

Evaluation of Glare Potential for Photovoltaic Installations

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Introduction

Photovoltaic (PV) panels have been in use for decades to provide “off-grid” power in both remote applications (for example: navigation buoys; cell towers; cathodic protection; remote dwellings), and more visible off-grid applications (for example: highway call boxes; railroad crossing signals; parking meters).

Over the past decade, typical PV installations have become much bigger, covering large tracts of land or large roof areas, and increasingly are deployed in more highly populated areas and integrated with the electrical grid. A common question concerning the impact of these systems on neighboring structures and activities has to do with reflected sunlight from the solar panels. In certain installations it is important to know both where the reflected light will go and what the intensity of the reflected light will be at any particular point in time. Reflection calculations at the system design stage are used to avoid either nuisance glare from reflected light or, more importantly, to avoid glare that might interfere with activities in nearby areas. Airport sites are particularly sensitive to potential glare issues with respect to control structures, runways, taxiways and flight paths.

The vast majority of PV panels have a front surface made of glass. As far as reflection is concerned, PV panels behave much like building facades; skylights; automobile windshields and other common glass surfaces, as well as the water (or ice) surfaces of ponds and swimming pools. Glare analyses for PV installations are therefore similar to analyses already familiar to airport authorities considering siting for nearby structures involving glass.

In many designs, appropriate siting and orientation of the PV array can prevent any glare from reaching sensitive areas. In these cases, the magnitude of the reflected light from the array is irrelevant, and design approval should be straightforward.

In other instances, reflected light may encroach on sensitive areas but only very early or late in the day and from nearly the same direction as the rising or setting sun itself. In these cases, the magnitude of the reflected light is also irrelevant, as the direct light of the sun is the dominant issue. This is similar to the case of a car driver heading directly into the setting sun, a case in which the glare that is of concern is the direct light of the sun coming through the windshield and not the reflected light from the hood of the car.

Finally, there are cases in which site constraints dictate that the array orientation does cause reflected light to encroach on sensitive areas in ways that may be problematic. In these cases, it is possible to modify the glass surface used in standard PV modules so that reflected light is scattered, rather than

reflected directly. These “diffuse” reflections do not cause glare and therefore eliminate any potential problem.

Formulation of the Analysis

Calculations of reflected light are of course site-specific and system design-specific and require the following information:

1. The position of the sun in the sky for the actual installation site, as a function of both time of day and time of year.

The sun acts very nearly as a collimated point source of light which of course moves along a predictable path during the day (actually, the solar disk covers an angle of about 0.52° , but can be considered a point source for the purposes of this discussion). The United States National Oceanic and Atmospheric Administration (NOAA) provide (in the form of an Excel spreadsheet) public domain calculations of the sun’s position for any time of day and any location on earth¹.

2. The intensity of the sunlight reaching the solar array, also for the actual installation site, as a function of both time of day and time of year.

The National Renewable Energy Laboratory (NREL) maintains public domain data tables of historical weather data for hundreds of meteorological data stations around the world. For many stations there is sufficient data, covering decades in time, to construct what NREL defines as a “Typical Meteorological Year” (TMY). This virtual “year” is constructed by taking the most typical, for example, January in the database, then the most typical February, and so on until one gets a typical “year” which consists of the twelve most typical individual months within the larger database. The present version of this compilation is referred to as “TMY3”.

For many sites outside of the United States and its territories, equivalent data is available online from the World Radiation Data Center (WRDC) located in St. Petersburg, Russia through an NREL website².

The TMY database (or its international equivalent) is the most appropriate one for predicting general meteorological site parameters for the future. The database is ideal for airports because these are generally the sites of the meteorological data collection stations as well³. The resolution of these data sets is typically one hour. That is, the data in the table represents the average of, for example, temperature or light intensity for the one hour period **ending** at the time shown.

¹ The calculations of sun angle are found in the table “NOAA_Solar_Calculations_day.xls” at <http://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html>

² <http://wrdc-mgo.nrel.gov/>

³ The source for the “Typical Meteorological Year” (TMY3) data is http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3.

These databases contain a very large set of weather data, only one parameter of which is required for the analysis of reflected glare. This is the Direct Normal Irradiance (DNI) parameter, which is the intensity of irradiation on “a surface normal to the sun” due to the direct light from the solar disk (“received in a collimated beam”)⁴. The units of this parameter are Watts per Square Meter (W/m^2). As a “rule of thumb”, the maximum intensity of sunlight is on the order of $1,000 W/m^2$, occurring around noon on a bright, cloudless day.

In addition to the DNI radiation, the solar array also receives diffuse radiation from the sky itself. This component, referred to as “Global” irradiance, can be a significant part of the total radiation received, particularly when the sun’s disk is obscured by clouds, dust, haze or atmospheric humidity. However, this component has no directionality, appearing to come uniformly from all directions, and thus does not reflect in any specific direction where it could be perceived as glare.

For the purposes of a glare study then, the only relevant TMY3 parameter is the intensity of the direct irradiance component, DNI.

3. The orientation and extent of the specific solar array itself: footprint; angle of tilt and direction of tilt of the panels. This allows the actual angle of incidence of the sunlight onto the panel to be calculated from the information in Items #1 and #2 above as a function of both time of day and time of year.

This information comes from the system designer. Most PV arrays are “fixed plate” systems, that is, the solar panels are mounted rigidly in a fixed orientation and do not move to “follow the sun” in any way. Reflection considerations for “tracking” systems that move in one or more axes to follow the sun across the sky are more complex since both the sun and the solar array are in motion. The specific management of the tracking system, particularly during its “wake-up” and acquisition phase in the morning must be considered.

Calculation of the actual angle of incidence of the sun on the array for the specific site location, time of day and time of year is done using a Suniva in-house spreadsheet model.

4. The reflectivity of the solar panels as a function of angle of incidence of the direct sunlight onto the panel (this includes any polarization effects).

PV panels consist of a photoactive device, which can be made from a number of different materials and through a number of different processes, and which is either constructed upon or adhered to the rear surface (the surface that does not face the sun) of a transparent material. This material is most frequently glass, but can also be any one of a number of transparent polymers, most of which are optically similar to glass. The performance of a PV module as a generator of electricity depends on the properties of all of the module materials and of the module’s exterior and interior surfaces.

By their nature, PV devices are made to absorb as much light as possible and therefore to reflect as little as possible. Because of this, essentially all of the light that passes through the front surface of

⁴ TMY3 User’s Manual (PDF), http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3

the module is trapped in the layers below so that, **in terms of reflection, the only significant surface is the front surface of the module.**

Reflection from this front surface can be calculated from the Fresnel Equations⁵ and is a function both of the index of refraction of the front surface of the module and of the angle at which the light is incident onto the module. The angle of incidence must be determined for a specific location and time of day in order to properly calculate the components of reflection.

Calculation of the actual angle of incidence for the specific site location, time of day and time of year is done by Suniva, Inc. as an Excel spreadsheet calculation⁶.

Light that is reflected from solar modules, like light reflected from water, is polarized. For reflection from a horizontal surface, the two polarization modes come to an upright observer always with the same orientation, so that one of the modes may be effectively reduced by transmission through polarized sunglasses. For a tilted solar panel however, the direction of polarization with respect to an observer will vary according to both the observer's position relative to the panel and over the course of the day.

Therefore, there is no uniformly predictable attenuation of the reflected light by polarized glasses and it is sufficient for modeling purposes to consider the "worst case" without polarization. The spreadsheet model does calculate the two polarization modes for further study in specific installations if desired.

5. The degree of diffuse (non-directional) versus specular (directional or mirror-like) reflection.

This is a function of the surface texture of the front module surface. Most contemporary solar modules have a slight surface texture that does little to diffuse the reflected image. The calculations in the present study do not assume any reduction in reflected intensity due to diffusion of the reflected light, and are therefore "worst case" in that sense.

It is possible to provide a front surface texture to solar glass which will convert the reflected light from effectively entirely specular to entirely diffuse. **In installations where glare is thought to be an issue not resolvable by appropriate siting of the solar array, the use of an appropriately textured front surface can eliminate glare problems completely.**

6. The position of any potential observers that might be impacted by glare from the panels: adjacent buildings; roadways; airport facilities; flight paths.

These considerations are of course site-specific and are provided by the system designer.

⁵ The Fresnel Equations can be found easily with an internet search as well as in any introduction to the classical theoretical physics of light, see for example: *The Cambridge Handbook of Physics Formulas*, G. Woan, Cambridge University Press, 2010, [ISBN 978-0-521-57507-2](https://doi.org/10.1017/9780521575072)

⁶ Stephen P. Shea, Suniva, Inc. "PV System Reflectance Model – Suniva"

General Discussion of Reflection

The great majority of solar modules are made with a front surface of “Solar Glass”. This is a tempered “soda-lime” float glass very similar to tempered window glass except that it has a much lower Iron (Fe) content. The lower Fe content makes solar glass much more transparent than regular window glass, (which has a slightly greenish tint due to absorption of light by Fe oxide complexes within the glass). Soda lime glass has an index of refraction of about 1.50-1.52. As stated above, the reflection from the first surface is a function of index of refraction alone, and does not depend on the Fe content. **Thus, while solar glass is more transparent than window glass, its reflection properties are very similarly.**

As is the case with window glass, solar glass can be treated in ways that change the index of refraction of the front surface in order to minimize reflection. This treatment can take the form of either a coating or of a chemical modification of a shallow layer of the glass itself. Both treatments are optically the same, but the chemical treatment lasts longer in the field because it modifies the surface of the glass, rather than being a coating on the surface that can be more easily damaged or worn away. Generally, these treatments create a front surface index of refraction between 1.20 and 1.30. Glass treated in either of these ways is referred to as “Anti-Reflective” (AR) glass. Window glass is often treated in the same manner and with optically the same effect.

So the reflectance of sunlight from solar panels is in its essence simply a variation on the commonly understood phenomenon of reflectance from glass used in, for example: building facades; skylights; automobiles and other common objects.

Air has an index of refraction of 1.00, and reduction of reflection when light coming through air strikes a surface is basically a matter of reducing the index of refraction of that surface as close to 1.00 as possible (if the surface has an index of exactly 1.00, then it is optically identical to the air, and the light responds as if the interface surface is not even there). A familiar reflective material is water, which has an index of refraction of 1.333. In windless weather a quiet pond will have a very smooth, reflective surface. Reviewing the information above, one would expect that non-AR glass would be more reflective than the pond water (Index 1.52 versus Index 1.333), while AR glass would be less reflective than water (Index 1.20-1.30 versus Index 1.333).

Indeed, this is the case. Figure 1 is a chart of reflection from all three surfaces as a function of angle of incidence (where angle of incidence is measured from “normal” incidence in which the light strikes the glass or the water straight on). Note that, for all angles, the reflectance from the water surface falls between the reflectance curves for the two different types of glass. Note also, that the calculation for the water surface assumes that the water is completely still, so that all the reflection is specular (like a mirror). This is of course the worst case for glare from the water. Any wind across the water surface will “roughen” the surface and create a more diffuse reflectance and therefore less intense glare.

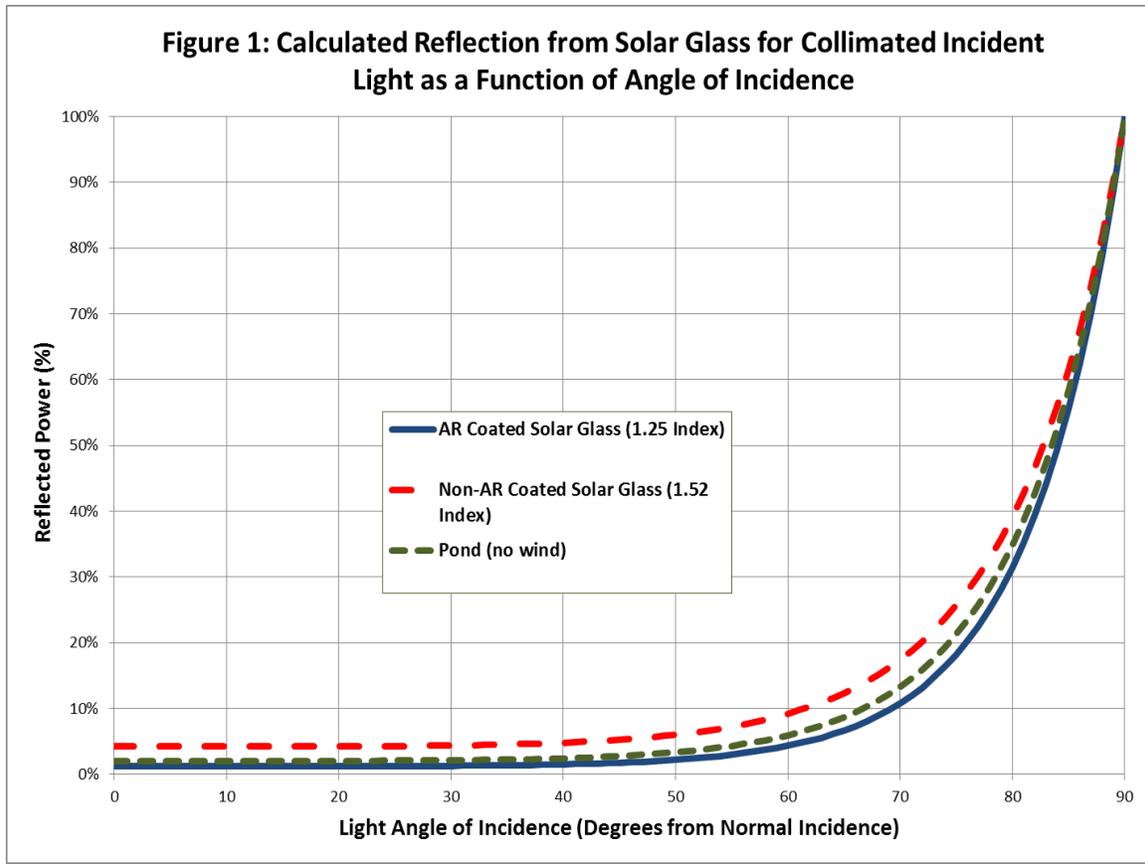
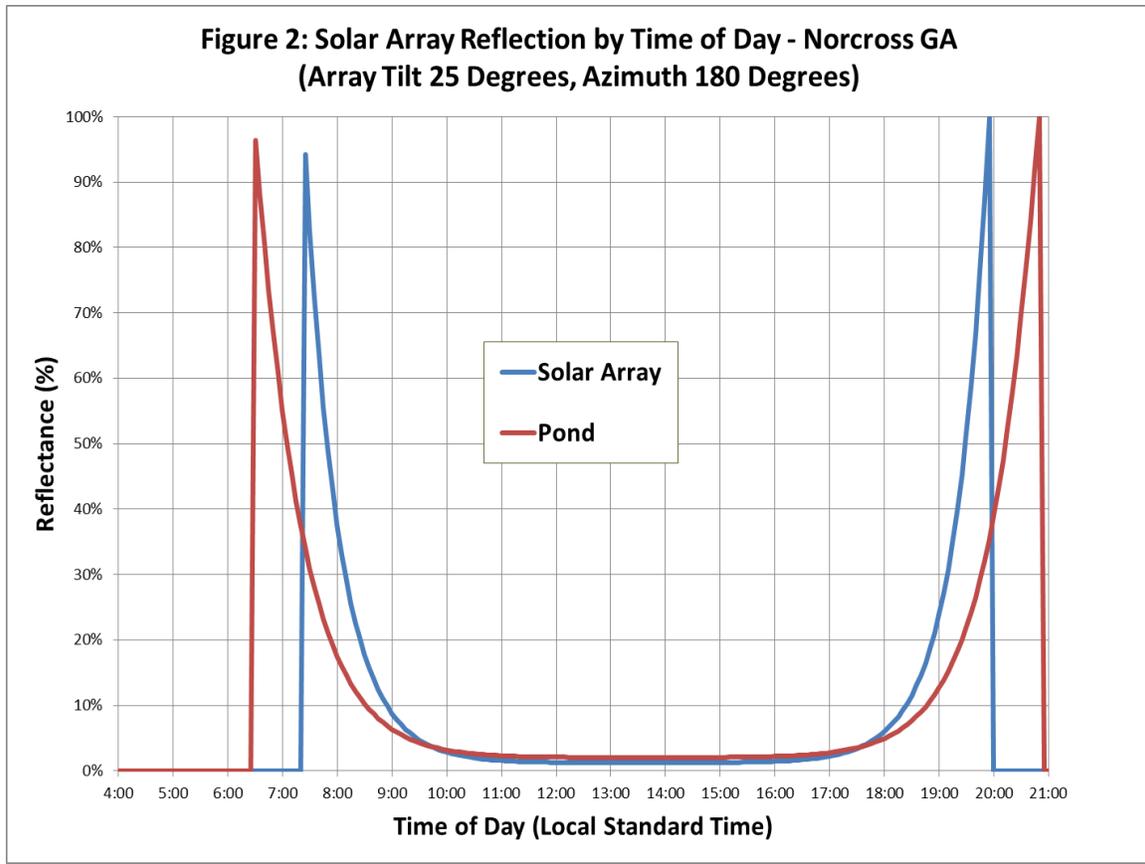


Figure 1 shows the reflected intensity of the light (“Power”) as a percentage of the incoming intensity. It is immediately apparent that the reflected intensity is quite low with respect to incoming intensity for incident angles below 60° to 70°, and then rises rapidly for higher (more “glancing” angles). That is, the percentage of the incoming sunlight that is reflected is low for high sun angles (most of the day) and increases for very low sun angles (near dawn and sunset). Since the sun covers a sky angle of 15° in an hour, the reflection will be above about 20% for roughly the first hour and the last hour of the day.

In Figure 2 the same relationship is shown as a function of time of day at the Summer Solstice for the Suniva location in suburban Atlanta. Note that the pond “wakes up” in terms of reflection before the solar array and “shuts down” later. This is due to the tilt angle of the solar array. The flatter the array angle, the closer the two curves will match. In both cases, the reflection is low during most of the day, and only exceeds 20% of full sunlight in the morning and evening when the intensity of the sun is already substantially lower than at mid-day.

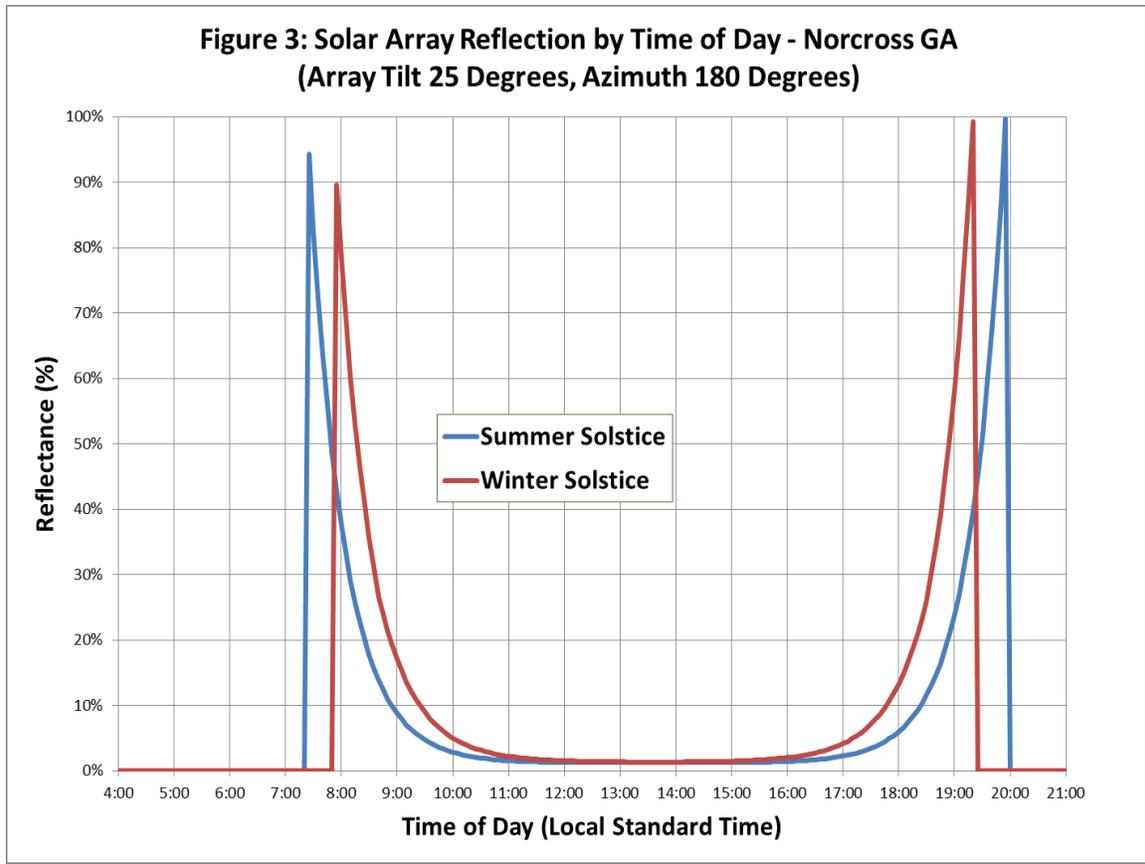


Design Considerations

Note that there are two degrees of freedom that the system designer has which can influence these curves:

1. As one can see by comparison of the solar array response with the response of the horizontal pond surface, the system designer can influence the effective length of the day for the panels by varying their tilt angle of the array. Higher angles move the “turn-on” of the panel later in the day and the “turn-off” earlier in the day, while lower angles have the opposite effect. This will also impact the direction of the reflected light versus time of day and may be used to “steer” reflections away from areas for which glare might be a problem. Fortunately, PV system electrical performance is not very sensitive to tilt angle for typical sites.
2. The array modeled here faces due South. By varying the azimuth angle of the array the system designer can shift the **effective** day either earlier or later. Again, this will impact the direction of the reflected light versus time of day and may be used to “steer” reflections away from areas for which glare might be a problem. For most sites, PV system electrical performance is not very sensitive to azimuth +/-15° from due south.

For reference, Figure 3 below shows the array reflected power by time of day for both the winter and summer Solstice dates. The full reflectance analysis goes through the entire year in five minute increments to make certain that all possible sun angles are evaluated.



Conclusion

In general, properly anti-reflection (AR) coated solar panels are slightly less reflective than water and very similar in reflectance to AR coated window glass. High reflectance only occurs early and late in the day, when the angle of the sun is low with respect to the plane of the solar array. **The tilt angle and the azimuth angle of the solar array can both be adjusted during the design phase in order to minimize potentially bothersome glare angles.**

In cases where even minimized glare is thought to be problematic, consideration should be given to using solar glass with a light-diffusing texture on the front surface.

The spreadsheets used for the figures in this report allow a detailed analysis of actual reflected intensity as a function of time of day for an entire meteorological year at the subject site. Suniva would be happy to assist with more detailed analysis for a formal system design.

In addition, Suniva has models that join the optical model presented here with the system electrical performance and the local meteorological data to provide accurate estimates of system performance over time that in turn can be used as inputs to financial models for revenue streams, payback times and Levelized Cost of Energy (LCOE).