



Task 15 Enabling Framework for the Development of BIPV

SDP
2026

Glare Legislation and Assessment Methods for BIPV Modules and Systems

2026



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What is IEA PVPS Task 15?

The objective of Task 15 of the IEA Photovoltaic Power Systems Programme is to create an enabling framework to accelerate the penetration and deployment of BIPV products in the global market of renewable energies and in the construction sector, resulting in a level playing field for BIPV products, BAPV products, and conventional building envelope components, while addressing mandatory, aesthetic, reliability, and financial considerations.

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INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Glare Legislation and Assessment Methods for BIPV Modules and Systems

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LIST OF ABBREVIATIONS

IEA	International Energy Agency
PV	Photovoltaics
BIPV	Building-integrated photovoltaics
BAPV	Building applied photovoltaics
BRDF	Bi-directional reflectance distribution function
ARC	Anti-reflective coatings
CIE	International Commission on Illumination
UGR	Unified Glare Rating
DGP	Daylight Glare Probability
VCP	Visual Comfort Probability



EXECUTIVE SUMMARY

While photovoltaics (PV) represents the cheapest form of renewable energy in most places of the world and is a major driver in the green transition, PV Systems in urban environment or sensitive areas are sometimes facing pushback due to possible impacts on nearby people and property. One major aspect is glare caused by high intensity reflections of sunlight from PV modules, which can present significant obstacles both during the permitting and operational phases of PV systems. This is especially true in building-related contexts; however, glare also applies to utility-scale installations.

Unfortunately, regulations for outdoor glare from buildings consist of a “patchwork” of requirements that vary between, and often within, individual nations, with regulations dedicated to PV on buildings often missing entirely. Some instances can be found where glare studies are required in the building permitting process, particular for projects near critical infrastructure, such as airports, railways and highways more likely requiring glare analysis than other locations. In other instances, “nuisance” reflections are only assessed in court and have led in some cases to alteration or outright removal of PV installations.

However, glare risk of PV installations can also be mitigated, for example through modification of the front module surface or other interventions, though many post-installation modifications either negatively impact the yield and economics of a project, are difficult to execute or carry a high uncertainty regarding their long-term reliability. Therefore, preliminary glare analyses are advisable regardless of requirements, so that the most effective and least intensive mitigation measures can be applied.

This report provides an overview of selected glare regulations, both to support practitioners in navigating this “patchwork” in the short term, as well as to aid harmonization efforts in the long term. In addition, it provides a general overview of the topic and definition of terms as well as a summary of possible assessment and mitigation strategies.



1 INTRODUCTION

Photovoltaic (PV) energy generation capacity has seen significant expansion over the last two decades, with representation of both large commercial installations as well as smaller residential systems. Continued capacity expansion faces pushback in some countries, often driven by concerns regarding the use of agricultural land, aesthetics, and other effects on the surroundings. One persistent concern is the possible occurrence of glaring reflections, which may negatively affect the surrounding of PV installations. This is especially true for installations in urban areas and at or near transportation infrastructure, particularly airports.

Attempts have been made to regulate glare from PV installations mostly at national and regional levels, with little effort for harmonized regulations across, and often within, nations. This challenges PV manufacturers and installers, who must navigate a set of highly diverse, sometimes conflicting, and in many cases unclear requirements.

This report aims to provide a comprehensive overview of glare regulations throughout the world to form the basis for subsequent harmonization of regulations. It also provides a high-level overview of different glare assessment methods and mitigation strategies.

1.1 Definition of glare from PV modules and systems

Glare from PV modules and systems refers to reflections of sunlight, which can impair the vision of observers in the surrounding environment. Overstimulation of light receptors in the human eye can lead to distraction, reduced visual acuity, temporary flash blindness (after-imaging), or in rare cases, permanent damage. Though it is important to note that retinal damage is extremely unlikely from conventional photovoltaics – it is generally only a concern for concentrating solar thermal systems.

The International Commission on Illumination (CIE) defines glare as a “condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme luminance contrasts” [1]. Consequently, glare can be categorized non-exclusively as “disability glare”, which impairs the vision of objects [2] and/or “discomfort glare”, which causes discomfort [3].

For quantifying glare from light sources within building interiors, the Unified Glare Rating (UGR) has been established in the EN 12464-1 standard. The threshold limit (TL) metric is also commonly used when assessing glare from night-time road lighting (e.g. AS/NZS 4282). For the assessment of indoor glare in side-lit rooms, a Daylight Glare Probability (DGP) metric has been adopted in the EN 17037 standard.

However, none of these methods and metrics are suitable for assessing glare caused by reflective surfaces in outdoor environments [4]. Instead, most common approaches rely on limit values of measurable quantities to establish whether glare is taking place, albeit with a large spread of values being used by different tools and approaches.



1.1.1 Physical causes of glare

Reflection of light occurs at all optical interfaces between media with different refractive indices (describing how light propagates through a material). This is a fundamental natural phenomenon as described by the Fresnel equations: At normal incidence, the reflectance is proportional to the square of the relative difference in refractive indices. As the incidence angle increases, the reflectance becomes polarization-dependent, with s-polarized reflectance increasing monotonically, while p-polarized reflectance decreases to zero at the Brewster angle before increasing rapidly towards grazing incidence angles. The Fresnel reflections at a flat air-glass interface can be seen in Figure 1.

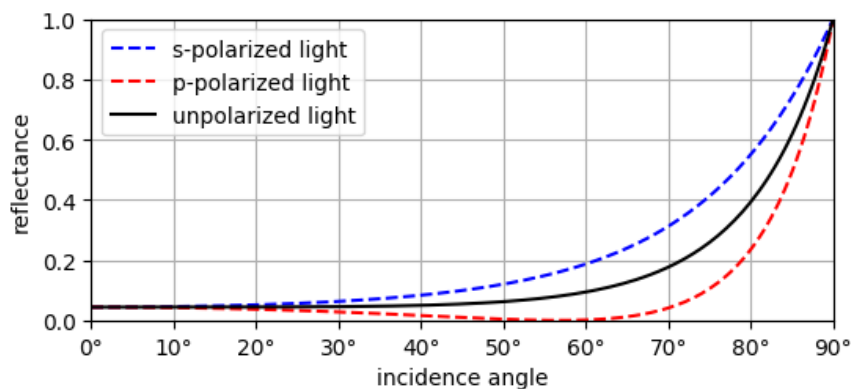


Figure 1: Fresnel reflections for an air-glass interface as a function of incidence angle

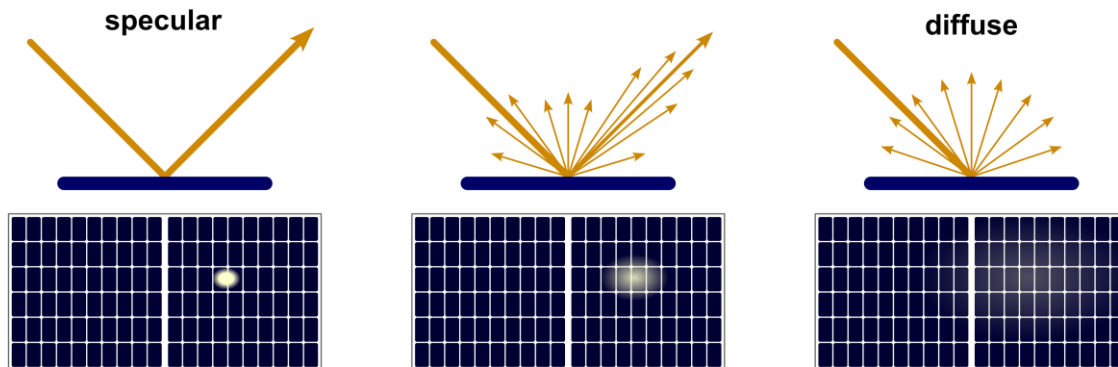


Figure 2: Different modes of reflection from PV modules, ranging from purely specular to completely diffuse. Most modules exhibit some degree of scattering (centre)

For smooth surfaces, the light maintains its collimation upon reflection, creating “specular” reflections at an angle of reflection equal to the angle of incidence (Snell’s Law). These specular reflections are generally the principal source of glare as they still retain a significant fraction of their original energy and travel in a single direction which can lead to viewers being suddenly exposed to the light. Conversely, textured surfaces (at scales significantly larger than the wavelength of light) scatter reflected light, spreading reflections over wider angular ranges, thereby reducing the intensity of light viewed from any given direction and thus the glare risk. Strong light scattering can lead to almost entirely diffuse reflections from surfaces, which pose limited risk of glare to a viewer. An overview of different reflection modes can be seen in Figure 2.



Cell-to-module loss analysis reveals that most light is reflected at the air-glass interface, with the glass-encapsulant and encapsulant-cell interfaces playing a less significant role. In some cases, however, reflections from metallic ribbons may be relevant as well.

Most standard PV modules consist of highly transparent, rolled low iron glass with an anti-reflective coating to maximize the amount of light reaching the solar cells [5]. This reduces primary reflections below that of unmodified air-glass interfaces (~4% at normal incidence). However, since most PV glasses are only textured to a light degree, if at all, reflections from PV modules are primarily specular. Different ways of mitigating the glare from PV modules and systems are presented in Chapter 4.

1.1.2 Glare categories and assessment

In general, the effects of glare can be categorized in three tiers:

- Retinal burn damage occurs at very high retinal irradiances and can lead to permanent loss of vision in affected areas. Glare from flat PV modules generally does not reach these levels.
- Flash blindness is the temporary bleaching of retinal pigments, which can take several seconds to recover from [6]. As the name suggests, this effect can be experienced from flash photography in a dark room, and can occur from PV reflections, though it is not very common.
- Discomfort and disability glare occurs at much lower irradiance levels and is a common occurrence with sunlight reflections from PV modules. Depending on the ambient conditions, angles, time of day and other factors, this may range from a minor annoyance to a major debilitating effect. However, factors unique to the viewer can also play a large role with these metrics due to the inherent subjectivity of “discomfort”.

Glare assessment is mainly carried out through a combination of reflectance measurements of PV modules and simulations to account for different sun positions and observer locations throughout a day and year. Based on this assessment, time periods where certain threshold values of reflected radiance are exceeded can be detected and evaluated. In many cases, minor occurrences of glare are deemed acceptable if they do not occur in too high frequency, whereas for other cases (i.e. affecting road and air traffic), all instances of glare must be prevented.

An overview of currently established assessment procedures as well as possible evaluation metrics and threshold values is given in chapter 3.

1.2 Impact of PV in the built environment

Solar glare from glazed and other reflective surfaces on buildings is an established issue, which has gained notoriety due to a limited number of drastic failures [7]. Both building-applied (BAPV) and building-integrated (BIPV) photovoltaic installations face similar issues due to the use of glass as front cover in most modules. This not only applies to façade-mounted systems, but also roof-mounted systems, which has led to glare risk being considered a possible obstacle for residential PV installations.

Legislation and regulations do not always treat PV and inactive building glass surfaces (i.e. windows or other reflective cladding materials) equivalently. Similarly, ground-mounted PV installations may be treated differently from systems which are applied or integrated into buildings. It is therefore essential to not only consider specific applications but rather investigate glare regulations in a holistic manner.



Figure 3: Glare caused by the glass façade of Universitätsbibliothek Freiburg, Germany (Source: Fraunhofer ISE/Janina Willmann)



2 LEGISLATION OF GLARE FROM PV SYSTEMS

The potential for glare from a photovoltaic (PV) system (or even just the belief that glare may occur) can mean that economically and energetically viable PV projects cannot be realized. There is no international standard so far to define the glare limits for PV modules for different installation types (especially for PV attached or integrated in buildings and/or infrastructure). In several countries, national regulations exist, in others they do not. Even within nations, there can be variation in the requirements at the state/province level or even at the county or municipal levels.

Given the lack of a harmonized guideline for glare measurement, several research and testing institutes have developed their own procedures. This makes it difficult to ascertain glare risks from specific products or specific installations prior to installation. Together with unclear regulations, this results in high uncertainty for PV installers, as the conformity of PV installations may only be verifiable through court cases long after installation, potentially leading to decommissioning of working systems [8].

The map below gives an overview of national regulations concerning glare from PV and BIPV installations collected in this report. Further details on each country are provided in the following sections.

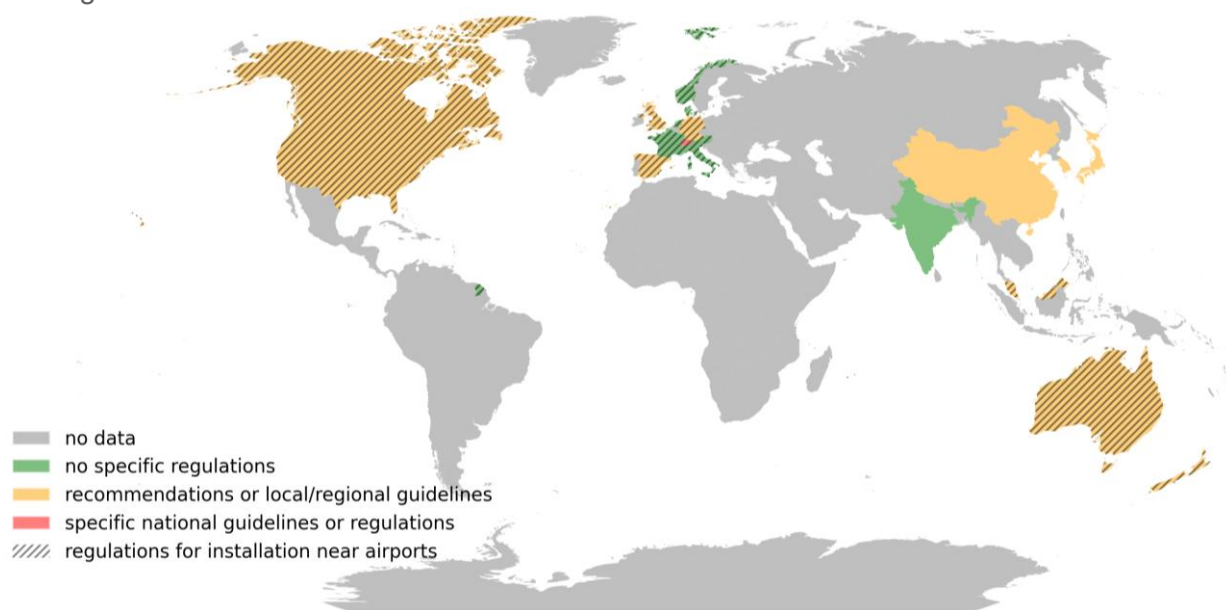


Figure 4: Overview of national regulations concerning glare from PV and BIPV

2.1 Europe

There are no general regulations for glare from PV installations on a pan-European or EU level, however many countries have implemented national, regional, or local regulations.

The only area of transnational regulations concerns itself with airports. At the European level, the EU regulation “Easy Access Rules for Aerodromes” [9] specifies that dazzle in the aerodrome vicinity can represent a risk and should be prevented. It specifically mentions solar panels, specifying a maximum acceptable luminance value of 20 000 cd/m², however without providing specifications of assessment methods [9].



2.1.1 Austria

In Austria, there are currently no active legal requirements and regulations for measuring and minimizing the glare effect of solar modules and no standardized building regulation that specifically addresses the issue of "glare from glass facades or building products in general." Thus, Austrian manufacturers and/or installers – due to the lack of their own national regulations – generally apply the Swiss or German regulations or guidelines to the Austrian market.

Glare from PV installations is generally considered an emission and can be objected to in court if it "exceeds the standard measure and impairs the customary use" of a neighbouring property. The Austrian Photovoltaics Association has published a short report outlining the legal framework for different kinds of PV installations [10], however it does not provide guidelines for assessment or limits.

Previously, a technical guideline published by the Austrian Electrotechnical Association [11] describing the glare regulations for PV systems was in force for 8 years and was repealed in December 2024. A successor is currently under development with the aim to harmonize glare assessment methods and requirements for both PV systems as well as other building materials.

The repealed guideline defined daily and annual glare duration thresholds, above which glare would represent a significant disturbance or hazard (see Table 1). The primary evaluation metric was the duration of glare events experienced by an affected observer (e.g., resident, driver, pilot).

Table 1: Glare duration limits as per OVE R11-3 (repealed)

Observer Type	Max. Daily Glare Duration	Max. Annual Glare Duration
Residential neighbours	30 minutes/day	30 hours/year
Road users (drivers)	0 minutes	0 hours
Air traffic / pilots / ATC	case-specific (risk analysis required)	No fixed value

Recently, a national research project has formulated measurement and assessment guidelines for evaluating glare from PV installations [12].

2.1.2 Denmark

In Denmark there is no specific legislation for glare and glare is regulated by a general practice of the courts that "annoyance" (where glare is one of the possible sources), should not exceed what is "reasonable or tolerable in the light of the general societal development" ("naboretlige tålegrænse"). Unless local regulations exist, annoyance from glare must be treated in a civil court case.

This limit is not quantified but relies on a specific evaluation case by case where a holistic assessment of the characteristics of the annoyance as well as the character of the neighbourhood and other relevant factors is done, via an audited professional. Certain professional auditors tend to adapt the UGR method for outdoor use as the best objective measure. As this is a general practice, no differentiation between PV modules and other building materials are made. Several court cases have established a practice for quantifying the tolerable level of glare, and court cases exists, where both glazed tiles and solar modules have been required to be removed.



Generally, glare is not tolerable when its (negatively) impacting the use of the property both inside and outside.

Municipalities have the power to make local regulations, which applies to specific neighbourhoods within a municipality, and these exist in many varieties ranging from limiting the reflectance or gloss values from building materials over soft phrasings like “shiny and reflective roofing materials cannot be used” to prohibiting special roofing materials such as glazed tiles – and these are generally not based on a scientific approach.

For utility scale PV plants, a simulation-based approach using e.g. Forge Solar is required to quantify the glare risk and is a part of a mandatory report that helps quantify the compensation to the surrounding neighbours. This report also includes assessment of noise and other annoyances.

2.1.3 France

In France there is no specific legislation concerning glare management. The only legislation in force came from the Directorate General of Civil Aviation (DGAC) and it is now considered to be non-blocking or at most consultative. While technical solutions must demonstrate a commitment to manage glare issues as effectively as possible, there is no obligation to achieve specific results if, for instance, there are no suitable products available.

A request to study visual impact remains mandatory for any building license and has to be performed before it is finally submitted. In the French building and housing code, there are no specific constraints concerning the risks of external glare. There is no specification of glare level, intensity or duration. The constraints are currently linked to users inside buildings to meet comfort requirements as detailed in the labour code. The aim is to manage lighting levels.

In addition, for any impact studies including the use of photovoltaic systems (mainly for ground-mounted structures or rooftop solutions) a guide has been published by the Ministry of Ecology [13]. It mentions solar glare as a possible impact, especially near airports, however without providing any guidelines for its assessment.

In the most recent technical information note (NIT) [14] published in October 2024 by the DGAC (version 6), specific glare constraints for photovoltaic solar power plants located within the “airport footprint” (an area roughly corresponding to the terminal manoeuvring area) or less than 2 km from an airport have been removed. In this last version, several recommendations are made, the note has been reorganized to make the instructions more readable, and the expectations for safety studies were revised. This simplification is intended to facilitate the integration of photovoltaics in sensitive areas while maintaining high aeronautical safety standards, including glare assessment.

This technical note concerns exclusively PV projects located within the corresponding area and whose total panel surface area is greater than 2500 m², unless it is located on a roof with a similar photovoltaic tilt inclination as the roof. For new projects within this restricted area, an online tool is offered as a web service [15] to assess potential glare risk. It is intended to ensure that the topic of glare is addressed sufficiently, however it is not used to determine project cancellation or rejection.

2.1.4 Germany

In Germany, no specific legislation concerning glaring reflections from PV modules exist, however several general regulations apply:



Light is considered an emission according to the German Federal Immission Protection Law (“Bundesimmissionschutzgesetz, BImSchG”), which applies to most technical facilities. Guidelines for the evaluation of light emissions have been published in the “Light Guideline” (“Licht-Leitlinie”) [16][17], of which Appendix 2 specifically addresses PV installations. They are applicable only to the “neighbourhood worthy of protection” relative to the location of light emission [17]. The guideline specifies that a PV system which causes glare for longer than 30 minutes per day or 30 hours per year is rated as an “appreciable disturbance” according to the BImSchG. For evaluation according to the Light Guideline, the assumptions made include the sun as a point source of light and an ideally reflecting PV module (i.e. following the law of reflection, “angle of reflection equals angle of incidence”).

There is no specific regulation for rack-mounted PV systems along Federal motorways or State roads in Germany. Instead, sometimes the Light Guideline is inappropriately applied also to the transport sector, although the regulation is not suited to these scenarios.

Recently the Working Group on PV Systems – Glare Effects and Glare Evaluation (“PV-Anlagen – Blendwirkung und Blendgutachten”), led by the German Federal Office for Long-Distance Roads (“Fernstraßen-Bundesamt”) has published a guideline specifying under which conditions a glare assessment has to be carried out, as well as establishing requirements for such assessments [18].

2.1.5 Italy

Italy does not have a single standard for glare regulation for PV or buildings, and BIPV is still rare. However, in civil law, glare is considered an “emission” (*immissione*), like smoke or noise, which must not exceed “normal tolerability” (*normale tollerabilità*) [19]. While there is no fixed definition of normal tolerability, in at least one case [20] a PV facility was ordered to adjust the panel tilt to eliminate glare impacts on a nearby home. Given this precedent, it is reasonable to assume that BIPV systems would be treated similarly.

It is common practice for utility scale PV to undertake glare studies as part of the environmental impact assessment process required by provincial, regional and/or municipal authorities. Various approaches are used, but they must include as assessment of nearby roads, residential buildings and railways.

The most complete glare requirements come from the Italian air safety authority’s (*Ente Nazionale Per L’Aviazione Civile, or ENAC*) report 2022/002-APT [21]. While this only applies to impacts on airport receptors, it does explicitly include a reference to BIPV (referred to a “PV Glass”) as a potential source of glare. The document summarises different qualitative and quantitative approaches for predicting glare, what (airport specific) analysis locations need to be studied, and the types of output data ENAC expects to receive. While the ForgeSolar tool is explicitly mentioned, the document notes that no specific software is required so long as “evidence of the calculation [methodology]” is provided.

The study is required to show the “...absence of persistent glare phenomena both for approaching pilots and for aircraft during take-off/taxing...” as well as “...the total absence of reflection in the direction of the control tower operators...”. The criteria for proving this varies depending on if qualitative or quantitative measures are used. Though the quantitative assessment criteria are similar to what was initially published by the United States Federal Aviation Administration (FAA) in 2013 (refer to section 0) but notably does not seem to include the FAA’s more recent guidance, since the ENAC still requires flight paths to be assessed.



2.1.6 The Netherlands

BIPV is part of a building and in the Netherlands, all building constructions have to follow the “Besluit bouwwerken leefomgeving” [22]. The new regulation started from January 1, 2024, and is the replacement of the Bouwbesluit 2012 (Buildings Decree 2012).

There is no regulation about glare from solar systems or glass facades. However, for nuisance to local residents, all relevant aspects must be considered in the context of good spatial planning and maintaining a good living environment. Reflection nuisance can be considered in this context. While several cases about hindrance from glare have been brought to court over the past 10 years, they have been largely unsuccessful.

Property owners are free to install solar modules on their own property without the need to apply for a building permit. In general, PV is widely accepted in the Netherlands, and many rooftop systems exist. The main concerns are large systems (ground based or floating) and systems along highways. In this context, guidelines for road users have been issued regarding light reflection from noise barriers along roads [23], [24].

Research has been carried out on glare assessment in several national projects, and reports on glare evaluations have been published by several consultancy agencies [23].

2.1.7 Norway

Norway’s national framework for managing glare and reflections between buildings derives from the Planning and Building Act (*Plan- og bygningsloven*, *PBL*) [25] and the Technical Regulations *Forskrift om tekniske krav til byggverk* (*Byggteknisk forskrift* - TEK17) [26] administered by *Direktoratet for byggkvalitet* which sets national requirements for the construction industry. TEK17 includes performance-based requirements for daylight, solar shading control, and indoor visual comfort (§14-1 through §14-3), and mandates assessments and documentation for façade design to mitigate reflective glare. However, it contains no explicit guideline governing glare or reflections from exterior building surfaces, including building-integrated photovoltaics (BIPV). The daylight requirements in section 13-7 focus on indoor illuminance and access to daylight. Consequently, glare from BIPV systems is not directly addressed in TEK17. While TEK17 doesn’t specify exact luminance thresholds, international best practices and standards, such as ISO 9211, Veiling Luminance, Daylight Glare Probability (DGP), and Visual Comfort Probability (VCP), are routinely referenced in Norwegian practice.

At the local level, municipalities like Oslo and Bergen implement these national provisions through their municipal master plans and detailed zoning regulations, enforced via building permits. Municipalities have the regulatory ability to evaluate and, where necessary, restrict glare-related effects. They require visual impact assessments, often including glare studies, during planning applications, with oversight from county governors under the Local Government Act (*kommuneloven*) to ensure legally compliant urban development. Under the *Plan- og bygningsloven*, all façade modifications, such as the installation of BIPV can be subject to the building application regime [25]. This act provides the legal basis for municipalities to assess whether highly reflective façades or strong solar reflections constitute an unacceptable nuisance or a visual or safety problem in each local context. Additionally, individual projects and façade engineers frequently use tools like DGP and veiling luminance, referencing guidance from international bodies (e.g., IES) to ensure compliance with both TEK17 mandates and emerging best-practice standards for façade materials and coatings. In practice, glare concerns linked to BIPV façades are therefore handled case by case during the building application or planning process, rather than through national regulations.



2.1.8 Spain

The reference document for buildings in Spain is the CTE (Código Técnico de la Edificación) [27]. The CTE does not specify glare requirements, although it does include some comments that may be relevant. One of its sections, DB HE 3 [28], refers to limiting glare from light sources by calculating Unified Glare Rating (UGR).

Apart from the CTE, there are specific regulations associated with different types of infrastructure, such as airports, roads, railways, maritime navigation areas, astronomical facilities, and telecommunications or radar installations. As they are more common, road, rail and airport traffic cases are discussed below.

For road traffic or railways, there is no 'single national law' that specifically regulates the glare; the matter is dealt with on a case-by-case basis by the relevant authority. The Road Demarcation Authority (Demarcación de Carreteras) require glare studies when there is a risk to national roads coming from utility-scale photovoltaic plants [29]. For regional or local roads, equivalent bodies may ask for glare analysis during the environmental assessment. In railways, regulations and technical specifications require visibility of signals and signalling criteria; therefore, any installation that may interfere (including glare from PV) is evaluated and a technical report or conditions under consideration could be requested [30]. There are technical standards on lighting and glare applicable to road infrastructure and lighting, which serve as the technical basis for requiring mitigation [31]. Therefore, in projects of a significant size close to this type of environment, it may be advisable to include a glare study. However, for small installations, this would generally not be necessary.

In the case of a nearby airport, restrictions may apply if the building is located within its zone of influence. Here, AESA (Agencia Estatal de Seguridad Aérea) is responsible for granting authorisation for any construction or modification. Recently, AESA has exempted photovoltaic installations smaller than 100 m² dedicated to self-consumption from the requirement to apply for any type of permit [32]. For larger installations, AESA could require glare analysis simulations, alignment of the panels with respect to approach procedures, and analysis of the impact on navigation aid systems (ILS, VOR, radar). This is based on different laws, which state that any installation that could represent an obstacle to air navigation or affect the safety of airport operations must be assessed and, where appropriate, authorised by the AESA [33], [34]. This includes installations that could generate glare that interferes with flight operations.

2.1.9 Switzerland

In Switzerland, there are specific guidelines and regulations to minimize glare from PV installations. These guidelines are intended to balance the need for solar energy with the protection of public safety and comfort.

PV systems installed on roofs in buildings and agricultural zones do not require a building permit if they are deemed "sufficiently adapted." Instead, they must be reported to the appropriate authority [35]. To meet the criteria for being sufficiently adapted, the PV systems must be constructed with low reflection in accordance with industry standards [36]. It is important to note that simply reporting on the installation does not exempt the owner from adhering to the Environmental Protection Act and other relevant laws.

According to case law, sunlight reflections from PV systems are considered impacts under the Environmental Protection Act. To prevent these impacts, measures must be taken at the source to limit them through emission-reducing techniques that are technically feasible, operationally practical, and economically reasonable [37]. This means that there is a legal



requirement to minimize even minor sunlight reflections with appropriate actions, such as adjusting the system size, altering the mounting, modifying the module surface, or using visual barriers like planting trees. If the reflections are deemed to be harmful or bothersome, stricter emission limits will be enforced under the Environmental Protection Act.

Assessing the harmfulness or nuisance of light emissions must be done on a case-by-case basis according to the Environmental Protection Act. Unlike noise and air pollution, there are no specific limit values for light rays. The key factor is whether the light emissions cause a significant disturbance to well-being. The duration and intensity of the light reflections play a crucial role in this assessment, and input from experts and specialized organizations can also be considered. The Federal Office for the Environment (BAFU) proposes different assessment procedures for glare from reflections, ranging from simple site assessment up to the determination of luminance values at different times [36]. It does not provide specific threshold values on light emissions in their implementation guide due to a lack of empirical evidence.

However, EnergieSchweiz, in collaboration with Swissolar, has published a non-binding but practical guide with recommendations [35]. According to these recommendations, sunlight reflections from PV systems in residential areas should not exceed certain guideline values in terms of glare duration:

- maximum 30 minutes of glare duration per day on any number of days per year;
- maximum 60 minutes of glare duration per day on a maximum of 60 days per year;
- maximum 120 minutes of glare duration per day on a maximum of 20 days per year;
- maximum 60 hours of glare per year.

For these considerations, reflections are considered to be at risk of causing glare when the luminance of the reflective surface is higher than 50 000 cd/m² and certain geometric conditions are fulfilled. It is further noted that a reduction of this luminance threshold is likely in the future [35], with a follow-up report proposing a dynamic limit depending on incident angle [38]. Individual court decisions may assume different thresholds for permissible glare durations, with 20 – 30 minutes per day typically being considered acceptable [36].

Additional restrictions are in place concerning glare at or near airports where the Swiss Federal Office of Civil Aviation (FOCA) is concerned, requiring careful planning of solar projects near airports to ensure that glare does not interfere with aircraft operations.

2.1.10 United Kingdom

For new building construction in the United Kingdom reflected glare (or 'dazzle' as it's referred to) needs to be considered under BS209 as part of the standard building planning process. However, specific methodology and criteria are not included, and analysis may not be required for all buildings. Generally, studies are only required for particularly large projects, or those adjacent to major motorways and railways. Generally, the veiling luminance metric is used to define visual glare risk with a threshold value of 500 cd/m² per Hassall [39]. However, no limits are defined for how much glare is too much. The City of London has produced two "Planning Action Notes" indicating that both the visual and thermal impacts of reflected sunlight should be investigated with criteria only set for the maximum permissible thermal intensity.

Specific glare regulations for PV systems only exist in the realm of impacts to airport and pilots. No formal criteria exist from the UK's Civil Aviation Authority (CAA) and thus several approaches ranging from simple geometric arguments to the use of ForgeSolar's GlareGauge tool.



That said, as discussed above, rules do exist that require glare from buildings to be analysed during the planning process, particularly for buildings near rail ways. PV elements (building integrated or otherwise) would generally be expected to be included in such studies.

2.2 Asia and Oceania

Many cities in the Asia-Pacific region also require glare studies to be conducted for new buildings to protect those in adjacent buildings and in public spaces. Singapore and Kuala Lumpur require the use of the Daylight Glare Potential (DGP) metric to define glare, whereas in Australia an approach similar to the UK is used. In all cases, there are no thresholds that define how much glare is “too much”.

2.2.1 Australia

Australia’s national aviation authority (like many nations) defaults to following the same guidance as the American FAA for PV projects which may impact airport or pilots. Outside of this some states include additional measures.

The New South Wales Department of Planning and Environment’s Large scale Solar Energy Guideline [40] provides a high-level methodology and criteria for assessing glare from utility scale PV projects. It also sets acceptability thresholds for how often glare is possible which are the same as those used for shadow flicker from wind turbines.

The state of Victoria also provides a methodology for utility scale PV [41] but does not include a threshold for the duration of glare that is problematic.

Queensland’s guidance for PV farms [42] mentions that glare assessments should be done, but does not provide a methodology or criteria.

As mentioned above, many states and cities also have requirements to study glare from buildings in general, though there is no single nation-wide regulation. PV systems would typically need to be included in any such assessments.

Sydney’s Design Control Plan [43] prohibits materials with a “light reflectivity” of above 20% but also notes that a reflectivity study “may be required” for tall buildings. No methodology or criteria is stated but general practice is to predict the veiling luminance and ensure it is below 500 cd/m².

Most other major cities have similar requirements, with the city of Parramatta being the only one that also includes a thermal impact requirement. (No reflections exceeding 1000 W/m² in intensity).

2.2.2 China

In China, there are no specific regulations for glare from PV systems. However, there are some regulations for glare from glass curtain walls. If the BIPV modules are mounted on the façade and defined as part of the glass curtain wall, they should also comply with these regulations.

According to the mandatory national standard GB 55016-2021 General code for building environment [44], article 3.2.8, the control of glare from glass curtain walls focuses on projects near residential buildings, hospitals, schools, main road intersections and areas with heavy traffic flow. For these projects, an analysis of the impact of reflected light from the glass curtain walls shall be conducted. The specific requirements of the analysis are as follows:



- In places where people work or stay for a long time, the continuous retention time of reflected light from the glass curtain walls on their windowsills shall not exceed 30 minutes;
- Within a driving distance of 100m, at a vertical angle of 20° and a horizontal angle of $\pm 30^\circ$ in the driver's forward direction, the glass curtain wall shall not cause continuous harmful reflected light to motor vehicle drivers.

There's also a recommended national standard GB/T 18091-2015 Optical and thermal performance of glass curtain wall [45]. It requires as follows:

- Glass curtain walls shall adopt glass with a visible light reflectance no greater than 0.30.
- For glass curtain walls on buildings within 20m on both sides of urban expressways, main roads, overpasses, and viaducts, and within 10m on ordinary road sections, glass with a visible light reflectance no greater than 0.16 shall be adopted.

In some cities, there are also local standards that give more detailed provisions. For example, the Shanghai Municipal Bureau of Ecology and Environment has put forward very detailed requirements regarding the analysis of the impact of reflected light from the glass curtain walls [46].

2.2.3 India

Glare regulations pertaining to the PV installations and Building Integrated Photovoltaics (BIPV) are not known to exist in Indian context yet. A new regulation is currently being developed and expected to be published soon.

2.2.4 Japan

In Japan, there are no regulations in laws such as the Building Code that regulate reflected light (glare) from buildings. While glare is not regulated in building-related laws and regulations, it is mentioned in guidelines regarding solar power generation issued by various government ministries and local governments [47].

While solar power plants of 30 MW or more must comply with the Environmental Impact Assessment Act, the guidelines are also intended for smaller facilities. Specifically, they encourage voluntary environmental measures for solar power generation facilities of 10 kW or more that are not otherwise subject to the Act or local ordinances. The goal is to ensure that power generation companies are aware of environmental issues, including glare, during the site consideration and design stages for these smaller installations.

The Ministry of the Environment established the "Environmental Consideration Guidelines for Photovoltaic Power Generation" in 2020, and Chapter 4 of those guidelines addresses the impact of reflected light. This section addresses the impact of large-scale solar power plants (more than 1 MW capacity) on surrounding buildings, airports, roads, and other facilities. Essentially, glare shall be evaluated through calculations and simulations, though no specific methods are specified, and if there is a direct impact, the guidelines recommend the following measures:

1. Adjust the orientation of the PV array
2. Adjust the placement of the PV array
3. Use anti-glare cover glass of solar power generation modules
4. Block the reflected light (glare) with fences or plantings.



The Agency for Natural Resources and Energy has been formulating its "Photovoltaic Power Generation Business Planning Guidelines" since 2017 [48], which address the impact of reflected light (glare) as part of environmental surveys and consideration for the surrounding environment.

To address reflected light (glare), the angle of the reflected light from the solar cell module should be calculated to ensure that it does not negatively affect surrounding residential areas. Depending on the situation, it may be necessary to consider design changes or the use of anti-glare modules. For specific design information, it has recommended that guidelines created by private organizations be used as a reference.

Among the guidelines created by private organizations is "Preventing Problems with Reflected Light in Solar Power Generation Systems," which was formulated by the Japan Photovoltaic Energy Association in 2010 [3]. The content of this guideline is aimed at rooftop-mounted solar power generation systems, not wall-mounted solar power generation systems. As such, it is applicable for rooftop installations such as Categories A and B according to IEC 63092-1 [49], however, when it comes to vertical installations such as Categories C, D, and E, specific guidelines have not yet been established.

In addition, various local governments have also provided guidelines for reflected light, but the content is generally similar and focuses on rooftop solar power generation.

2.2.5 Malaysia

The Civil Aviation Authority of Malaysia (CAAM) defaults to following the same guidance as the American FAA for PV projects which may impact airports or pilots.

The city of Kuala Lumpur has recently introduced a recommendation (but notably, not a requirement) to study the potential for glare in new buildings from their surroundings [50]. No specific methodologies or metrics are noted. These are not specific to PV, but PV would presumably be required to be studied.

2.2.6 New Zealand

The regulation of glare is generally the same in New Zealand as what is seen in Australia with individual cities (primarily Auckland) placing requirements for glare analysis on new buildings. PV systems on buildings would presumably need to be included.

2.2.7 Republic of Korea

In Korea, there are no specific legal regulations or quantified standards for glare caused by photovoltaic (PV) systems and in general disturbances like glare from any surface should not exceed the "socially acceptable tolerance", and disputes are treated in civil court cases. However, some local governments have published recommendations which consider glare effects when installing PV systems.

For example, the Seoul Metropolitan Government recommends using matte materials that minimize light reflection when installing PV systems on public facilities [51] and recommends installing PV-systems of the upper surface of subway entrances, to avoid user glare and visual obstruction. When installing PV systems on retaining walls along roadsides, there are also general recommendations to consider the potential glare affecting drivers and road safety [51].

In addition, in December 2023, the Seoul Metropolitan Government introduced the "2023 Seoul Glass Curtain Wall Guideline" [52] to address the problems associated with glass curtain wall buildings. Although the guideline is not legally binding, it serves as a reference for planning



such buildings within Seoul. In this guideline a solar mitigation strategy was published for both curtain walls and PV modules mounted on exterior walls, which can be applied for almost all buildings.

According to the guideline, a Reflection Area Boundary (refer to section 3.1.1) must be created to visualize the glare affected from sunlight from sunrise to sunset on the spring equinox, autumn equinox, summer solstice, and winter solstice. Subsequently, mitigation plans must be established for any affected façades of nearby residential buildings expected to receive reflected sunlight if the maximum luminance exceeds 25,000 cd/m². These can include the avoidance of highly reflective materials or the use of shading devices.

Legal disputes have mostly focused on reflections from architectural surfaces rather than PV systems themselves and as of now, there have been no cases where glare from PV systems has been legally recognized as damage. Solar-reflection nuisance is principally assessed on whether the disturbance exceeds the "socially acceptable tolerance", referring to 25,000 cd/m² (the disability-glare threshold) and exposure duration. Because reflected light is an active intrusion arising from artificial façades, it is distinguished from daylight and is evaluated holistically. Primary focus is put on luminance and duration of ingress into main living spaces. In determining socially acceptable tolerance, courts consider the following aspects [53]:

- Intensity, angle, timing, and duration of incoming solar reflection
- Local area and environment considerations
- Compliance with public law regulations (e.g., building codes)
- Zoning, land use, and surrounding environment
- Existence of mitigation measures and possibility of avoiding damage

2.2.8 Singapore

Singapore does not have glare regulations specifically for PV or BIPV installations. However, the Building Control Regulations [54] specify a limit on reflectance of materials on building exteriors. Section P on daylight reflectance requires that "any reflection of sunlight off the external surface of the building does not result in a loss of amenity to occupants of other buildings in the vicinity" [54].

The guideline [55] specifies a methodology and requires the use of the DGP metric to predict glare potential, but does not specify what frequency/duration of glare is problematic

For installations affecting military sites and/or airports, glare analysis simulations have to be carried out to prove the absence of glare risk.

2.3 Americas

Generally, in North America there is little legal framework for glare from reflected sunlight, only for artificial light sources at night (e.g. from road lights, illuminated signs, etc.). In some places there are state-level (California) or city-level (Boston, Toronto) requirements for building developers to conduct a 'glare study' but there is little guidance on the level of detail required or criteria that need to be met. As such, the level of detail can range from simple letters of opinion from architects to highly detailed specialist studies focusing on the risks to vehicle drivers.

The exception to this would be PV or, more rarely, reflective buildings in proximity to airports which need to comply with the requirements of the United States Federal Aviation Administration (FAA) with respect to glare risk to Air Traffic Control Towers [56]. This guidance is also generally applied in Canada and elsewhere. Many jurisdictions in both countries also



require similar analyses to be undertaken for utility scale PV to assess the risk of glare to homes and drivers as well.

2.3.1 Canada

For PV projects near airports and helipads, Canada follows the same FAA requirements as discussed below for the United States. Outside of this, the regulator environment varies by province.

The province of Alberta currently has the most robust set of regulations, though only for utility scale PV. The Alberta Utility Commission's "Rule 007" [57] implies the use of the GlareGauge tool to assess glare potential for roads, dwellings and airports. Historically specific limits on glare were not set, however as of November 6, 2025, updated requirements are enforced. These requirements set "critical" and "conservative" fields of view for different receptor types (dwellings, local roads, highways, etc.) including air traffic control towers, flight paths and runways. For routes, yellow glare of any duration is not permissible within the critical field of view. No more than 30 minutes per day and 30 minutes per year of yellow glare is permissible within the conservative field of view. No glare is permitted on air traffic control towers within 4 km and the same 30 minute per day, 30 hours per year requirement is applied to dwellings within 800m.

Alberta Transportation sets separate requirements [58] for major/minor highways and rail lines which specifies that "no glare" in a driver's "inner field of view ($\pm 15^\circ$)". It is not made clear if this refers only to yellow glare, or green as well, but generally green glare is seen as a lower concern.

Also of note is that "sun masking" (i.e. when the sun is also in an observer's field of view and thus "masks" the impact of the much dimmer reflection) may be considered as a mitigating factor in Rule 007 analyses.

Given that the updated Rule 007 has only very recently come into force, it is not clear how the discrepancy between the requirements of Alberta Transportation requirements and those of Rule 007 are to be handled. However, it is likely that the more conservative Rule 007 requirements may take precedence. Similarly, it is unclear how the difference between Alberta's requirements at airports and existing practice will be handled, particularly as airports are regulated federally.

Other provinces and territories generally do not have specific requirements beyond that a study be done for utility scale PV, and glare studies at the building level are generally not required at the building permitting stages, unless specifically requested by the municipality.

2.3.2 United States

PV systems on federally obligated airport lands fall under the jurisdiction of the United States Federal Aviation Administration (FAA). After an incident involving rooftop PV at a small airport, Interim Policy 78 FR 63276 [59] was published. This policy required the use of a methodology first published by Ho et. Al. in 2011 [60]. This methodology was most easily conducted using the web-based 'Solar Glare Hazard Analysis Tool' (SGHAT) which at the time was made freely available by Sandia National Laboratories.

Since that time, the SGHAT tool was spun off into a commercial version. Now referred to as 'GlareGauge' it is actively developed by ForgeSolar, a spin-off company from Sandia.

As of 2021 the FAA has amended its guidance [56] which now permits other methods of glare assessment and limits the view locations that need assessment to only air traffic control towers



(ATCTs), as opposed to the approach and departure paths which were previously required. This document explicitly states that “no ocular impact” is allowable on air-traffic control cabs.

This document also explicitly says that it does not apply to airports without an ATCT or those that are not federally obligated, nor does it apply to PV systems off airport lands. However, proponents are “encouraged to consider ocular impacts” if close to airports even if the policy is not strictly applicable.

Similar to Canada, outside of an airport context, glare from utility scale PV is regulated in the United States in a range of ways and generally at the county level (if at all). Common practice is to analyse roads, nearby homes and other sensitive receptors using GlareGauge. Though strict criteria on what is or is not acceptable is generally not available.

At the building scale, regulations are generally set at the municipal level. Some examples include:

- The city of Boston requires solar glare studies to be done as part of the “Article 80” planning process for large buildings [61], though it does not specify how they should be done or provide any acceptability criteria. PV on a building is generally included in such studies, particularly given how close approach/departure paths from Logan International Airport are to buildings in Boston.
- Seattle’s Municipal Code 23.47A.022E [62] also requires that “glare diagrams” are required to identify adverse glare from buildings on residential areas and arterial roads if more than 30% of a façade is composed of clear or tinted glass. While the outer surface of a PV panel is generally glass and thus presumably should be included. It is unclear if this is the stance shared by the city.
- The city of Temecula, California requires all ground mounted-residential PV projects to conduct a glare study before approval. Though it does not include a description of the required level of detail, or acceptability criteria.
- The only state level ‘requirement’ for building glare studies is found in the California Environmental Quality Act (CEQA) [63] which requires an assessment of the potential for new adverse glare from a building project. Though again requirements for the methodology and quantitative significance criteria are not included though counties or cities are permitted to add elements so long as they are more stringent than when is specified in CEQA.



3 GLARE ASSESSMENT AND SIMULATION METHODS

3.1 Site-specific glare modelling

In order to predict the glare impact from a specific installation on its environment, a simulation of the sun path and the resulting reflection locations is necessary. A number of both commercial and free tools is available that can predict glare from PV installations. These tools range in complexity from geometric analyses with simplified approximations of the PV modules and physics – all the way to highly detailed simulations that account for specific material properties and rigorous representations of the physics of reflected light.

The following is a non-exhaustive overview of glare risk simulation tools:

3.1.1 Geometric Tools

Modern parametric 3D modelling software used for building design (Grasshopper for Rhino, Dynamo for Revit, etc.) can leverage analytic geometry techniques to estimate where reflections from defined surfaces can reach, mostly assuming specular reflections. These techniques are generally quite fast, but they are often limited in their ability to model specific reflection physics (e.g. scattering) and generally are not able to predict the actual intensity of the reflections. This can limit the usefulness of such techniques to early-stage assessments, such as to rule out locations where reflection glare is not physically possible. As such, these tools can be used to determine a reflection area boundary, specifying which locations have to be evaluated in a more detailed analysis, as shown in Figure 5.

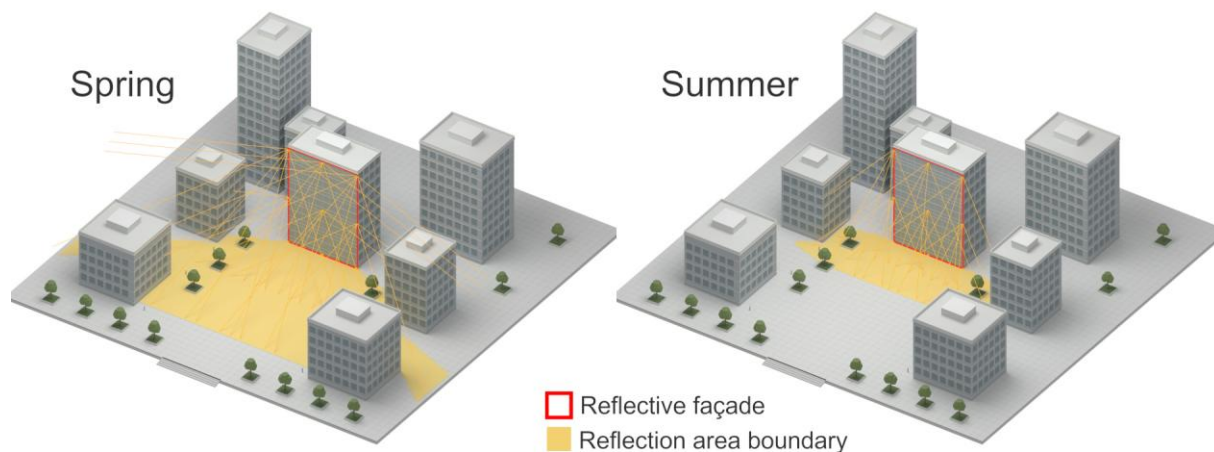


Figure 5: Example illustration of the reflection area boundary determined for different times of the year

ForgeSolar's GlareGauge is derived from the Solar Glare Hazard Analysis Tool originally developed at Sandia National Laboratories [60]. This methodology is a simplified geometric analysis that is highly tailored to studies of reflections from PV. Reflections are treated as mostly specular, with some scattering. It includes a small selection of PV types with different reflectances. The tool is capable of not only evaluating individual observer locations, but observer trajectories, such as flight paths or roads. Though it has limited ability to model obstructions and topography and some assumptions are highly conservative.

Blendtool is a free online glare evaluation tool published by the Canton of Bern, based on Swissolar guidelines [64]. It uses simple geometric calculations with bundle expansion to



detect locations of potential glare occurrence. Shading, incidence angle limitations and glare intensity are however not modelled and need to be accounted for by the users themselves.

3.1.2 Physics-based Tools

Radiance (<https://www.radiance-online.org/>) is a physics-based lighting simulation tool that rigorously represents the physics of how light travels within a scene including scattering and reflection and more detailed sky and atmospheric models. Historically it required significant expertise to develop a sufficiently accurate 3D model of the view scene to be studied, implement the material properties appropriately and then post process and interpret the results correctly. More recently, plugins such as ClimateStudio have simplified the process though expertise is still required in terms of setting up and interpreting the simulations, particularly given the lack of consensus around the metrics to be used.

3.1.3 Other

Numerous in-house tools have also been developed by researchers (TÜV Rheinland, TNO, etc) as well as specialist consultants (RWDI, Zehendorfer Engineering, etc) that fall within the spectrum of tools described above.

Physical measurements of glare impacts are also possible using specialized equipment (luminance meters, illuminance meters, calibrated HDR photography, etc.) though this can be challenging to properly assess due to the highly localized nature of glare impacts, the potentially limited dates and times when glare can occur and the impact of cloud cover. This also, by definition, implies that a problem has already occurred which should have been avoided. Thus, proactive assessment using simulation tools is considered good practice.

Regardless of the approach taken, care is needed by whomever is undertaking the analysis. Solar reflections are a nuanced and complex phenomenon to study and their impact on people and property can be dependent on a range of other factors, including highly variable personal factors (biases, preferences and physiology, etc.). This subjectivity combined with the lack of consensus on methodology and thresholds makes expert interpretation important to avoid both negative impacts to the surrounds and overly onerous mitigation.

3.2 Surface reflectivity characterization

The most critical parameters for accurate glare assessments of PV systems are the reflective properties of the installed modules. While some software solutions assume perfectly flat surfaces with purely specular reflections, scattering of reflected light can play an important role. As many PV modules use rolled glass and feature anti-reflective coatings, their impact on the optical reflectivity has to be considered as well.

3.2.1 Total reflectance measurements

Understanding the overall (i.e. specular and diffuse) reflectance of materials is somewhat common in the context of building cladding due to increasing awareness of the urban heat island effect and the focus on “cool” building materials. The ASTM provides standardized methodologies for calculating total reflectance both in the field (ASTM-E1918, ASTM-C1549) and in a laboratory setting (ASTM-E903). However, these measurements generally focus only on near-normal reflectance and do not distinguish between what is reflected specularly and the diffused reflected light. This limits its applicability for glare studies since understanding the reflectivity at multiple incidence angles and the specular component in particular, is paramount. Further, these tests are generally only applicable for homogeneous materials (as explicitly



noted in ASTM-E903). Using this approach with a PV module will be problematic as a measurement taken directly over a cell will be different from an area between cells, on the frame, etc. Care is also needed as various solar spectra could be used as inputs. Since glare is only a function of the amount of *visible* light that is reflected, using a wider spectrum as an input could yield misleading results.

Another common “reflectance” metric is the Solar Reflectance Index (SRI). This is a common metric used in green building standards. SRI measures a material's ability to reject solar heat, rather than absorb it, when exposed to direct sunlight. However, despite its name, SRI is *not* a reflectance measurement. It is a calculated quantity that includes a material's total reflectivity *and* its thermal emittance (emissivity), which is then compared against a reference white material (80% total reflectance, 0.9 emittance, SRI of 100) and a reference black surface (5% total reflectance, 0.9 emittance, SRI of 0). This makes values outside of that range possible. (Further details can be found in ASTM-E1980.) As SRI entangles thermal emissivity with reflectance, is expressed using a relative scale, and suffers from the same shortcomings as the standard total reflectance, it would not be appropriate to use as an input to glare simulations.

3.2.2 Gloss measurements

The Gloss Number is a common parameter in the paint and metal industry to quantify how matte or glossy a surface appears to a viewer. ISO-7668 and ISO-2813 provide further details of how this is measured for metals and paints respectively, but in short, a gloss number represents how reflective an object is for light of a specific wavelength at a specific angle of incidence as compared to a reference object (typically black glass with a refractive index of 1.567). It is presented as a whole number with a value of 0 indicating light was entirely absorbed/scattered and a value of 100 indicating the object is as reflective as the reference. Values above 100 are also possible. The angle at which the measurements are taken depends on the material. Highly glossy surfaces are measured at lower (i.e. Near-perpendicular) angles of incidence and matte surfaces are measured at higher angles.

At first glance, gloss numbers appear useful since they are measuring the “brightness” of the specular component of the visible reflected light. However, it is important to remember that like SRI, the gloss number values are *relative* to a reference sample. Thus, they cannot be used as a direct analogue for reflectivity. While ISO-7668 does include information regarding how specular reflectance can be computed, the non-homogenous nature of a PV module complicates the measurement process similar to the measurement approaches discussed above.

3.2.3 Goniometric measurements (directional)

A comprehensive evaluation of the directional reflections of materials requires measurements with a goniometer, allowing the determination of reflections in arbitrary directions for varying incidence angles. These goniometric measurements allow for the determination of a bi-directional reflectance distribution function (BRDF), describing the complex relationship between incidence and observation angles and reflection intensities.

A variety of goniophotometric measurement systems exist, however they are typically very specialized tools, and not all are suited for all kinds of glass surfaces. In any case, these measurements are time intensive and complex to analyse and interpret, which has prevented their wider adoption. In addition, there are currently no standards or guidelines for BRDF measurements, especially when it comes to glazed surfaces.



3.3 Glare threshold levels

Another important consideration for glare assessment studies is the threshold of reflected light to be considered sufficient to cause glare. At the moment there is no scientific or regulatory consensus on suitable limit values, though several studies have investigated this matter.

3.3.1 Physiological limits

From a physiological standpoint, the damaging effect of high irradiance on the retina can be categorized according to threshold values. At retinal irradiances of 100-400 kW/m², retinal burn damage can start to occur, leading to permanent loss of vision in the affected areas. However, this retinal irradiance is influenced by ocular optics and thus represents a much lower irradiance outside of the eye. Depending on pupil dilation and the size of the source, this is approximately equivalent to an in-plane solar irradiance of 1.3-5 kW/m² [6].

Flash blindness (a temporary bleaching of retinal pigments, which can take several seconds to recover from) can already occur at irradiances as low as 1-10 W/m², or retinal irradiances of 0.1-1 kW/m² [6].

Discomfort and disability glare may occur at significantly lower levels. However, this is subject to many contributing factors, including individual bias. Average discomfort glare thresholds of 5.2-4.7 logT_d (Troland, a unit for conventional retinal illuminance) have been reported in one specific study, which equates to approximately 1.5-4.8 W/m² retinal irradiance, equivalent to an in-plane irradiance of 20-60 mW/m² [65]. Background lighting and adaptation plays a significant role, however, resulting in likely higher thresholds in sunny conditions outdoors.

3.3.2 Measurement approaches and units

The conversion of these physiological limits into measurable quantities can be challenging as well, which has led to a mix of parameters and units in use:

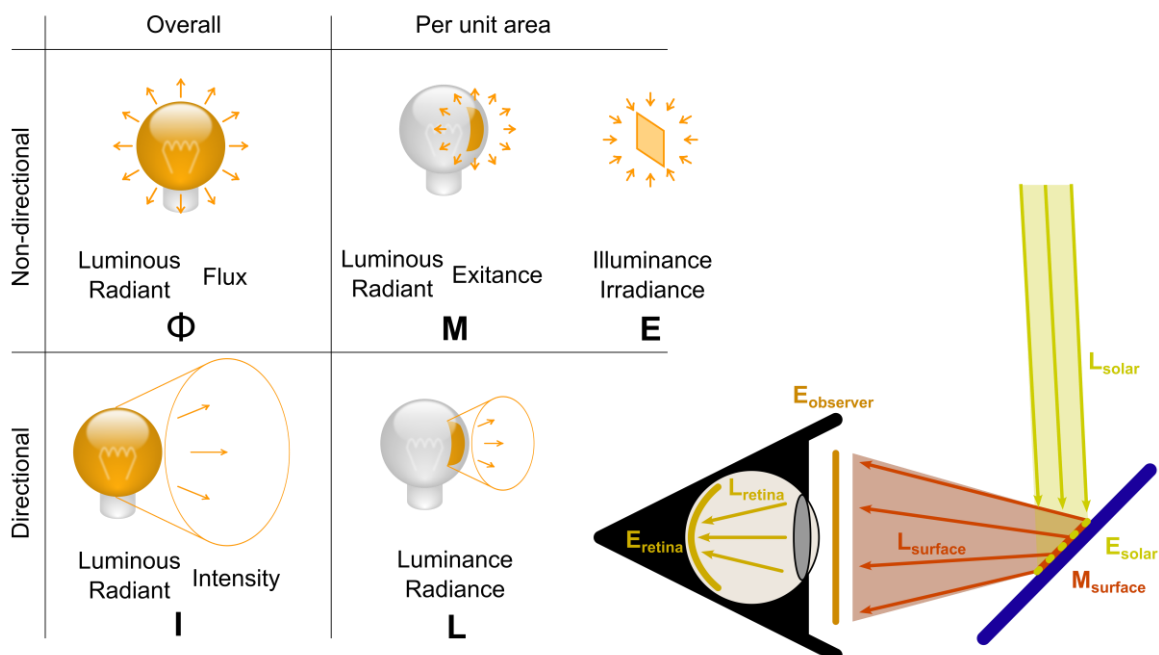


Figure 6: Parameters and quantities used to describe reflections and glare including ocular geometries (adapted from work by Cmglee https://commons.wikimedia.org/wiki/File:Photometry_radiometry_units.svg)



While radiometric power is responsible for energetic damage to retinal cells, perceived brightness is more commonly described through photometric quantities, relating the radiant power with the luminosity response of the human eye (i.e. “brightness”). Both radiometric and photometric units also distinguish between the energy/light leaving an emitter (radiance/luminance) and the energy/light falling onto a receiver (irradiance/illuminance). Figure 6 gives an overview of the different radiometric and photometric quantities useful in describing reflections and glare. Note that radiance/luminance can include light/energy that is reflected by an object and/or the light it may create.

Irradiance is most commonly expressed in watts per square meter (W/m^2) and its photometric counterpart is the lumen per square meter (lm/m^2), or more commonly, the lux. For the spectral distribution of sunlight (AM 1.5), the conversion factor from W/m^2 to lux is approximately 685.

Radiance and luminance are expressed per unit area of the emitter. This area is expressed in angular units (the steradian or square radian) since it is the viewable area of the source from a given direction which is important. As an example, based on astronomical distances, the average solid angle covered by the sun is 6.794×10^{-5} sr, which, assuming a circular source, corresponds to a source angle of 0.0093 rad.

Thus, radiance is expressed in $\text{W/m}^2/\text{sr}$ and luminance is expressed in cd/m^2 (where the derived unit candela [cd] is equivalent to a lm/sr). The luminance unit cd/m^2 is also commonly referred to as nits, particularly in the context of screen brightness. A typical computer display emits between 50 and 300 nits, and midday sun can be on the order of one billion nits.

3.3.3 Glare risk metrics

A common metric used in utility scale PV projects is the ‘ocular glare risk’ approach first proposed by Ho et al. [60], a graphical representation of which is shown in Figure 7. This metric ranks the risk of ocular impact based on the potential for the reflection to cause after-imaging in the eye faster than a typical blink response (and in the extreme the risk of retinal burns)

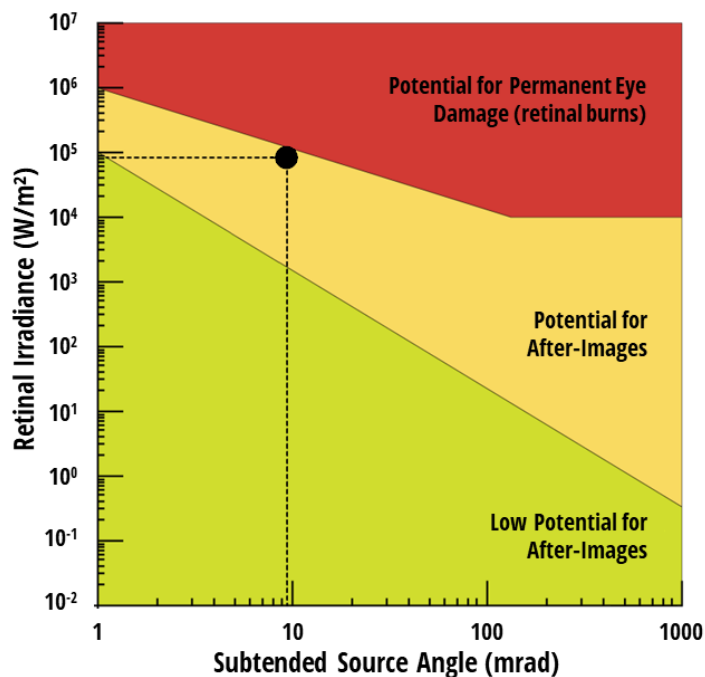


Figure 7: Glare risk metric based on Ho et al. (base illustration provided by RWDI)



using simple colour coded impact levels. Green represents a low risk of after-imaging, yellow indicates a risk of after-imaging, and red indicates a risk of retinal damage. This simpler scale (and the originally free to use tool produced as part of the initial research) made this approach very popular with regulators to evaluate utility-scale PV impacts on homes and vehicle drivers as well as pilots and air traffic controllers. The free to use tool has since been converted to a subscription-based tool known as GlareGauge which is maintained by the spin-off company ForgeSolar but remains popular.

The veiling luminance metric [66] is also commonly applied in some jurisdictions for glare impacts from traditional building materials, usually coupled with a limit of 500 cd/m² based on work by Hassall [39]. This metric includes an acknowledgment of where the glare source is relative to where a viewer is looking, as well as how age and eye colour influence veiling luminance.

There are also a range of metrics that aim to define glare risk for those within buildings. As discussed in [7], care is needed when applying them since many cannot be used for sources as bright as the sun (or reflections thereof) and most if not all were ‘calibrated’ against the expectations for those in side lit offices, making their use for outdoor glare assessments challenging due to the adaptation of the eye to brighter outdoor conditions and different expectations of those who are outside versus an indoor office-like environment.

At the moment, there is no scientific consensus on the proper metrics to use or appropriate threshold values [7]. Some experts recommend an absolute glare limit of 100 000 cd/m² [12], while others argue for a dynamic threshold value of 30 000 to 400 000 cd/m² depending on the incidence angle of sunlight on the PV module [67].



4 GLARE MITIGATION STRATEGIES

Glare can be mitigated both at the module level, through the use of appropriate materials, and on the system level; in particular, the use of a diffusing glass surface can nearly eliminate glare.

4.1 Module-level glare mitigation

Since the dominant source of reflected light is the front surface of the outer glass layer, the most effective approach to mitigate the glare originating from PV modules is to modify the front surfaces (facing the light source). Different options exist for module design, mostly concerning the choice of front glass texturing, with options such as satin-finished (frosted), sand-blasted, coated or structured glass. Alternatively, retrofitting solutions have been developed in the shape of foils or coatings that can be applied to existing modules.

While metallic ribbons inside the module can also reflect significant amounts of light, and, in the case of older modules with wide ribbons, can contribute to glare. That said, the current industry trend is to move towards multi-busbar cells using thin round wires as well as back contact cells, thus making their glare risk less significant. Covering the interconnects also offers aesthetic improvements, which can be relevant in the context of PV in and on buildings.

4.1.1 Anti-reflective Surface Treatments

Anti-reflective coatings (ARC) on the front glass of PV modules are industry standard, with nanoporous SiO_2 being the most commonly used material. While these coatings reduce peak reflection intensities, they typically are insufficient to mitigate glare due to only slight increases in light scattering from the surface, as can be seen in Figure 8.

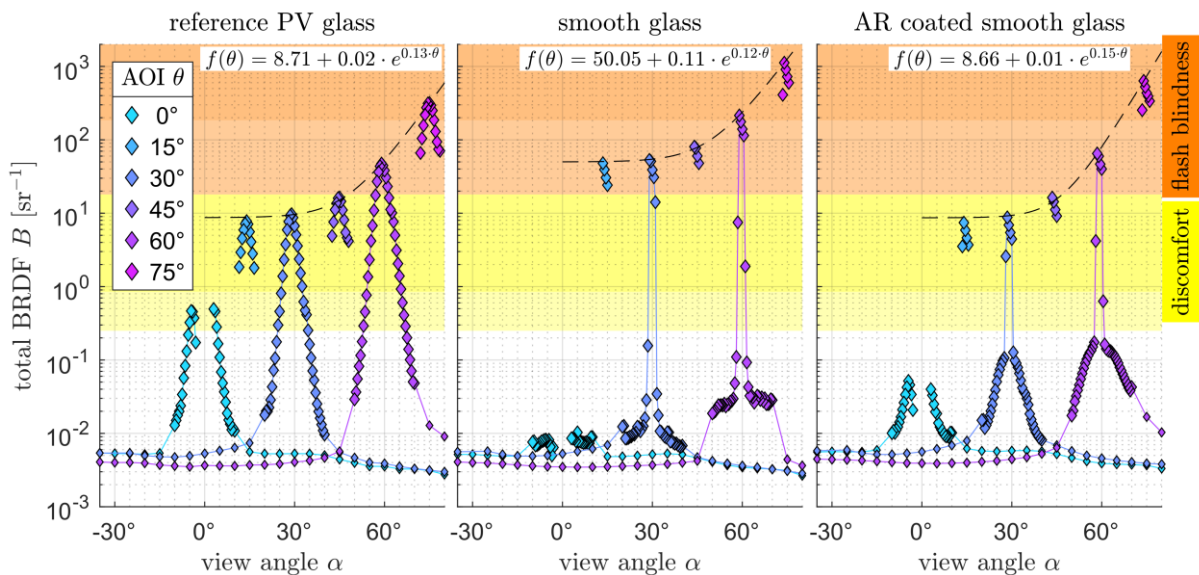


Figure 8: Glare risk evaluation based on in-plane BRDF measurements of different PV module glass surfaces (adapted from [67])

It shows in-plane BRDF measurements of PV modules featuring a reference PV glass (lightly textured), a smooth (float glass) as well as an ARC coated float glass. Each data series show the glare potential as a function of reflection angle for one angle of incidence. Significant glare risk is present for all three samples due to strong specular reflections and only minor scattering,



with the AR coating being insufficient to remove the risk of glare potential [68]. In addition, the expected increase in reflections can be seen with incidence angles.

Structured glasses or ornament glasses can also be used to create a more significant reduction in glare potential. The level of mitigation is strongly dependent on the geometry and size of the texture. An alternate option is to use satinized glass, where the glass surface is chemically or mechanically textured to scatter the incoming light. Examples of the in-plane BRDF of PV modules with such textured glasses are shown in Figure 9.

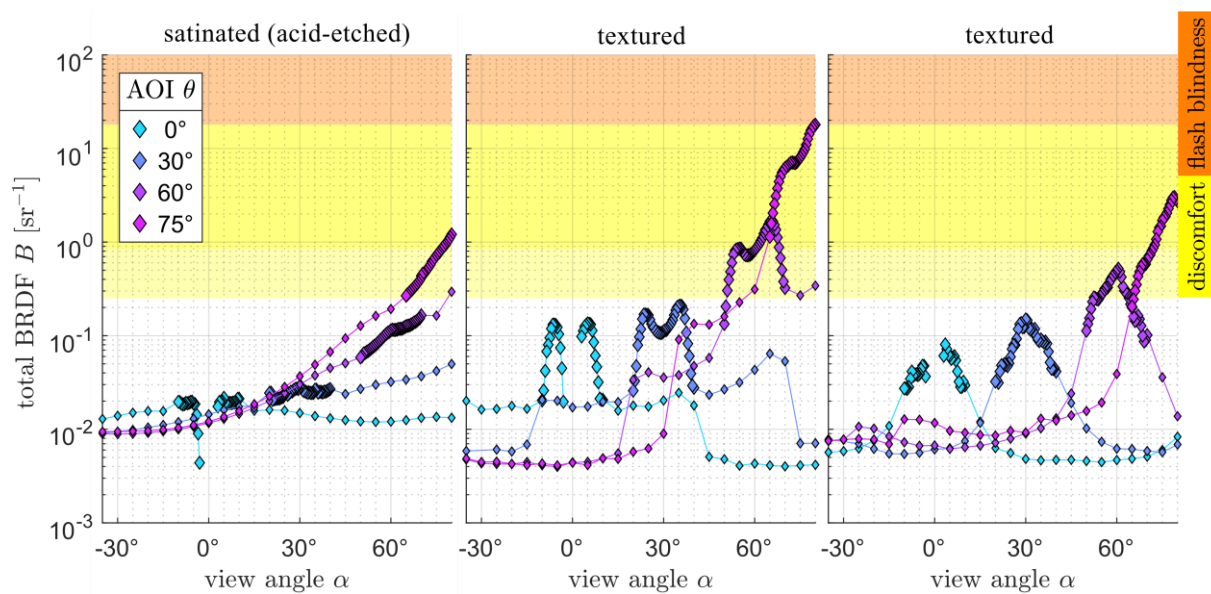


Figure 9: In-plane BRDF of textured PV module glass surfaces (adapted from [67])

Depending on the depth of the texturing, discomfort glare risk can occur for high angles of incidence however the risk of flash blindness is significantly reduced compared to standard flat glass. Satinated (or frosted) glass completely eliminates specular peaks, but reflections nevertheless increase at glancing angles. However, at these high angles the light source (i.e. the sun) will often be in the field of view [68] which makes any reflection much less noticeable. While a satinized surface can be achieved with both acid-etching and sandblasting, with similar reductions in glare risk, the transmission losses caused by sandblasting makes acid-etching the preferred choice for satinizing glass [69].

Most module manufactures provide “antiglare” solar modules as a standard. These are typically standard panels with anti-reflective coatings applied. Though, given that decreasing the glare risk can lead to improved module performance, several manufactures now offer modules with structured and satinized glass as well.

4.1.2 Coloured PV modules

With the goal of creating more aesthetically appealing PV systems, coloured coatings can now be applied to PV modules. If these coatings are applied on the outside surface, they can also contribute to lowering the glare risk. This effect largely depends on the coating’s surface roughness and resulting scattering properties. Coatings applied to the inside of glass substrate, or other colouring technologies, will have little effect on glare potential. It is also important to note that strongly scattering front coatings like satinized glass and interference-based anti-reflective coatings can lead to variation in the perceived colour of coloured panels.



This colour distortion can vary depending on viewing angle and thereby also affect visual comfort.

4.1.3 Glass-free PV modules

Flexible modules with different surfaces (typically thin plastics) are an increasingly popular choice due to their low weight and their ability to take on more organic, free-form shapes. Similar to glass, the plastic surface allows for the relatively easy creation of highly structured surfaces. The properties depend on the surface structure, which varies depending on the module.

4.1.4 Films

Films have the advantages of potentially being inexpensive and can possibly be applied to existing PV systems. However, while there are many manufacturers worldwide that create anti-reflection films for windows, only a few products for PV modules are available. Antireflective films for ordinary windows are unlikely to be appropriate for PV, given the much warmer surface temperatures the film would be subjected to and critical need to preserve high transmittance to the cells. Anti-glare properties vary from film to film, with some prototype films claiming to exceed the properties of frosted glass. Other films, however, exhibit undesirable reflection patterns of considerable intensity, not necessarily in specular directions.

The advantages are that films are potentially inexpensive and can possibly be applied to existing PV systems. A disadvantage might be the possible complexity of applying the film and transmission losses. Due to a lack of experience, no statement can be made regarding the durability of films used on PV modules. In general, however, durability is considered critical and, for most (polymeric) films, is likely to be significantly shorter than the service life of the PV modules themselves.

Although there are many film manufacturers worldwide, only few products for PV modules are known.

4.1.5 Liquid Coatings

Liquid coatings can influence the optical properties of glass surfaces and can be applied with a squeegee or by spraying. They form a thin film on the glass surface and influence the surface light scattering ideally towards more diffuse reflections. They have the potential to be applied retrospectively to PV modules similar to films. While several such coatings are being developed, achieving good visual homogeneity during retrofitting applications as well as long lifetimes remain challenging, and so far, no successful products have been demonstrated on the market.

4.1.6 Performance and reliability impacts

Surface treatments which texture the external surface of glass have the potential to reduce PV performance if not done with intention. For example, sandblasting has been measured to reduce the amount of light reaching the cells by up to 5%, however glass that has been acid-etched showed a loss below 1% [69]. Textured glass in general outperforms flat glass at higher incidence angles, capturing more light.

For coatings applied to the front glass surface, three parameters are of importance: Low absorption of light, good optical matching at the interface to minimize reflection losses and efficient scattering of the reflected light. Given the limited number of options currently available, care is needed when selecting coatings, especially in post-installation applications.



Of additional concern are the impacts of other environmental factors on treated glass. As these technologies are relatively new, it is unclear how texturing and coatings impact soiling rates, ice and snow retention, and how robust they are against commonly used cleaning techniques. Antireflective films for standard windows are generally warranted for at most 10 years, after that, replacement may be needed which can be laborious. Even if this were the case for PV films, this still represents a much shorter span than the expected service life of a PV system and needs due consideration.

4.2 System-level glare mitigation

At a system level, glare mitigation is much less common, but can be categorized as follows:

4.2.1 Siting and system design:

Reflection angles and the sun path can be considered in the installation design process to minimize the time periods where glaring reflections can occur. This however can lead to trade-offs in terms of overall system performance by choosing suboptimal module orientations and tilts. In cases where glare impacts are predicted only during very specific dates and times, and a tracking system is in use, it may be possible to eliminate the risk of glare through custom programming of the tracking logic to direct reflections away from sensitive locations. That said, tracking systems are rare outside of utility scale PV contexts.

4.2.2 Glare obstructions:

In some cases, structures may be erected in the path of reflected light to minimize glare occurrences. Care has to be taken not to substantially reduce light reaching the modules and thereby impacting performance. Obstructing reflections also may not always be feasible depending on the size of the obstruction needed and the willingness of the owner of the land where the obstruction needs to be located. Landscape based obstructions are common solutions, but care is needed to ensure the vegetation is of a sufficient size and, depending on the climate and species, retains its foliage when the glare is possible. The use of vegetated solutions also introduced an on-going maintenance requirement to ensure the plants stay healthy and replace any that die.

4.2.3 Operationalized approaches:

There have also been documented instances [70] where simple warning signs were erected to warn drivers that glare may be possible. Though, it is important to note that operationalized approaches, while not uncommon for other environmental hazards (e.g. warning drivers of blowing dust or snow), are rare in the context of reflected light and may not be acceptable to local authorities outside of cases where glare potential is relatively rare and other mitigation measures are not practical.



5 CONCLUSIONS

Photovoltaics are among the lowest cost paths to new electricity production in many nations, and their large-scale deployment is central to global decarbonization efforts. However, PV systems can impact nearby people and properties, and these effects should be carefully evaluated during the design phase. One such impact is the potential for solar reflections to produce glare.

The regulation of outdoor glare from the built environment currently exists as a patchwork of requirements that vary between, and often within, individual nations. In many jurisdictions no specific regulations exist for non-utility scale photovoltaics, let alone for BIPV applications. As such, this document aimed to present the range of glare regulations that do exist to help practitioners navigate this patchwork in the short term, and aid regulators in harmonization efforts in the long term. In cases where a glare analysis is not strictly required, we hope that this document provides a useful guide for those looking to understand the issues around this phenomenon and the various approaches to its prediction and mitigation.

In general, projects near critical infrastructure (e.g. airports, railways and highways) are much more likely to require a glare analysis regardless of the nation. Proximity to airports in particular is the most common trigger for glare studies which often come with the most detailed requirements. Airport requirements for PV also tend to be more consistent, with most tracking closely with US FAA requirements in either their initial form, or the 2021 revision. For projects planned close to such pieces of infrastructure, it is therefore prudent for design teams to proactively reach out to the relevant authority (or authorities) to understand their specific requirements and conduct the relevant studies.

While requirements for utility scale PV are relatively common, though rarely specific, dedicated requirements for PV on buildings, including BIPV, are rare world-wide. That said, several instances were noted of explicit requirements during the building permitting process for glare studies where BIPV would likely also need to be included. Further, legal precedents were found in several jurisdictions where ‘nuisance’ reflections from PV resulted in the arrays being altered or removed outright. As such, preliminary glare analyses are advisable as a due-diligence activity, particularly given the challenges associated with mitigating existing glare problems.

While post-construction mitigation measures do exist, they may negatively impact the economics of a project (e.g. changing module orientation or removing/replacing them), may be infeasible due to external constraints (e.g. building large obstructions), or have unclear long-term implications for the modules (e.g. post-construction coatings and films). Thus, early consideration of glare potential is paramount to allow for less intrusive mitigation measures (e.g. textured module surfaces, system level adjustments) to be made before construction.



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