (FAA) reported that glare from direct sunlight contributed to nearly a dozen aviation accidents on average each year during an 11-year study [4].

2. Potential Hazard of Glare
Reflective of solar installations are not dangerous in most of the time. But the glare for pilots is likely to present a hazard during critical phases of flight, such as especially approach and landing. The reason is that the pilot is locating at low angles of elevation in this situation. So the off-airfield facilities are
unlikely to present glare problems to pilots in the en route phase of flight. It is because that it is at higher angles of elevation.

According to literatures [2, 5], the impacts of glint and glare on eyesight can be classified into three levels based on the retinal irradiance and subtended source angle. The low level is potential for after-image. The middle level is potential for after-image. And the high level is potential for permanent eye damage. The flow diagram in literature shows the general method implemented to translate solar radiation to the after-image potential caused by energy received on an observer’s retina [1].

2.1 Retinal burn
Retinal burn is the eye damage. Previous studies are presented that temporary flash blindness is potentially hazardous to motorists or pilots. According to literatures [5], Sliney and Freasier presented maximum permissible retinal irradiance levels (W/cm²) based on retinal burn data using rabbits. The safe retinal irradiance, Ers (W/cm²) based on retinal image size, dr (m), assuming circular images and a 0.15 second exposure (typical blink response) is 12.7 W/cm². It is about 1.6 times greater than the retinal irradiance experienced from viewing the sun directly (~8 W/cm²).

2.2 Flash Blindness
Flash blindness is potential for after-image which is visual impairment during and following exposure to a light flash of extremely high intensity. It may last for a few seconds to a few minutes. Because vision loss is sudden and takes time to recover, flash blindness can be hazardous in aviation. Photometric units are used to characterize the levels of brightness (or luminance) (lumens/m²/sr) or luminance (lumens/m²) that cause flash blindness. From the research, it appears that a solar irradiance on the order of 1~10 W/m² or 1x10⁻⁴ ~ 1x10⁻³ W/cm² at the eye is sufficient to cause temporary flash blindness. These studies found that visual recovery times ranged from 4 - 12 seconds for luminance values ranging from 650 ~1,100 lumens/m². For light emitted within the solar spectrum, this corresponds to approximately 7 - 11 W/m² of solar irradiance with the eye. It appears that a solar irradiance on the order of 1 W/m² or 1x10⁻⁴ W/cm² with the eye is sufficient to cause temporary flash blindness.

3. Regulatory Provisions

3.1 FAA Regulatory
There is little formal published guidance on the assessment of glint and glare from solar Photovoltaic. FAA in the United States has published the technical guidance for Evaluating Selected Solar Technologies on Airports in November 2010 [6]. In the Chapter 3 of the technical guidance, glare is as one of the potential hazards of solar technologies on or near airports. The FAA study present that the degree of reflectivity of a PV panel will depend upon the intensity of the incoming light, the reflectivity of the panel surface, whether the reflected light is specular or diffuse.

The FAA guidance suggests that reflected light from a PV panel is primarily specular in nature. And the evaluation of impacts should be conducted. Such as qualitative analysis of potential impact in consultation with the airport authorities, a demonstration field test with solar panels at the proposed site in coordination with airport personnel, geometric analysis to determine the days and times when an impact is predicted, and so on. According to the requirement of FAA, the glare from the proposed plant is not a hazard to navigable airspace before construction of utility scale PV plants near airports in the United States. And the FAA guidance lists eight solar projects at or adjacent to airports in the USA which have completed FAA assessments. In all cases, the FAA has determined that it is not necessary to conduct a full review or to find no hazard.

3.2 CAA Regulatory
The Civil Aviation Authority (CAA) has published the document Interim CAA Guidance - Solar Photovoltaic Systems, dated 17 December 2010 in the UK [8]. According to the interim CAA guidance,
the key safety issue is perceived to be a potential for reflection from PV to cause glare, dazzling pilot or leading them to confuse reflections with aeronautical lights. The impact of PV systems which deployed further than 15km away from Aerodrome is including in this guidance. The interim CAA guidance does not contain any specific recommendations on the control of solar photovoltaic developments away from airfields. But CAA recommends that the photovoltaic developer provide safety assurance documentation, such as risk assessment.

4. Factors that Impact Glare
A number of factors can affect both the intensity and perceived impact of glare, such as direct normal irradiance, reflectance, distance, size and orientation of the reflecting surfaces, human factors, and so on. So the positions of the sun, the intensity of the sunlight reaching the solar array and Photovoltaic reflectivity will be discussed in this section. They are the main factors for glare near airports or within.

4.1 The position of the sun
The position of the sun at the installation site is as a function of both time of day and time of year. And the sun is very nearly as a collimated point source of light. So the moving trajectory of the sun can be predicted during the day. There is two forms for calculating the sun position [9]: first as a unit vector extending from the Cartesian origin toward the sun and second as azimuthal and altitudinal angles. The algorithm relies on the latitude, longitude and time zone offset from UTC in order to determine the position of the sun at every time step throughout the year.

4.2 The intensity of the sunlight reaching the solar array
The intensity of the sunlight reaching the solar array in the actual installation site is a function of both time of day and time of year. It can be described by direct normal irradiance (DNI). The variable DNI feature scales the user-prescribed peak DNI using typical clear-day irradiance profile. Normalization is based on the amount of time between sunrise or sunset and solar noon. The intensity of the sunlight can be described by using observed historical values or be calculated. Historical values are used in this paper.

4.3 PV reflectivity
Solar photovoltaic panels are through absorbing the sunlight and using the photoelectric effect to generating the power. There is only a small amount of the sunlight which is reflected by PV compared to most other everyday objects. The glass is one of the uppermost and important components of PV. The reflection of the glass in PV is about 2-4%. According to the previous research results, most solar panels reflect significantly less light than flat water. The figure 1 is the scale of reflectivity of surfaces [9].
In addition to the reflectivity, the sunlight reflection is also related to the incidence angle. Incidence angle is defined as the angle between the direct component of insolation and a ray perpendicular to the module. If the incidence angle is zero, the angle between the surface of the module and the direct component of radiation is 90°. The reflectance at 633 nm of a PV module is a function of the incidence angle as seen below in Figure 2[8].

Figure 2 the function between the reflectance and angle of incidence

According to figure 2, the reflectance is the function of the incidence angle. The reflectance does not describe the character of the PV. So it is difficult to describe the characteristics by only the reflectance. The bidirectional reflection distribution function (BRDF) is used as a tool to evaluate the impact of the glare in this paper.

5. bidirectional reflection distribution function

5.1 BRDF definition
One of the most general means to characterize the reflection properties of a surface is by using the bidirectional reflection distribution function. It is defined by the spectral and spatial reflection characteristic of a surface [10-11]. The BRDF of a surface is the ratio of reflected radiance to incident
irradiance at a particular wavelength. Because the BRDF is a ratio, the values are independent of the strength and geometry of the light source.

\[ BRDF = \frac{dL}{dE} \]  (1)

Where \( E \) is the irradiance, that is the incident flux per unit area, and \( L \) is the reflected radiance, or the reflected flux per unit area per unit solid angle. The units of BRDF are thus inverse steadies. Intuitively the BRDF represents, for each incoming angle, the amount of light that is scattered in each outgoing angle.

5.2 A evaluate tool based on BRDF

According to define of BRDF, the brightness of the reflected can be obtained if the irradiance of the incident light and the model of BRDF is known. Then the BRDF model can be obtained by testing the specified panel. The irradiance value of the incident light can be obtained by historic observed or be calculated by latitude, longitude and time zone offset from UTC. So the step of a evaluate tool based on BRDF is the following:

1. According to the latitude, longitude and time zone offset from UTC, the position of the sun can be obtained. And from the law of reflection, the direction of incident light is determined. It is the base of evaluation.

2. The envelope of the irradiance value can be getting from the historical observation data. It is as the intensity of the sunlight reaching the solar array.

3. On the basis of the BRDF equation, the reflected light brightness can be determined.

4. It is compared the reflected light brightness and threshold in 3.1 and 3.2 the PV installed is not effected the safety of aircraft if the threshold is not exceeded in all year. Otherwise there is some impact in the airport.

6. Evaluate the Glare

The photovoltaic will be mounted to ground or roof. It is believed that these will be erected in rows facing south and will be positioned at an angle between 25 and 30 degrees from the horizontal. Photovoltaic panels typically reflect 5% of incident light.

6.1 The incident angle

The angle of incident is determined by the sun position, which is calculated from longitude and latitude. The algorithm relies on the latitude, longitude and time zone offset from UTC in order to determine the position of the sun at every time step throughout the year. The calculation method is described in 4.1. So we can calculate the zenith angle and the sun azimuthal angle of the sun. Once the sun position is known for each time, the reflection equation can determine the reflected sun vector of the Photovoltaic panels.

6.2 The incident irradiance

In order to study, the Beijing new airport is as a research object in this paper. It uses the local historical data observation for enhancing the accuracy. The maximum irradiance of the total radiation day, which is the observed, is shown in figure 3. And the data line of 30 days is red. The variation of maximum irradiance on total radiation day in different months is shown in figure 4.
According to the figure 3, the maximum appears at July 1, 2009. And in figure 4, we can draw a conclusion that the maximum irradiance of more than 1000w/m² on the all radiation day is about 5%. And the monthly mean value on may is the largest. These irradiance values are as the basis for the evaluation of glare.

6.3 The result of BRDF
In order to explore the reflectivity of photovoltaic panel, the typical photovoltaic is selected and tested by the national institute on metrology of china. So the BRDF model was established. The BRDF line is shown in Figure 5.

From figure 5, we can be seen that the mainly reflect of the photovoltaic is the specular reflection. According to the 6.1 and figure 4, the intensity of reflected light at some point exceeds the FAA defined threshold. So it is likely affect the flight safety when the sun is at noon and the sun reflected is facing on approach and departure of runway.

7. Summary and conclusions
This paper has presented methods to evaluate potential glare hazards from specular and diffusely reflected sunlight from solar photovoltaic panel. Firstly, a review of previous data and standards was performed metrics used to determine ocular impact. The ocular impact of view glare can be classified into three levels. Secondly, the regulatory provisions of FAA and CAA for guidance relating to solar photovoltaic systems are analyzed. So we can determine the safety retinal irradiances. In addition, the main factors of impacting glare were analyzed. The factors were including the position of the sun, the intensity of the sunlight reaching the solar array, and PV reflectivity. And bidirectional reflection distribution function was used to calculate the intensity of reflected light at some point. Finally, an example of glare evaluating by using BRDF in this paper was presented. The results show that the reflection of PV will affect the flight safety in the special time. The risk assessment should be
performed prior to installation.

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