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Analysis and quantification of visual glare caused by photovoltaic panels installations in urban canyons

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Abstract

The abundant use of solar panels in dense urban areas is causing severe visual discomfort because of the reflection of sunlight falling on their surfaces. These intense reflections can cause a disabling glare, which impairs the surrounding building occupants' vision and hinders them from performing their daily tasks. In order to better predict glare caused by photovoltaics panels (PV) the research study will present comprehensive simulations to measure the amount of light reflected of PV arrays to accurately calculate the probability of glare occurring on such case studies. Glare simulations will be conducted for every hour in the entire year. Additionally, detailed glare analysis will be performed by creating High Dynamic Range (HDR) renderings in multiple locations within an office building facing a building facade that is fitted with PVs. Subsequently, the simulation results will be statistically analysed to explore the effect of PVs on occupants'' visual comfort. A detailed conclusion of the outcome of the quantitative glare analysis will be introduced as well as a brief discussion on future studies needed to improve visual comfort in dense urban areas.

Keywords: glare, photovoltaics, solar panels, occupants comfort, urban canyon,

1. Introduction

Solar elements have been increasingly integrated in building façades as architectural elements to generate electricity and to improve the aesthetic features of new and existing buildings [1]. Building-integrated photovoltaics (BIPV) are photovoltaic (PV) materials used to replace traditional building envelop materials, such as roofs, light shelves, or façades (Hammer, 2014). They are incorporated into the construction of new buildings; additionally, they are used for existing building façade retrofits. BIPVs are becoming popular because their initial cost is redeemed by reducing the cost spent on the building materials used to build the part of the building envelop that the BIPV modules replace. Another advantage of using PV and BIPV modules is that their installations can earn up to three Leadership in Energy and Environmental Design (LEED) credits, making them highly desirable to architects and clients [2]. Reflective glazing is another popular architectural element that has been widely used in facades. The international style that massively employed the glazed facades in buildings is still a source of inspiration for the building designers around the world, in spite of the wide variation in the illuminance availability and thermal requirement among the different climatic regions. The increasing preference to use reflective glazed facades in office and public buildings, regardless of the geographical location or climatic region, is a major contributor to discomfort glare in indoor spaces. The vast majority of PV panels have a front surface made of glass. As far as reflection is concerned, PV panels behave much like glazed building facades; some sunlight is reflected off PV modules into surrounding buildings.

The abundant use of solar panels in dense urban areas is causing severe visual discomfort because of the reflection of sunlight falling on their surfaces. These intense reflections can cause a disabling glare, which impairs the surrounding building occupants' vision and hinders them from performing their daily tasks. A new installation of a photovoltaics (PV) array, consisting of 2,478 panels, at a Massachusetts airport has caused severe specular reflections that prevent visibility of the aircraft on the taxiway. It has also caused a disabling glare, resulting in difficulty viewing the computer screens inside the airport control tower (Jakubiec & Reinhart, 2014). Similarly, a 42-story high-rise museum in Dallas, Texas, was fitted with a large array of PV panels on its façade, which caused intense specular reflections into the adjacent Nasher sculpture museum that resulted in glare and extreme heat gain inside the museum damaging the sculpture in display, sculptures had to be moved away from the window to protect them from being damaged by the reflected sun rays. Museum officials spent three years and more than $1 million working on possible solutions to the problem [3].

Glare impairs visual performance and well-being, leading to premature fatigue and headaches, blurred vision and eyestrain. Glare problems can worsen in office environments where there is a need for frequent and extended computer usage. The increasing use of various digital technologies in offices can create substantial challenges for offices occupants in processing information and performing visual tasks throughout the day. Kuratorium et el stated workers switch views back and forth between manuscript, keyboard and computer monitors up to 30,000 per day [4]. Therefore, creating a visually comfortable environment in office areas could help reduce strain on workers' eyes that must constantly adapt to different visual tasks and ultimately increase workers' productivity.

For the last decade, researchers have focused on creating well daylit indoor spaces specifically within office environments. Researches often emphasised the benefits of daylighting such as health improvements and energy savings. Research has shown that daylight has a beneficial effect on the physical and psychological health of humans. The Lighting Research Center suggested that our biological clocks are regulated by light levels and wavelengths characteristic of daylight and that changes to this cycle can affect our circadian rhythms, causing fatigue [5]. In 1999, the Heschong Mahone Group studied the relationship between exposure to daylight and the performance of school students and concluded that students in classrooms with the most daylighting progressed 20% faster on math tests and 26% faster on reading tests over the course of a year than those in classrooms with the least daylighting [6].

Most research studies have focused on increasing illuminance levels on work planes disregarding the effect of glare on workers' visual comfort causing fatigue and less productivity. Glare can occur due to poor daylighting strategies that allow open views to sky. Recently, some research studies emphasized the need to investigate glare in environments that are being occupied for long hours such as schools and office buildings. [7] This research study will focus on analysing glare caused by sunrays reflected of photovoltaics panels installed on buildings that exist in dense urban canyons. Glare analysis is carried out in high-rise office building located across from a building façade that is fitted with a Photovoltaics array.

2. Methodology

2.1 Geometric Model

To better analyse solar glare caused by PVs arrays two high rise office buildings are modelled in Rhinoceros, a 3D NURBS (Non-Uniform Rational B-Spline) modelling program. The location of the modelled buildings is set to Houston, Texas, USA (location latitude and longitude of 29.8° N, 95.3° W respectively). The month with the highest historical solar radiation values in Houston is June with an average of 5.54 kWh/m^2, followed by August at 5.45 kWh/m2 and July at 5.44 kWh/m2 [8]. the office building is 20-floor high. Both buildings lie across from each other on the sides of a 15m wide urban canyon, a typical street width in downtown Houston [9]. The first building is 25-story high, its facade is fitted with a photovoltaics array and faces south. While the other building is modelled as an office building and its perimeter consists of 10 medium sized offices (5m x 4m), each office has one window that is 4m wide by 1.25m high and faces north, ceiling height is 3m (Figure 1).

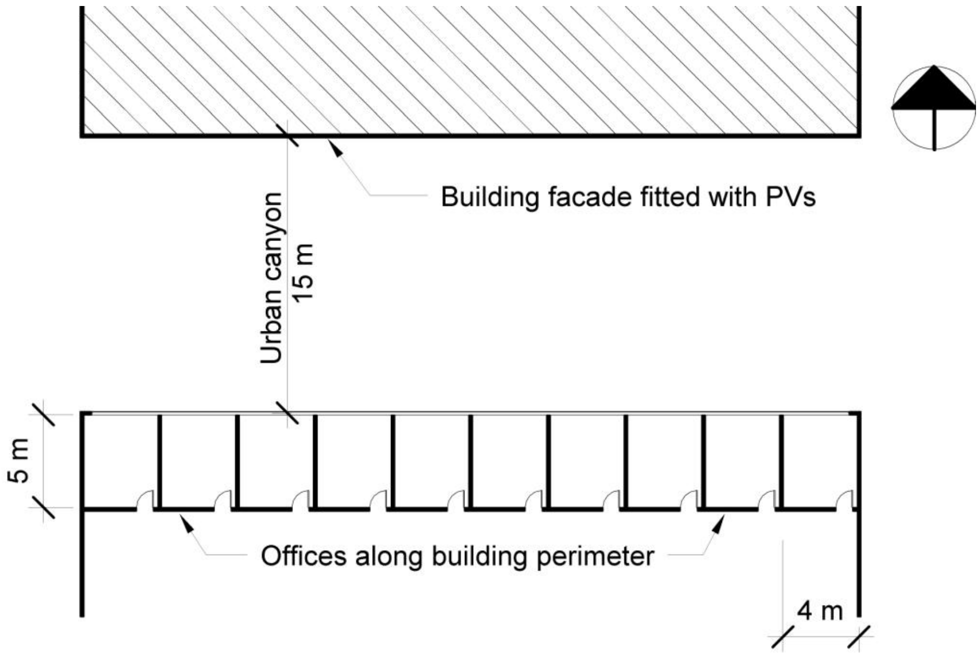

Figure 1: Floor plan of both modelled buildings.

2.2 Simulation tools

Given the complexity of the daylighting simulations being carried over, the use of a parametric modelling environment was determined to be essential for the purpose of this study. Therefore the modelled buildings were exported to Grasshopper; Rhino plugin, which is a graphical editor that allows designers to create algorithmic geometries without programming [10]. Grasshopper, facilitated the integration of various simulations data for detailed analysis and examination. In addition to Grasshopper, two daylighting analysis plug-in were used, DIVA 3.0 which stands for Design Iterate Validate Adapt [11] was used for rendering high dynamic range (HDR) views for detailed glare analysis. The other plug-in is Honeybee-Ladybug (HB-LB) which was used for manipulating different Rhino views and performing annual glare analysis for all interior views. Both plug-ins call Radiance engine, a ray-tracing daylighting simulation engine [12] and Daysim engine.

2.3 Model setup and Glare anaylsis

Several glare indices have been developed over the past decade to assess glare in views within interior spaces. One of the most commonly utilized methods to measure Daylight Glare is the Daylight Glare Probability (DGP) developed by Wienold and Christoffersen and based on laboratory studies in daylit spaces in two different locations; Freiburg, Germany, and Copenhagen, Denmark, in order to assess glare, the study tested 72 different objects under various daylighting conditions. DGP showed remarkably high correlation with the user response regarding Glare perception [13]. Another widely used metric is a luminance based one that uses a luminance value threshold to specify high luminance values that represent glare in the examined view [14]. For the purpose of this study DGP was used for annual glare analysis and luminance-based method was used for specific views that were determined to have intolerable glare numerous times during the year.

To better evaluate glare caused by PVs a base case study was setup where the building across from the office building was modelled with a façade that have traditional double glazed windows with window to wall ratio of 70%. A second case study was setup where glazing was replaced by a large array of PVs that covers the entire building façade facing the office building being examined in this research study.

Assigned Radiance materials and their properties are listed in Table1. Unfortunately, reflection data for PV panels is unavailable from PV panels manufacturer. However, in a study completed by Protogeropoulos and Zachariou from Phoenix Solar EPE, located at Athens, Greece, a PV module reflectivity was calculated using an accurate spectrometer. PV Reflectance was determined to be 15% for incident angles of up to 45^{o} [15]. Radiance parameters used for glare simulations are listed on Table 2.

Model object	**Radiance Matreial Property**	**Model object**	**Radiance Matreial Property**
Office interior wall	20% refelectance	Office ceiling	80% refelectance
Office window	80% transmittance	Photovoltaics glass	15 % refelectance
Office floor	20% refelectance	Street ground	20% refelectance

Table 1: Model Radiance material assignment and their properties.

In both case studies a Rhino view was created in each office (a total of 200 interior views for the entire office building model), Later all 400 views were analysed for annual glare by calculating DGP for each hour in the entire year. DGP values from all 400 were analysed to determine views with highest peak of glare. Finally, those were rendered to create 180 degrees fisheye HDR images. High Dynamic Range renderings have been used in assessing glares which is caused by a high ratio of luminance between the task that is being looked at and the glare source. HDR rendering is capable of a representing the full dynamic range from brightest light (direct sunlight) to darkest spots such as deep shadow in the examined scene, making it one of the best tools to assess glare [16]. Both annual glare simulations and HDR renderings used CIE standard clear sky [17]

3. Results and discussions

The data obtained from Radiance was enormously large to be analyzed manually. For each case study 200 text files were generated, each file contains DGP index for each hour of the year (HOY), that means that each file contains 8760 DGP values. To facilitate accurate and fast analysis for such a large set of data, computer scripts were written in Python, a computer programming language, to extract DGP values from the obtained text files and, which were also manipulated by a custom built Python script to automatable perform statistical analysis and create graphs. For better visualization of the data results, extra set of JavaScript and HTML codes, were written to create dynamic graphs, those dynamic graphs can serve as a real-time display of the generated data without effort from the researcher or architect’s side making those graphs an easy tool for the non-technical designer to quickly estimates glare conditions, additionally, they facilitate various trade-offs in the early design process. The availability of trade-off options in early stage design is proved by multiple research studies to be an invaluable asset for designers and architects to achieve performance optimized design [18]. Dynamic graphs can’t be displayed on paper media; however, some static images of the graphs are shared within this paper.

Statistical analysis of DGP values within all 200 views for each case study were sorted by hour in order to investigate the possibility of glare occurrence during the entire year from hour 6 to 18. DGP values less than 0.35 means that the view has imperceptible glare, a view with a DGP value between 0.35 and 0.4 that the view has a perceptible glare occurrence, a DGP value between 0.4 and 0.45 means that the view has a disturbing glare occurrence, lastly, a view with a DGP value over .45 is considered a view with intolerable glare. DGP were relatively higher during the time between 11 and 15 where the median values DGP values for the case study with the traditional glazed façade are between 0.31 and 0.32 and the 75th percentile of the hourly DGP values are between 0.37 and 0.38. Although the case study showed some high glare occurrences, the statistical analysis for the second case study that includes a Façade fitted with PVs showed higher DGP values for all 200 views where the median DGP values between the hours 11 and 15 are between 0.36 and .37 and the 75th percentile of the DGP values are between 0.42 and 0.43.

A similar statistical analysis was performed to determine the most glare occurrences by month, similar pattern was detected; DGP value were higher in views within the second case study that has a façade fitted with PVs. For instance, the median, 25th percentile, and 75th percentile DGP values on the month of November for the first case study with the traditional glazed façade are 0.25, 0.19 and 0.32 respectively and for the second case study are 0.29, 0.20, and 0.41 (see table 2).

Case study with glazed facade	Month	25th percentile	Median	75th pecentile	Case study with PVs fitted facade	Month	25th percentile	Median	75th pecentile
	1	0.06	0.25	0.30		1	0.08	0.27	0.37
	2	0.21	0.26	0.32		2	0.21	0.28	0.36
	3	0.22	0.28	0.34		3	0.22	0.30	0.38
	4	0.25	0.29	0.34		4	0.25	0.31	0.38
	5	0.26	0.30	0.34		5	0.27	0.32	0.36
	6	0.27	0.30	0.35		6	0.28	0.32	0.36
	7	0.27	0.31	0.36		7	0.29	0.33	0.37
	8	0.25	0.30	0.34		8	0.26	0.32	0.38
	9	0.24	0.29	0.35		9	0.24	0.32	0.40
	10	0.22	0.28	0.34		10	0.22	0.31	0.39
	11	0.19	0.25	0.32		11	0.20	0.29	0.41
	12	0.06	0.25	0.30		12	0.08	0.27	0.37

Table 2: Statistical analysis of the DGP values obtained for both case studies.

Similarly, a detailed analysis of the hourly DGP values were performed for each individual view. Three views were chosen to further investigate the effect of installing PVs in dense urban areas. View A is a view inside an office in the middle of the building that is located on the first floor. View B is a view from inside the office in the middle of the building and is located on the 10th floor, view C is a view from inside the office in the middle and is located on the top floor. To make reading the results easy and avoid any confusion, views A, B, and C within the case study with glazed facade are named A1, B1, and C1, and A2, B2, C2 within the second case study with the PVs fitted facade respectively. As shown in Figure 2. The maximum increase in DGP median values were between the hours 9 and 17 when the median DGP values were increased by up to 18% in view B2. View A2 had increased median DGP during the hours between 9 and 17, while DGP median values were increased by up to 20% in early morning and late afternoon hours. Figure 3. shows Increased median DGP values on A2, B2, and C2 as compared to view A1, B1, and C1. the maximum peak in DGP values happened in the winter when sun is low in the sky.

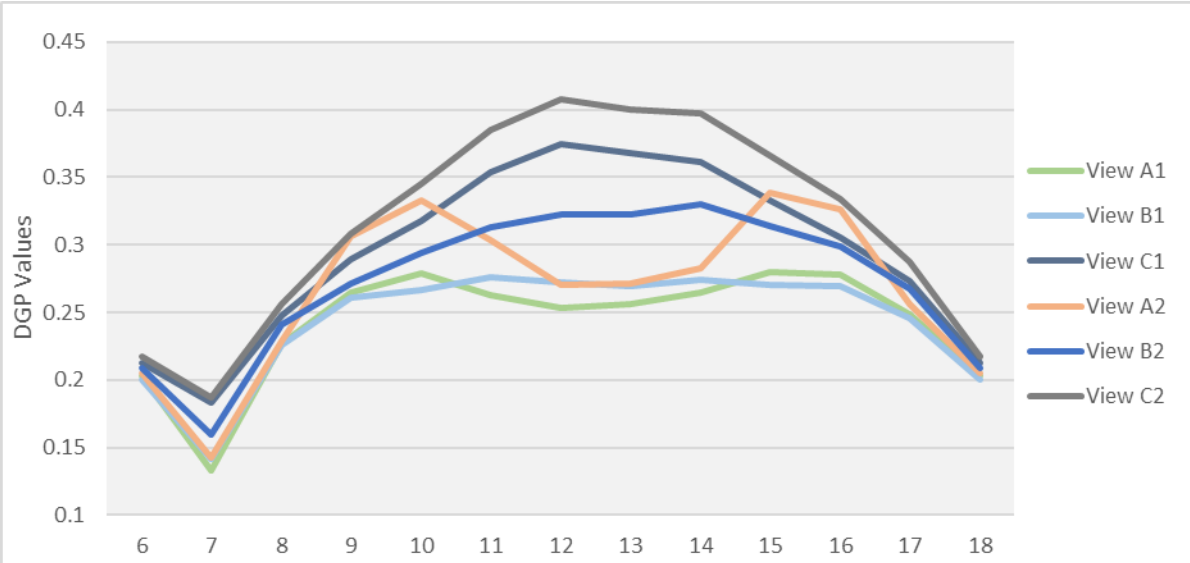

Figure 2: Median hourly DGP values between the hours 6 and 18 values for views A, B, and C for both case studies

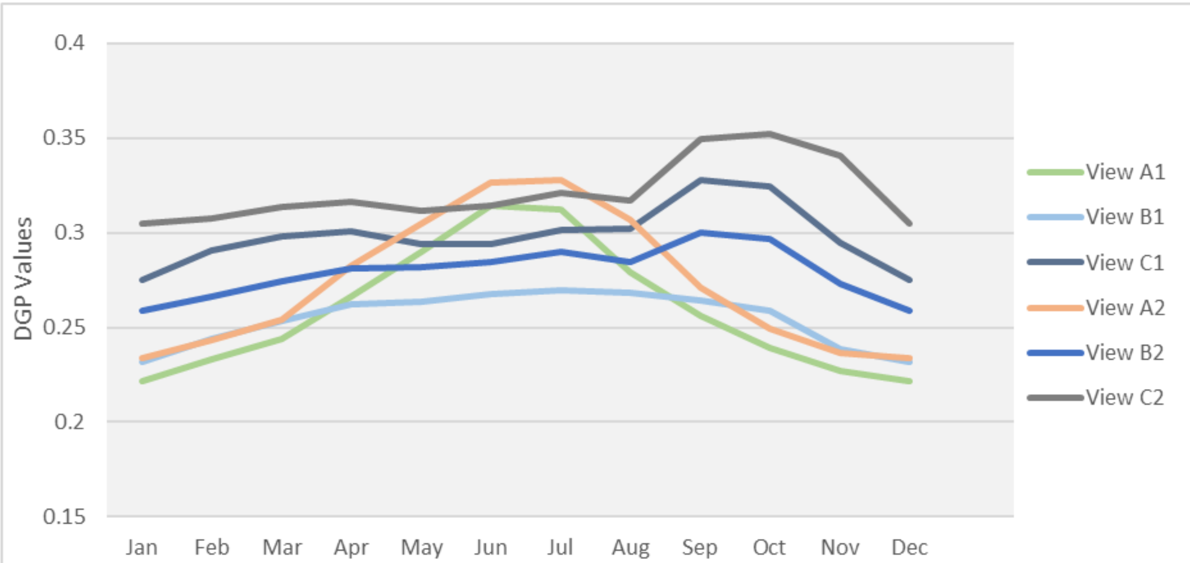

Figure 3: Median monthly DGP values for views A, B, and C for both case studies

Figure 4 and 5 show a static image of the dynamic graphs created to show continuous hourly DGP values of view B1 and view B2 between the hour 6 and 18 for the entire year. It is clear that DGP values were increased throughout the entire year in view B2 due to the sunlight reflection off the PV module installed on the façade. Additionally, Glare in view B2 becomes intolerable in early morning and late afternoon on January, February, November and December,

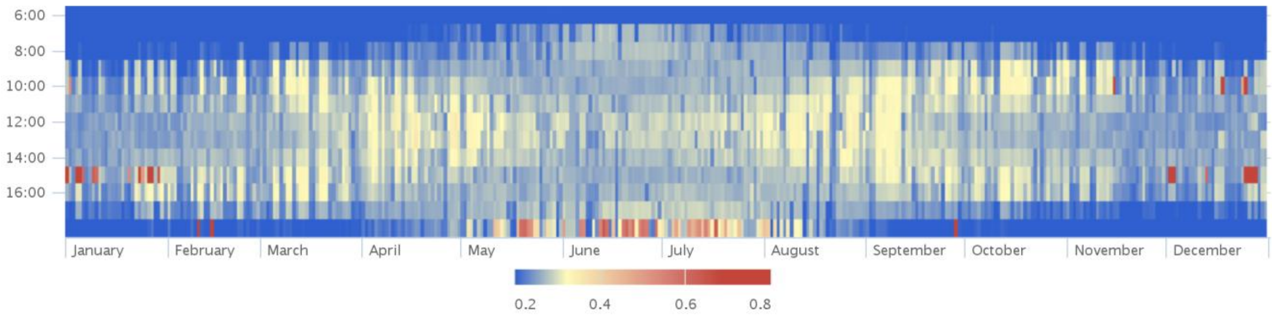

Figure 4: Continuous DGP values for the hours between 6 and 18 (view B1)

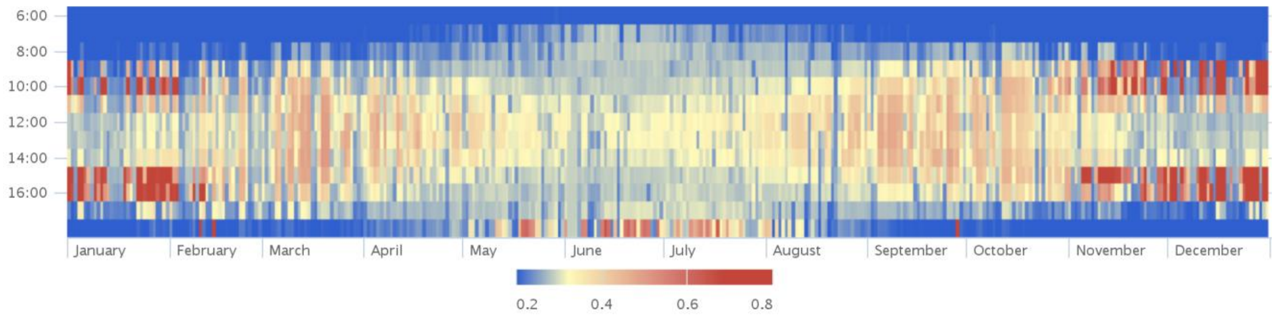

Figure 5: Continuous DGP values for the hours between 6 and 18 (view B2)

4. Recommendations for future work

Although there are various PVs that are widely available from manufacturers worldwide, there is a lack of optical properties of those PV modules. Optical properties facilitate simulating materials using proper Radiance definition. Therefore, there is an increased need for measured PV optical properties that could help architects and designer accurately simulate various PV modules to better evaluate their effect on occupants' visual comfort specifically in dense urban areas. For the purpose of this paper a PV reflectivity of ! 15% was adapted for the glare simulations however, PV reflectance value can increase up to 40% for higher incident angles [15]

Furthermore, there is a significant lack of research on the impact of thermal reflections from PV installations in densely populated places on people. Future work is needed to explore and quantify the thermal effects of PVs within urban contexts.

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