Assessing Rooftop Solar PV Glare in Dense Urban Residential Neighborhoods: Determining Whether and How Much of a Problem

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November 16, 2014

ABSTRACT

A substantial growth in solar photovoltaic (PV) energy production has given rise to concerns amongst some of the impact of glint and glare on surrounding properties, particularly in dense urban residential neighborhoods. This discussion finds that rooftop solar PV panels are unlikely to generate substantial glare. It further concludes that glare is unlikely to be a problem to immediate abutters in an urban neighborhood.

There has been substantial growth in photovoltaic ("PV") solar energy production in Massachusetts in recent years. In the third quarter of 2013, non-residential solar energy in the Commonwealth grew 62%. Between 2010 and 2012, the number of residential solar installations in Massachusetts nearly quadrupled, from 737 in 2010 to 2,882 in 2012. One local industry observer in Massachusetts states that "Massachusetts has become a shining example of explosive PV growth." He reports that:

> In 2007, shortly after taking office for the first time, Governor Deval Patrick called for Massachusetts to develop 250 MW of new solar PV capacity by 2017. He led the way to passage of legislation that dramatically expanded the public support for solar PV development. By the spring of 2013, a full four years earlier than first proposed, the Commonwealth had reached the 250 MW goal. Recently, the Governor announced a new, dramatically expanded goal of installing 1,600 MWs of solar capacity by 2020. If that target is reached, solar would equal

> roughly 12 percent of the state's total currently-installed electric generating capacity and, at that time, would be expected to contribute about 4 percent of the state's annual electricity supply.[2]

Accompanying the expansion of solar energy, however, is a rise in concerns about how local government planners and zoning enforcement officers can and should respond in order to protect the interests of the community from unintended consequences. One local concern involves worries that solar panels might create glare that would, at a minimum, be a nuisance to neighboring residential properties. In Belmont (MA), for example, the local planning board approved a solar project proposal for a local elementary school after months of delay. Neighbors had expressed concerns that the solar panels would deflect glare into their homes or around the neighborhood.

Under Massachusetts statutes, local governments are, at least in theory, substantially constrained in the restrictions they might place on solar facilities. A Massachusetts statute (Chapter 40A, Section 3) specifically provides that "[n]o zoning ordinance or by-law shall prohibit or unreasonably regulate the installation of solar energy systems or the building of structures that facilitate the collection of solar energy, except where necessary to protect the public health, safety or welfare."

This statute, however, might provide less protection than envisioned by its drafters. Belmont's solar zoning by-law (Section 3.3), for example, allows for rooftop solar PV units "by-right" in all zoning districts in the community, subject to "site plan review." The Belmont by-law (Section 4.3.8(c)(6)), however, provides that "solar Collector Panels shall be placed and arranged such that reflected solar radiation or glare shall not be directed onto adjacent buildings, properties or roadways."

Under the Belmont zoning review process, the municipality's Planning Board may not disapprove a proposed solar project. Under the local "site plan review," the Planning Board is authorized to impose reasonable terms and conditions on the proposed use, but it does not have discretionary power to deny the use.

Despite this limitation, the Planning Board can effectively deny a project simply by repeatedly continuing the public hearing, thus never bringing the solar proposal to a vote. Under Belmont's zoning by-law (Section 7.3.3(c)), for example, the planning board must issue a final decision no more than 20 days subsequent to closing the public hearing unless the applicant agrees to a longer period. No restrictions exist, however, on when the Planning Board must close the public hearing.

Developers might thus benefit from addressing solar glare issues in their initial zoning application.

The purpose of this article is to consider the potential glare[3] problems presented by rooftop solar units in a dense urban neighborhood. Part 1 below will consider basic principles of solar PV panels and light reflectivity in assessing whether glare might arise from a solar PV installation at all. Part 2 will consider basic characteristics of a rooftop-mounted solar module and the surrounding neighborhood that will affect the presence of solar glare. Part 3 will consider basic principles of light reflectivity in assessing the extent to which, if at all, glare that might be produced is likely to be seen by neighboring properties given the expected elevation and horizontal direction of the glare. Part 4 sets forth conclusions and recommendations.

1 The likelihood that solar PV panels might reflect "glare" to neighboring properties.

Glare is caused by reflected sunlight. The purpose of solar panels is to convert sunlight into electricity. By design, therefore, solar PV panels do not reflect substantial amounts of sunlight. Since sunlight will not produce electricity if reflected (Morelli, Pfaff), to the extent that sunlight *is* reflected, PV panels lose their capacity to generate electricity. In general, since the whole concept of efficient solar power is to absorb as much light as possible, while reflecting as little light as possible, standard solar panels produce less glare and reflection than does standard window glass. On a more technical level, solar panels use "high transmission, low iron glass" which absorbs more light, producing smaller amounts of glare and reflectance than normal glass does (Shields).

Certain design attributes of PV panels increase the absorption of light by, and reduce reflection from, solar PV panels. (Good Company). Initially, anti-reflective coatings on PV panels reduce the reflection of sunlight for PV panels. (TetraTech, Meister Consulting, Good Company). PV panels use silicon to convert sunlight to electricity. Since silicon is naturally reflective, all PV panels are coated with anti-reflective materials that allow light to pass through the silicon and minimize reflection. In fact, what causes the dark appearance of PV panels (e.g., dark blue, black) is the fact that monocrystalline wafers, the main component of PV modules, are combined with anti-reflective coatings to maximize absorption. (ACRP; TetraTech).

In addition to the anti-reflective coatings, the surfaces of PV panels are roughened, a process called "stippling." (Shields, TetraTech). Stippled surfaces –sometimes referred to as "dimpled" surfaces—diffuse reflection (ACRP, Encyclopedia of Earth, Morelli, TetraTech) and thus eliminate glare. (Morelli, Shea). "The basic concept behind stippling is for the surfaces of the glass to be textured with small types of indentations. As a result, stippling allows more light energy to be channeled/ transmitted through the glass while diffusing the reflected light energy.

This concept is why the reflection off a SunPower solar module will look hazy and less-defined than the reflection from standard glass. This occurs because the stippled SunPower glass is transmitting a larger percentage of light to the solar cell while breaking up the intensity of the reflected light energy." (SunPower).

To understand the impact of stippled surfaces, one must understand the difference between "specular" and "diffuse" reflection. Specular reflection occurs when sunlight hits a smooth surface such as a mirror. Under these circumstances, the sunlight is directly reflected in only one direction. In contrast, sunlight striking a "stippled" (or "dimpled") surface results in a multi-directional (diffuse) reflection. Because the reflection is scattered in many directions, glare does not occur. The difference between specular and diffuse reflection is illustrated in Figure 1 below.

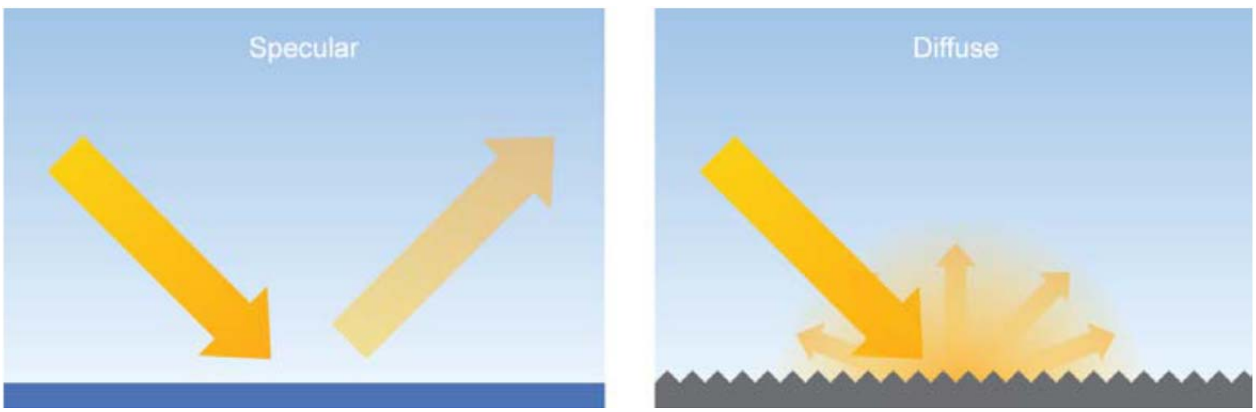


Figure 1. Direct "Specular" and Diffuse Reflection Schematic. (ACRP)

The combination of anti-reflective coatings and stippled surfaces is an effective mechanism to eliminate glare. The reflection of sunlight from solar panels has been reduced to a few percent of the sunlight striking the panel. (Good Company).

Finally, aside from the basic design features of anti-reflective coatings and stippled surfaces, some solar panels use "light trapping." Light-trapping uses mirrors and natural surface textures to "trap" light within the layers of the solar cell. This allows even less light to reflect/escape the solar PV panel, thus allowing even more sunlight to be converted into electricity. (Shields). Light-trapping is illustrated in Figure 2 below.

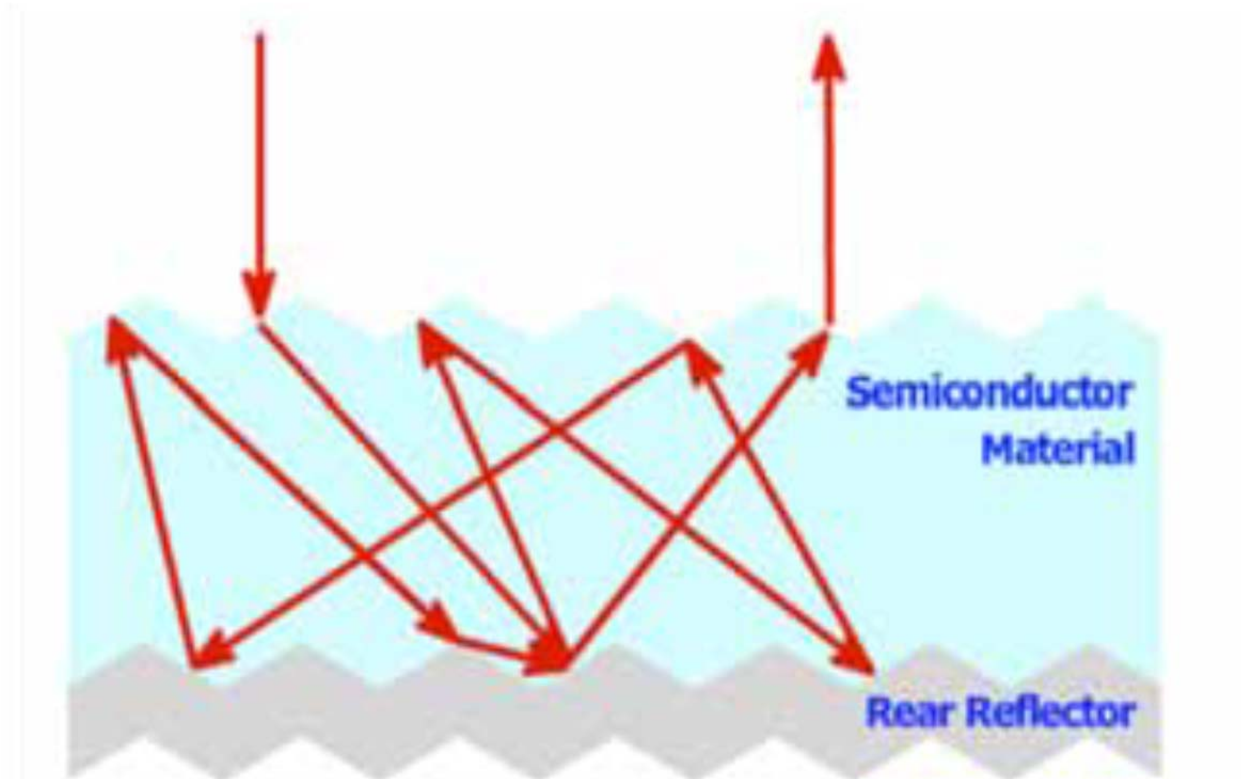


Figure 2: Light Trapping. More light energy is absorbed by the cell with each ensuing reflection of the initial light beam. (Shields).

The reflectivity of solar panels, as with any other material, is measured by the material's "albedo." (TetraTech). The albedo of materials –"albedo" is a measure of the fraction of the sun's radiation reflected from a surface-- ranges from 0 (no reflection) to 1.0 (100% reflection). (American Concrete Pavement Association). Through a comparison of albedos, the glare potential of solar PV panels can be compared to the glare potential of other common materials.

Because of the need of solar PV panels to capture sunlight in order to convert that sunlight to electricity, the albedo of solar panels is much less than that of other common surfaces. In an urban setting, for example, solar panels reflect more sunlight than black asphalt, but less than bare soil and vegetation (see, Figure 3). In a technical guidance prepared for the U.S. Federal Aviation Administration, SunPower reported that the glare from PV modules is "decisively less" than house windows (SunPower), as well as less than white concrete and snow. (WIRSOL).

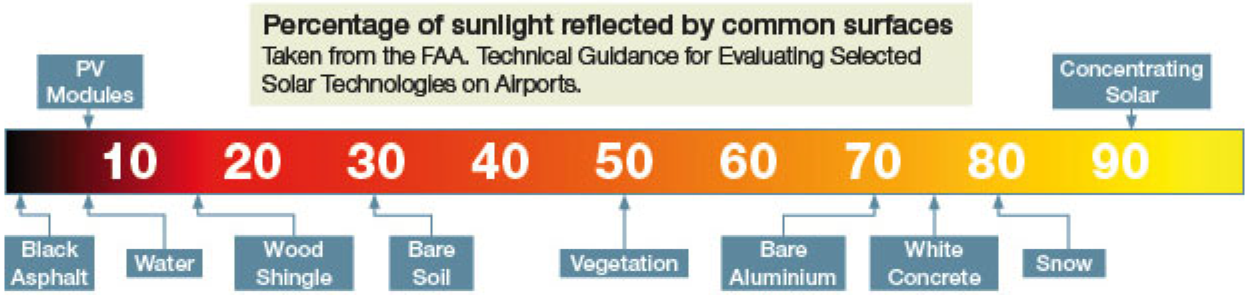


Figure 3. Comparative Reflectivity of Common Surfaces.

The glare from PV modules is less than the glare from roads. (ACRP, TetraTech, WIRSOL) The glare from solar panels is less than the glare from needle leaf (coniferous) trees, grass type vegetation, and broadleaf (deciduous) trees. (Encyclopedia of Earth, Good Company). (See, Figure 4 below). Solar panels reflect less glare than do wood shingles. (ACRP). Modern solar panels reflect as little as 2% of incoming sunlight. (ACRP; American Planning Association; DOE Myths; Pager Power; Spaven).

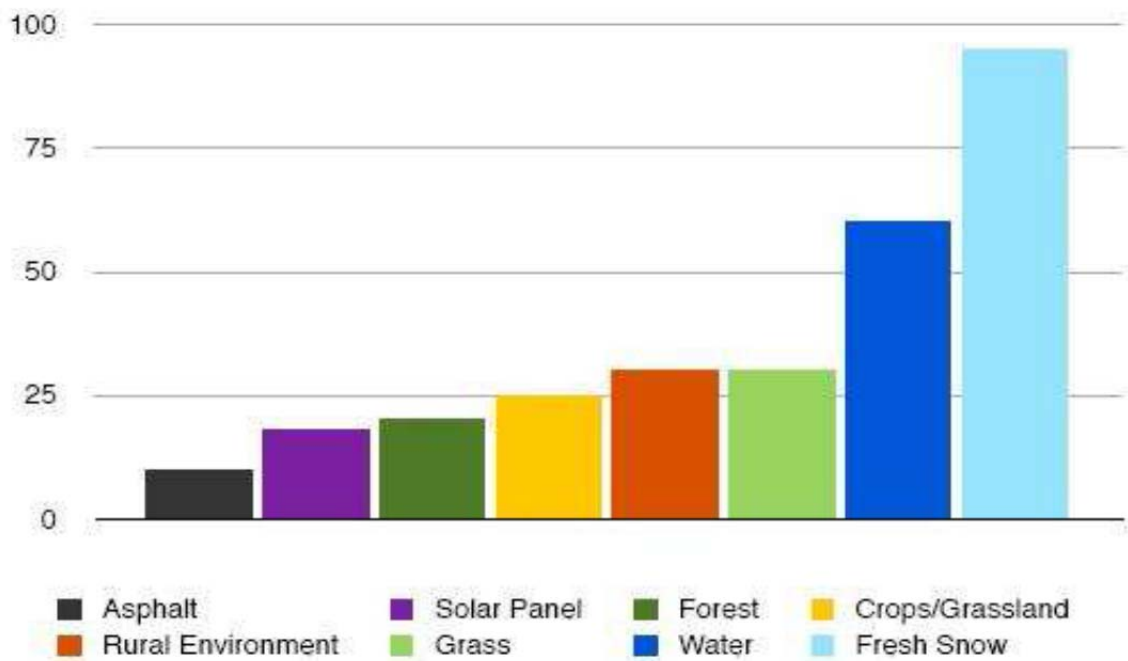


Figure 4. Comparative Reflectivity Analysis. (Spaven).

In a dense urban setting, and with new buildings, it is particularly important to note that solar PV modules reflect less light than do modern rooftops. New construction today is usually designed with white rooftops, which reflect sunlight (and therefore heat), thus helping to control internal building energy costs. White "energy efficient" roofs are designed to have a high albedo and there are known glare issues with these roofs. PV panels may well reduce those glare impacts.

Installing solar PV panels on a white roof, in other words, will reduce, not increase, the potential for glare to occur. (Hsu; Potter).

Based on the discussion and data above, it would be reasonable to expect solar PV panels to create little, if any, glare to neighboring properties. Nonetheless, when a solar developer submits papers to local officials for a review and local zoning determination of the glare impacts, if any, that a proposed rooftop solar PV module might generate for abutting locations, a developer might reasonably submit, at the time of application, documentation of the following attributes of the proposed rooftop solar PV modules:

- Do the solar cells used in the modules have antireflective coatings?
- Is the surface of the solar modules smooth or stippled?
- Do the solar modules incorporate any type of "light trapping" technology?
- Is there documentation from the panel manufacturer of the albedo (reflectivity) of the panels?
- What is the color of the roof on which the solar modules are installed in the absence of the solar modules?

2 The likelihood that glare, if any, from a rooftop solar PV module might be seen by an urban abutter.

Assuming, solely for the sake of analysis, that solar panels in a dense residential neighborhood might generate glare of sufficient magnitude to be a possible nuisance to abutters, a second inquiry should assess the extent to which, if at all, that glare might be visible to a third party observer given the elevation and direction of the glare. Even if glare occurs, in other words, unless it is directed toward, and seen by, an abutting property (referred to below as a "receptor" or "observer"), the glare will not pose problems.

Before considering the mathematics of sunlight reflectivity, it is important to understand several fundamental limitations that exist on the extent to which glare might be visible to abutting properties.

First, for glare to appear, the observer must be able to see the tops of the PV panels. (Morelli). For this to occur, at a minimum, the receptor must be able to see the top of the roof on which the solar PV modules are located. To the extent that the solar panels are installed at some level above the roof, the receptor would need to be at a height sufficient to look down at the tops of the solar modules. In an urban neighborhood, for example, if solar panels are placed on the top of a flat two-story roof, and no gradient exists between the solar installation and the receptor, persons at ground level, as well as people living in two-story abutting properties, will not be affected by any glare. Moreover, people living in buildings having more stories than the building upon which the solar modules are installed will also not be affected by solar glare unless the observers live in a story that is physically higher than the solar installation.

Second, for glare to appear, the altitude of the sun must be above the tops of the solar PV panels. Unless the sun is above the panels, sunlight cannot strike the panels to be reflected. While this may seem self-evident, this observation has particular significance for rooftop solar PV units in an urban setting. For rooftop solar PV panels in a dense urban setting in particular, since the sun will not likely be high enough in the sky in the early morning hours to be above the tops of the solar PV panels on rooftops, the sun will not likely be high enough in the sky for sunlight to be generate glare in the early morning hours. To create glare in these early morning hours, the sun must not only be above the horizon, but must also be above the top of the roof and above the tops of surrounding buildings. (In this respect, solar installations in dense urban neighborhoods will differ from solar panels installed at airports.)

It is important to understand how high the sun is required to be for light to reach the tops of solar PV panels. Since light travels in a straight line, the angle at which sunlight strikes a solar PV panel (known as the angle of incidence) will be equal to the angle at which the sunlight reflects from the PV panel (known as the angle of reflectance). Accordingly, the higher the sun is in the sky, the more any reflection is directed back into the sky (upward) rather than being directed horizontally toward neighboring properties.

Third, glare is insignificant when the location of the sun in the sky is close to the glinting object seen by an observer. The closer the observed angle between the sun and the object from which glare is reflected comes to zero degrees, the more the glare, if any, will be masked by the direct light from the sun. (Morelli). If glare occurs only in the early morning or late afternoon, in other words, it is likely to exist only when an observer would need to be looking directly into the sun to be exposed to the glare in any event. In these circumstances, glare will not be a problem.

Finally, glare is avoided when vegetation or other impediments stand between the observer and the solar panels. These impediments do not shade the solar panels. Rather, they act as sight barriers between potential observers and any solar panels. (Morelli). Neither must these sight barriers be next to the solar PV panels. They need only be between the solar PV panels and a potential observer. A home, for example, may be in the general neighborhood of a building with solar PV panels. That house, however, is at no risk of exposure to solar glare if other homes stand between it and the solar panels.

Sight barriers can be of two types. On the one hand, sight barriers can be permanent solid structures (such as buildings). This type of barrier provides screening from any potential glare irrespective of season. In a dense urban neighborhood, in other words, glare is not a "neighborhood" problem. Glare, if any, will affect only immediate abutters. A home two buildings away from a solar installation will be screened by the intervening structures.

On the other hand, sight barriers may be vegetative. Unlike buildings, vegetation is seasonally important. If glare will occur in the fall/winter season, seasonal vegetation may not be available to serve as a sight barrier. In contrast, if the glare will occur in the spring/summer seasons, seasonal vegetation would prevent glare, if any, from reaching potential observers. (Parsons Brinckerhoff). Key points in the solar cycle to consider in relation to glint include: longest day (worst case scenario: greatest glint); shortest day (best case scenario: least glint); autumn equinox (sun rises at north 90 degrees east and sets at north 90 degrees west; spring equinox (sun rises at North 90 degrees east and sets at north 90 degrees west).

Sight barriers have daily implications as well as seasonal implications. Reflections that might be seen as glare by neighbors will be horizontal (not skyward). Horizontal reflections, however, occur only twice a day: (1) to the west in the morning (when the sun is in the east); and (2) to the east in the afternoon/evening (when the sun is in the west). (Morelli, TetraTech). The usefulness of sight barriers as a screen against potential solar glare depends on their location *vis a vis* the solar PV panels at the time of day that glare might occur. Vegetation impeding glare reflected west will not be helpful as a screen against glare in the evening. Vegetation impeding glare reflected east will not be useful as a screen against morning glare.

Based on the discussion and data above, when a solar developer submits papers to local zoning officials, it might be beneficial for the developer to also submit, at the time of application, documentation of the following:

- The extent to which there exist immediately abutting buildings having a height that would provide sightlines that include a view of the top of the solar panels.

- The sight barriers that exist between buildings having a height that would provide sightlines that include the top of the solar panels, distinguished by whether these sight barriers are useful at screening potential glare at the time of day in which the glare is likely to occur.

The mathematics of the nuisance potential of glare from solar PV panels is discussed in further detail below, along with additional recommendations on what documentation might be presented at the time a solar PV application is submitted.

3 The mathematics of solar PV glare in an urban neighborhood (elevation and directionality).

Basic principles of light and mathematics can be used to document the potential of solar glare occurring to the detriment of properties that abut an urban rooftop solar PV system. Two basic concepts need to be understood to assess the glare potential: (1) the vertical nature of glare (i.e., “elevation” or “altitude”, terms which are used interchangeably herein); and (2) the horizontal nature of glare (i.e., “azimuth”). An assessment based on each of these concepts leads to the conclusion that glare from rooftop solar PV modules is unlikely to be a problem in an urban neighborhood.

3.1 Calculating the elevation of possible solar PV glare.

The elevation of glare, if any, from rooftop solar PV modules is likely to be above neighboring properties. The basic concept to understand in any discussion of glare elevation involves the relationship between the “angle of incidence” and the “angle of reflectance.” “In physics, the Law of Reflection states that the direction of incoming light (the incident ray) and the direction of outgoing light (the reflection) produce the same angle with respect to a perpendicular line drawn from the reflecting surface. Glare may be experienced if a viewer is located in or near the direct path of reflection.” (TetraTech).

Assessing potential glare from a solar PV panel requires creating the “normal.” The normal is an imaginary line at 90 degrees to the reflective surface (i.e., the surface of the solar panel). Two calculations are then made relative to the normal:

- The “angle of incidence” is the angle at which light strikes the surface (at the point where the normal intersects the surface). (Parsons Brinckerhoff).

- The “angle of reflectance” is the angle formed by the reflected beam of light and the same perpendicular line at the point of incidence. (Parsons Brinckerhoff).

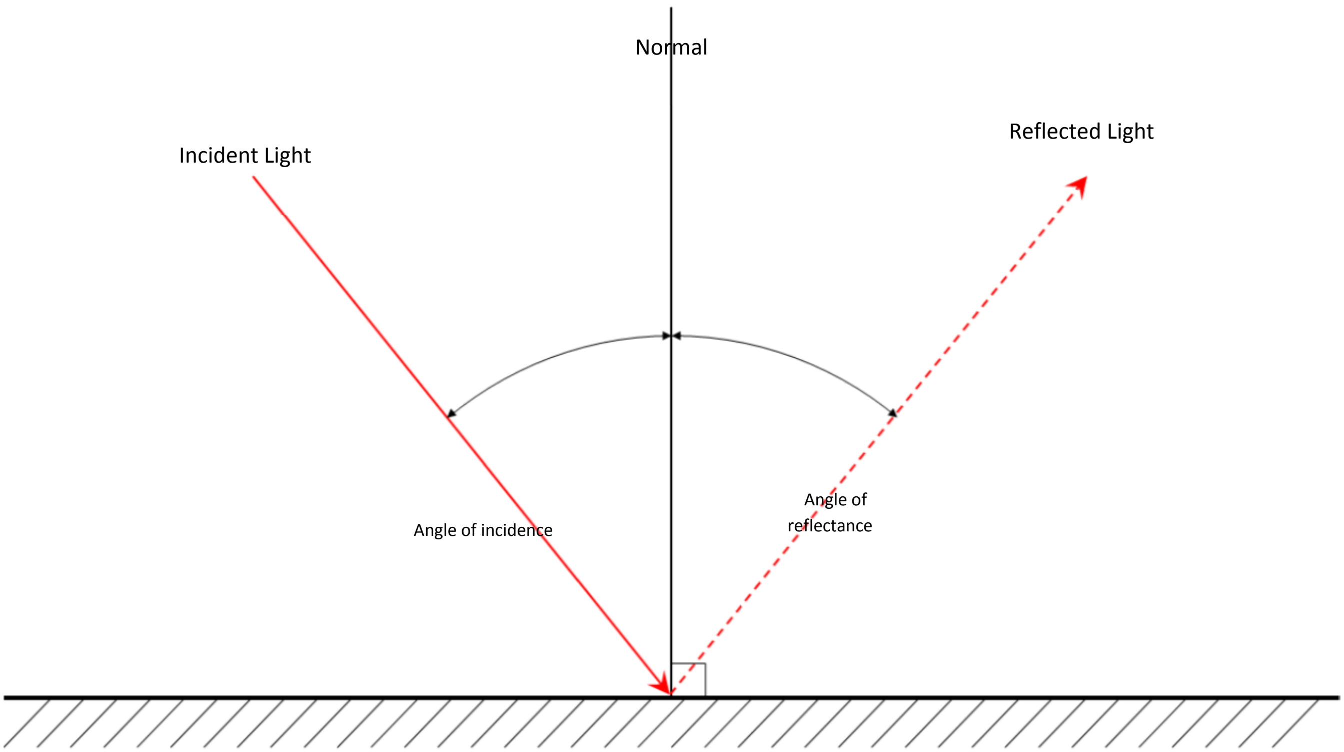


Figure 5. Angle of incidence equals angle of reflectance.

Since light travels in a straight line (Parsons Brinckerhoff), the angle of incidence is always equal to the angle of reflectance. (Shields). The empirical inquiry is then whether the potential observer is within the altitude of reflection given the distance of the observer from the solar PV panel. At any angle of reflectance, as a potential observer is further and further away from the solar PV panel, the elevation of the reflected sunlight (i.e., any glare) is more likely to be above the observer and thus not seen. In contrast, at a high angle of reflectance, the elevation of reflected sunlight will likely be above the observer even at short distances.

Given the basic principle of light reflectivity stated above, evaluating the angle of reflectance from a solar PV panel must begin with a determination of the altitude of the sun (in degrees) relative to the ground. The "solar altitude" is the angle of the sun in degrees above or below the horizon. A positive angle would be after sunrise and before sunset, while a negative angle would indicate the sun's position before sunrise or after sunset. (IB Group). The altitude of the sun differs based on a number of different factors, including: (1) the time of day; (2) the season of the year; and (3) the latitude at which the solar PV panel is located.[4]

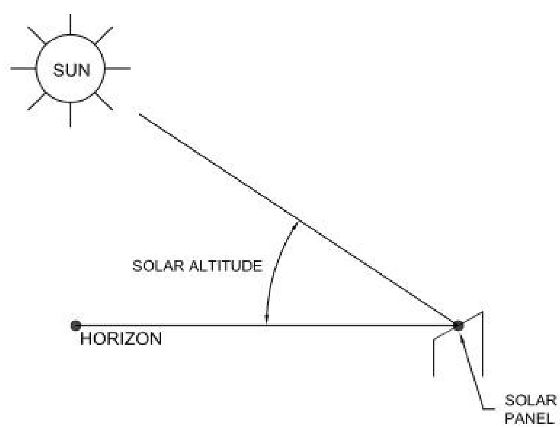


Figure 6: Solar Angle (IBI Group).

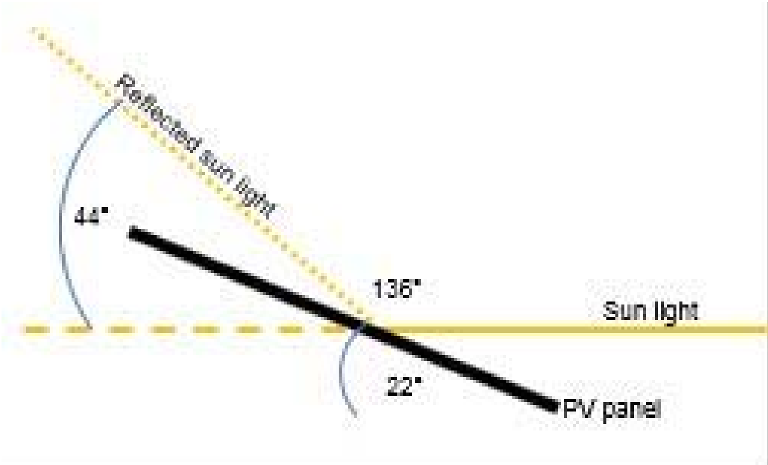


Figure 7. Lowest possible reflection angle (altitude of sunlight equals 0°). (PagerPower).

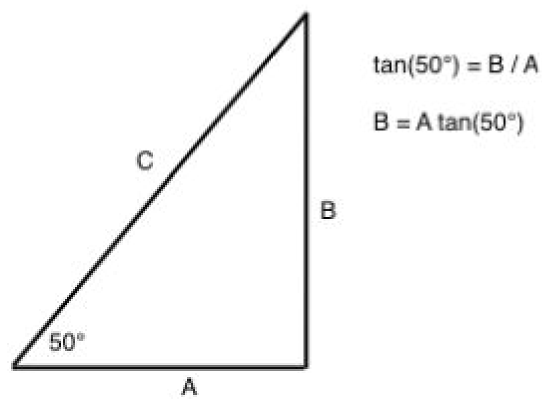
The minimum possible elevation for *any* solar reflection occurs when the angle of the sun in respect to a solar PV panel is 0°. A rooftop solar PV panel with a slope of 22°, for example, produces an angle of reflection of 136°. Since the altitude of reflection is 180° minus the angle of reflection (PagerPower), the minimum altitude of reflection will be 44° for a solar PV panel with a slope of 22°. The sum of the angle of reflection and the altitude of reflection will be a straight line (180°). Accordingly, the altitude of reflection will be 180° minus the angle of reflection.

As the angle of the sun in relation to the solar PV panel increases, the angle of reflection will decrease and the altitude of reflection will increase. Given a solar altitude of 30° and a PV panel slope of 22°, the angle of reflection would be 106° and the altitude of reflection would be 74°. With a solar altitude of 60° and a solar PV panel slope of 22°, the angle of reflection would be 76° and the altitude of reflection would be 104°. A step-by-step illustration of how to calculate the altitude of reflection is presented in Attachment A to this article.

The final step in an assessment of whether a potential observer falls within the altitude of reflection of the glare, if any, from a solar PV panel is to determine the height of the glare at the distance the observer is from the solar PV panels. Given the altitude of reflection, calculating the height at various distances is a very straightforward process. Given an angle of x-degrees, the height (B) at distance (A) is calculated through the following equation:

$$Tan(X) = \frac{B}{A}$$

Where:
A = distance from solar PV panels
B = Height of reflection
X = Angle of reflection



The illustration to the left shows that this equation can be rewritten so that the height of the reflection (B) equals the distance from the PV panels times the angle of reflection (B = A * tan(X)).

In applying this calculation, it quickly becomes apparent that the glare, if any, from rooftop solar PV panels is not likely to adversely affect surrounding properties in a dense urban neighborhood. Four dates can be selected for analysis to signify the "best case" and "worst case" scenarios: (1) the winter solstice; (2) the summer solstice; (3) the spring equinox; and (4) the fall equinox. For each of those four dates, three times of day can be selected for review: (1) sunrise; (2) noon; and (3) sunset. (IBI Group).

Data for Belmont (MA) has been selected for illustration. The Belmont data (altitude of sun; altitude of reflection) for the dates listed above is set forth in the Table below:

Calculating Altitude of Reflection for Belmont (MA) /a/

Dates (2014)	Sunrise			Noon			Sunset		
	Time	Sun Altitude°	Altitude of Reflection°	Time	Sun Altitude°	Altitude of Reflection°	Time	Sun Altitude°	Altitude of Reflection°
Spring equinox (DST)	7:00	1.80	150.2	12:00	47.62	104.38	6:30	4.21	147.49
Summer solstice (DST)	7:00	18.08	133.92	12:00	70.86	81.14	8:00	3.25	148.75
Fall equinox (DST)	7:00	4.60	147.4	12:00	47.49	104.51	6:30	1.62	150.38
Winter solstice	7:30	2.52	149.48	12:00	24.12	127.88	4:00	1.75	150.25

2014: Spring equinox: March 20; Summer solstice: June 21; Fall equinox: September 22; Winter solstice: December 21.

NOTES:

/a/ The sun altitude for Belmont (MA), by date and time of day, was obtained from: http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html.

Given these calculations of the altitude of reflection (in degrees) at different times and days, it is then possible to determine the altitude (in feet) at which an observer at given distances would be affected by the glare, if any, from a solar panel; the observer would also need to be within the direction of the reflection. Glare occurs if a receptor is in or near the direct path of reflection. (TetraTech). In addition, it is important to understand how long the sun stays within that angle.

(Morelli, TetraTech). The sun covers 15 degrees in one hour. (Shea). The data is set forth in the Table below.

Elevation of Reflection (feet) by Distance from Solar PV Panels (feet), Time of Day, and Date

Distance From PV Panel (Feet)	Elevation (feet) Spring Equinox			Summer Solstice			Fall Equinox			Winter Solstice		
	Sunrise	Noon	Sunset	Sunrise	Noon	Sunset	Sunrise	Noon	Sunset	Sunrise	Noon	Sunset
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.6	3.9	0.6	1.0	6.4	0.6	0.6	3.9	0.6	0.6	1.3	0.6
5	2.9	19.5	3.2	5.2	32.1	3.0	3.2	19.3	2.8	2.9	6.4	2.9
10	5.7	39.0	6.4	10.4	64.2	6.1	6.4	38.6	5.7	5.9	12.9	5.7
15	8.6	58.5	9.6	15.6	96.2	9.1	9.6	58.0	8.5	8.8	19.3	8.6
20	11.5	78.0	12.7	20.8	128.3	12.1	12.8	77.3	11.4	11.8	25.7	11.4
25	14.3	97.5	15.9	26.0	160.4	15.2	16.0	96.6	14.2	14.7	32.1	14.3
30	17.2	117.0	19.1	31.2	192.5	18.2	19.2	115.9	17.1	17.7	38.6	17.1
35	20.0	136.5	22.3	36.3	224.5	21.2	22.4	135.2	19.9	20.6	45.0	20.0
40	22.9	156.0	25.5	41.5	256.6	24.3	25.6	154.6	22.7	23.6	51.4	22.9
45	25.8	175.5	28.7	46.7	288.7	27.3	28.8	173.9	25.6	26.5	57.8	25.7
50	28.6	195.0	31.9	51.9	320.8	30.3	32.0	193.2	28.4	29.5	64.3	28.6

The shaded columns document for Belmont that as the sun rises higher in the sky, and increases the angle at which sunlight strikes the solar panels (i.e., the angle of incidence), the reflected light will be upward (toward the sky) rather than at neighboring properties. At noontime, when the sun is at its highest altitude in the sky (in degrees), the Belmont data shows that:

- In the spring and fall, at an observer distance of only 20 feet from the solar panels, the noon-time elevation of glare, if any, would be nearly 80 feet. By the time the distance of an observer from the solar panels reaches 35 feet, the noontime elevation of any glare would be more than 135 feet in the air.

- In the summer, at an observer distance of only 20 feet from the solar panels, the noon-time elevation of solar glare would be nearly 130 feet. By the time the distance of an observer from the solar panels reaches 35 feet, the noontime elevation of any glare would be nearly 225 feet in the air.

- In the winter, at an observer distance of 20 to 35 feet from solar panels, the noontime elevation of solar glare, if any, would be between 25 feet and 45 feet in the air.

In interpreting these elevation figures, it is, of course, important to remember that the elevation of the glare is not from ground level, but rather from the level of the solar panels. If the solar panels being reviewed are rooftop units, the elevation of the glare needs to be increased, at each distance level, by the height of the building on which the solar panels are located. If the solar PV panels are on top of a flat-roof two-story building, in other words, an additional 30 to 35 feet should be added to each elevation. In Belmont, for example, the maximum building height in a residential zone is either 33 feet or 36 feet, depending on the type of residential zone.

In a residential neighborhood, buildings high enough to be within these altitudes of reflection are unlikely to exist.

The distance of the observer from the solar panel installations is one of the most, if not the single most, critical factors to consider. The distance to be used to determine the elevation of the solar reflection would depend on whether the solar reflection is directed toward the side of a home or toward the front/rear of a home. Minimum distances can be determined by using the minimum set-back requirements contained in any zoning by-law. In Belmont (MA), the minimum side-yard set-backs in a residential zone are established at either 10 or 15 feet, depending on the specific residential district in which the solar panel might be located. If two buildings are each at the minimum side-yard set-back, therefore, one of which has a solar PV installation and the other of which is a potential observer, the minimum distance between the solar PV panels and the potential observer would be 20 feet.

The minimum front-yard set-backs are 20 to 30 feet, while the minimum back-yard set-backs are 20 to 40 feet. The distance between the solar PV panels and the potential observer would thus vary depending on the relative location of the potential observer to the solar PV panels. Back-yard to back-yard, for example, would be a greater distance than front-yard to front-yard. Various configurations could be developed.

The extent to which actual dwelling units differ from the minimum set-back requirements established in the zoning by-law, either greater or lesser, would need to be taken into account.

In addition to building set-back requirements within a land parcel, to the extent that sidewalks and streets exist separating the building with solar PV panels and the potential observer in the dense urban neighborhood that this article is considering, the width of that right-of-way --it is the width of the right-of-way, not merely the width of the street, that would be the distance to consider -- would need to be added to the distance to be used in calculating the elevation of any solar reflection. The presence of a street between a set of solar PV panels and a potential observer would likely, unto itself, add a distance of 50 feet or more separating the panels and the potential observer. (Ben-Joseph, Pioneer Institute).

Based on the discussion and data above, when a solar developer submits papers to local zoning officials it may be beneficial for the developer to also submit, at the time of application, documentation of the following:

- The altitude of reflection for the solar modules in the early morning, at noon, and in the late afternoon/early evening for the spring equinox, summer solstice, fall equinox and winter solstice;

- An identification of illustrative neighboring properties along with the distance of those properties from the closest solar module;

- An identification of characteristics, both of the property on which the solar modules are located (e.g., parking lots, green space) and of the immediately surrounding neighborhood (streets, alleys) that increase the distance from the solar modules to the neighboring properties; and

- The elevation of reflection on the above dates and times for the illustrative neighboring properties plus/minus some reasonable band of impact assessment.

3.2 Calculating the directionality of possible solar glare.

Determining the azimuth of the sun is important for purposes of assessing the potential glare from a solar installation. At any given site, the sun not only moves across the sky every day, but its path in the sky changes during various times of the year. This, in turn, alters the destination of resultant reflections. (Pager Power). Since light travels in a straight line, the sun's movement more to the north or more to the south in different seasons affects the direction of reflection since the angle of reflection will be the same as the angle at which the sun hits the panel. (IBI Group; Parsons Brinckerhoff).

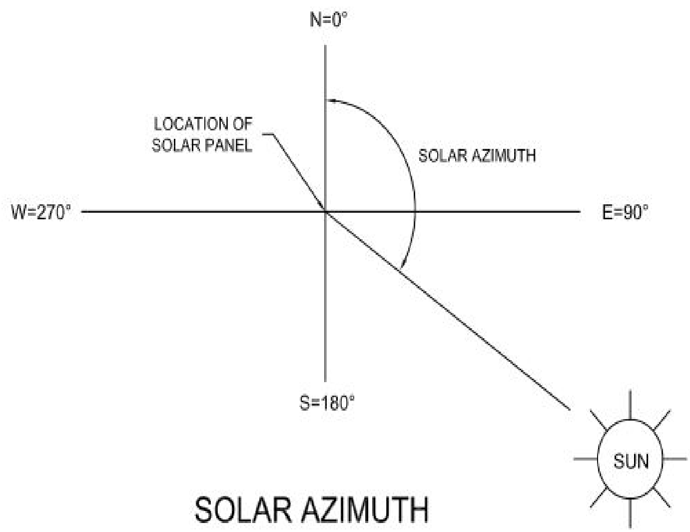


Figure 7. Solar Angle, IBI Group.

The horizontal direction of glare, if any, from rooftop solar PV modules will, by definition, be away from most neighboring properties at any given point in time. (Since light reflection is in a straight line, any neighboring property not within that line of reflection will not be subject to glare.) The basic concept to understand in any discussion of glare directionality involves determining the significance of the azimuth of the sun. Azimuth is the sun's position relative to True North (percent clockwise). (Pager Power). True North is 0° while True South is 180°. The sun's position in the sky can accurately be described for a specific location (latitude, longitude, time, date). (Pager Power).

Most importantly for purposes of glare analysis, the azimuth of the sun affects whether there will be direct or indirect glare from the receptor's focus of view. (Morelli). The "focus of view" is the observer's direction of vision. (Morelli). If a potential observer is not within the horizontal angle of reflection from the solar PV panel, the observer will not see glare.

Glare has little nuisance effect when it is at moderate angles (45 degrees or less) from the observer's focus of view. (Morelli). Since PV panels reflect light in a specific direction, the PV reflection when viewed from a substantial angle of azimuth is much less intense than when viewed directly. (PagerPower). Moving just 30% off of direct reflection reduces the intensity of sunlight reflection by 80%. (Good Company). Glint has virtually no effect when the angle of azimuth is close to or greater than 90 degrees from the observer's focus of view. (Morelli).

The azimuth of the sun is important, also, to determine the direction of the direct sunlight reflection from a solar PV panel. Reflections facing south at low to moderate angles of inclination near horizontal reflections are confined to: (a) just north of due east to approaching southeast; and (b) just north of due west to approaching southwest. Reflections at any given vertical angle happen twice a day in opposite directions. Reflections to the west occur in the morning (with the sun in the east); reflections to the east occur in the afternoon/evening (with the sun in the west). (Morelli). In contrast, during the day, reflections are skyward. (Morelli, TetraTech).

The dual consideration of the elevation and the directionality of reflection are interrelated tasks to undertake. The first step is to determine the elevation of reflection which might have a glare impact on neighboring buildings. The second step is to determine the direction of reflection. For glare to pose a nuisance value to a neighboring building, that building must be *both* at the elevation of the glare *and* in the direction of the glare at the same time. A consideration of one or the other of these steps might render the other moot. For example, if no buildings are within the elevation of glare, calculating the direction of glare becomes unnecessary.

Based on the discussion and data above, when a solar developer submits papers to local zoning officials, it might be beneficial for the developer to also submit, at the time of application, documentation of the following:

- The azimuth of the sun at sunrise, noon and sunset for the latitude of the solar PV panels and the critical dates and times identified above.

- A listing of buildings within the direction of reflection, given the azimuth of the sun at those times and on those dates.

- A determination of whether the buildings in the direction of reflection will *also* be at the altitude of reflection at those times and on those dates.

4 Conclusions and Recommendations.

Electricity generated through solar PV panels is providing an increasing share of the energy used in Massachusetts homes and businesses today. As solar panels become more common, however, there is a corresponding increase in the concerns by some that those solar PV panels may have an adverse impact on the communities in which they are located. One particular concern that has been expressed in dense urban neighborhoods is whether rooftop solar PV panels will result in glare being directed toward surrounding buildings.

There is little possibility that solar PV panels will generate glare. Given that the purpose of solar PV panels is to convert sunlight into electricity, solar panels are designed to absorb rather than to reflect light. Sunlight that is reflected, after all, is lost energy production potential. In addition to being covered with anti-reflective coatings, the surfaces of solar PV panels are “stippled” (or “dimpled”) to increase their ability to capture rather than to reflect sunlight.

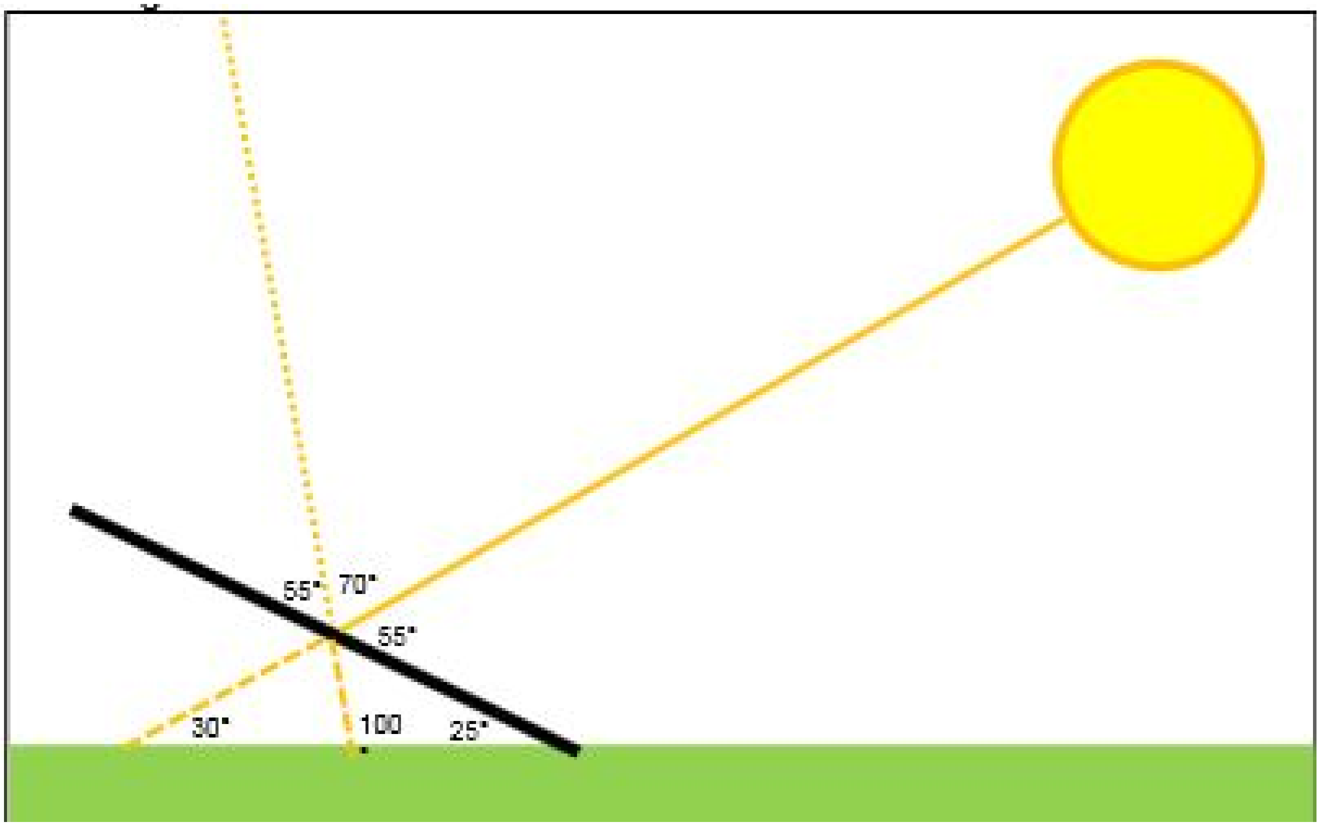
When reflectivity is measured (in terms of “albedo”), solar panels are found to reflect less light than either broadleaf or coniferous forests, as well as less light than wood shingles. Indeed, solar panels that are installed on white roofs –roofs are often made white for the very purpose of reflecting light and thus controlling building energy costs-- will reduce rather than increase the reflection of sunlight from those roofs.

In addition to the nature of solar panels, in urban neighborhoods, the elevation of solar panels will likely be higher than any potential neighboring viewer. In order to see glare, if any, from a solar panel, a viewer would need to be able to see the top of the solar panels, unlikely to occur in an urban neighborhood.

In addition, given basic tenets of light reflectivity, the angle of reflected sunlight is likely to be directed sufficiently skyward that it would go over the tops of neighboring buildings at even short distances removed from a building with solar panels on its rooftop.

While concern with glare is an understandable one, an objective consideration of the factors that affect the creation of glare leads to the conclusion that solar PV panels installed in an urban neighborhood will not result in glare problems to neighbors.

Attachment A: Calculating the Angle of Reflection from a Solar PV Panel.



Solar reflection geometry (when solar altitude is 30° with a 25° slope to the panel. (PagerPower).

The diagram above depicts the geometry of calculating a solar reflection. (Good Company; Pager Power). The diagram shows the following:

- Solar altitude relative to the ground (30°).
- Slope of solar panel (25°).
- It is simple algebra that all angles in a triangle add to 180°. Accordingly, 180° - (25° + 30°) = 125°.
- It is simple geometry that a straight line is 180°, so the corresponding angle to fit the slope of the solar panel is 180° - 125° = 55°.
- Since the angle of reflection is a vertical angle to this angle, the angle of reflection is also 55°.

- Since the angle of reflection is equal to the angle of incidence, the angle of incidence is also 55^{o}.

- The vertical angle to the angle of incidence would thus also be 55^{o} (whenever two straight lines intersect, four angles are formed; each opposite pair of angles are called "vertical angles" and are congruent, i.e., equal measure).

- It is simple geometry that the sum of the angles of a triangle equal 180^{o}. Accordingly, the altitude of reflection is $180^{o} - (25^{o} + 55^{o}) = 100^{o}$.

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Notes

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[2] David O'Connor (June 14, 2013). "Solar PV Capacity Quickly Expands when States Provide the Right Incentives," http://www.mintz.com/newsletter/2013/Advisories/3138-0613-NAT-ECT_OConnor/index.html#n1, citing, "Massachusetts 2012-13 State Profile," ISO New England Inc., February 2013, http://www.iso-ne.com/nwsiss/grid_mkts/key_facts/final_ma_profile_2012-13.pdf (last accessed, January 27, 2014).

[3] There is a difference between "glint" and "glare." "Glare" involves a generalized reflection of light from the sky surrounding the sun. "Glint" is a reflection of the direct light from the sun. Since popular vernacular does not recognize this technical distinction, however, the generic term "glare" is used in this article to encompass generically all reflected light from a solar PV installation.

[4] The altitude of the sun, by latitude, for each hour of each day of the year is available through a variety of public sources. See, e.g., http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html; see also, http://www.gaisma.com/en/; http://www.timeanddate.com/worldclock/astronomy.html; http://www.susdesign.com/sunangle; http://www.pveducation.org/pvcdrom/properties-of-sunlight/sun-position-calculator.