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Power Generation and Visual Comfort Performance of Photovoltaic Toplighting Technologies in Transient Spaces

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ABSTRACT
Advances in long-span glazed structures and interest in high-performance building design has proliferated semi-conditioned spaces with large areas of overhead glazing. These spaces are often programmed with intermittent occupation where variability of the indoor climate is an intentional factor of the experience. Technological options for glazed canopy structures have likewise evolved, gaining functions such as power generation which diversifies the benefits of overhead glazing beyond weather protection and daylighting. Here we model the multiple benefits of current and emerging toplighting technologies deployed in the overhead glazing of a train station and compare power generation and visual comfort. A common building integrated photovoltaic system comprised of monocrystalline cells embedded in the interlayer of laminated glazing is compared with a dynamic, tracking solar collector technology that concentrates and largely intercepts direct solar energy but is transmissive to diffuse sky radiation. The concentrating system generates 6% more power annually with a 70% higher peak power production compared to a typical fixed PV system while at times significantly reducing glare.

KEYWORDS
Concentrating Photovoltaics, Building Integrated Photovoltaics, Daylighting, Active Envelopes, Glare

INTRODUCTION
Transparent and semi-transparent canopies are deployed in architecture to hybridize indoor and outdoor environments, providing the benefits of light and open space with some control of the indoor climate. These structures date to the first moments of technical possibility, with the cast iron and ribbon glass pavilions of the Victorian era, such as London's Crystal Palace in 1851. Contemporary designers incorporate emerging technologies into canopies to improve their performance against criteria of aesthetics, comfort, climate control, and the project's net energy use profile. The large surfaces of transportation structures offer unique opportunities to introduce photovoltaic (PV) generation. If employed correctly, PV not only generates power, but tempers the risk of over lighting and over heating the space under a canopy. Glazing-laminated building-integrated PV (LBIPV) has gained traction in this capacity.

The power output of LBIPV relative to fully opaque fixed panel photovoltaics has limited their desirability in larger projects. Alternatives to LBIPV are under development to increase power generation and lighting benefits. An Enclosure-Integrated, Daylighting, Tracking Solar Collector (EIDTSC) is designed to reduce glare and over-lighting by separating direct and diffuse insolation with Fresnel optics (Figure 1). By treating the direct and diffuse forms of energy differently, sky-sourced luminance is transmitted through the optics to remain useful as light, but direct-beam energy is intercepted, and focused on multi-junction concentrator PV cells. Efficient generation, shading, and diffuse daylighting are simultaneously provided.

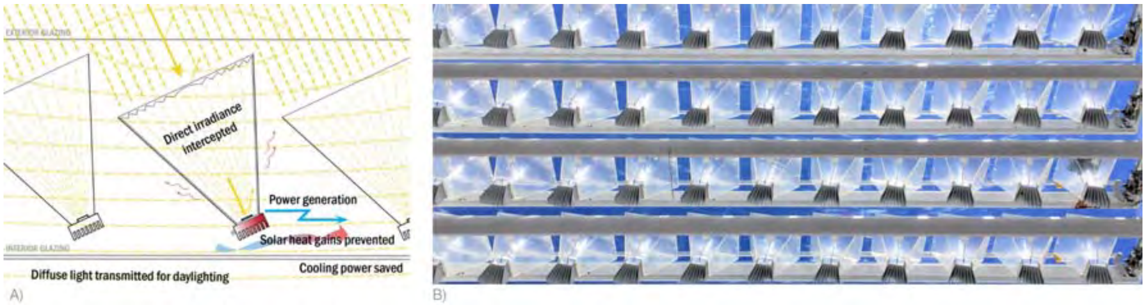

Figure 1. Envelope integrated daylighting tracking solar concentrator, A operational diagram and, B pre-production hardware. Image: HeliOptix LLC.

With physical mock-ups and testing, the EIDTSC is shown to moderate the solar luminance through a fenestration system, by reducing the intensity from direct sun, predominantly allowing diffuse daylight to transmit, and buffering fluctuations due to passing clouds or external shadows (Novelli et al., 2018). Additionally, simulations indicate the system produces power at levels similar to silicon flat-panel photovoltaics but incorporates less than 1% the semiconductor material (Novelli et al., 2015).

METHODS

A typical LBIPV system and an emerging EIDTSC system are simulated in the canopy over a transit platform in southern California and compared for power generation and visual comfort. Simulations assume TMY3 weather data from station #722970 with a 85m wide by 318m long canopy, for a total area of ~27,000m^2, oriented -2.6° from North. To manage simulation times, glare renderings use a subset of the canopy 85m wide by 132m long.

The total number of cells or tracking modules for both systems was non-trivial when deployed across the large area of the train station roof and required material functions and parametric scripting to manage the geometry. Additionally, the EIDTSC system tracks the direct beam of the sun to maintain high optical concentration ratios which requires a dynamic repositioning of the modules and racking in the model for each timestep requiring further parametric scripting. Simulating power generation for the two systems also required distinct methods due to the dynamic nature of the EIDTSC system. Where PV Watts (Dobos, 2014) is used for simulating the power output of the static LBIPV scheme, a custom model is used to calculate the EIDTSC output on an hourly timestep basis (Novelli, 2015). While the EIDTSC concept is capable of simultaneously producing both electricity and useful thermal energy, this study describes a version which is passively cooled and does not actively collect heat. Visual comfort and discomfort glare from train platform views are modeled using Radiance tools (Ward, 1994) and Evalglare (Wienold and Christofferson, 2006). The material representation of the LBIPV system employs a *mixfunc* material with a *perforate.cal* function (Mischler, 1993; Roudsari and Waelkens, 2015) which is suitable to describe the orthogonal array of PV cells in planar glazing. The EIDTSC system uses a custom material to model the concentrating optics also based on a *mixfunc* material with a *icsf4.cal* function (Aly et al., 2015). The *icsf4.cal* function reduces the transmittance to zero within a 2° angle of acceptance to model the concentration and absorption of light by the optical train and receiver assembly. Rays incident at an angle greater than 2° are transmitted according to the base *glass* material.

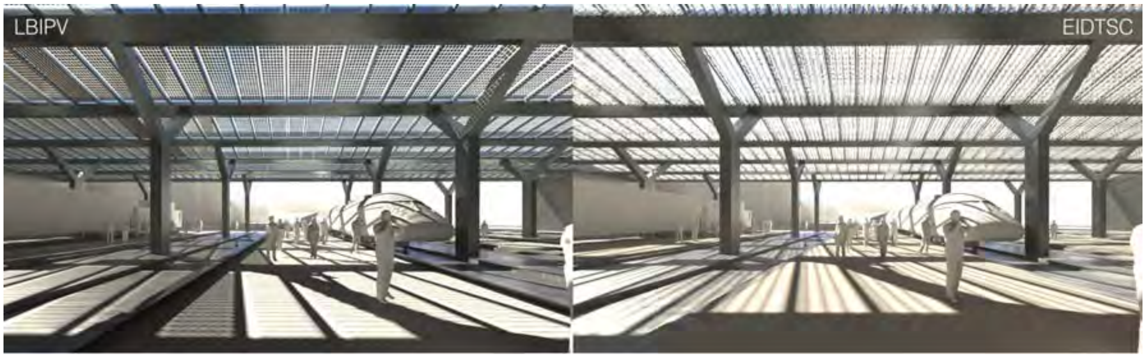

Figure 2. Visualizations of the train station canopy using laminated building integrated photovoltaics, LBIPV (left), and the envelope integrated daylighting tracking solar concentrator, EIDTSC (right).

The 3-d geometry of the train station is modelled in Rhinoceros using the Grasshopper plugin to parametrically generate and position the EIDTSC system geometry. For a glazing unit the custom grasshopper scripts will generate an array of concentrating Fresnel lenses, rear receiver assemblies, and aluminium racking rails based on dimension and clearance tolerance inputs. The EIDTSC array is aligned to track the sun using the Michalsky (1988) solar position algorithm with custom Grasshopper scripts. Additional Grasshopper plug-ins for various supplementary purposes include Elefront, and Ladybug/Honeybee.

Methods for simulating BIPV power generation are well-developed. Here we employ the PV Watts calculations (Dobos, 2014) to simulate the LBIPV, assuming monocrystalline silicon (CSPV) cells laminated into canopy glazing. Simulation of the EIDTSC is based on previous work by Novelli (2015), although the thermal generation described in that work is not modelled, only electricity. Multijunction CPV, Fresnel concentrating lenses, and active tracking is employed in this system. Table 1 lists relevant simulation parameter values.

Table 1. System simulation parameters for EIDTSC and LBIPV.

System Simulation Parameter	LBIPV	EIDTSC
PV type	CSPV, full wafer	MJ-CPV, 64mm^2 format
PV or CPV efficiency	20.30%	38.50%
Temperature coefficient	-0.38/°C	-0.05%/°C
Active aperture – glazing area ratio	71%	79%
Cell-glazing area ratio	71%	0.06%
Initial degradation (sun exposure)	1.50%	0%
Wiring losses	2%	2%
Soiling losses	2%	2%
Module mismatch losses	2%	2%
Connector losses	0.50%	0.50%
Deviation from reference conditions	1%	1%
Optical Efficiency		85%
Range of motion limit		72°
Glazing transmittance (external)		87%
Parasitic losses (motor control)		5%

Visual comfort and glare under the glazing canopy of the train station are simulated from South and West facing viewpoints using Radiance validated software tools and Evalglare to calculate the Daylight Glare Probability (DGP) and Daylight Glare Index (DGI) from rendered views (Wienold and Christofferson, 2006; Hopkinson, 1973). Both daylighting systems modelled here require custom material definitions. The individual 0.152 m diameter cells of the LBIPV system are spaced at a distance of 0.16 m for an opaque coverage of 71%.

To reduce the LBIPV model geometry the glazing unit (1.52m width x 4.57m height) is modified with a *mixfunc* radiance material primitive that mixes a *glass* background material with a *plastic* foreground/cell material using the *perforate.cal* function developed by Georg Mischler (1993) to create an orthogonal array of dots to represent the LBIPV cell array with equal percent coverage. The glass material uses a 0.87 transmittance for a 6mm clear/1.52mm PVB/6mm clear laminate built in LBNL Optics. The plastic material uses a 0.02 reflectance material for the silicon cells. This mixfunc material definition allows for an accurate and fast representation of the BIPV array.

While the EIDTSC system cannot be accurately reduced to a bulk material property as is used for the LBIPV, components of the system can. Within a 2° cone of acceptance from the surface normal, the Fresnel concentrating optics focus direct normal solar radiation onto secondary optics and a high efficiency solar cell, while off axis radiation refracts through the lens. In order to model the light loss from the concentrating optics a custom material is defined for the planar lens geometry where transmittance drops sharply to 0 within the 2° angle of acceptance. Details of this material definition can be found in Aly (2015). This material definition allows for a reasonably accurate and fast representation of the complex optics useful glare renderings.

RESULTS AND DISCUSSION

The EIDTSC system generates 6% more power annually with a 70% higher peak power production compared to the LBIPV system while at times significantly reducing glare. The available surface incident insolation for the two systems is 1304 and 1970 kWh-I.m^{2}a respectively. While the concentrating EIDTSC system has a higher effective annual power conversion efficiency of 19.3% it concentrates and converts only direct-beam insolation compared to the LBIPV system which can convert both direct and diffuse insolation. This higher available incident insolation for LBIPV in part accounts for the similar net annual power generation. However, the EIDTSC system generates a significantly higher peak power output of 202 W/m^2 compared to the LBIPV peak power of 119 W/m^2. Simulated power generation results are described in Table 2 and Figure 3.

Table 2. Simulated power generation of LBIPV and EIDTSC.

	LBIPV	EIDTSC	unit
Surface-incident insolation available	1970 (global)	1304 (direct)	kWh-I/m^{2}a
Net annual power generation	237	251	kWh-E/m^{2}a
Effective (annual) efficiency	12.0%	19.3%	
Peak power	119	202	W/m^2

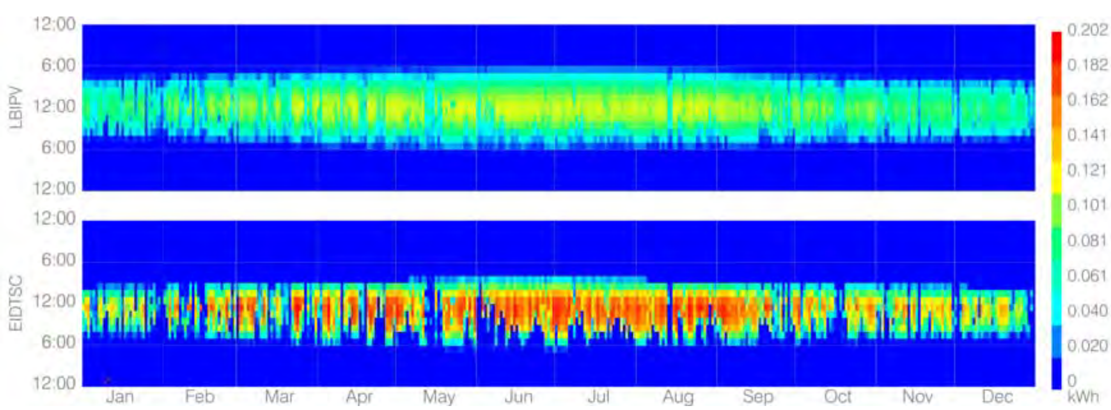

Figure 3. Annual power generation of LBIPV (top) and EIDTSC (bottom).

At times glare in the space is significantly reduced with the EIDTSC system due to the concentration and absorption of the direct beam component of the sun. This feature of the EIDTS system provides more even illumination under the canopy with less disturbing contrast between directly transmitted sun and diffusely illuminated shadows. However, the reduction in glare is not uniform at all times simulated particularly when the EIDTSC modules do not provide overlapping coverage around noon. At these times the EIDTSC canopy maintains or even slightly increases glare. In both canopies, when the sun is aligned through a gap in the PV cells or concentrating modules with the observer's viewpoint, glare is inevitable.

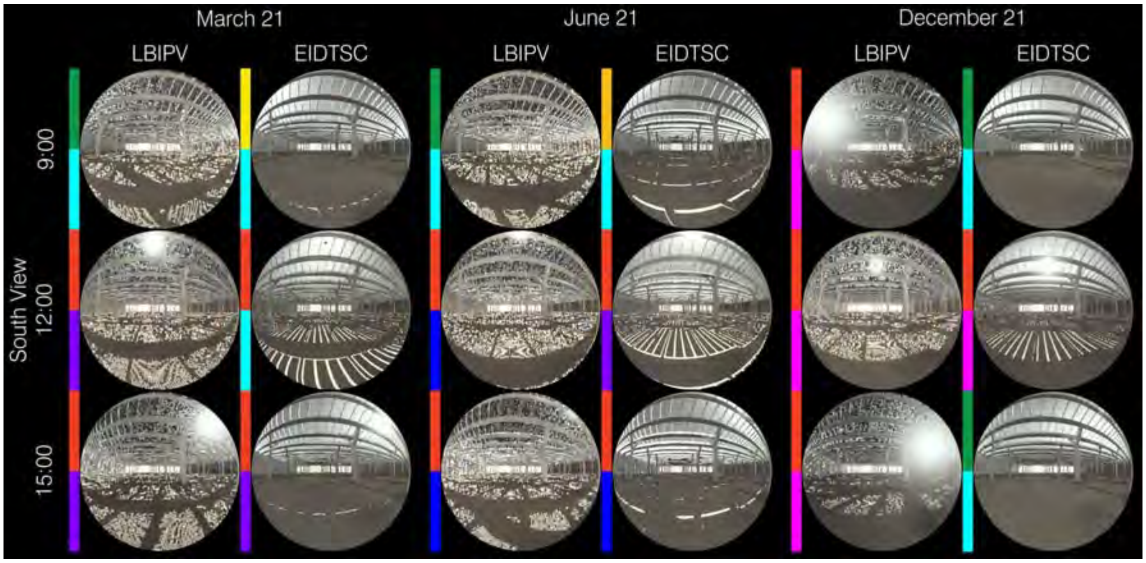

Figure 4. Daylight Glare Probability and Daylight Glare Index from a South facing viewpoint for the LBIPV and EIDTSC canopies at the solstices and spring equinox.

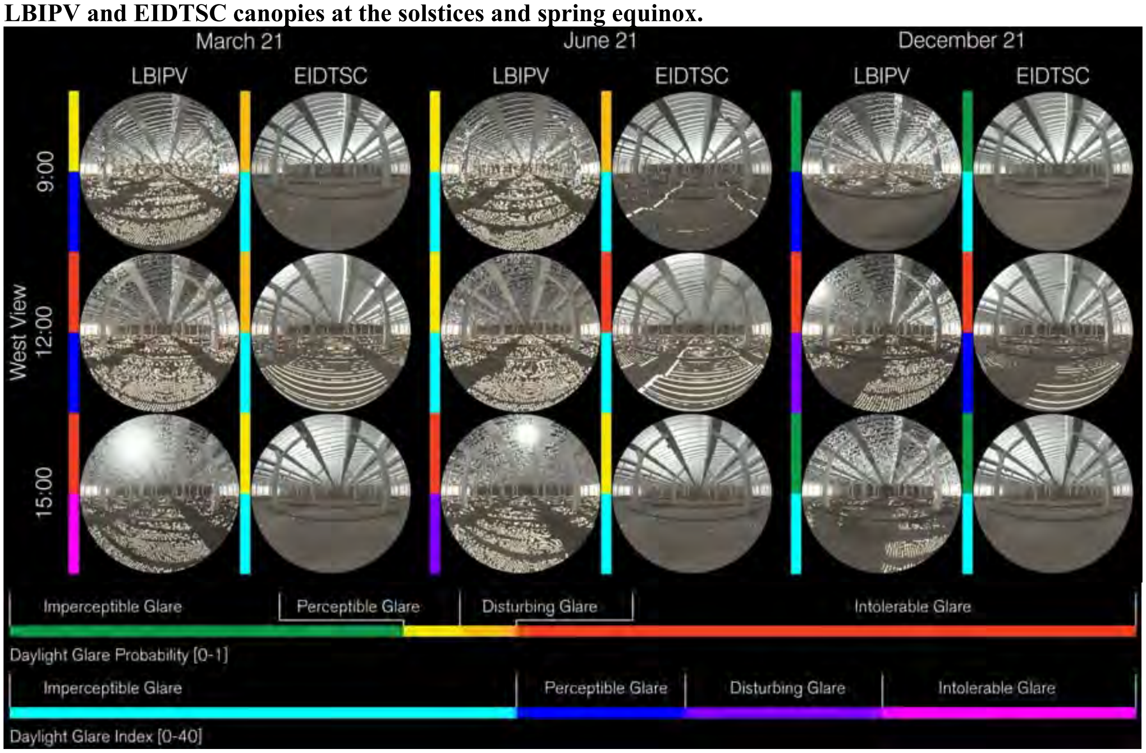

Figure 5. Daylight Glare Probability and Daylight Glare Index from a West facing viewpoint for the LBIPV and EIDTSC canopies at the solstices and spring equinox.

The DGP and DGI metrics do not always agree in magnitude across the times simulated, however the general trends of reducing or increasing the likelihood of glare are somewhat consistent. While DGP is generally considered to be the metric with better correlation in sidelit office settings, both of these commonly accepted daylight glare metrics may be inadequate for bright toplit spaces (McNeill, 2016). Modelling of the concentrating optics of the EIDTSC canopy may be further improved employing a high-resolution tensor tree BSDF with photon mapping for combined forward and backward ray tracing (McNeil, 2013; Schregle, 2015).

CONCLUSIONS

The large surfaces of transportation structures offer unique opportunities to introduce photovoltaic glazing canopies. If employed correctly a photovoltaic toplit roof canopy not only generates power but tempers glare in the space. The typical laminated BIPV system and emerging envelope integrated daylighting tracking solar concentrating system simulated here have comparable annualized power generation. However, the concentrating canopy enables a 70% higher peak power output and can at times significantly reduce glare. The EIDTSC canopy may be better suited in climates where direct solar loads dominate thermal and visual comfort. While the glare results are non-uniform for all timesteps simulated, annual simulations, improved optical representation of the concentrating optics, and the further development of metrics for brightly daylit spaces can reduce uncertainty.

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