Diminishing the glare that obscures

PV panel reflection | The increasing deployment of PV systems in dense urban areas has drawn attention to the issue of glare and the public discomfort arising from the sun's reflection on the PV panels. Licheng Liu, Yong Sheng Khoo and Thomas Reindl of the Solar Energy Research Institute of Singapore (SERIS) and Julius Tan of Sunseap Energy discuss ways of fine-tuning system designs and alleviating visual discomfort, while not compromising on the energy yield of PV systems

The steep decline in prices of solar PV modules in recent years has catalysed the adoption and deployment of solar PV systems globally for private, commercial and industrial uses, all the way to utility-scale installations of several hundreds of megawatts. Grid parity for solar electricity has been reached in many countries, including Singapore. In other words, the levelised cost of energy (LCOE) generated from PV is equivalent to, or less than, the price of electricity from the power grid, which has made investments in PV systems financially attractive, even in the absence of monetary support schemes, such as feed-in tariffs. In early 2014 the Singapore government announced the SolarNova initiative, led by the Singapore Economic Development Board (EDB) to encourage the adoption of solar PV in the public sector. The target is to achieve 350MWp of installed solar PV capacity on the rooftops of government-owned buildings by 2020.

With the increasing adoption rate, one relatively rare issue related to solar PV installations has started to surface: glare from PV modules. The smooth glass encapsulation on the front side of solar panels can cause glare effects through the optical reflection of direct beam irradiance.

Sunlight reaching the earth comprises a direct component and a diffused component. *Direct sunlight* is the portion of solar radiation that is not blocked by clouds when it passes through the earth's atmosphere, whereas *diffused sunlight* is experienced when the incoming solar radiation travels through clouds or is reflected off matt objects, such as white walls. Because of the tropical nature of the weather conditions here (high moisture content in the air, frequent cloud formations), the solar radiation experienced in Singapore has a relatively high share of diffused irradiance (55–60% on average). The potential glare effects are therefore inherently lower than in other locations that have a higher percentage of direct sunlight.

Glare (a continuous source of bright light) is one of the two potential impacts of optical reflections; the other is *glint* (a brief flash of light), which can result in momentary loss of vision (flash blindness). The impact of glare on individuals typically depends on several factors, including background luminance and the distance and luminance level of the glare source. A glare effect is normally experienced when there is a sharp contrast between the intensity levels of the background luminance and the glare source. If the intensity level of the background luminance is very high, for example during broad daylight, the sensation of the glare impact would be reduced. The distance of the glare source and the solid angle also influence the degree of attenuation of glare, as does the luminance level of the glare source, which, in the case of solar modules, is a function of the reflection level of sunlight.

Generally, there are two types of reflection, namely specular reflection and diffused reflection. *Specular reflection* from a surface is the case where light from a single incoming direction is reflected into a single outgoing direction, whereas *diffused reflection* is the reflection of light from a surface where an incident ray is reflected at many angles. The luminance of a specular reflection is usually higher than that of a diffused reflection. As the surface of the glass encapsulation of most solar panels is smooth, the reflection off them is usually specular, which may result in glare under certain conditions, as described in detail below.

There are several indices for evaluating the level of visual discomfort brought on by glare, such as the British glare index (BGI), the discomfort glare index (DGI), the Cornel glare index (CGI), and the discomfort glare probability (DGP). However, the different indices are typically applied in very specific scenarios and are often limited in other situations, especially since they also involve a number of subjective measurements. It is therefore difficult to isolate a specific index to evaluate the glare from PV systems.

In the following sections, the severity of reflection from solar panels is discussed, followed by recommendations for system designs in order to ease the discomfort from glare. Analyses of the reflectance and glare arising from PV systems have been performed for various module tilt angles and orientations in order to derive a balanced solution to the issue of glare. The solution is further reinforced with simulation models that provide a comprehensive visualisation.

Reflection from a solar PV module

Sunlight reaches the surface of the earth as packets of energy, commonly known as *photons*, with which different materials interact differently in terms of reflectance, transmittance and absorptance. Fig. 1 shows the AM 1.5 solar spectrum, which graphically describes the distribution of solar energy received on the earth's surface as a function of different wavelengths. It can be seen that at low wavelengths of less than 400nm (ultraviolet light), not much solar energy reaches the earth's surface. The highest fraction is in the wavelength range of visible light (400–700nm); from around 500nm the solar energy decreases with increasing wavelength.

A solar cell is designed to absorb as much sunlight as possible and convert it into electricity, and any photon reflected off a solar cell is in fact an undesirable loss in

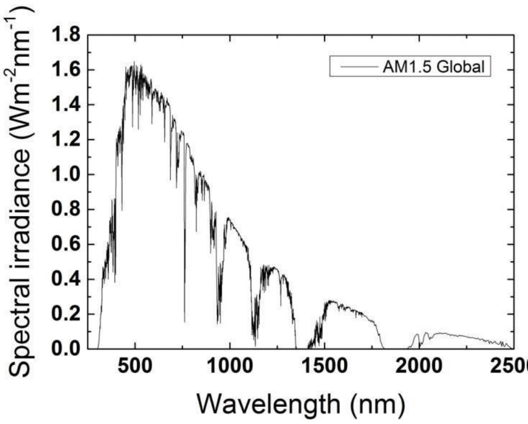


Figure 1. Standard solar spectra at AM 1.5 (IEC 60904-3).

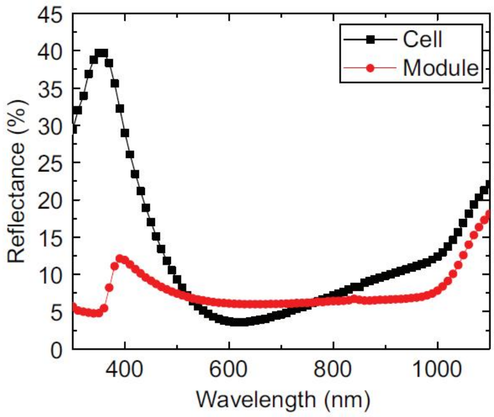


Figure 2. Wavelength-dependent reflectance of a typical solar cell (black squares) and module (red circles) [1].

the energy yield. In order to maximise the energy yield, a layer of anti-reflection (AR) coating is therefore deposited onto the front surface of a typical solar cell to minimise the reflectance. However, it is not economically viable to reduce the reflection of the cell surface over the entire solar spectrum; in consequence, the refractive index of the AR coating is tuned to minimise reflection in the visible light spectrum range in order to cover the largest portion of the solar energy reaching the earth's surface.

Fig. 2 shows the wavelength-dependent reflectance of a solar cell with an AR coating as well as the reflectance of a solar module, i.e. after packaging the cell into a durable panel with a glass surface. Although the refractive index of the AR coating is designed to minimise the reflectance of light in the wavelength range 400–700nm, it can be seen that the reflectance at wavelengths of less than 500nm increases (with a peak below 400nm), i.e. in the blue, violet and ultraviolet (UV) ranges; this explains why typical

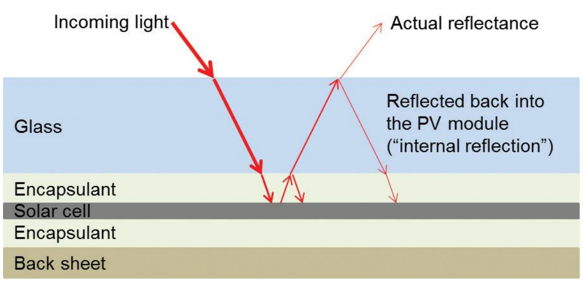


Figure 3. Schematic of light paths in a solar module.

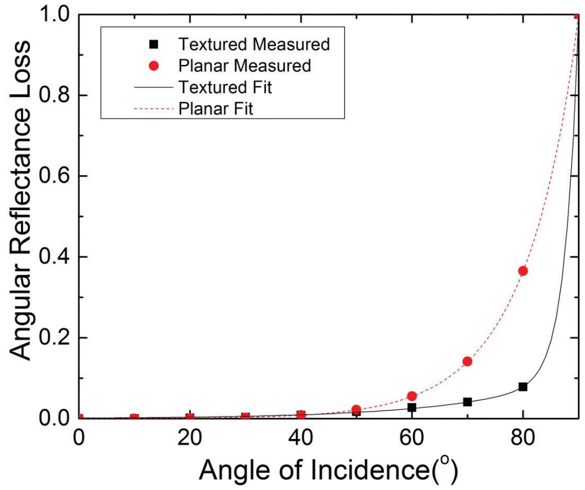


Figure 4. Angular reflectance loss of a solar panel [2].

solar cells appear blue in colour. When solar cells are assembled and encapsulated into a solar module, the reflectance of high-energy light in the UV range decreases significantly because of the 'light-trapping' effect of the glass encapsulation in a solar module.

Fig. 3 demonstrates this light-trapping effect by outlining the possible paths of sunlight when it reaches the surface of a solar module. The sunlight is refracted through the glass and the encapsulant before arriving at the surface of the solar cell, where it encounters a certain degree of reflection. The fraction of high-energy light which is not immediately absorbed by the solar cell, and hence reflected from the solar cell surface, will then encounter internal reflection again at the encapsulant–glass interface, as well as at the glass–air interface, back to the solar cell. The energy of such reflected light is partially reduced, which enhances its absorption by the solar cell thereafter.

Thanks to the light-trapping effect, the weighted average reflectance (WAR) of a solar module is reduced to below 10%. This is comparable to the reflectance of typical window glass (6–10%) and significantly below the reflectivity requirement of the Singapore Building and Construction Authority (BCA) for reflective surfaces on buildings, which is 20%.

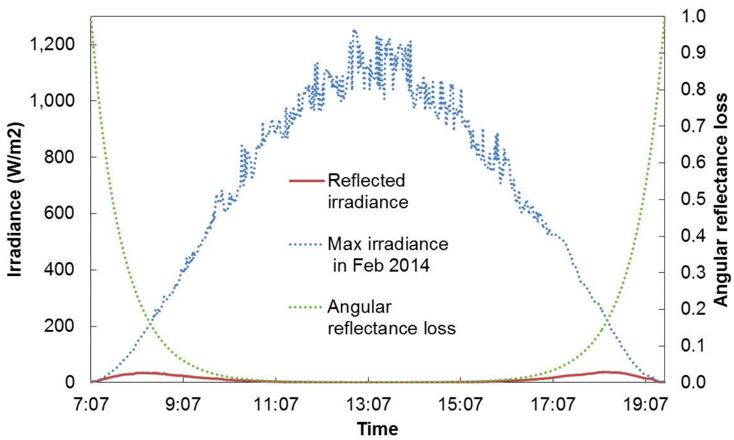
As with any reflecting building element, there are, however, possible situations and scenarios in which glare from a solar panel can potentially occur. The reflectance measurements for the solar cell and solar module as shown in Fig. 2 are taken at a normal (0°) incidence, i.e. the incoming light is perpendicular to the solar cell and the solar module. Fig. 4 shows the angular reflectance losses, relative to normal incidence, of typical solar modules with a textured glass and a planar glass (for a solar module, such reflectance reduces the absorption and the yield and is hence considered a 'loss'). It can be seen that the angular reflectance loss starts increasing dramatically when the angle of incidence goes beyond ~70°.

For a horizontally installed solar panel, such high reflectance at high angles of incidence can occur only in the early morning or late afternoon hours, when the sun is close to the horizon. However, as the solar irradiance is low at those times, the energy of the reflected light at that point in time is also low, as shown in Fig. 5. The blue dotted curve describes the worst-case irradiance profile when plotting the maximum observed irradiance at 1min intervals in the case of Singapore (taken in February 2014, which was particularly dry and hot). The red solid curve represents the reflected irradiance obtained by multiplying the irradiance profile by the angular reflectance loss. The maximum reflected irradiance under such circumstances is calculated to be only 37W/m², which is similar to the amount of light emitted from a light bulb used in residential applications.

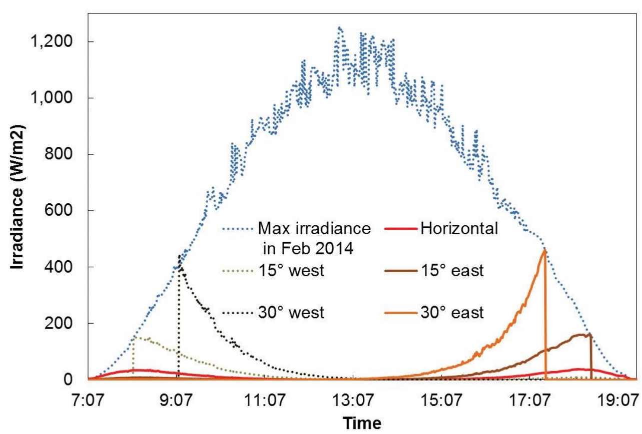
Solar modules are typically installed at tilt angles close to a location's latitude. In the case of Singapore, this suggests near-horizontal installation, but they are in reality installed rather tilted at an angle of 10–15° to facilitate the so-called 'self-cleaning' effect, which helps to clean the surfaces from dust and dirt through natural rainfall. Many PV systems in Singapore are installed in an east–west orientation, which helps to generate a slightly higher energy yield compared with a north–south orientation [3], and hence allows the harvest of solar energy to be maximised in a space-constrained location like Singapore.

It can be seen from Fig. 6 that the maximum reflected irradiance increases with larger tilt angles of the module, because the high reflectance at high angles of incidence occurs later in the morning or earlier in the afternoon, when the solar panels are tilted towards the west and the east respectively. This could then increase the level of discomfort brought on by glare from the PV system, as the relative irradiance levels are higher. For a PV system with solar panels tilted at 15° to the west and east, as an example, the maximum reflected irradiance would be ~160W/m² at 8:10am (W) and 6:20pm (E), compared with a horizontally installed PV system, which reflects only 37W/m².

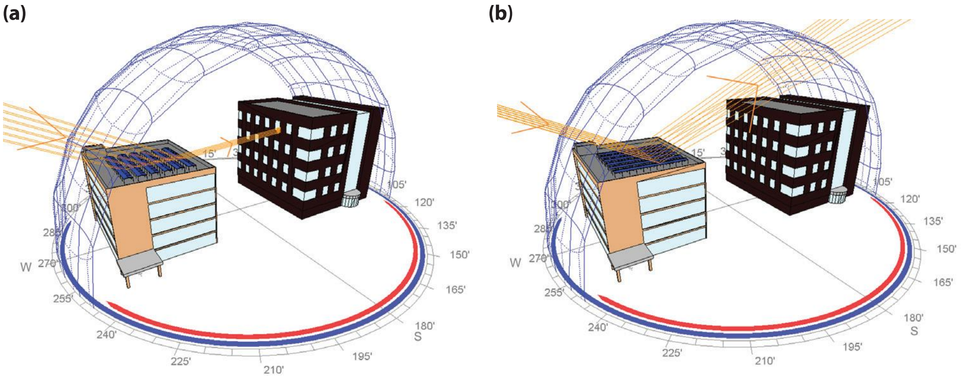
If the tilt angle of the solar panels is further increased to 30° to the west and east (which would only happen if a PV installation has to follow the given larger tilt angle of the underlying roof, e.g. on private residential buildings – see also 'Private residential buildings' section below), the maximum reflected irradiance would be ~450W/m² at 9:10am (W) and 5:30pm (E). Such higher levels of reflected irradiance



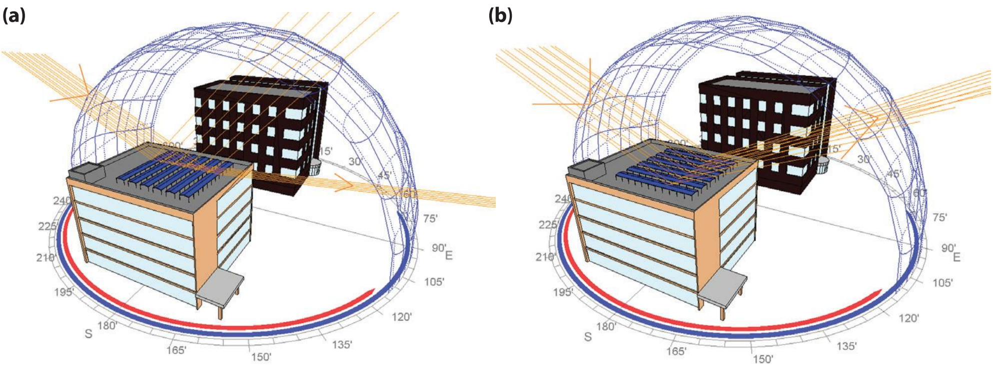
▲ **Figure 5. Plots of maximum irradiance, angular reflectance loss and reflected irradiance for Singapore in February 2014 with respect to time.**



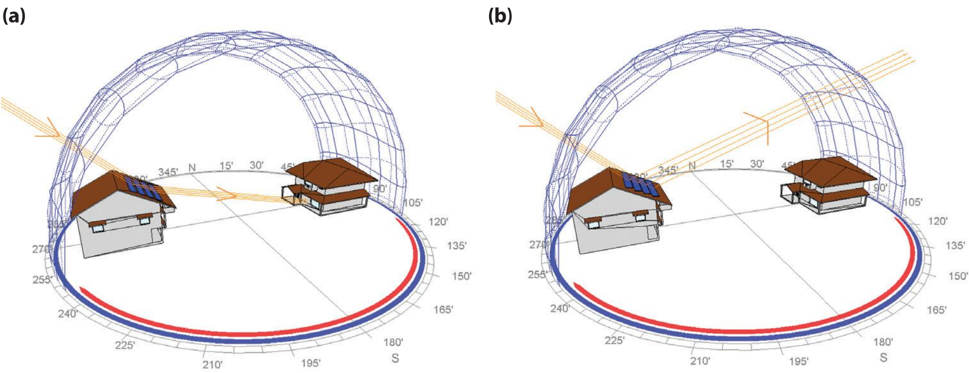
▲ **Figure 6. Variation in the reflected irradiance profile with module tilt angles and orientations.**



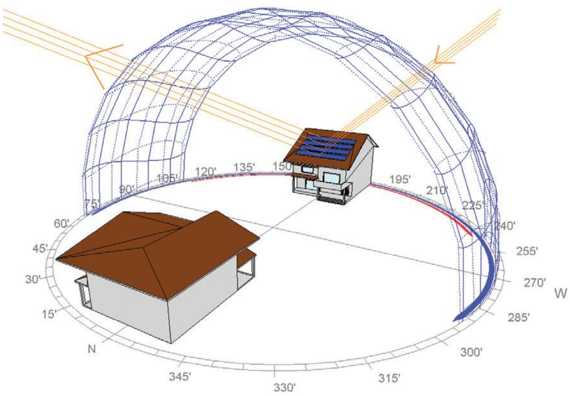
▲ **Figure 7. Model of a PV system tilted at 10° on a commercial/industrial building. The buildings are positioned in an east–west orientation at a distance of 25m. The PV system is installed in (a) an east–west orientation, and (b) a north–south orientation.**



▲ **Figure 8. Model of a PV system tilted at 10° on a commercial office building. The buildings are positioned in a north–south orientation to each other at a distance of 25m. The PV system is installed in (a) an east–west orientation, and (b) a north–south orientation.**



▲ **Figure 9. Model of a PV system on a private residential house: (a) system tilted at 25°, following the tilt angle of the pitched roof; (b) system tilted at 10° by adding mounting structures. The two houses are positioned in an east–west orientation to each other.**



◄ **Figure 10. Model of a PV system on a private residential house, where the system is tilted at 25°, following the tilt angle of the pitched roof. The two houses are positioned in a north–south orientation to each other.**

can then possibly result in visual discomfort. Nevertheless, from ~20° onwards, the yield of a PV system in Singapore starts to drop significantly; hence the vast majority of PV installations here will be tilted between 10 and 15°, to prevent both losing yield and reflecting too much irradiance. Since the issue of glare from a PV system becomes more prominent when the panels are installed at high tilt angles in an east–west orientation, the most straightforward way to mitigate the problem is through adjustments to the system design by changing the tilt angle and/or orientation of the PV panels. This is discussed further in the next section.

System design

Although it has already been established in the previous section that the maximum reflected irradiance increases with increasing tilt angles of the solar panels, it should be assessed in more detail under what circumstances this could cause glare. For that, it is important to visualise the effect of the reflected irradiance from a rooftop PV system onto the neighbouring buildings. Rooftop PV systems in Singapore are predominantly installed on two types of building: commercial/industrial buildings and private residential houses. Case studies for both types were therefore carried out using Ecotect software to simulate the paths of the incoming sunlight and the reflected light. For each type, a PV system was modelled on one of the buildings. The orientation and tilt angle of the solar panels were varied under different building orientations to investigate the effect of glare from the PV system on the respective neighbouring buildings.

> "Potential glare issues can be avoided by assessing the situation of neighbouring buildings during the system design stage and by taking proper measures to avoid glare in the first place"

Commercial/industrial buildings

In the installation of PV systems on

reinforced concrete (RC) rooftops, the solar panels are usually tilted bidirectionally in a wave-like manner. In other words, if one row of solar panels is tilted towards the east, the next row is tilted towards the west, and so forth.

When designing the orientation of a PV system on a commercial/industrial building, it is essential to know the relative orientation of its neighbouring buildings. In the worst-case scenario, when two buildings are positioned in an east–west orientation, which coincides with the sun path, then there is indeed a possibility that the nearby building will be subjected to a glare effect, depending on its height and the distance from the PV installation. One possible (and easy) solution would then be to tilt the solar panels away from the neighbouring building, possibly all the way to a north–south orientation. This may not always be possible, though, for slightly tilted metal roofs.

Fig. 7 shows a model in which a commercial/industrial building and an office building are positioned in an east–west orientation at a distance of 25m. It can be seen that if the solar panels are tilted at 10° in an east–west orientation, the reflected irradiance will hit a certain row of windows of the neighbouring building in the late afternoon, which might result in visual discomfort of the occupants of that building (Fig. 7(a)). Under such circumstances, it is advisable to tilt the solar panels away, for example in a north–south orientation. This would result in the incoming sunlight being reflected to a much higher location (above the office building), and therefore not dazzling the occupants of that neighbouring building (see Fig. 7(b)).

If the buildings are positioned in a north–south orientation, as shown in Fig. 8, the orientation of the solar panels does not matter, since the orientation of the buildings does not coincide with the sun path of the reflections from the PV system.

Finally, for vertically installed PV systems on the facade of a building, the glare effect is no worse than that of any glass curtain wall, which is commonly used in many buildings in Singapore.

Private residential buildings

In the case of the installation of PV systems on the pitched rooftops of private residential houses, other than the dependence of glare on the orientation of the houses, the tilt angle of the solar panels usually follows that of the pitched roof. As a result, some PV systems are tilted at 30–40°, which has two possible effects. First, as mentioned earlier, the overall irradiance received by the PV modules is lower because they will not be able to receive direct sunlight before or after a certain time of the day, depending on the orientation (the so-called 'internal shading' effect). Second, the maximum reflected irradiance will also be higher and could possibly increase the level of visual discomfort to neighbouring buildings (again, depending on the orientation).

Similarly to flat-roof or low-angle installations on commercial/industrial buildings, the potential glare effect is higher if the buildings are oriented east–west with respect to each other. In this case, if technically possible, it would be advisable to employ a smaller tilt angle for PV systems on the roofs of private residential houses. This can be achieved, for example, through special mounting structures to adjust the tilt angle downwards to ~10°; such a measure, however, may be subject to aesthetic considerations.

A model of two private residential houses in an east–west orientation is shown in Fig. 9. The pitched rooftop of the house on which the PV system is installed has a tilt angle of 25°, and hence the tilt angle of the solar panels is also 25°, as shown in Fig. 9(a). It can be seen that the reflected irradiance directly strikes the front window of the neighbouring house at 4:15pm for ~20min, which might result in a certain level of visual discomfort. This can be avoided, for example, by using mounting structures that decrease the tilt angle of the solar panels, as shown in Fig. 9(b). At a resulting lower tilt angle of 10°, the path of the reflected irradiance is well above the roof of the neighbouring house, thus eliminating the effect of glare.

Similarly to the case of commercial/industrial office buildings, if the private residential houses are positioned in a north–south orientation, then glare is not an issue, because the reflected light does not come into contact with the neighbouring house, as shown in Fig. 10.

Conclusion

It can be seen from this study that the reflectance of solar panels is ~10%, which falls within the same range as normal window glass and is significantly lower than Singapore BCA's reflectivity requirement for reflective surfaces on buildings (which is 20%). The vast majority of PV systems in Singapore have been, and will be, installed at tilt angles of around 10–15° in order to maximise the yield and to ensure regular 'automated' cleaning through rainfall.

In rare cases, however, it is possible that neighbouring buildings experience glare from PV systems during certain times of the day, depending on the actual tilt angle and the relative orientation of the two buildings. It has been demonstrated through calculation and modelling that such potential glare issues can be avoided by assessing the situation of neighbouring buildings during the system design stage and by taking proper measures to avoid glare in the first place.

The rule of thumb is to ensure a low tilt angle for the solar panels, in the range 10–15°, to minimise the reflectance. If the buildings are positioned in an east–west orientation, and if there is freedom to vary the system orientation, it is advisable to tilt the solar panels away from the neighbouring building, possibly all the way to a north–south orientation. In the case of any uncertainty, SERIS has the capability to carry out simulations to determine a site-specific possibility of the occurrence of glare. ■

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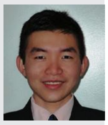

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