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AI-Enabled 3D Glare Assessment Framework for Urban Solar Planning

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1. Introduction

Singapore, a highly urbanised city-state with severe land constraints, has rapidly expanded solar photovoltaic (PV) deployment, achieving 1.5 GWp of installed capacity and progressing towards at least 2 GWp by 2030 [1]. Due to limited availability of land for ground-mounted and floating PV systems, the majority of existing and future installations are deployed on buildings, including rooftops, building-applied, and building-integrated photovoltaics (BAPV and BIPV).

As urban solar deployment scales, intelligent planning and optimisation become critical, particularly in high-density cities where competing spatial, visual, and safety constraints must be considered. One key challenge is glare from solar PV modules, which can affect aviation safety, road users, and occupants of neighbouring buildings. While glare assessment is well established in controlled contexts such as airports, it has emerged as a broader urban safety and visual-impact concern as PV systems proliferate across dense city environments.

However, most existing glare assessment tools rely on simplified assumptions, such as unobstructed line-of-sight between the sun, PV surfaces, and observers. These assumptions rarely hold in complex urban settings with dense buildings and infrastructure. This limitation motivates the need for scalable, obstruction-aware, and georeferenced glare assessment methods that can support automated, city-scale decision-making for PV deployment across both urban and airport contexts, where AI is used to accelerate scientific assessment and enable intelligent urban systems.

2. Related work

Existing glare assessment methods largely rely on simplified geometric assumptions and offer limited scalability for complex urban environments. Compared with indoor glare assessment, outdoor glare assessment remains less standardised. Regulatory frameworks and tools such as the Solar Glare Hazard Assessment Tool (SGHAT) [2], adopted by the U.S. Federal Aviation Administration, evaluate glare using retinal irradiance and geometric relationships, while assuming unobstructed line-of-sight between the sun, PV modules, and observers. In dense urban settings, however, these assumptions are frequently violated due to occlusions, shading effects, and complex visibility conditions introduced by surrounding buildings and infrastructure. As a result, current approaches are often not able to support large-scale urban analyses or systematic evaluation of multiple deployment scenarios, particularly in high-density cities and aviation-sensitive contexts.

3. Methodology

This work presents a standalone, AI-assisted and georeferenced 3D glare assessment framework, implemented entirely in Python, for scalable glare assessment of PV deployments in dense urban and airport-adjacent environments. The framework integrates physically based 3D ray tracing with AI-assisted automation and algorithmic coordination and incorporates a georeferencing module that accurately locates PV systems and observer viewpoints in real-world coordinate systems. This enables seamless application across urban districts as well as airport flight-path contexts.

The framework integrates AI-assisted automation and algorithmic execution to:
(a) estimate annual glare occurrences for geolocated observer viewpoints at hourly temporal resolution;
(b) automatically identify and visualise spatial regions surrounding PV installations that may experience glare;
(c) classify glare severity to detect hazardous conditions such as glint; and
(d) quantitatively evaluate the effectiveness of glare mitigation strategies.

Unlike commercial or plugin-based tools, the proposed workflow supports end-to-end automation across the glare assessment pipeline, including automated PV layout generation with explicit control over panel tilt and orientation, adaptive sampling of PV surfaces and geolocated viewpoints, and constraint-aware scheduling of large ray-tracing workloads across complex urban geometries. Obstruction-aware ray tracing explicitly accounts for shading and visibility constraints imposed by surrounding buildings and infrastructure, enabling physically accurate glare assessment under real-world conditions.

The framework is validated through a case study in a densely built public housing precinct in Singapore. A hypothetical PV system is deployed on the rooftop of a four-storey car park, and year-round glare simulations are conducted at hourly intervals. Observer viewpoints are automatically distributed across surrounding building façades with multiple orientations (i.e. south, north, east) and height ranges (e.g. 15-27 m, 36-72 m). All simulation parameters, including geolocation, are defined within the Python workflow, enabling reproducibility and extensibility across different deployment contexts.

3. Results and Discussion

In the proposed glare assessment framework, a glare event is recorded when a reflected sunlight ray from a PV surface reaches a defined observer viewpoint. Glare occurrences are subsequently mapped across all viewpoint planes and PV deployment areas. Glare severity is classified into two categories: green glare, indicating a low potential for after-image formation, and yellow glare, indicating a higher potential for after-image effects. Extremely severe red glare, associated with a risk of permanent eye damage, is rarely observed in dense urban environments and was not a dominant concern in this study. In addition, the framework evaluates the effectiveness of multiple glare mitigation strategies, including:

(a) Plan A: excluding PV installations with the highest 10% of annual glare occurrences;
(b) Plan B: excluding PV installations with low annual solar irradiance (< 1200 kWh/m^2/yr);
(c) Plan C: adjusting the azimuth and tilt angles of PV panels to shift glare away.

The spatial and temporal distribution of glare occurrences across PV installations and observer viewpoints is visualised using the developed tool (Figure 1). To facilitate interactive exploration and result interpretation, dashboards were generated to illustrate the yellow glare events for different viewpoints and to quantify the effectiveness of the mitigation strategies in reducing glare hazards (Appendix. A).

The case study yields several key findings. First, glare occurrence exhibits strong dependence on both the location and orientation of observer viewpoints. In the analysed scenario, yellow glare predominantly occurs before 10:00 hrs for east-facing viewpoints, while glare events for north- and south-facing viewpoints are concentrated after 12:00 hrs. Second, PV panels associated with the highest 10% of glare occurrences generally receive relatively low annual solar irradiance, typically below 1200 kWh/m^2. Third, for the studied PV configuration, mitigation Plans A and B achieve a reduction of 78.1% in yellow glare occurrences for north- and south-facing viewpoints, but only a 27.5% reduction for east-facing viewpoints, highlighting the directional sensitivity of glare mitigation effectiveness.

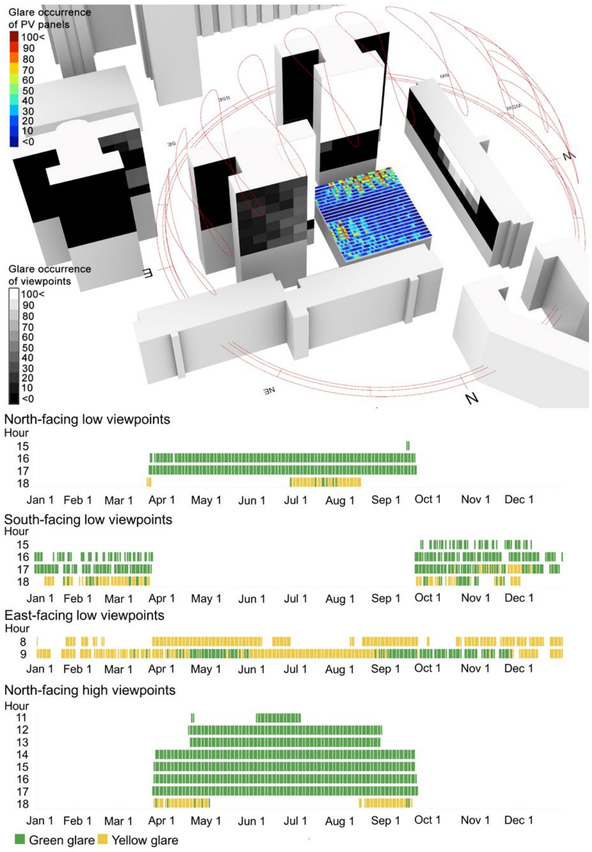

Fig.1: Visualization of hourly and annual glare occurrences across viewpoints and PV surfaces

Conclusions

We present an AI-assisted, georeferenced 3D framework that casts urban-scale glare assessment as a constraint-based planning problem. By combining rule-based automation, heuristic search, and large-scale ray tracing into a unified decision-support pipeline, the framework enables scalable and reproducible glare risk evaluation for urban and airport PV planning, demonstrating the practical impact of AI-driven methods on real-world sustainability challenges.

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[2] Ho CK, Sims CA, Yellowhair J, Bush E. Solar Glare Hazard Assessment Tool (SGHAT) Technical Reference Manual. 2015.

Appendix A. Glare mitigation strategies

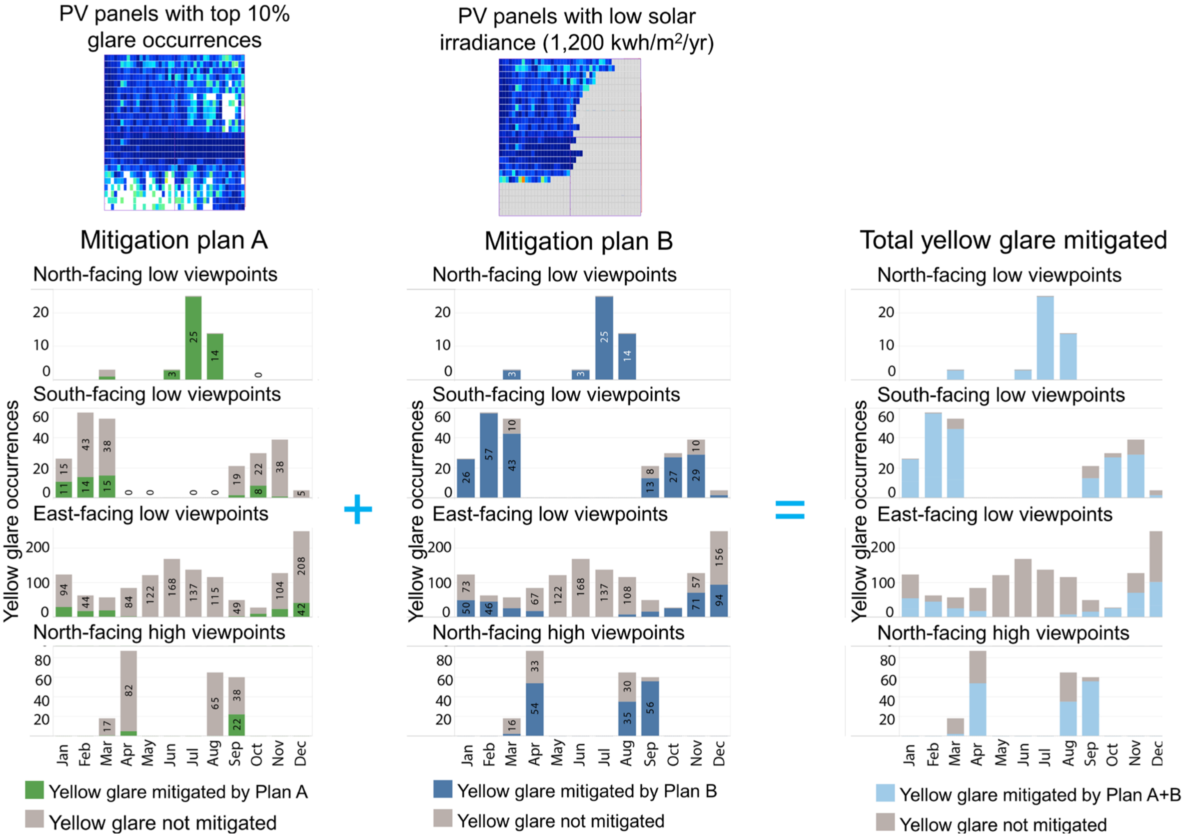

Fig. A1: Yellow glare occurrences reduced by different mitigation strategies