Glare from photovoltaic systems

Developing an assessment method

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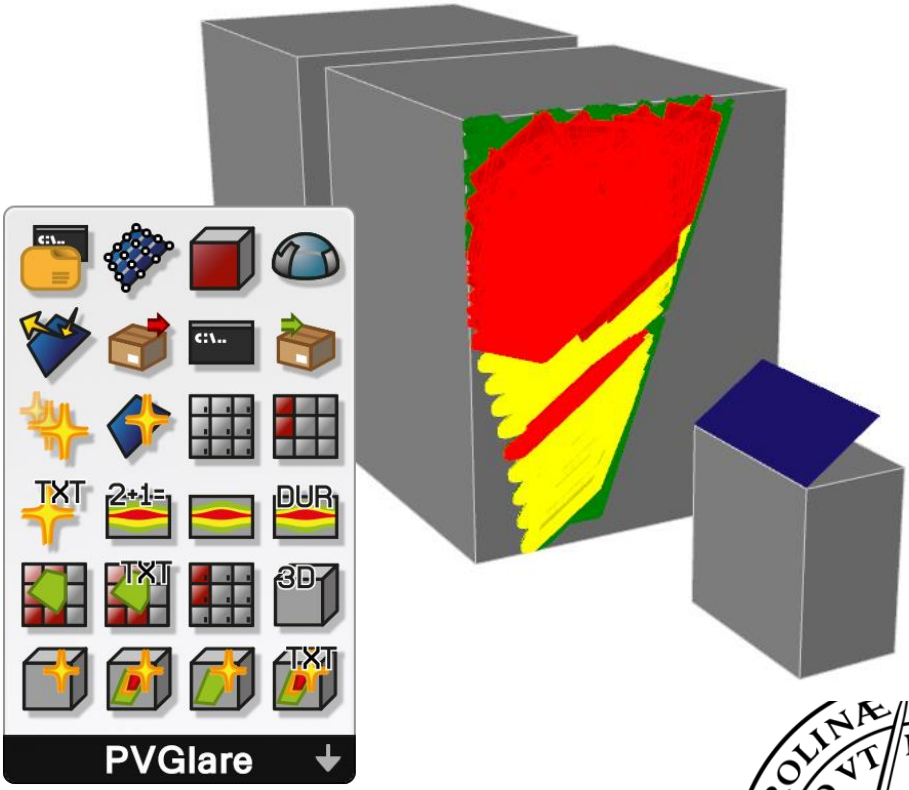
Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University



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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Keywords: Assessment, Glare, Photovoltaic, Luminance, Simulations,

Thesis: EEBD - 15 /17

Abstract

With an increasing usage of photovoltaic panels also in urban context the cases of glare caused by photovoltaic systems are raising. Many countries have low or no regulations regarding outdoor glare caused by daylight, therefore legal cases can be complicated. Even though there are thresholds agreed upon for glare indoors there are no thresholds determined for outdoor daylight glare situations, therefore the thresholds suggested so far are compared. Due to the lack of an approved assessment method the aim of this study is to create a method which can be used to assess glare from photovoltaic panels. A comparison study based on the method of the Daylight Glare Potential and a study to determine thresholds for the sun disk luminance were performed to evaluate the functionality of the suggested method. It can be concluded that with additional verifying studies the method can be a way to decrease the cases of glare caused by photovoltaic systems and raise the awareness of this problem already during the planning phase.

Acknowledgements

We would like to thank our supervisor Jouri Kanters for guiding us through this work and helping us meet challenges, especially in context of grasshopper.

And we would like to thank our co-supervisor Niko Gentile for giving us important impulses throughout the thesis and trying his best to make it possible for us to take measurements, which unfortunately could not be realised.

We would also like to thank Henrik Davidsson for getting us in contact with a Danish Photovoltaic-manufacturer to perform measurements, even though in the end no measurements could be performed.

Lastly, we would like to thank our families and friends for the support they have given us throughout our studies.

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Nomenclature

cd/m²	Unit for luminance	Photometrical quantification of brightness.
DGP	Daylight Glare Potential	The potential of glare from daylight
.epw	Weather file format	EnergyPlus weather data format
HDR-image	High Dynamic Range image	Imaging format to visualize a similar range of luminance as possible with the human eye
HOG	Hour Of Glare	Hour step with the case of glare
HOI	Hour Of Interest	Hour step with the case of reflection and therefore possibility of glare
HOY	Hour Of the Year	Hour step of the year, division of the year into individual steps in an hour increment
ms	Milliseconds	One thousand of a second
PV	Photovoltaic	Renewable energy source utilizing solar radiation
TSOG	Time Step Of Glare	Correspondingly to HOG, however in smaller increments of 15 minutes
TSOI	Time Step Of Interest	Correspondingly to HOI, however in smaller increments of 15 minutes
W/cm²	Unit for irradiance	Photometrical quantification of optical radiation

1 Introduction

1.1 Background

With an increasing urbanisation, the need for space for new homes is growing constantly (Boverket 2014). However, the areas around cities are currently often used as farmland, which is important to provide the citizens with food (Miljöbalken 1998). Therefore, it is more and more common to construct high-rise buildings, in order to preserve the much-needed farmland. The increase in high-rises is accompanied by a growing need for electricity. As the awareness of the need for non-fossil energy sources is increasing as well and it has become increasingly popular to install PV-panels (Energimyndigheten 2016). This method is applied in order to produce as much electricity on site as possible and to minimize the need for bought electricity.

This is not only beneficial for the economy but also for the environment as the main source of electricity in most countries is non-renewable (World Energy Council 2013). However, this solution does not come entirely free of down-sides, as there is a risk of exposing the surrounding buildings to glare from reflections of the flat surfaces of the PV panels. Glare needs to be taken seriously as it can be highly disturbing, or even dangerous, as it might occur in traffic or it can even be the cause of health problems, as high luminance levels can irreparably damage the eyes (Boyce 2014).

Currently, the problems with glare are mostly noticed after the installation of the system. Also with the existing methods it is hard to determine the risk of glare for the entire year. Therefore, it became necessary to find a method to determine whether or not a planned PV installation will cause glare.

1.2 Research questions and objectives

The aim of this study is to investigate the current state in regulations and standards and thereafter develop a methodology that can be used to determine whether or not a photovoltaic panel will cause glare onto surrounding buildings. This is done to make it easier to plan and evaluate such installations in urban areas before mounting them. Thereby minimizing the risk of making a bad investment. The goal is that this methodology can be used by engineers and other instances that are part of the planning process of projects involving photovoltaics, or by glare experts in case there would be a legal conflict. To evaluate the developed methodology, it is also compared to the widely-accepted method of Daylight Glare Potential.

The following research questions were identified:

1) What is the current state-of-art in regulations?
2) How can glare be defined?
3) What are the thresholds of glare?
4) How can a method to assess glare caused by PV panels be developed and how does the method look like?

1.3 Contribution

The study was conducted in a shared work. Erik Hjorth was responsible for the theoretical background excluding the description and effects of PV panels, the German legal system and legal cases. The methodology and grasshopper component was developed by Florian Wochele in discussion with Erik Hjorth. Furthermore, the description and effects of PV panels, the German legal system and the legal cases were described by Florian Wochele.

2 Theoretical background

In order to be able to develop an assessment method for glare caused by PV panels, the definitions of the different types of glare and a study on the existing thresholds was performed. From that the development of the assessment method needed for the simulations could be performed. Further information regarding the different steps can be found in the corresponding chapters.

2.1 Description and effects of a PV panel

In this chapter the construction of a regular PV panel, possible effects caused by the PV panel and the differences to normal glass surfaces are described.

Photovoltaic panels usually consist of several layers; a common construction is shown in Figure 2.1. The front of the PV panels usually is a glass (a)) with high transmissivity and low reflectance values, it is also possible that the glass is specially treated or has a coating to lower the reflectance even more. As structural layer usually the backsheet (d)), typically a polymer, together with the glass are used. Between the glass and the backsheet are the solar cells together with the electrical circuits (c)), they are usually bound together by encapsulating materials (b)) on the front and back of the PV cell layer. For further stability and protection of the edges of the panels a frame, usually made from aluminium, is used. (Honsberg and Bowden, 2017, Module material)

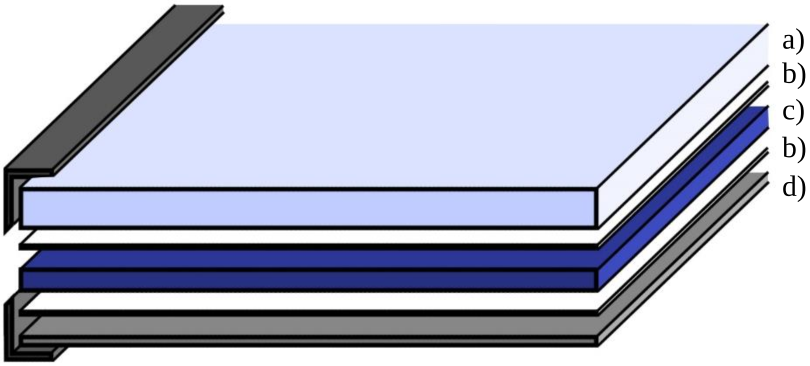


Figure 2.1: Construction of a regular PV panel

Optical effects of a PV panel depend on the reflectivity, absorptance and transmittance. PV panels are usually designed in a way that the highest possible amount of radiant energy hits the PV cells in the panel, therefore the glass layer has to have high transmittance values. To increase the transmittance the outer surface of the glass layer often is structured which also leads to lower reflectance values or treated by a low-reflection coating. Due to the structured surface the amount of spectral reflection is lower compared to regular glass. The amount of light reflected of glass is also depending on the angle of incidence and the refractive index of the glass. (Honsberg and Bowden, 2017, Optical properties)

Considering all the factors mentioned above the glass used in PV panels usually has lower reflectance values than regular window glass. Therefore, the reflections of regular window glass are stronger than the reflections by PV panels. Even though this study is focused on glare caused by reflections from PV panels the developed methodology can also be applied to sky lights or glass facades by changing the material properties in the simulation.

2.2 Regulations regarding glare

Since different countries have more or less extensive regulations regarding glare, it was decided to study the regulations of the native countries of the authors, Germany and Sweden, as well as countries in which the majority of the people have English as their first language. However, the regulations for Canada and Australia could not be acquired due to the costs for accessing them.

2.2.1 Germany

In Germany neither the Federal Building Code (*Baugesetzbuch BauGB, 2015*), which is responsible for urban land-use planning, nor the building regulations on State level (*Musterbauordnung MBO, 2012*) mention the problem of glare specifically. The Musterbauordnung, MBO, states in §13 that buildings must be positioned and constructed in a manner that no chemical, physical or biological influences cause threats or intolerable nuisance. Immissions of such kind are further considered in the Federal Immission Control Act (*Bundes-Immissionsschutzsgesetz BImSchG, 2016*). Paragraph 1 of the BImSchG states that the aim of this Act is to protect humans, animals, plants, the soil, the water, the atmosphere, cultural artefacts and immovable property from harming environmental impacts and to prevent the development of such impacts. However, the BImSchG does not state specific thresholds or approaches to define and determine immissions which cause harming impact. In order to give a general approach the Lichtleitlinie (*Leitlinie des Ministeriums für Umwelt, Gesundheit und Verbraucherschutz zur Messung und Beurteilung von Lichtimmissionen, 2014*), a guideline for light immissions, was published in May 1993 and updated lastly in May 2014. Paragraph 8 of the most recent version of the Lichtleitlinie is dedicated to glare caused by reflections of photovoltaic panels.

The general approach of §8 of the Lichtleitlinie is as a first step to determine if the probability of glare is high based on the relative location of the place of immission to the photovoltaic system. In addition, only places of immission in a radius of approximately 100 metres around photovoltaic systems are considered to be in a zone which could be affected by glare.
The criteria are:

a.) Place of immission is in a radius of 100 metre around the PV system
b.) Place of immission is not north of the PV system (certain cases are recommended to be investigated)
c.) Place of immission is not south of the PV system unless the PV is wall mounted.

These criteria result in the recommendation of the Lichtleitlinie to mainly study cases where PV system and place of immission are on an east-west axis. Furthermore, the basis for calculation is simplified. The sun is point-shaped, the modules are perfectly specular and the astronomically maximal sun hours are considered. These assumptions are used and necessary for further simulations. An intolerable light immission (glare) is reached when glare occurs for longer than 30 minutes a day or 30 hours per year in total. Measures which can be taken against glare from PV panels are also mentioned. However, there is no threshold mentioned above which glare occurs. This is still a matter of opinion of the individual expert conducting the simulations.

2.2.1.1 German legal cases

Even though there are some legal regulations to decide whether a PV system causes glare, there is no consensus about which factors should be considered and even how to assess glare.
Five legal cases, which all came before courts in the south of Germany, were studied in order to understand the process of court decisions. The verdict in three of the cases said, the PV system had to be changed or removed in some way and in two of the cases the PV system could remain. However, three of the cases were appealed, two of them even twice. This can be an indication how uncertain court decisions can be, since the decisions are appealed frequently.

The Heidelberg land court (*LG Heidelberg S 21-08, 2009*) and the Higher Regional Court Karlsruhe (*OLG Karlsruhe U 184-11, 2013*) state that as a general guideline the intensity and duration of glare is not important, as a first decision guidance it must be evaluated how typical a PV system is in the affected area (village or city district). For this not just the occurrence of PV systems is important, it is also important that these PV systems cause glare in an equal way as the PV system which is subject to the legal case. If there are more PV systems causing glare in the area, the prosecuting party must accept the fact that glare occurs. If there are no other PV systems causing glare the defendant party must take measures against the caused glare.

As a general guideline, also in the decisions of Higher Regional Court Stuttgart (*OLG Stuttgart U 46-13, 2013*) and the Administrative courts Augsburg (*VG Augsburg K 12.399, 2012*) and Würzburg (*VG Würzburg U 07.1055, 2008*), not the actual prosecutor as a person has to be used as an indication for glare, a reasonable, average human is used as a point of reference, however this human is not defined. Furthermore, according to the Land court Heidelberg glare does not just depend on kind, strength and duration of the light immission but it also depends on the kind of area of the immission, the level of protection of that area, the social adequacy and the general acceptance of glare. It also should be considered if measures at the place of immission can be taken or if they would be disproportionate.

However, courts like the administrative court Würzburg carried out minor studies solely based on geometrical dependencies and the position and type of affected rooms. It can be said that the higher the level of the court is in the court system the more detailed studies are carried out unless the prosecuting or defendant party commissions expert surveyors, which was the case in the legal case of the administrative court Augsburg. Even though experts are commissioned the results of their studies are often not considered as totally reliable and are sometimes considered as not detailed enough. This circumstance can lead to long legal cases going through three levels of court. Also for example the Higher Regional Court in Karlsruhe says that the Lichtleitlinie cannot be used as a guideline since it lacks the character of a law or standard.

The most detailed legal case came before the administrative court Augsburg. A PV system installed right next to a byre was causing significant amount of glare into the cow barn according to the prosecutor. After a first report of a glare expert was denied because the report was not stating times, duration and intensity of glare, additional measurements were taken. The result showed luminance values up to 60 000 cd/m² and glare durations of up to 45 minutes per day and estimated annual glare durations of 79 hours. The state environmental agency denied this report again since only simulations or an annual measurement period can prove the actual amount of glare. However, after also consulting a veterinarian the court decided that the system had to be removed in order to protect the animals in the cow barn.

These legal cases show the necessity of a more detailed legal framework for example as a standard. The Lichtleitlinie is a first step, but due to its status as a guideline not completely accepted by courts.

2.2.2 Ireland

In this chapter the Irish regulations regarding glare will be described. Since regulations regarding glare could not be found in the building code it was necessary to examine other sources.

In the Guide to the Safety, Health and Welfare at Work (General Application) Regulations, Chapter 5 of Part 2: Display Screen Equipment, from 2007, the following is stated in subchapter 2. Environment part (c) Reflections and glare:

“ (i) Workstations shall be so designed that sources of light, such as windows and other openings, transparent or translucent walls and brightly coloured fixtures or walls cause no direct glare and, as far as possible, no distracting reflections on the screen.

(ii) Windows shall be fitted with a suitable system of adjustable covering to attenuate the daylight which falls on the workstation.”

However, as this regulation only mentions how workstations shall be designed, and windows fitted with proper shading devices, it does not contribute further to the study.

2.2.3 South Africa

Described in this chapter is the regulations regarding glare of South Africa. Although no part about glare could be found in the building code, The Minister of Manpower wrote about the workplace conditions in a government notice.

In the Government Notice, R:2281 from the 16th of October 1987 from the South African Department of labour, the following is said about glare:

“ **Lighting**

3. (1) Every employer shall cause every workplace in his undertaking to be lighted in accordance with the illuminance values specified in the Schedule to these regulations: Provided that where specialised lighting is necessary for the performance of any particular type of work, irrespective of whether that type of work is listed in the Schedule or not, the employer of those employees who perform

> such work shall ensure that such specialized lighting is available to and is used by such employees. […]
> (3) With respect to the lighting to be provided in terms of sub-regulation (1), the employers shall ensure that –
>
> (a) the average illuminance at any floor level in a work place within five metres of a task is not less than one fifth of the average illuminance of the task;
>
> (b) glare in any workplace is reduced to a level that does not impair vision;”

Like the Irish regulations, the measures against glare described only takes into account how workstations should be designed to avoid glare, and is therefore also not contributing to the study.

2.2.4 Sweden

In this chapter the Swedish regulations regarding glare will be described.

The Swedish National board of Housing, Building and Planning (Boverket) states in chapter *6:3 Light* in their Building code (Boverket 2012) that:

> “Buildings shall be designed to ensure that satisfactory light conditions can be achieved without the risk of injury or harm to human health. The light conditions are adequate when sufficient light intensity and the correct brightness (luminance) is reached and when there is no glare or interfering reflections and thus the appropriate lighting intensity and luminance distribution are present”.

Furthermore, in the Planning and Building Act (2010:900), which was translated to English by Boverket in 2016 and which the Building codes are based on the following is stated in chapter 2, section 9:

> “Planning of land and water areas, as well as the location, placement, and design of construction works, outdoor signs, and light source facilities in accordance with this Act may not occur so that the intended use of the construction works, outdoor signs, or light source facilities could result in the impairment of ground water or surroundings that would entail a danger to people’s health and safety, or cause a significant impact in another way.”

While the building code and the Planning and Building Act does mention that there should not be glare and that health and safety should not be compromised, it does not cover the glare from reflections of solar panels and is therefore also not contributing more to the study.

2.2.5 The United Kingdoms

This chapter describes the British regulations regarding glare. Similarly to other countries these regulations were not found in the building codes and it was therefore necessary adduce other sources.

The British Department for Communities and Local Government (2014) mentions in their guidance for light pollution that:

> “Glare should be avoided, particularly for safety reasons. This is the uncomfortable brightness of a light source due to the excessive contrast between bright and dark areas in the field of view. Consequently, the perceived glare depends on the brightness of the background against which it is viewed. It is affected by the quantity and directional attributes of the source. Where appropriate, lighting schemes could include ‘dimming’ to lower the level of lighting ([e.g.] during periods of reduced use of an area, when higher lighting levels are not needed).”

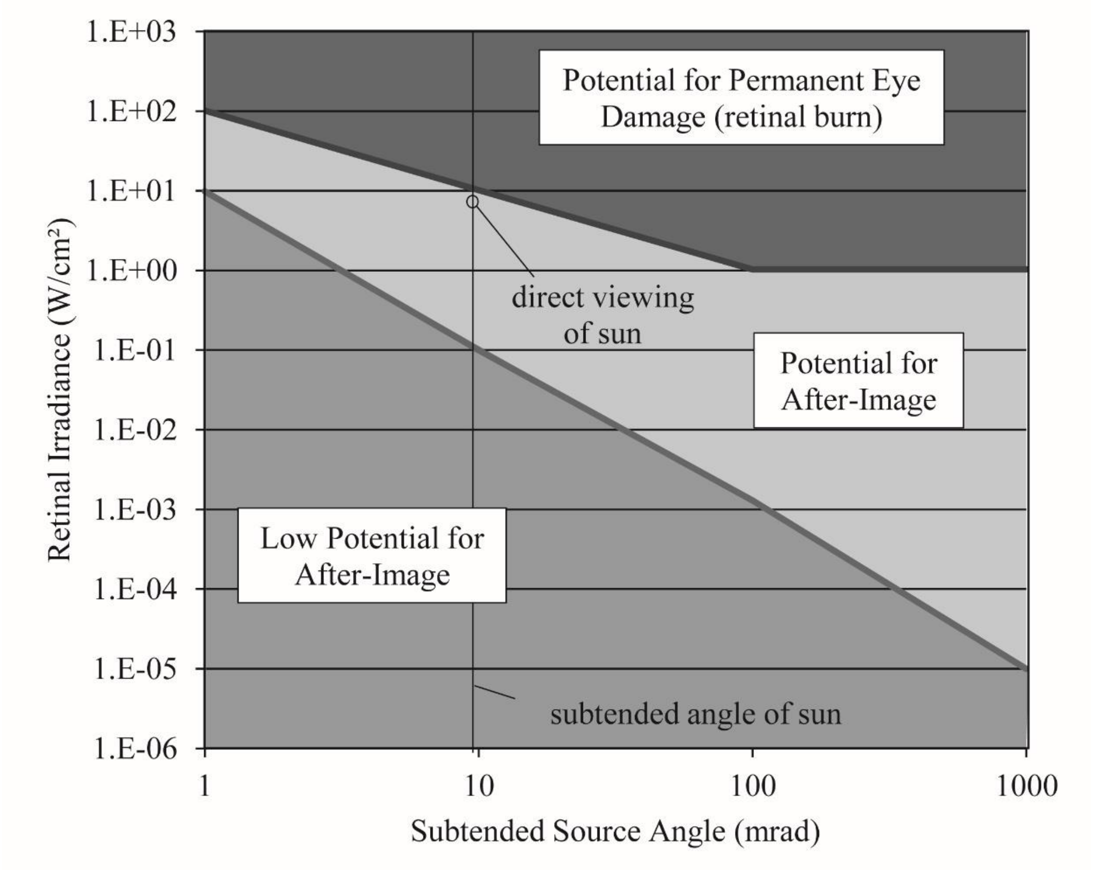
While the regulation covers glare indoors, there is a small amount of work done for outdoors. However, it is focused on the glare from billboards and other bright sources during night and therefore it is not contributing to the study.

2.2.6 The United States of America

In the USA there are no national regulations on glare. Instead, every state has its own codes and regulations which differ considerably. However, the Federal Aviation Administration formulated guidelines (Department of Transportation, 2013) that are valid nationwide and that concern glare from PV-panels in the vicinity of airports. The guideline states the following about measuring ocular impact:

> *“**Standard for Measuring Ocular Impact***
> *FAA adopts the Solar Glare Hazard. Analysis Plot shown in Figure 1 below as the standard for measuring the ocular impact of any proposed solar energy system on a federally-obligated airport. To obtain FAA approval to revise an airport layout plan to depict a solar installation and/or a ‘‘no objection’’ to a Notice of Proposed Construction Form 7460–1, the airport sponsor will be required to demonstrate that the proposed solar energy system meets the following standards:*
> *1. No potential for glint or glare in the existing or planned Airport Traffic Control Tower (ATCT) cab, and*
> *2. No potential for glare or ‘‘low potential for after-image’’ (shown in green in Figure 1) along the final approach path for any existing landing threshold or future landing thresholds*
> *(including any planned interim phases of the landing thresholds) as shown on the current FAA-approved Airport Layout Plan (ALP). The final approach path is defined as two (2) miles from fifty (50) feet above the landing threshold using a standard three (3) degree glidepath. Ocular impact must be analyzed over the entire calendar year in one (1)*
> *minute intervals from when the sun rises above the horizon until the sun sets below the horizon. “*

Figure 2.2 below is an adaptation of the figure mentioned in the abstract of the FAA guidelines, and shows a Solar Glare Ocular Hazard Plot, which is described in the following way by the FAA:



Solar Glare Ocular Hazard Plot: The potential ocular hazard from solar glare is a function of retinal irradiance and the subtended angle (size/distance) of the glare source. It should be noted that the ratio of spectrally weighted solar illuminance to solar irradiance at the earth's surface yields a conversion factor of ~100 lumens/W. Plot adapted from Ho et al., 2011.

Chart References: Ho, C.K., C.M. Ghanbari, and R.B. Diver, 2011. Methodology to Assess Potential Glint and Glare Hazards from Concentrating Solar Power Plants: Analytical Models and Experimental Validation, J. Solar Energy Engineering. August 2011. Vol. 133. 031021-1 – 031021-9.

Figure 2.2: Solar Glare Hazard Analysis Plot from the FAA guidelines

As the guidelines from the FAA does include glare from PV-panels it contributes to the study. However, as the German regulations are both more extensive and more general, the German regulations will be used as basis for the study.

2.3 Definitions of the different types of glare

As there are different types of glare which all have different ways of affecting people it is necessary to have a clear picture of which type of glare is included in the study. However, the division of glare in different types does not mean that it is not possible to experience a combination of the different types. Some of the definitions only describe one specific aspect. In the book *Human Factors in Lighting,* P.R. Boyce (2014) refers to eight different types of glare described by J.J. Vos (1999, cited in Boyce, 2014), as well as to some other forms of glare. In the following paragraph the different types of glare are listed and explained.

- **Flash blindness** means a short moment of complete blindness due to a sudden exposure to an extremely bright light source.
- **Paralyzing glare** is what occurs when a person briefly freezes after being illuminated suddenly during night by a bright light.
- **Exposure to light bright enough to cause retinal damage** is a phenomenon that can occur if a person looks directly into a light source with a high-energy radiation. Even 100 ms of exposure to retinal irradiances between 50 and 1000 W/cm², depending on the size of the retinal image, is enough to cause damage.
- **Distracting glare** occurs when flashing bright lights, for example from emergency vehicles, are seen in the peripheral visual field in environments with low light levels.
- **Dazzle / Saturation glare** occurs when a big area of the visual field is too bright, which is painful and for which the normal response is to somehow shield the eyes from the light source. Common ways to do that is to use low-transmittance glasses or to shield the eyes by using slits. These methods are used in environments from the beaches of California to the ice-fields of the Arctic. Even though the lifestyles and cultures of the people living in the mentioned climates have great differences the necessity to protect the eyes from high luminance values is common in both places. Saturation glare is more common outdoors than indoors and it has been theorised by Lebensohn (1951, cited in Boyce, 2014) and Vos (2003, cited in Boyce, 2014) that the sensation of pain probably is caused by a spasm of the iris sphincter. Saturation glare occurs when the eye is affected by high luminance values during a long time.
- **Disability glare** is the glare which occurs when light scatters in the eye, forming a luminous veil over the retinal image of parts near the scene (Vos, 2003). There are two effects of this phenomenon. First, the luminance contrast of the retinal image is reduced, which in turn reduces the scene visibility. Second, the threshold contrast is reduced by the increased retinal illumination, which increases the visibility. The first effect almost always dominates the second (Patterson et al., 2012, cited in Boyce, 2014).
- As described in *Human Factors in lighting* (Boyce, 2014), **Discomfort glare**, on the contrary to disability glare, is something that is not well understood. It reportedly occurs when the presence of a bright light source, luminaire or window causes visual discomfort to people. The cause for discomfort glare is not proven. Although discomfort and disability glare are separated it does not mean that visual discomfort

cannot be caused by disability glare or that discomfort glare cannot cause a reduction of visibility.

- **Overhead glare** occurs when a light source outside of the field of view affects elements around the eyes with high luminance values. These high luminance values changes with every head movement which causes distraction. It has been found that the phenomenon occurs at luminance levels over 16 500 cd/m², a value which is easily exceeded by certain light sources.

In addition to Vos' types of glare, **Adaptation glare** and **Veiling reflections** are also mentioned in *Human Factors in Lighting* (Boyce, 2014).

- **Adaptation glare** is described as a phenomenon that occurs when the visual field is suddenly exposed to an escalation of the luminance affecting it, for example, when leaving a long tunnel and being blinded by the sunlight. The sensation of glare is caused by the eye being oversensitive to bright lights after adapting to the relatively low luminance levels of the tunnel and then abruptly being exposed to the bright sunlight. Adaptation glare is momentary due to that the sensitivity of the visual system and will adjust to new conditions soon after entering a new environment, (IESNA, 2011, cited in Boyce, 2014).
- **Veiling reflections** on the other hand, is a phenomenon that occurs due to reflections on a specular or semi-matte surface which alters the visual stimulus by affecting the visual task contrast. Veiling reflections have similarity with disability glare due to that it also changes the contrast of the retinal image. However, it is different in that it affects the luminance contrast of the task instead of the retinal image of the task. The nature and magnitude of veiling reflections are determined by the geometrical positioning of the observer, the surface and other highly luminous sources as well as the specular characteristics of the surface of interest. As veiling reflections depend on the specularity of the surface it is impossible for the phenomenon to occur on a perfectly diffuse surface. Instead it occurs when the viewing angle is close to the angle of reflection of a specular or almost specular surface.

Moreover, there are other ways to describe glare. For instance, in the German light guidelines (Lichtleitlinie, 2014) **Physiological** and **Psychological glare** is used to define different kinds of glare. **Relative** and **Absolute glare** are also other ways proposed to define glare, as well as **Direct glare**, **Indirect glare**, **Viewing direction glare**, P**eripheral glare**, **Simultaneous glare** and **successive glare**. In the following paragraph these types of glare are described concisely:

- **Relative glare** occurs due to high luminance differences in the visual field which disturb the adaption process of the eye. The retina needs to adapt differently for different parts, also known as local adaption. This process to adapt differently over the retina takes a long time and disturbs the attentiveness (Strahlenschutzkommission, 2006).

- **Absolute glare** occurs when the luminance affecting the eye is too high and makes it physically impossible for the eye to adapt. This happens in the range of 10^4 to $1.6 \cdot 10^5\ \mathrm{cd/m^2}$ when the luminance levels simply exceed the range in which the eye can sufficiently adapt to them. This also leads to a risk of retinal damage. However, when one is looking straight into a powerful glare source there is a subconscious reaction that triggers a wink reflex (Strahlenschutzkommission, 2006).
- **Direct glare** occurs when glare sources as well as other light sources are visible in the field of view (Strahlenschutzkommission, 2006).
- **Indirect glare** occurs when the glare source comes from a reflection and not from a visible source (Strahlenschutzkommission, 2006).
- **Viewing direction glare** occurs when the glare source is in the direct line of sight (Strahlenschutzkommission, 2006).
- **Peripheral glare** occurs when a glare source is present in the peripheral part of the visual field (Strahlenschutzkommission, 2006).
- **Simultaneous glare** is described by A. Arnulf (1962) in *Research and visual problems in night-driving* to have two causes. These are:
  “
  - *Diffusion of the light by the mediums of the eye – to which can be added the diffusion by the windscreen and the atmosphere. This diffusion places a veil of light before the object, thus diminishing the contrasts in the less lighted parts of the field.”* And secondly.
  - *“Strong light in one part of the field reduces sensibility of the eye in the less lighted parts; visual acuity and contrast sensitivity diminish.”*

- **Successive glare** is also described by A. Arnulf (1962) in the following way:

  > “*In the successive glare, the most lighted parts of the retina have lost their sensitivity. This is the phenomenon commonly called ‘the black hole’* “.

  This can be explained as an after image that appears after looking into a bright light source.
- **Physiological glare** can, according to the German Lichtleitlinie (2014), even occur if a light source is far away, so that the brightness in the area/room is not changed. The nuisance occurs due to consistent and involuntary distraction towards the light source, which makes the eye constantly trying to adapt to the glare source.
- **Psychological glare** is described in the German Lichtleitlinie (2014) to be the decrease in the ability to see by scattered light in the eyeball.

The types of glare listed above were compiled in the literature study. Some of the glare types are more focused on artificial light sources during night and not daylight or are impossible to occur in connection with photovoltaic panels. Therefore a demarcation was performed and only the types that are of interest were used thereafter. The following list only contains those types of glare which can be presumed to be relevant to the study:

- Disability glare;
- Discomfort glare;

- Overhead glare;
- Veiling reflections;
- Absolute glare;
- Indirect glare;
- View direction glare;
- Peripheral glare;
- Physiological glare, and lastly;
- Psychological glare.

2.4 Thresholds for glare

In order to be able to determine whether or not glare occurs a threshold must be established and only after that it is possible to achieve a result. If the threshold is exceeded, there is glare in the studied situation. Glare from daylight can be measured for indoor situations as well as outdoor situations. However, it is easier to measure indoor daylight glare as methods are well established, whereas the methods for measuring outdoor glare from daylight are not.

2.4.1 Indoor thresholds

When measuring glare indoors the standard method is to compare contrasts. This is a widely used method. However, there are different threshold values suggested by numerous researchers.

In the study on the impacts on the daylight quality in offices by shading devices, luminance thresholds based on the guideline for energy efficient offices from Swedish National board for Industrial and Technical Development (NUTEK) are discussed by M. C. Dubois (2001). The guideline states three luminance thresholds concerning absolute glare, which are the following: luminance values above 2000 cd/m² anywhere in the room, luminance values between 1000 - 2000 cd/m² in a field of view (peripheral) and finally, luminance values between 500 cd/m² - 1000 cd/m² in a field of view. However, Dubois states that the values recommended in the NUTEK guideline need to be multiplied by a factor of two in case the glare source is natural light. Dubois also mentions a recommendation from NUTEK regarding luminance ratios that says:

> *"[…] luminance ratios within the work area between the task, the direct surrounding and the remote surrounding do not exceed 10:3:1. Moreover, this norm recommends that the luminance ratios between any points within the field of view should not exceed 20:1[…]*".

In their paper, A. Jakubiec and C. Reinhart (2012) describes the DGI (Daylight Glare Index) metric which was first formulated in 1972 by R.G. Hopkinson. The DGI is used to investigate large glare sources, more specific the glare from a diffuse sky seen through a window. However, since it only takes into account the brightness of the visible sky through a window and no interior sources, this metric is not reliable to use when direct light or specular reflections are studied. The DGI has four different levels; these are *Imperceptible glare, Noticeable glare, Disturbing Glare and Intolerable Glare.*

While developing DGP, (Daylight Glare Potential), J. Wienold and J. Christoffersen (2005) discovered luminance thresholds with slightly more detailed glare level categories than previous studies had shown. These levels apply when the field of view is parallel with the window and has the following luminance values: *perceptible glare* at 2000 cd/m², *acceptable glare* at 4000 cd/m², *uncomfortable glare* at 6000 cd/m² and finally *intolerable glare* at 8000 cd/m².

DGP, which builds up on the DGI, is a glare rating model with a range between 0-1 that is used to determine the level of glare indoors. DGP does not only take the luminance of the glare source into account, but also the luminance of the background. To calculate the DGP the vertical illuminance of the eye is needed as well. The glare range values for the different levels for DGP are the following:

- Imperceptible glare: <0.30
- Noticeable glare: 0.30-0.35
- Disturbing Glare: 0.35-0.45
- Intolerable Glare: >0.45

The numbers for DGP were described in *Degree of eye opening: A new discomfort glare indicator* by J.A.Y. Garretón et al. (2014).

As mentioned when describing overhead glare in Chapter 2.3 above. 16 500 cd/m² is the threshold for the probability that this phenomenon can occur. This threshold is mainly used for luminaires, but can also include strong light sources with high luminance values, such as the sun.

2.4.2 Outdoor Thresholds

As the overall outdoor luminance values are much higher than indoor luminance values and therefore the method of comparing contrasts is not applicable, absolute values are used instead to determine whether glare exists or not. Therefore, and because the field of outdoor glare thresholds is not as thoroughly researched as the field of indoor thresholds, the thresholds for outdoor glare have a bigger margin.

M. Schiller and E. Valmont (2006) mention in their report about glare from facades with highly reflective materials that a measured luminance value of 12 000 cd/m² has to be considered problematic and that the surface needs to be treated in order to make sure that the specularity decreases. However, this paper is predominantly focused on the overheating of surrounding buildings and the landscape around it rather than on the glare problems from reflected sunlight and therefore the threshold is excluded for this study.

In the paper by X. Yang et al. (2013) where reflections from glazed facades were simulated in Grasshopper, a threshold of 10 000 cd/m² was used to for the reflected façade luminance. However, it was not mentioned where this threshold comes from or why it is employed. This threshold is, however, supported by a paper published one year before by J.Y. Shin et al. (2012) in which 10 000 cd/m² was the threshold for rating glare intolerable or uncomfortable. The glare rating scale comprised three levels, *acceptable glare, just uncomfortable glare* and *intolerable or uncomfortable glare*. In this scale the level *acceptable glare* was achieved at luminance values of 1 000 - 3 200 cd/m², *just uncomfortable glare* at 5 600 cd/m² and as previously mentioned *intolerable or uncomfortable glare* at 10 000 cd/m².

In their paper J.Y. Suk et al. (2016) compare some of the previously mentioned thresholds and come to their own conclusion: a threshold of 4 000 cd/m² that is supposed to be more reasonable for the *absolute glare factor*. The authors also stated that further research is needed in order to determine whether or not that value can be used for daylight glare.

In a study about the reflections of PV panels at an American airport, A. Jakubiec and C. Reinhart (2014) proposed and used 30 000 cd/m² as a maximum brightness threshold. In their paper they justify the value with:

> "Generally, the human eye can recognize between two and three orders of magnitude of luminance variation at any time. Taking the mean brightness of the two task luminance values, approximately two orders of magnitude of luminous difference can be visualised. This means that in order to view planes on the taxiway while still maintaining the ability to read the monitor, luminance levels in the line of sight need to be less than 30 000 cd/m² observing these two orders of magnitude as a rule. Therefore, the authors propose a brightness of 30 000 cd/m² as a threshold at which the probability of experiencing disability glare is likely."

Mostafa et al. (2016) mention in their paper experimental work with the FAA tool (SGHAT) at French airports which showed an, according to them, acceptable reflected luminance at values below 20 000 cd/m².

As the thresholds for outdoor daylight glare conditions are not yet as widely accepted as the thresholds for indoor daylight glare, all of the mentioned thresholds, except the 12 000 cd/m² that were excluded earlier, will be studied further in the assessment methodology.

3 Methodology

In context of developing an assessment method for outdoor glare, it was necessary to study the luminance of the sun disk. Additionally, the developed method was compared to the widely-accepted method of DGP in order to determine the reliability of the new method.

3.1 Outdoor glare assessment method - PVGlare

A Grasshopper script was developed in order to answer the three important questions regarding glare from PV systems in urban contexts:

- a.) Where does the PV reflect light to?
- b.) When does the PV reflect light onto surrounding buildings?
- c.) Does the reflected light cause glare?

Grasshopper (Davidson, 2017) is a graphical algorithm editor integrated into the 3D modelling tool Rhinoceros (McNeel, 2017), which can be expanded by plug-ins.

These questions had to be answered one by one and the results combined afterwards to determine if and where reflections cause glare. In order to accomplish this, first a geometrical calculation of the direction of the reflection and then a simulation of the intensity of the reflection were carried out, as shown in Figure 3.1.

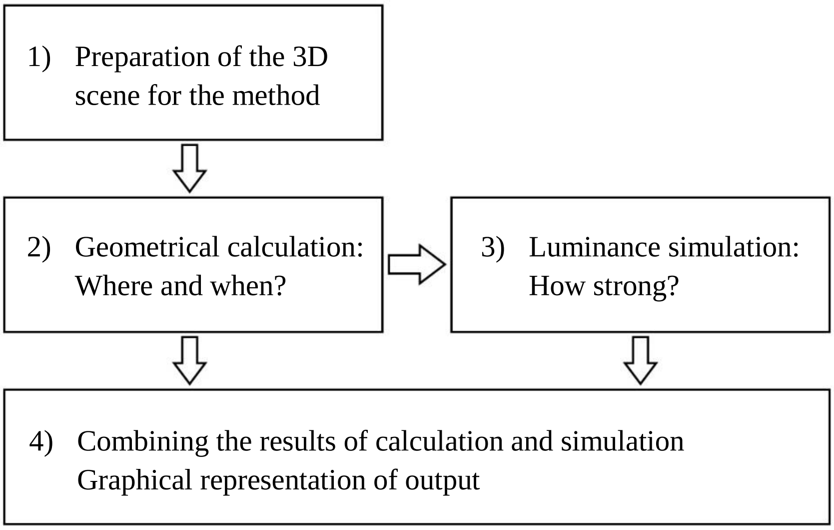


Figure 3.1: Flow chart of assessment method

As an input for the simulation only the 3D model of the surrounding area, the PV panel geometry and an .epw-file with the local climate data are necessary.

Additionally, the script contains components to create the folder structure needed. This component uses the input of a folder path in order to create seven sub-folders and two batch-files for processing the result files of the calculations and simulations. These result files are then imported by another component.

Before it is possible to focus on answering the questions, where, when and how strong reflections occur, the 3D file needs to be prepared as a first step, as shown in Figure 3.1.1, in order to enable time-effective simulations. Since the focus is on the building surfaces around the PV panel the conclusion was drawn that all the building surfaces, which are not facing the panel, are obsolete and therefore can be neglected in the simulation in order to minimize the amount of geometry used in the script. Therefore, as the first step in the script, all the surfaces facing the PV panel are selected to be used in the further steps. An assumption here is that the surrounding area in a radius of 100 m is supposed to be studied. This assumption is based on the recommendation in the German Lichtleitlinie (2014), mentioned in chapter 2.2.1. It states that the danger off significant durations of glare further away than 100 metre is low. This, however, can depend on the size of the PV installation as well.

After this initial step, it is possible to work on the first and second question, the position of the reflected light and the time of the year in which a reflection occurs, mentioned as step 2 in Figure 3.1. For this step, it is assumed that the biggest portion of the reflected light is reflected specularly, which means that the law of reflection applies. The PV panel is divided into grid points used as points of incidence of the solar vectors and starting points of the reflection vectors. The smaller the grid size the more grid points are created, which increases the calculation and simulation time drastically. It is only possible to use one panel surface. If there is a linear array of panels they should be created as one surface, rather than several panels attached to each other.

For a successful reflection of light two requirements must be met: The incoming solar vector to the PV panel must not be blocked by a surrounding building, thus the direct sunlight does not impinge on the PV panel. And the reflection vector must hit the surface of a surrounding building. This leads to three possible cases, as shown in Figure 3.2:

a.) The solar vector is blocked.
b.) The solar vector is not blocked but the reflection vector does not impinge on a building.
c.) The solar vector is not blocked and the reflection vector impinges on a building.

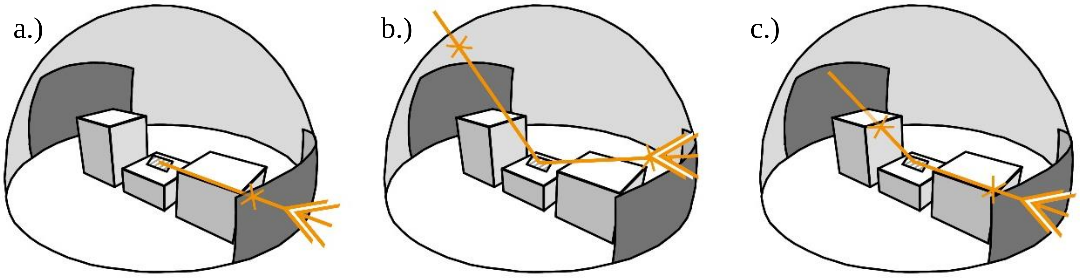


Figure 3.2: Three possible cases in context of the reflection of sunlight from the PV panel

Only the third case is going to be considered during the further study.

In order to determine whether the solar vector is blocked by a surrounding building or not a sky dome for each grid point on the PV panel was created. These sky domes show the portion of the sky visible from these particular points. In this context it is important that the biggest portion of the sky dome needs to be visible from the grid points, otherwise wrong areas of the sky dome could be considered as visible. If the solar vector and the respective sky dome intersect, the solar vector is not blocked by a building and therefore can be considered for creating a reflection vector. In a next step, the reflection vector is tested for an intersection with a surrounding building surface. In case of multiple intersections with building surfaces, which frequently occurs in dense areas, the intersection closest to the grid point (origin of the reflection vector) is considered as the impinging point of the reflection. This calculation is carried out for the whole year in steps of 15 minutes, giving a total of 35 040 time steps a year.

As an output of this geometrical calculation, the coordinates of the points where the reflection vectors impinge on the building surface (impinging point), the normal of the building surface at the impinging points and the time step of interest (TSOI), the time step the reflection occurs, is determined.
For these TSOI, the luminance of the reflection spot of the sun on the PV panel is now required as a third step, as shown in Figure 3.1. The only reliable way to determine the luminance of surfaces is by using an image-based simulation ran with Radiance. However, these image-based simulations do not have any output in numeric form, which is necessary for the script and for analysing the results.

In the image-based simulation scene the camera is set to be positioned one meter away from the centre of the panel in the direction of the reflection vector facing the centre point of the panel. The ashik2-material made by A. Jakubiec (2017) was used. Also, there is no other geometry in the scene in order to reduce the simulation time as far as possible. The resulting HDR-images are then opened in the Radiance executable file pextrem.exe using a python script returning the extreme luminance values in RGB and their position. From this output the RGB values for the maximum luminance are extracted and the luminance is calculated using Equation 1 from Radiance (Jacobs, 2014).

$$L_{max} = 179 \times (0.265R + 0.67G + 0.065B) \text{ [-]} \tag{1}$$

With this method, times in which glare from the sun overpowers the glare caused from the reflections by the PV panel are considered as well. In order to take this into account two thresholds must be set: first the threshold for glare and second the threshold for the luminance of the sun disc.

This threshold for the luminance of the sun disc was determined in a supporting study. Glare from the sun disc can occur when the angle between the view angle on the panel and the angle of incidence of the sun on the panel is too small.
For this a simple imaged-based simulation was carried out in order to determine the maximum luminance in the scene caused by the sun itself. The camera was always set to directly face the sun and no geometry was created to disturb the simulation. In order to minimize the simulation time only hours were simulated in which there is direct radiation in the scene and in which the solar altitude is positive or zero. The study was carried out with the .epw file for Copenhagen. Other weather files might result in different thresholds, due to different times of sunrise and sunset, other climates and different times and rates of sky cover.

Thus, the time steps of glare by the PV (TSOG) are determined.

In a fourth and final step, mentioned in Figure 3.1, the results from both the geometrical calculation and the image-based simulation are used in combination. It is possible to both visualize where glare is likely to occur throughout the year and when glare occurs.

The results can be either presented in a temporal map showing the time steps of the year, a) the time steps without reflection, b) without glare, c) with glare from the sun and d) with glare from the PV panel or it can be presented in a 3D view. An example for a temporal map is shown in Figure 3.3.

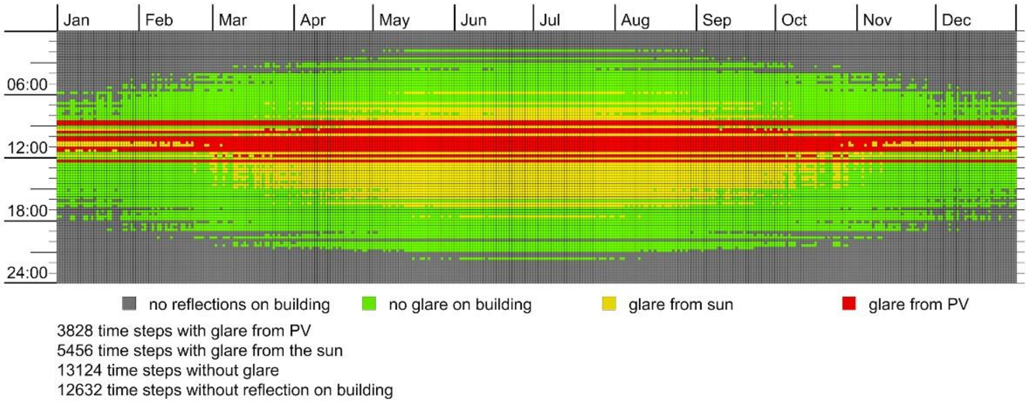


Figure 3.3: Example of a temporal map showing time steps without reflection (grey), without glare (green), with glare from the sun (yellow) and with glare from the PV panel(red)

There are two possible ways to visualize this: either only one time step at a time is shown, in order to make it possible to see at which time glare occurs or all the time steps are shown simultaneously in order to show where areas with high glare possibility are located.

Since it is often a point of interest in which area of the building surface glare occurs, the façade can be divided into nine sub-areas, derived from the study mentioned in chapter 3.4, which can then be visualised separately or in every necessary combination. This is only possible for one building surface at a time. In case several building surfaces have to be analysed, different sets of the components have to be used parallel. This was also done in order to be able to compare the results of the script with the DGP simulation script, described in chapter 3.4.

As an additional question to the originally mentioned three questions it can be necessary to add:

d.) For how long does glare occur sequentially?

Since the simulation is not just carried out for one-hour steps during the year but steps of 15 minutes it is also possible to have a look at the duration of glare. Considering the German Lichtleitlinie for example, which is mentioned in 2.1.1, the duration of glare is crucial for the acceptance of PV panels as well. Here the Lichtleitlinie mentions a duration of maximum 30 minutes which is considered acceptable for glare. With this threshold a temporal map of all the durations longer than 30 minutes can be shown and the number of durations can be obtained as an output. This temporal map again can be created either for the whole building surface or a set number of areas. The temporal map however only shows if no glare (grey) or glare durations longer than 30 min (red) occur. There are no green or yellow marks; an example is presented in Figure 3.4.

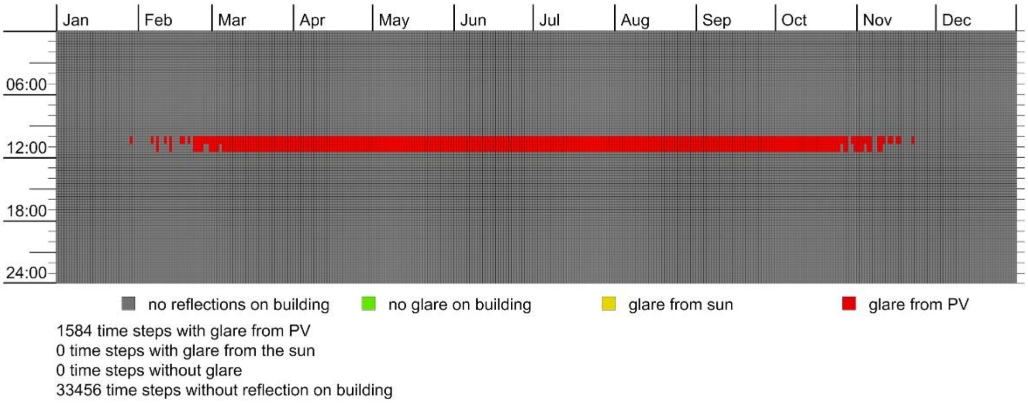


Figure 3.4: Example of a temporal map of the Glare duration

On a laptop with an Intel Core i7-3740QM (2.70GHz) and 24 GB RAM the calculation step was finished within two hours, the luminance simulations however required 24 hours of simulation time.

The installation guide and manual for the Grasshopper script methodology and its components can be looked up in Appendix A.

3.2 Description of case study scene

In order to judge the performance of the developed assessment method, a case study scene was constructed, shown in Figure 3.5. The PV panel is placed on top of a smaller building which is located at a distance of 10 metre to its direct neighbouring building. Furthermore, the PV system itself is 10 by 5 metre and is tilted 35˚ directly towards south. The dimensions of the neighbouring building were chosen so the PV panel is placed directly relative to the centre of the building façade. With this scene the possibility for glare was considered to be high.

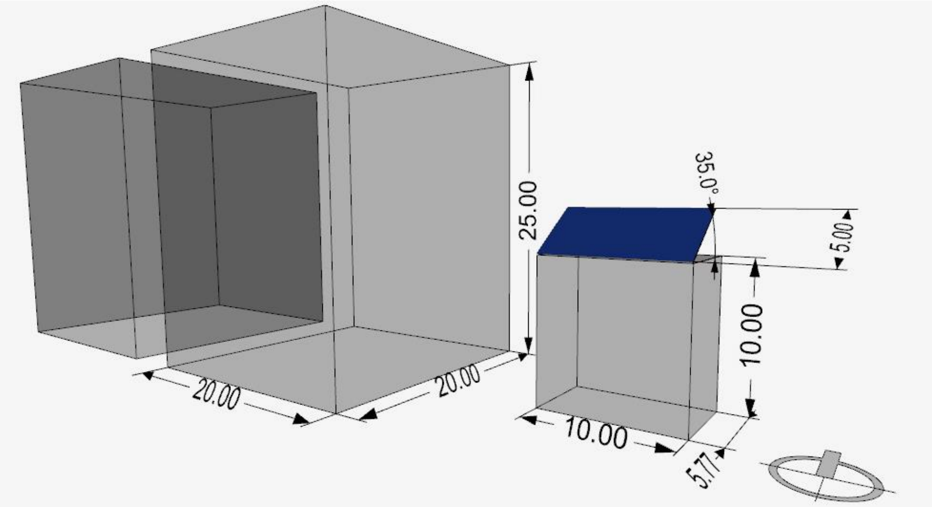


Figure 3.5: Case study scene

3.3 DGP simulation

Since there are no scientifically proven and widely accepted ways to determine glare outdoors, the possibility of comparing the results of the outdoor glare study to the results of a scientifically accepted simulation of the DGP was seen as helpful, in other words a problem connected to outdoors was converted to an indoor problem. The study was conducted on the one hand to compare if the occurrence of glare according to DGP is related to the occurrence according to the outdoor glare methodology and on the other hand to find out which of the thresholds for glare from PV panels give the closest resemblance to the DGP values.

For this a script was created which can be used with the same 3D file as applied in the outdoor glare script. This script creates a standardized room which is pre-set in the script and thus enables regular DGP simulations.

Like in the outdoor script first the building surfaces facing the panel are selected. In case of two adjacent non-parallel building surfaces one of the surfaces must be deselected manually. For each building surface nine standardized rooms are created: four in the corners, four in the middle of the sides and one in the centre, as shown in Figure 3.6

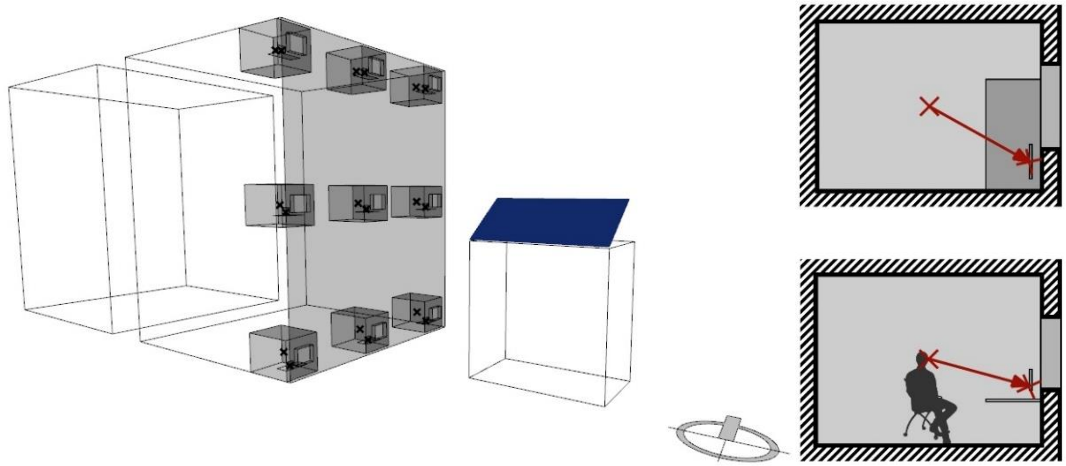


Figure 3.6: Building surface with standardized rooms towards the PV panel; floor plan of the standardized room (top right), section of the room (bottom right)

All the necessary geometry as well as the points determining the view point and direction are created. Additionally, the building surface is extruded creating a realistic wall thickness. This leads to the limitation that the viewing direction in the room is set in a way, which may raise the occurrence of glare. The remaining materials for the room are set to be standard average reflectance values.

Starting from these rooms normal image-based simulations are carried out and checked for the DGP of the scene. The DGP thresholds mentioned in chapter 2.4.1 were considered and values above 0.35 (disturbing glare) were identified as problematic. With this threshold the occurrence of glare can be compared. However, it is not possible to identify whether glare is caused by the sun itself or reflections. Therefore, the temporal map, as presented in Figure 3.7, portrays all the glare as glare from the PV (red) and no yellow time steps with glare from the sun are marked.

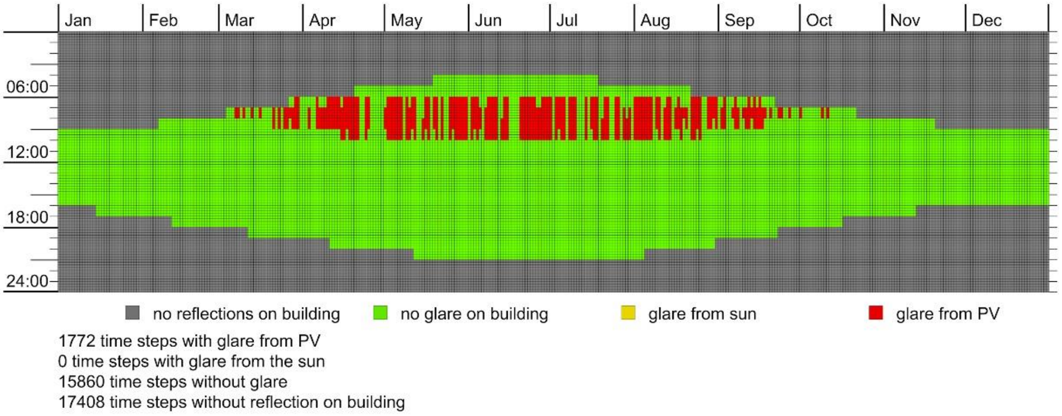


Figure 3.7: Temporal map showing the results of the DGP study, all glare is marked as glare from PV

This leads to temporal maps comparable to the ones from the outdoor simulations. Since the simulations are only carried out for full time steps in order to minimize simulation time the resolution is not as high as for the outdoor script.

4 Results and Discussion

The regulations regarding outdoor daylight glare in some countries do not cover glare on a deeper level than “there should not be glare”, as stated in chapter 2.2. On the contrary, other countries, such as Germany, have more elaborate regulations. At the same time, the regulations consider mainly glare indoor or glare in traffic situations and exclude the exterior daylight glare. Therefore, it is not very surprising that the methods for determining glare indoors are more extensively researched than those for exterior cases. However, it is also possible that research in the field of indoor glare and glare from artificial light sources was carried out to formulate standards and regulations.

When considering which type of glare is relevant for different situations it is important to keep in mind that certain definitions describe different aspects of the same kind of glare and that it is possible to be affected by a combination of different types of glare at the same time.

There are many different suggestions for the outdoor thresholds and some are even stated by the writers themselves to be only suggestions. Consequently, it is quite clear why the assessment of glare outdoors is currently not as easy to be performed as the indoor glare assessments. With regard to the last-mentioned, the methods are not only more researched but also widely used and accepted.

From the authors’ point of view, even the current German legislation and guideline system is not sufficient and a widely accepted methodology is required. Furthermore, it was not possible to assess what kind of glare thresholds were used in the reports mentioned in the German legal cases, which also gives uncertainties regarding the comparability of the said reports.

The results of the sun-disk-luminance-threshold-study, described in chapter 3.4, are shown in Figure 4.1 and Figure 4.2. Both graphs show the values in ascending order, to accomplish this the time steps were filtered and sorted according to the luminance values at the different time steps. Time steps without luminance values are omitted, which leads to a total of 2955 considered time steps in the results.

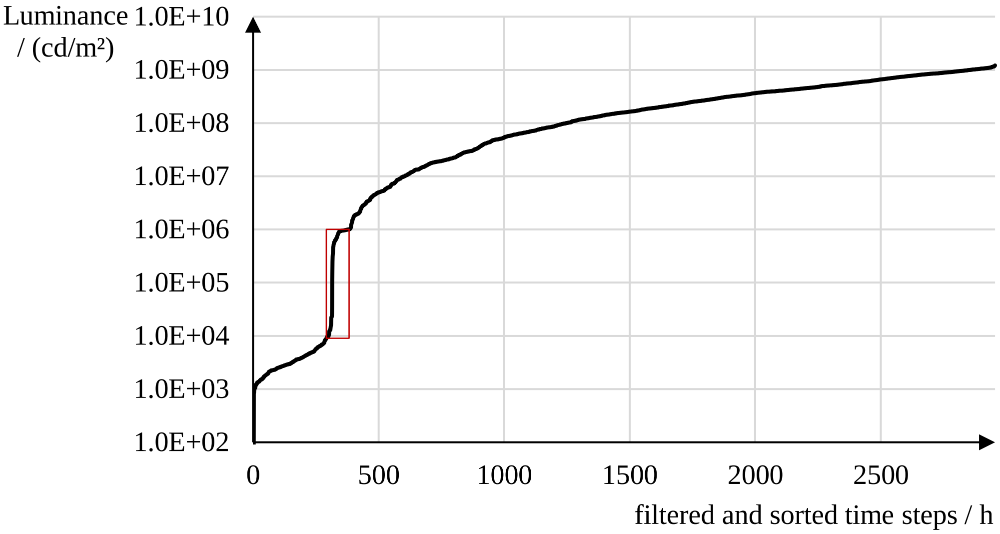


Figure 4.1: Result of the sun disk luminance simulation for Copenhagen.

Altogether, it can be recorded that for most of the time steps studied there are high luminance values. This made it necessary to show the results with a logarithmic scale. Since the simulation is based on measured weather data both the extreme low and extreme high luminance values were disregarded for thresholds. Low luminance values might occur at times with a very low solar altitude or times with very low direct radiation. Extreme high luminance values occur at times during the day with high solar altitudes and high direct radiation. However, solar panels are predominantly directed towards the sun for times with high radiation and high solar altitudes. This makes it highly unlikely to have situations in which the angle between the view angle on the panel and the angle of incidence of the sun on the panel is very small. Therefore, the range with the first steep incline, marked in Figure 4.1, was considered to be of further interest and is shown in Figure 4.2.

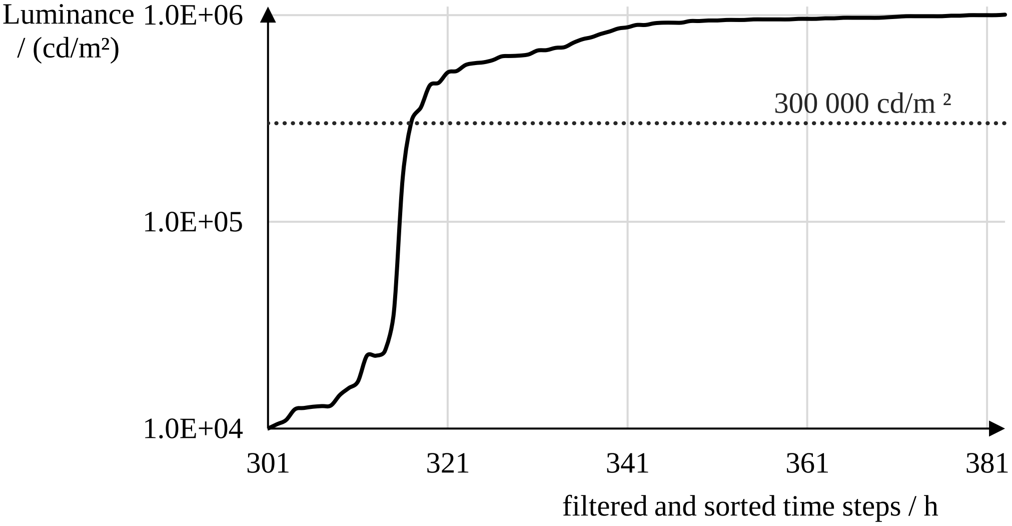


Figure 4.2: Segment of the results of the sun disk luminance study.

As shown in Figure 4.2 the further studied region has fast raising luminance values in the beginning as well and then stabilizes at higher indices. This fast increase was considered as a sign that luminance values in this magnitude are rather rare. A slow increase on the contrary shows that these values are rather common. The point on which the fast-increasing trend in luminance values start to shift to a slower incline is considered as a possible threshold. As portrayed in Figure 4.2 this happens at around a value of 300 000 cd/m² which therefore is used as a threshold for glare from the sun in this study.

The results of the simulations carried out with the developed outdoor glare methodology, described in chapter 3.1, show that reflections occur on mostly the left and middle third of the building surface, as it can be seen in Figure 4.3. For almost all the areas with reflections there are also times with glare, glare from PV panels is indicated by red areas, glare form the sun by yellow areas and green areas represent areas without glare at that given time step. However, it is clearly visible that in the upper half of the affected areas glare is mostly caused by reflections of the PV and in the lower half glare is mainly directly caused by the sun. In this visualization the glare threshold suggested by A. Jakubiec and C. Reinhart (2014) of 30 000 cd/m² was applied. The glare pattern is most probably evoked by the fact that the glare from the sun only occurs during morning hours when the angle of incidence of the sun on the panel is rather small. Figure 4.3 gives a general understanding where glare occurs and whether it is caused by the sun itself or by the PV installation. Albeit, it does not give an understanding on how often and at which times glare occurs.

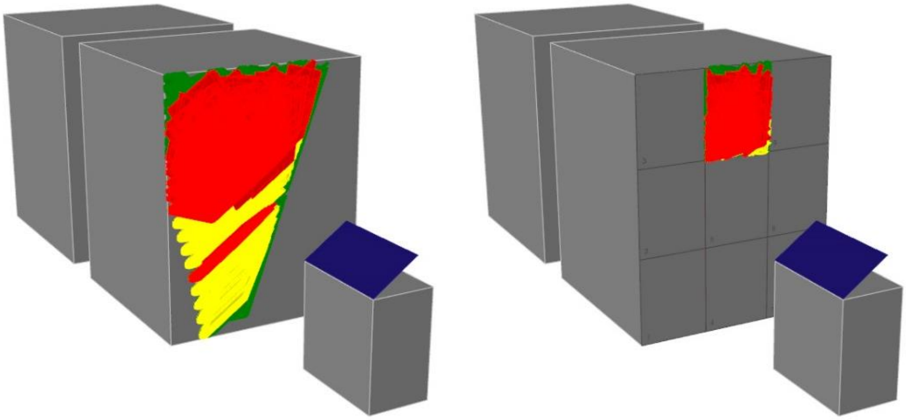
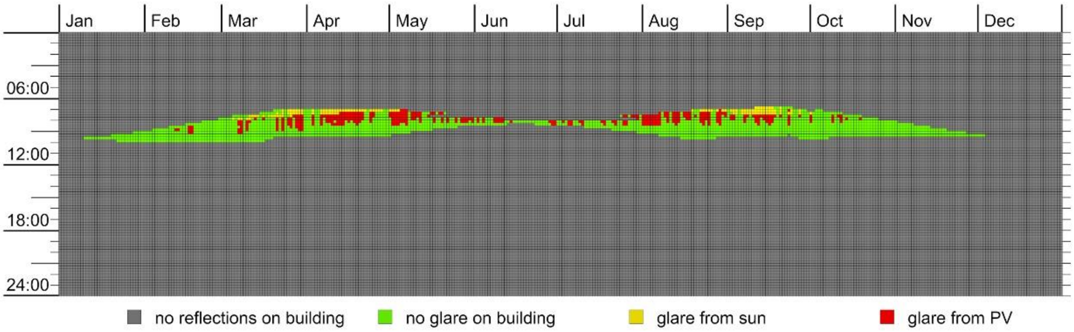


Figure 4.3: 3D visualization of the results of the study, for the whole surface (left) and for just one of the areas (area 6) (right)

In order to obtain an understanding of the points in time in which glare occurs it is more helpful to have a look into the representation of the results in a temporal map, as shown in Figure 4.4.



372 time steps with glare from PV
123 time steps with glare from the sun
1651 time steps without glare
32894 time steps without reflection on building

Figure 4.4: Temporal map of the study results for the area 6 of the building surface (area 6 is shown in the visualization on the right in Figure 4.3)

Since the component highlights the areas where glare occurs which is caused by the PV over areas with glare from the sun or times with no glare the 3D visualization gives the idea that the problem with glare is immense, and therefore there must be glare at an extensive amount of the time. The temporal map shows, however, that only for 372 time steps of the 2146 time steps with reflection, that means around 17% of the studied time steps, glare is caused by the PV. During these 372 time steps of glare from the PV there are 65 periods longer than 30 minutes, as shown in Figure 4.5. This shows that there are problems with long glare durations during spring and late summer between around 7:00 till around 9:00.

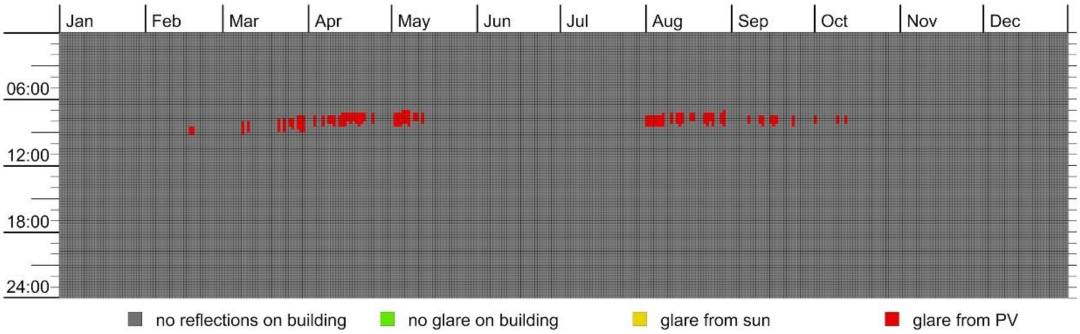


Figure 4.5: Temporal map for glare durations longer than 30 min (red)

To sum up the outcome of this study it can be stated that the PV panel, the way it was located in this scene, should be part of a further study since it causes severe glare to its neighbouring buildings. However, this result is favoured by the circumstance that the scene was specially designed for a high probability for glare in order to test the developed methodology.

A next step after this study would be to test placements further away from the neighbouring building or to test different orientations and tilt angles of the panel.

After carrying out a case study in a small 3D scene, as mentioned in chapter 3.2, for both the outdoor glare assessment and the DGP methodology, described in chapter 3.4, the results were used to compare whether the outdoor glare methodology gives similar results to the DGP. Figure 4.6 shows the temporal maps of the DGP study and the outdoor glare assessment, with an overlay for the months May and June.

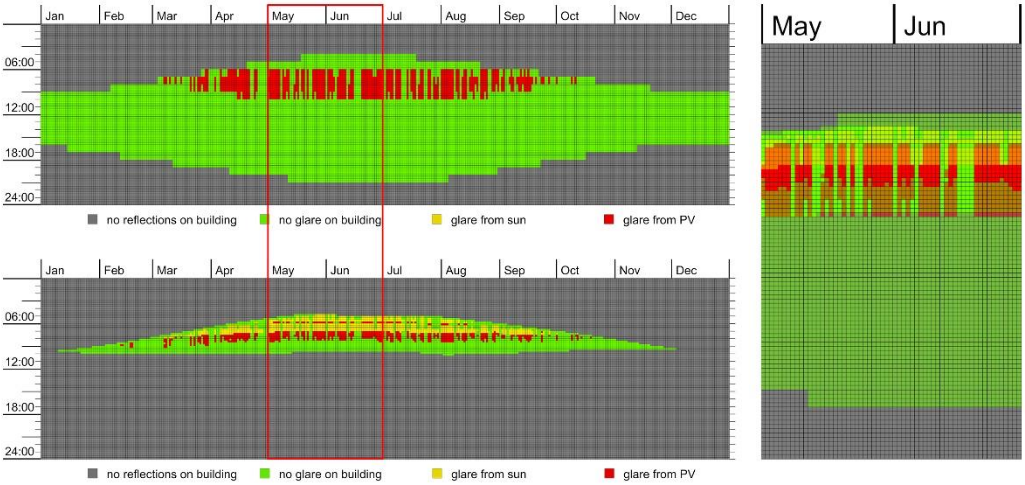


Figure 4.6: Overlay of the temporal maps of the result of the DGP and the outdoor glare simulations

As it can be assessed both methodologies detect glare mostly at the same days. The outdoor glare methodology, however, detects slightly more days with glare during the early spring and late autumn periods. In general, the results correspond with regard to the biggest amount of days. It becomes evident that the outdoor methodology detects glare earlier whereas the DGP shows glare for a longer period during the day, which can be seen in the overlay shown in Figure 4.6. This can have several reasons. As already mentioned in the methodology the DGP script considers all surfaces in the scene as potential glare sources. The outdoor script, however, only considers the PV panel itself. Furthermore, the viewing direction in the DGP strongly deviates from the view direction in the outdoor script. And lastly the DGP study was carried out for hour time steps, whereas the assessment method was made with 15 minutes time steps. Considering that both methodologies are based on different types of criteria, the DGP on the contrast and the outdoor script on the absolute thresholds, there is still a considerable overlap of glare times.
Furthermore, the two studies were also compared in order to determine which of the suggested thresholds comes closest to the results of the DGP simulations. This comparison is illustrated in Figure 4.7.

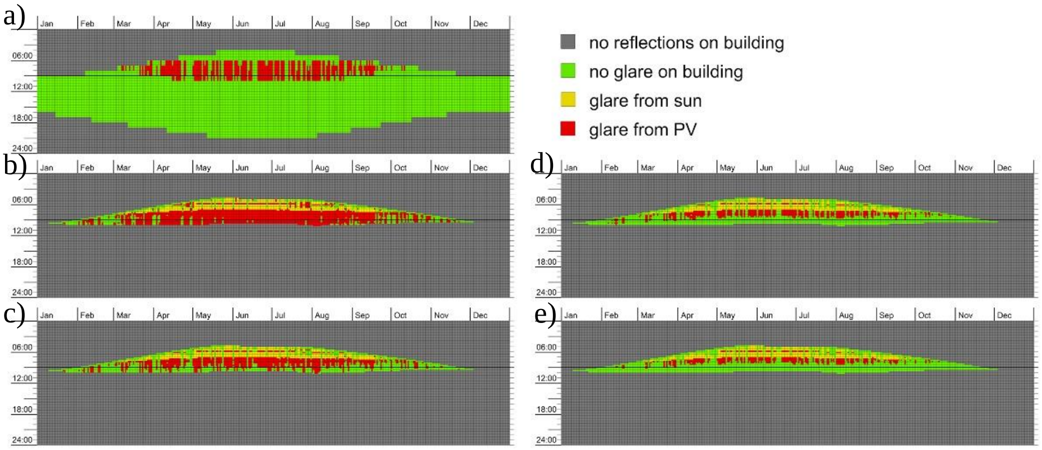


Figure 4.7: Comparison of the temporal map of the result of the DGP simulation (a) with the temporal maps of different glare thresholds [b) 4.000 cd/m²; c) 10.000 cd/m²; d) 20.000 cd/m²; e) 30.000 cd/m²]

As the figure illustrates the rather low threshold of 4 000 cd/m² indicates glare for almost all the time steps studied. Even at days and daytimes the DGP study shows no glare at all. On the contrary, the high threshold of 30 000 cd/m² shows glare caused by the PV for only a very small fraction of the time indicated by the DGP. This comparison suggests that the chosen threshold should be somewhere between the thresholds of 10 000 cd/m² and 20 000 cd/m². As mentioned above it has to be considered that there are several factors in the simulation of the DGP which could affect the result in a way that misleading conclusions are drawn. Therefore, it is better to study different thresholds and their effect on the outcome of the simulations simultaneously for now.

5 Conclusions

After considering the current legal frameworks and the studies conducted during this work, the results reveal that at the current point in time both the scientific and the legal situation considering glare outdoors and glare caused by photovoltaic panels require substantial improvement. In most of the countries the legal situation does not consider glare from PV systems at all or if it is mentioned it is not considered explicitly enough. Legal cases in this area are therefore extremely uncertain and the decisions can differ at different courts which can lead to long and expensive court proceedings.

Furthermore, there is a requirement of further research in the area of absolute glare thresholds in scenes with higher overall luminance values, like outdoor daylight situations. Moreover, a closer cooperation between photovoltaic manufacturers and glare experts should be aimed for in order, to make glare analyses more reliable. For example material data which are needed for reliable simulations are often not existent and if existent very expensive, since manufacturers have no or limited use of these information and carrying out measurements require expensive equipment. Therefore further research is needed to develop methodologies which produce reliable, approximated measurements and material data without the need of expensive equipment such as goniophotometers.

The assessment methodology developed in this study has to be verified by supporting simulations and studied in a higher number of cases. With a better understanding of thresholds for glare outdoors and a possible verification through further studies the method can be used as a reliable way to determine the possibilities for glare caused by PV panels.

In general, the assessment method for outdoor glare can be used for both existing PV systems which cause glare or planned PV systems to determine whether they will cause glare. In context of legal cases it can be used as a source of values about time, place and duration of caused glare and the method can also be used to investigate the effectiveness of measures which are planned to be taken against glare in case of already existent PV systems.

At the current state the assessment method is rather time consuming which has to be considered during the planning process. If there is doubt about the occurrence of glare the method can be used to determine the risk. In case of studies of already existent PV systems the assessment method, however, is a more time effective alternative to annual measurements. Considering the acceptance of such studies and reports by judges, as seen in the legal cases in Germany, it has to be clarified beforehand if the methodology would be accepted.

6 Summary

With the increasing trend of PV panel installations, there is also an increasing risk of glare from PV. Therefore, this thesis was performed to develop an assessment method to determine, if there is risk of glare on the surrounding buildings from a PV installation.
To determine the basis and limitations of the method, the theoretical background needed to be researched, this was done in three parts, with an aim to answer the first three research questions.

The research questions that were set for the thesis were as following:

1) What is the current state-of-art in regulations?
2) How can glare be defined?
3) What are the thresholds of glare?
4) How can a method to assess glare caused by PV panels be developed and how does the method look like?

First, a study of the legal situation in Germany, Ireland, South Africa, Sweden, The United Kingdom and the United States of America were performed to find out if there were any laws, regulations or guidelines regarding glare. It was found that only Sweden and Germany had laws about glare and that South Africa was the only country of those studied that did not have any regulations about glare. Furthermore, all countries had guidelines about glare, but only Germany and The US had specific guidelines for glare from PV panels and thus the first research question was answered.

In the second study for the theoretical background, the different ways to define glare were investigated. As many as twenty ways to define glare were found from various sources and the second research question was thereafter answered.

The third study for the theoretical background focused on investigating the existing thresholds for daylight glare for both indoor and outdoor situations. As indoor glare is something that has been extensively studied, the thresholds for indoor conditions are widely accepted. However, since outdoor daylight glare is not as extensively studied, with no subjective testing, the existing thresholds for outdoor conditions are more suggestions than widely accepted. With this the third research question was answered.

In the end of the three studies for the theoretical background it was concluded that the German regulations would be the basis of the study, that a few ways to define glare were of interest to the study and that all the existing outdoor thresholds needed to be considered in the assessment method.

With the basis and thresholds decided, the methodology could be developed. Beginning with preparing the 3D-geometry to minimize the simulation time, by removing all geometry that did not face the PV panel of interest. Thereafter, geometrical calculations were performed to see when there is risk of glare. This was done by looking at how the solar vector reflected upon the solar panel, with three different outcomes. The first, where the solar vector is blocked by a surrounding building and therefore never reaches the panel; the second, where the solar vector is not blocked, but does not reflect on a surrounding surface; and last, where the solar vector is not blocked and reflects onto a surrounding surface.

With the outcome of the third case, luminance simulations could be performed to determine the intensity of the reflected light to determine if there is glare. This was done with image based simulations where a camera was set, facing the panel against the reflection vector. From those simulations, the maximum luminance values for every timestep could be acquired.

The calculations and simulations could thereafter be combined to show where and when glare occurs. It was also needed to perform two supporting studies, in the first study a threshold for when direct glare from the sun occurred instead of reflection from the PV panels were decided. In the second study, the results of the methodology were compared to the results of a DGP study, performed with the same geometry, to get a better view on how the developed method performed.

In the end, it was concluded that outdoor thresholds for daylight glare need to be researched further and that the accessibility of the optical properties of PV panels needs to be increased. The legal situation also needs to be improved in all the studied countries, as the country with the most extensive and general rules still gave too much room for personal judgement. However, once this study has been verified it can be used in the early planning process and to make it easier for courts to make judgement. It can also be used for other surface materials and are therefore not only limited to only PV panels.

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Appendix A: Manual for the Grasshopper script

INSTALLATION

The Grasshopper User Objects have to be saved in the Special Folder>User Object Folder, after that they are installed in the “PVGlare” tab. The following plug-ins must be installed:

- Ladybug
- Honeybee
- Horster Camera
- DIVA
- Mosquito

MANUAL

1. The **CreateFolder+Batch** component has to be placed and the desired file path of the main folder has to be plugged in.

   This creates the needed folder structure for the result .txt-files and the batch files which combine them are written. It is suggested that the file path should be local for the computer since an excessive amount of files is going to be created.
2. The **ExportCalculations** component has to be placed and connected to the CreateFolder+Batch component. Also a toggle has to be placed in order to toggle the function of the component, whether result files are written or not.

   The component, in case the writeResultFiles function is switched on, writes the data for TSOIFloat, TSOIInt, LL, NPOI and POI for each calculated time step to the sub-folders created earlier. This is based on the input of ImpPointInView, NImpPointInView and TSOY.
3. After the structural components are placed, the first component connected to the project can be placed. This is the panel geometry (surface, brep) which is then plugged in into the **PVgrid** component. As a second input the grid size is needed in meters.

   The grid surface will be divided into an equal grid, which means that the actual grid size can slightly differ from the plugged-in grid size since the closest to the given size which creates an even distribution of the grid is used. The grid therefore does not have to consist out of squared regions. It is also important that the panel surface should not touch or intersect with the geometry of a surrounding building.

4. The PVGrid is then used as one of the inputs of the **BuildingFacingPanel** component. This component filters the building surfaces facing the PV panel from all the building surfaces plugged in. Therefore, another input is the geometry of the surrounding buildings. The two other inputs are the radius of the studied area in meters and the decision if the surfaces which are sharing the same plane with the origin should be included in the geometry (True) or not (False).

   It is not possible to use curved geometry or meshes. Curved geometry has to be triangulated, which can perhaps cause some margin of error.

5. With the output of both the PVGrid and the BuildingFacingPanel component the **SkyDome** component can be used. As an input for RadiusOfStudy the same radius as for the facades facing the panel should be used.

   Due to high computing loads while creating the SkyDomes it is suggested to internalize the created SkyDome geometry and disable the component after the first run. However, it has to be kept in mind for changes in the geometry to rerun this component. Also the biggest portion of the sky has to be visible to the PV panel, otherwise it might be possible that a wrong part of the SkyDome is considered to be visible to the panel.

6. With the panel geometry, the PVGrid points, the FacadesFacingPanel, the visibleSkyDome and the radius all the necessary input from other components is created. To be able to run the **ReflectionCalculation** component only the day, month and hour value of the TSOY and the file path of the .epw weather file is required. To obtain the day, month and hour values it is suggested to use the calculator from ladybug since it can handle hour values outside of an integer format.

   With this input connected to the component and a slider connected to the Ladybug_Day_Month_Hour calculator, only the output of the ReflectionCalculation component has to be connected to the ExportCalculations (from step 2) and also the slider for the TSOY, which is plugged in into the Ladybug component has to be connected to this component.

7. With all this set up the calculations can be carried out. To accomplish this the slider plugged in into the **Ladybug_Day_Month_Hour** calculator has to be animated. The results of the calculations are automatically saved to the sub-folders created in step 1.

   The maximum frame count for animated sliders in grasshopper is 10.000 frames. Therefore, four sliders have to be created (0-9.9999, 10.000-19.999, 20.000-29.999 and 30.000-35.040). To simplify the alternation between the sliders it is suggested to interpose a data component between slider and Ladybug_Day_Month_Hour calculator.

8. After finishing all the calculations the result .txt files have to be combined. This is done by running a batch file which was created in step 1. In order to do this the **RunBatch** component is used, by connecting first the file path of the parent folder and then a button to the resultCalculation. The batch file can be activated with a click on the button.

   Even though it might be more handy to just use one button for both batch files it is suggested to use two buttons, in order to not rerun the resultCalculation batch file later in the process.

9. After combining the result .txt files the results have to be imported back to grasshopper again. This is done with the **ImportResults** component. Only the

parent folder file path is needed and two togglesin order to activate the import of the results.

As long as the imported information is needed the toggles have to stay on True, however if the result .txt files change, for example by rerunning the batch files, the toggle has to be set to False and then True again.

10. After calculating the points of incidence the luminance of the glare spot has to be determined. The **SimulateLuminance** component has to be placed on the canvas. As an input the Radiance material, the ResultTSOIFloat from the ImportResult component, the panel geometry, the folder paths for MaxL and MaxLTSOI and the file path of the weather file are needed. Further on toggles are needed in order to write the result files and to run the simulations. Based on the ResultTSOIFloat input the NumberOfTSOI is given out by the component. This number is needed to set the slider which has to be plugged in into the index input. Afterwards the writeResultFiles and runSimulation toggles can be set to True. After the first simulation is finished the slider can be animated to accomplish a simulation process without need of supervision.

    It is also possible to set the number of CPUs of the computer to speed up the simulations.

11. After finishing the simulations step 8 and 9 have to be repeated for the simulation results.

    Congratulations the calculations and simulations are finished.

12. With the results of TSOIFloat, TSOIInt, LL, NPOI, POI and MaxL and the thresholds for glare from the sun and glare from the PV the **GlareResult** component can be used.

    Thresholds for both PV and sun can either be set manually or the GlareThreshold component can be used. Here the PVThresholdValue can be chosen to be either 4.000, 10.000, 20.000 or 30.000 cd/m² according to the literature study conducted, and the SunThreshold is fixed at 300.000 cd/m² according to our sun luminance study. This component also has a text output stating the threshold and the researcher it is based on.

After this step it has to be decided in which way the results are supposed to be presented. In general, there are two major ways of presentation: either as a 3D view of the scene or as a temporal map. For both ways the results can be either shown for the whole surface or for one or several regions of nine predefined regions of the building surface (the function to divide the surface so far only works for one building surface at a time). For temporal maps there is the additional function to show only periods with a glare duration of more than 30 minutes. For the 3D view it can be chosen if all the time steps are supposed to be shown at the same time or whether the index of the time step of interest is used as a way to navigate through the year.

3D view of the whole surface with all the time steps at the same time

1. To create a 3D view of the whole surface, the GlareIndex, ReflectionAreaTrueFalse and ReflectionArea input from the GlareResult component have to be plugged in into the **GlareGeometry** component.

   This component creates the GlareGeometry.

2. The GlareGeometry and the GlareIndex from the GlareResult component then have to be used as input for the **UnisonGlareVisual** component.

   Like in the temporal map component red reflection areas show areas with glare from the PV, yellow areas are areas with glare from the sun and green areas are areas with no glare.

3D view of the whole surface one time step at a time

1. To create a 3D view of the whole surface the GlareIndex, ReflectionAreaTrueFalse and ReflectionArea input from the GlareResult component have to be plugged in into the **GlareGeometry** component.

   This component creates the GlareGeometry.

2. The GlareGeometry and the GlareIndex from the GlareResult compontent then have to be used as input for the **TSOIGlareVisual** component. By using a slider for input as the TSOIIndex the desired time step can be selected.

   Like in the temporal map component red reflection areas show areas with glare from the PV, yellow areas are areas with glare from the sun and green areas are areas with no glare.

3. A text flag can be added on the upper left corner of the surface showing the date of the displayed glare situation. For this the ResultMaxLTSOI, the ReflectionAreaTrueFalse, the FacadesFacingPanel and the TSOIIndex input are needed to put in into the **TSOIGlare3Dtxt** component.

   To ensure that the correct date to the shown GlareGeometry is depicted it is helpful to use the same slider for the TSOIIndex input for step 2 and 3.

3D view of glare in specific building surface areas for one time step at a time

1. The building surfaces are divided into a grid with 9 subareas by the **AreaIndex** component. For this the StudiedSurface and the resultPOI2 input are needed.

   It is only possible to use this component for one surface at a time, so the list_item component should be used to select the desired surface.

2. With the next component called **ShownAreas** it can be decided which of the areas of the building surface is supposed to be studied. This is done by using the IndexOfAreasShown as an input. Furthermore, resultPOI2 and resultNPOI2 from the GlareResult component are needed.

3	6	9
2	5	8
1	4	7

Figure A: Indices of the nine sub-surfaces

The indices for the nine surface areas are shown on the left in Figure A. The index 0 shows all the points outside the studied surface. It is possible to set one or several indices as study area. If for example the middle horizontal level of the building is of interest, the indices 2, 5 and 8 can be used. The **FacadeAreas** component shows the area grid on the left in the 3D view in order to make it easier to visualize the different areas.

3. In order to visualize the chosen area the component **AreaVisual** is used. It needs the ShownAreas information from the ShownAreas component and the GlareIndex. Furthermore, it needs the TSOIIndex of the time step which is supposed to be shown.

   If several time steps are supposed to be shown at one time they have to be set as a tree with a separate branch for each index.

4. Like for the other 3D views it is also possible to add a 3D text flag to the surface by using **txtAreaVisua**l. The studied surface geometry, resultMaxLTSOI, ReflectionAreaTrueFalse and TSOIIndex are needed as input.

   This component is only functional for single time steps.

Temporal map

1. The same steps as in “3D view of glare in specific building surface areas for one time step at a time” steps 1 and 2 have to be made.

2. The results can also be shown in a temporal map. For this the component **TempMapCalc** is used. As input resultPOI2, the GlareIndex, the ShownAreas, TSOIFloat and ReflectionAreaTrueFalse are needed.

3. In order to visualize the temporal map the component **TempMap** has to be used.

   In case there is no origin set, the origin will be at {0,0,0}.

Temporal map – Duration

1. The same steps as in “Temporal map” have to be followed.

2. However, the output of the **TempMapCalc** component has to be used as input of the TempMapDuration component, which also needs the TSOIofPVGlare as input.

3. The output of the **TempMapDuration** component then can be used as input data for the TempMap component.

   Only periods with 30 min or more of glare from the PV are considered. It also has a text output of the number of glare periods.

Information text

1. The component **txtGlareInfo** gives output about the length of the glare season, the time steps with no glare, with glare from the PV and with glare from the sun. For this the TSOIofPVGlare and the GlareIndex input are needed.

Nomenclature

Abbreviation	**Full name**	**Explanation**
TSOIFloat	Time step of interest float	Time step of interest in a float format (e.g. 526.25)
TSOIInt	Time step of interest integer	Time step of interest in a six digit integer format (e.g. 052625)
LL	List length	Length of the list of points of incidence from the reflection at building surfaces
NPOI	Normal of point of incidence	The normal vector of the building surface at each given point of incidence
POI	Point of incidence	The coordinates of each point of incidence
ImpPointInView	Impinging Points in View	The coordinates for all the impinging points of reflections on a building surface in direct view from the PV panel, also POI
NImpPointInView	Normal at Impinging Points in View	The normal of the building surface for all the impinging points of reflections on the surface in direct view from the PV panel, also NPOI
TSOY	Time step of year	Similar to HOY (hour of year) the time step of year with a smaller interval
MaxL	Maximum luminance	The value of the maximum luminance in the scene
MaxLTSOI	Maximum luminance time step of interest	The time step on which the corresponding maximum luminance occurs

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