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A photovoltaic window with sun-tracking shading elements towards maximum power generation and non-glare daylighting☆

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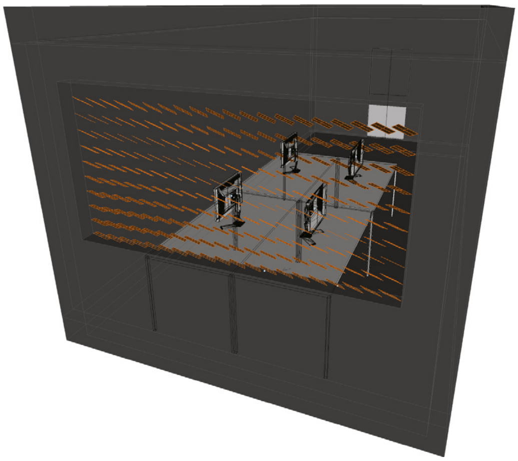
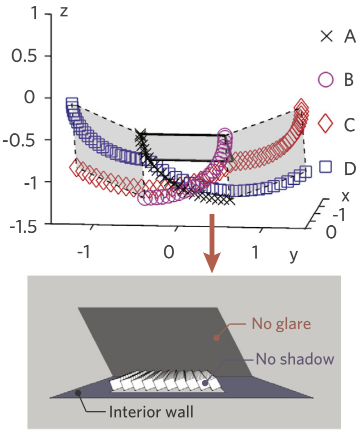
HIGHLIGHTS

- Rh/v is defined to estimate the potential of solar energy on the vertical area.
- Sun-tracking PV shading elements integrated with windows are modeled and analyzed.
- Novel optimum sun-tracking methods and cell layout are first proposed.
- Annual energy generation and average efficiency are improved by 27.40% and 19.17%.
- Optimum sun-tracking methods reveal great ability to protect glare from the sun.

GRAPHICAL ABSTRACT





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ABSTRACT

Vertical space bears great potential of solar energy especially for congested urban areas, where photovoltaic (PV) windows in high-rise buildings can contribute to both power generation and daylight harvest. Previous studies on sun-tracking PV windows strayed into the trade-off between tracking performance and mutual shading, failing to achieve the maximum energy generation. Here we first build integrated models which couple the performance of sun-tracking PV windows to the rotation angles. Secondly, one-degree-of-freedom (DOF) and two-DOF sun tracking are mathematically proven to be not able to gain either maximum power generation or non-glare daylighting under reasonable assumptions. Then we derive the optimum rotation angles of the variable-pivot-three-degree-of-freedom (VP-3-DOF) sun-tracking elements and demonstrate that the optimum VP-3-DOF sun tracking can achieve the aforementioned goals. When the restriction of the proposed model is relaxed, the same performance can be achieved by the optimum one-DOF sun tracking with extended PV slats and particular design of cell layout, requiring less complicated mechanical structures. Simulation results of nine

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☆ See the supplementary document for more information.

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global cities show that the annual energy generation and average module efficiency are improved respectively by 27.40% and 19.17% via the optimum VP-3-DOF sun tracking over the conventional perpendicular sun tracking. The proposed optimum sun-tracking methods also reveal better protection against sun glare. The optimum VP-3-DOF sun tracking is also demonstrated to be applicable to horizontal PV windows, as those applied in the sun roof of a glass greenhouse.

1. Introduction

1.1. Motivation

A photovoltaic (PV) window is a daylight-management apparatus with photovoltaic solar cells, modules, or systems embedded on, in, or around a window [1,2]. PV windows take full advantage of vertical space in congested urban areas, where available horizontal lands are scarce, and local energy consumptions are tremendous. The annual installed capacity of building integrated photovoltaic (BIPV) worldwide is predicted to exceed 11 GW by 2020; and the total BIPV market is projected to grow from about US$3 billion in 2015 to over $9 billion in 2019 and surge to $26 billion by 2022 [3]. To evaluate the equivalent horizontal area (EHA) of available vertical surfaces of buildings, we define $R_{v/h}$ as the ratio of the annual solar energy received on the sunward (e.g. equator-facing for temperate zones) vertical unit area to that received on the horizontal unit area, i.e.,

$$R_{v/h} = \frac{\int G_{v,global}(t)\,dt}{\int G_{h,global}(t)\,dt}, \tag{1}$$

where $G_{v,global}(t)$ indicates the global irradiance on a sunward vertical plane; and $G_{h,global}(t)$ indicates the global irradiance on a horizontal plane. The integration time here is an entire year (365 days). According to reliable climate data [4], the calculated value of $R_{v/h}$ for Shanghai is 0.8717. More specifically, the EHA of the highest skyscraper (632 m) in Shanghai equals to the area of 3.5 standard football fields, which occupy 15.6-fold horizontal areas as the building does (see Supplementary Note 1). $R_{v/h}$ for nine selected cities is calculated and shown in Table 1. Considering all the urban high-rise buildings around the world, vertical area holds enormous potential for the utilization of solar energy, especially the window area, which is relatively large in modern buildings. Besides the potential of power generation, PV windows also contribute to the energy balance of modern architectural environment via daylight control and heat insulation.

1.2. Previous studies

The nature of PV windows is to manipulate photons in order to turn incident light partially into electricity and partially into transmitted light. Most reported approaches are implemented by integrating transparent, semi-transparent, regionally transparent PV, or light-directed materials with window glazing. Regionally transparent PV windows can be simply formed by distributing available opaque solar cells discretely onto window glasses, resulting in undesired partially-blocked view and spotted shadows. Sellami et al. designed and optimized a static window-integrated concentrating PV system, which combined solar concentrators with the distributed opaque solar cells on the window glass [5]. Though the solar concentrator improved the irradiance on the individual solar cell, it also decreased the incident light inside the room and affected the visibility of the window. Lien et al. developed a novel type of image-patterned translucent amorphous silicon PV module, resulting in the appearance of desired image with 10% transmittance [6]. Such modules are more suitable for esthetic decoration or special signs than windows, which need to provide good visibility and adequate daylighting. The visual effects of PV windows are possibly improved by shrinking the size of opaque solar cells. Cossu et al. reported a semi-transparent PV technology integrated on the roof of a greenhouse. The semi-transparent module was formed by interconnecting spaced opaque spherical micro-cells (1.2 mm diameter), whose density was adjustable. When the cell density was 2 cells per cm^2, the perpendicular light transmissivity was 73%; and the module conversion efficiency was 0.2% [7]. Kapsis et al. proposed the concept of three-section façade configuration, which contained the upper daylighting section (silicon-based spaced PV cells), middle viewing section (semi-transparent thin film PV), and lower section (opaque spandrel). However, spaced cells still cast spotted shadows in the room; and semi-transparent thin film PV affected the color rendering properties of the window [8]. Another approach to fabricating see-through solar cells based on opaque materials is punching small holes on the opaque surface. Takeoka et al. developed a new type of see-through amorphous silicon solar cell. Multiple microscopic hexagonal holes were formed by the laser patterning method [9]. The visual effects were possibly improved, however, at the cost of complicating the manufacturing process.

Unlike opaque PV materials, semi-transparent solar cells reveal uniform transmittance with colored or neutrally-colored appearance. Since photons are selectively transmitted, semi-transparent photovoltaic (STPV) materials [10] present lower efficiency compared with the corresponding opaque materials. Myong et al. developed a series of colored thin-film silicon semi-transparent PV modules, including green, sky blue, gray, etc. The highest conversion efficiency was found in the design of opaque back contact (OBC)-type module (7.2%) [11]. Lim et al. fabricated semi-transparent amorphous silicon solar cells using thin absorber and high-bandgap-energy n/i-interface layers. The highest power conversion efficiency (PCE) was 6.92% with 23.6% average visible transmittance (AVT) [12]. Han et al. found that amorphous silicon PV cells integrated in a double-pane window with low-emittance coatings dramatically reduced the heat transfer by radiation [13]. Peng et al. investigated a ventilated photovoltaic double-skin façade in a cool-summer Mediterranean climate zone. Results showed that in Berkeley, the natural ventilation led to 35% reduction in electricity per year; and about 50% of lighting electricity was saved in the winter. Overall, about 50% net electricity was saved compared to other commonly used glazing systems [14]. To improve the color rendering properties of STPV, neutrally-colored solar cells were developed by different approaches. Colsmann et al. demonstrated semi-transparent organic solar cells with good transparency perception and rendering properties closed to white light. The color rendering index (CRI) was 86 under the illumination of a Standard Illuminant A; and the PCE was about 3% [15]. Eperon et al. fabricated neutrally-colored semi-transparent perovskite solar cells by creating micro-structured arrays of perovskite “islands”. CRI was not calculated, but the color coordinates

Table 1
$R_{v/h}$ of nine selected cities around the world.

City	$R_{v/h}$
Shanghai	0.8717
New York City	0.9128
Tokyo	0.9345
Beijing	0.9629
London	1.0233
Los Angeles	0.7799
Toronto	0.9289
Paris	0.9669
Berlin	1.0181