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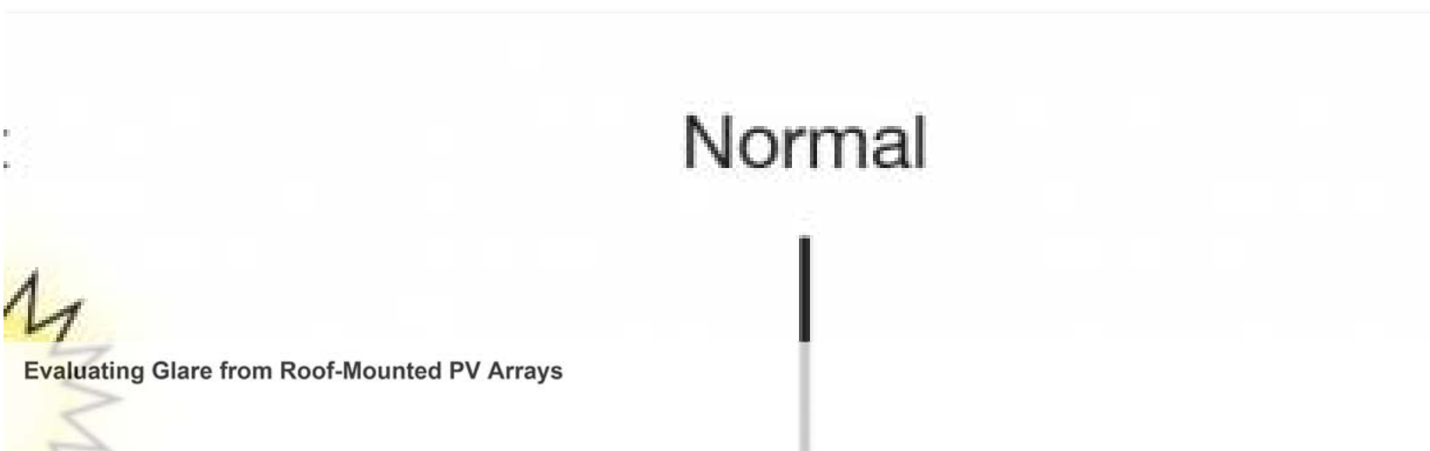
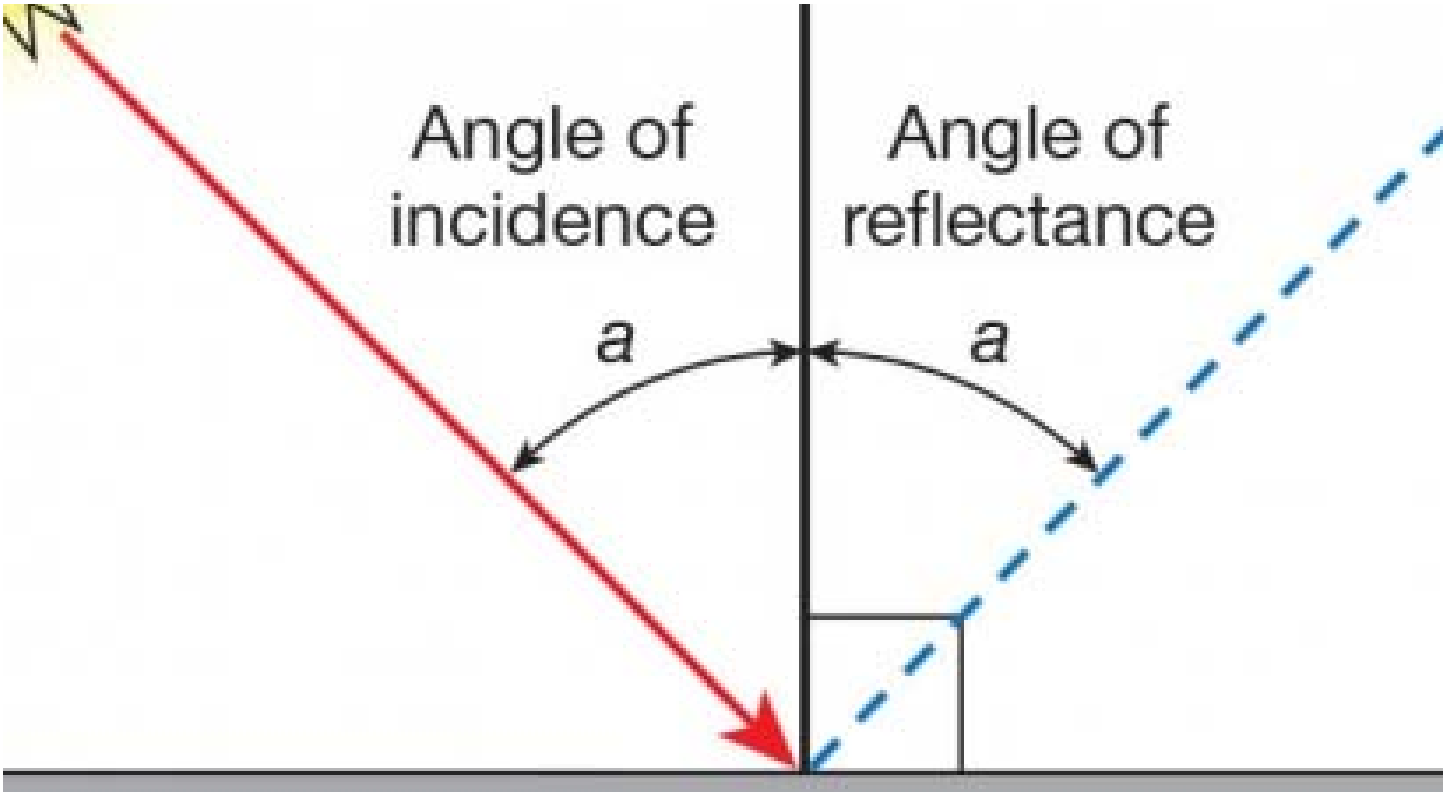
Evaluating Glare from Roof-Mounted PV Arrays

By: Roger Colton (/Profile/roger-colton)

Design & Installation (/design-installation)





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INSIDE THIS ARTICLE

As more homeowners choose to install PV systems, jurisdictional authorities and other stakeholder groups are increasingly scrutinizing the potential impacts of rooftop PV arrays. One recurring concern is that the reflected sunlight associated with roof-mounted PV may adversely affect residential neighborhoods.

Surface Reflectance

Reflected sunlight causes glare. However, the surface reflectance of different objects or building materials varies. For example, fresh snow reflects 80%–95% of the light striking its surface, whereas black asphalt reflects only 5%–10%. The reflectivity of a PV array, as with any other surface, is a function of its *albedo,* which is a measure of the fraction of the sun's radiation reflected from a surface. The albedo of different materials ranges from 0 (no reflection) to 1 (100% reflection). You can compare the glare potential of PV arrays to that of other materials by comparing albedo values. For example, Figure 1 is based on data published by the Federal Aviation Administration (FAA) in the report "Technical Guidance for Evaluating Selected Solar Technologies on Airports."

Generally speaking, the albedo of glass is closer to that of snow than it is to that of asphalt. However, PV modules do not use conventional glass, since they cannot generate power from reflected sunlight. PV modules must absorb as much light as possible, while reflecting as little light as possible. Manufacturers typically accomplish this by using low-iron, high-transmission glass that is treated with an anti-reflective coating. In some cases, they texture the surface of the glass to increase its light-trapping properties. Texturing and the use of anti-reflective coatings also minimize the surface reflectance of individual PV cells.

As a result, the surface reflectance of solar modules and arrays is considerably less than that of other common surfaces. As shown in Figure 1, solar arrays reflect less sunlight than concrete, vegetation, bare soil and even wood shingles. FAA guidelines note that, depending on the angle of the sun, PV modules with anti-reflective coatings may reflect as little as 2% of the incoming sunlight.

Based on these data, you would not expect PV arrays to generate much glare, if any, toward neighboring properties. However, the FAA report also notes that light reflected off smooth, polished surfaces—such as PV arrays—is more concentrated than light reflected off rough surfaces such as roads, trees or choppy water. Therefore, the FAA requires that PV installations in the vicinity of airports undergo a geometric glare analysis. To facilitate this process, Sandia National Laboratories' website (sandia.gov/phlux (http://sandia.gov/phlux)) hosts a "Solar Glare Hazard Analysis Tool" and a suite of related tools.

Because large-scale PV systems are installed at or near airports in many cities—including Boston, Denver, Indianapolis, Oakland, San Jose and San Francisco—glare hazard analyses generally indicate that PV arrays present no hazard to air navigation. While FAA standards apply to PV arrays at or near airports only, concerns about glare and reflectance associated with PV arrays also arise in other settings. For example, project developers occasionally conduct glare studies for large-scale PV power plants, perhaps due to proximity to a prominent road or landmark.

Mathematics of Glare

Glare studies are seldom, if ever, required in residential settings. However, it is not uncommon for neighbors to express concerns about potential glare or reflectance related to a proposed PV installation. While these concerns are understandable, they are also unfounded. Using basic physics, math and trigonometry, you can show that even if a PV array reflects some sunlight, it is highly unlikely that a third-party observer will see glare effects, especially if the potential viewer is located on an abutting property. Sunlight reflected off a residential roof-mounted PV array is most likely to travel skyward, up and over adjacent structures.

Law of reflection. Sunlight striking a smooth surface behaves in a predictable manner according to the *law of reflection.* As illustrated in Figure 2, the law of reflection states that when sunlight strikes a flat surface, the angle of incidence equals the angle of reflectance, as measured on either side of the line that is normal (perpendicular) to the reflecting surface. In effect, the direction of the reflected light mirrors that of the incoming light.

Location of sun. For viewers to experience glare from the reflected sunlight in Figure 2, they would have to be located in or near the direct path of reflection. The location of the sun is a primary variable in any glare hazard analysis. The altitude angle of the sun determines the altitude angle of the reflection, according to the law of reflection, as measured off a line normal to the surface of the array. Further, the solar azimuth angle determines the plane along which the reflected light travels.

One of the simplest ways to identify the location of the sun for a glare hazard analysis is to use the University of Oregon Solar Radiation Monitoring Laboratory (SRML) sun path chart program (solardat.uoregon.edu/SoftwareTools.html (http://solardat.uoregon.edu/SoftwareTools.html)). You can generate an annual sun path chart for a specific location by simply entering a zip code or the site latitude and longitude. Figure 3 is a sample sun path chart generated for Belmont, Massachusetts.

Angle of reflectance. The altitude angle of the sun varies according to the time of day and year. The lowest altitude angle occurs daily at sunrise and sunset; the highest altitude angle occurs at solar noon on the summer solstice. A glare hazard analysis for a full year typically includes altitude angle calculations for reflected sunlight at representative times of the day (sunrise, solar noon, sunset) and year (spring equinox, summer solstice, fall equinox, winter solstice). Since most residential roof-mounted PV arrays are installed at a tilt angle rather than horizontally, you must account for this tilt angle in your calculations. One way to do this is to use basic trigonometry.

Figure 4, for example, assumes an array tilt angle of 25° and a solar altitude angle of 30°. Because all the angles in a triangle add up to 180°, we know that the angle between the incident light and the back of the module equals 125° (180° − 25° − 30°). Since the angles that make up a straight line also equal 180°, we know that the angle between the incident light and the front of the PV array equals 55° (180° − 125°). The law of reflection dictates that the reflected light and the plane of the array mirror this 55° angle. Because opposite angles resulting from intersecting straight lines are congruent, two opposite angles on the backside of the PV array both equal 55°. You now have all the information needed to solve for *x,* which is the angle of the reflected light as measured off the horizon line. In this example, *y* equals 100° (180° − 25° − 55°), which means that *x,* the angle of reflected sunlight relative to an abutting property, is 80°.

This example illustrates that sunlight reflected off a residential roof-mounted array generally goes skyward, where it is most likely to travel over the top of neighboring buildings. The higher the sun is in the sky, the higher the angle of reflectance. Even if the solar altitude angle in Figure 4 were 0°, the minimum angle of reflection relative to an abutting property would be 50°.

Height of reflection. The distance between a PV array and neighboring properties also factors into a glare analysis. When the angle of reflectance is high, reflected sunlight travels above neighboring residences, even those located close to the array. When the angle of reflectance is at its lowest, the elevation of the reflected sunlight increases linearly with distance. Therefore, the more distance there is between a PV array and a neighboring home, the more likely the reflected sunlight is to travel over the top of that building.

Sunlight reflected off a PV array presents a problem only when the array directs it toward a neighboring property at a height that an observer can see from that property. Therefore, a thorough glare analysis for a PV array determines the height of reflected sunlight, either based on the distance of specific landmarks or at a representative set of distances. Once you know the angle of reflection, *x,* you can calculate its height, *h,* at any distance from the array, *d,* using Equation 1.

$$h = \tan(x) \times d \quad (1)$$

When you apply this calculation at different distances, it quickly becomes apparent that sunlight reflected off a PV array is unlikely to adversely affect surrounding properties in a residential neighborhood. Even if a PV array generates some glare, a neighbor is unlikely to see that glare from the height of a residential building.

Case Study: Belmont, Massachusetts

Belmont, Massachusetts, is an inner-ring suburb of Boston comprised primarily of single- and two-family homes. The typical residence in Belmont is two stories tall. As such, Belmont is representative of many residential communities across the country. Based on local zoning rules and minimum setback requirements, structures on abutting properties are located at least 20 feet apart side to side and distances between structures are always larger front to front or front to back.

A simple two-step process evaluates the glare potential associated with a residential roof-mounted PV array in Belmont. In the first step, determine the altitude angle of the sun at representative times of the day and year and use these data to calculate the associated angles of reflection. Table 1 details the results generated in Excel.

In the second step, use Equation 1 to determine the height of the reflected sunlight at different distances from the array based on the previously calculated angles of reflection. Table 2 details the height of reflection seasonally for distances in the 20- to 50-foot range. For example, the height of sunlight reflected off a PV array at noon on the spring or fall equinox is nearly 80 feet above the array at a distance of only 20 feet from the array; by the time the reflection is 50 feet from the array, its elevation is nearly 200 feet. Note that the height of the reflected sunlight is not relative to ground level but originates at the installed height of the roof-mounted array.

These data clearly indicate that glare from roof-mounted PV arrays is unlikely to pose a problem for neighbors when the sun is highest in the sky. Based on the typical distances between residences in Belmont, Massachusetts, reflected sunlight is most likely to travel over structures on abutting properties. While this simple analysis may not rule out the potential for glare at sunrise or sunset, you can perform similar analyses that take azimuth angles into account. Generally speaking, if a PV array is facing south, incident sunlight at sunrise and sunset arriving from the east or the west does not directly strike the surface of a residential roof-mounted array. By the time sunlight does strike the array directly, its angle of incidence is high enough to preclude the visibility of any glare to neighbors.

*—**Roger Colton** / Fisher Sheehan & Colton / Belmont, MA / fsconline.com (http://fsconline.com)*

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