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Energy and cost analysis of semi-transparent photovoltaic in office buildings

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ABSTRACT

Solar energy conversion systems and daylighting schemes are important building energy strategies to produce clean energy, reduce the peak electrical and cooling demands and save the building electricity expenditures. A semi-transparent photovoltaic (PV) is a building component generating electricity via PV modules and allowing daylight entering into the interior spaces to facilitate daylighting designs. This paper studies the thermal and visual properties, energy performance and financial issue of such solar facades. Data measurements including solar irradiance, daylight illuminance and output power for a semi-transparent PV panel were undertaken. Using the recorded results, essential parameters pertaining to the power generation, thermal and optical characteristics of the PV system were determined. Case studies based on a generic reference office building were conducted to elaborate the energy and cooling requirements, and the cost implications when the PV facades together with the daylight-linked lighting controls were being used. The findings showed that such an integrated system could produce electricity and cut down electric lighting and cooling energy requirements to benefit the environmental, energy and economic aspects.

1. Introduction

Hong Kong has no indigenous fuels and most of the imported energy products are fossil fuels which are mainly for electricity generation [1,2]. There are many immediate adverse effects to the environment such as greenhouse gases and pollutants emissions from the burning of fossil fuels [3]. Electricity conservations mean fossil fuel saved together with the likely pollutants and greenhouse gases reductions [4]. Renewable energy can play an important role in meeting the ultimate goal of replacing certain amount of fossil fuels. Recently, solar energy has been identified as an appropriate technology for wide-scale use in Hong Kong [5]. One of the promising applications of solar-based conversion systems is the installation of photovoltaic (PV) facilities that generate power without emitting pollutants and requiring no fuel. However, PV applications are not popular in local building developments. The barriers are mainly the high initial costs, the large installation spaces required and the low output power produced.

In Hong Kong, most electricity is expended by building stocks and the commercial sectors account for 65% of the energy consumption [6]. The electricity used in commercial buildings is largely for creating a thermally and visually comfortable built-environment through air-conditioning and artificial lighting. Previous research work revealed that air-conditioning and electric lighting represent over two-thirds of total building electricity use [7]. Solar heat gain via fenestration contributes to a significant proportion of building envelope cooling load [8]. Daylighting has long been recognized as an important and useful strategy for visual comfort, and building energy efficiency and conservation [9,10]. People expect good natural lighting in their working places [11]. Energy savings resulting from daylighting mean not only low electric lighting and reduced peak electrical demands, but also reduced cooling loads and potential for smaller heating, ventilating and air-conditioning (HVAC) equipment size [12,13]. The initial, running and maintenance costs of a building due to a smaller HVAC plant capacity and peak electrical demand can be lowered. Renewable energy and energy conservation schemes would be an apposite building energy policy.

Semi-transparent building integrated photovoltaic (BIPV) panels can provide electricity and apt to daylighting schemes that enhance visual comfort, reduce peak electrical and cooling demands, and conserve building energy expenditures [14,15]. Building integrated installation can offset construction costs. Such a PV system would be appropriate for air-conditioned office buildings. Life cycle assessment of PV facility is an essential process for justification [16,17]. This paper studies the semi-transparent BIPV systems used in an air-conditioned building with daylight-linked lighting controls. Technical data including daylight illuminance, solar irradiance and output power are recorded and analyzed. The performance of such PV panels is elaborated in terms of energy,

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Nomenclature

A_f	floor area (m^2)
A_{in}	total indoor surface area (m^2)
A_w	window area (m^2)
E_a	energy savings due to electric lighting (Wh)
E_{in}	average indoor illuminance (lux)
E_s	design indoor illuminance (lux)
E_v	outdoor vertical illuminance (lux)
F_s	fractional energy saving (dimensionless)
h_i	heat transfer coefficient of the inside fenestration surface (W/m^2 K)
h_o	heat transfer coefficient of the outside fenestration surface (W/m^2 K)
LPD	installed lighting power density (W/m^2)
N_i	inward-flowing fraction of the absorbed radiation (dimensionless)
Q_f	solar heat gain via a fenestration system (W)
Q_r	radiant cooling load (W)
q_r	radiant heat gain (W)
R	mean reflectance of all indoor surfaces (dimensionless)
R_f	minimum light output ratio (dimensionless)
R_w	fractional power consumption (dimensionless)
SC	shading coefficient (dimensionless)
SHGC	solar heat gain coefficient (dimensionless)
SHGF	solar heat gain factor (W/m^2)
ST	solar transmittance (%)
T	total operating hour (h)
VT	visible transmittance (%)
τ	solar transmittance of the fenestration (dimensionless)
α	absorption of the fenestration (dimensionless)

environmental and economic aspects, and design implications are discussed.

2. Data measurement

The technical information provided under standard test conditions may never occur in practice [18]. Measured data are essential to give reliable and accurate information on the performance of PV system under actual operating conditions. Field measurements including solar irradiance, daylight illuminance and output power generated by a semi-transparent PV panel were conducted. An amorphous silicon (a-si) solar cell type PV module manufactured in Japan with an effective area of 0.84 m^2 was tested to obtain the technical data. Table 1 lists the performance parameters of the PV module provided by the manufacturer. The measurements were carried out in a domestic unit in July 2007. The room for the measurement was located at the 20th floor of a residential building facing close to west (260°) with the dimensions of 2.95 m (depth) × 2.14 m (along the window façade) × 2.46 m (height). An overhang was constructed to block part of the direct sunlight. The existing windows were fully opened during the measurement to allow more incident solar irradiance and daylight falling on the PV module though part of sky was obstructed by the overhang and window frames. Data were collected during the daytime with all the electric light fittings off. The PV module was connected to a solar controller to maintain the peak power output by tracing the maximum power point (MPPT) [19]. A battery of 12 V was used to store the generated electricity.

2.1. Equipment use

The measurements of solar irradiance, daylight illuminance and electricity generated by the semi-transparent PV panel were made by means of two pyranometers, two illuminance meters and a power analyzer, respectively. The two pyranometers manufactured and calibrated by Kipp and Zones, the Netherlands were used to record the solar irradiance incident on the solar panel and the transmitted solar irradiance. The pyranometers (CM3) with an accuracy of ±3% were connected to a virtual instrument called LabVIEW 8.20 calculating the global component at an interval of 1 min. The data from the LabVIEW 8.20 were sent to a notebook computer for storage through an USB cable. Similarly, the daylight illuminance data falling on and transmitted via the panel were collected by the two illuminance meters (T-10) produced by Minolta of Japan. The silicon photocells with cosine and colour corrections measure illuminances up to about 300 klux with an accuracy of ±2%. A multi-point illuminance measurement system was used. The receptor heads were connected serially with extension cables, which transmitted all the measured data to the main body adapter. A data management software namely, T-A30, was used to capture the measured results twice per second, averaged over 1 min. The logged data were sent to the same notebook computer for storage. A power analyzer (43B) including the accessories manufactured by Fluke, the Netherlands was used to measure the electricity generated by the PV module. A program called Fluke View Power Quality Analyzer V2 was used to transmit the data measured from the analyzer to another notebook computer for data collection. Again, the data were averaged over an interval of 1 min to match the measured solar irradiance and illuminance results. Quality control tests were conducted to eliminate spurious data and inaccurate measurements. Totally, about 2500 numbers of 1 min data for each parameter were gathered although there were some short periods of missing readings.

Table 1
Performance parameters of the semi-transparent PV module from manufacturer

Output power	44 W
Maximum power voltage	59.6 V
Maximum power current	0.74 A
Open circuit voltage	91.8 V
Short circuit current	0.97 A
Visible light transmittance	10.6%
Solar energy transmittance	10.0%
Shading coefficient	0.27

2.2. Daylight illuminance

Graphical representations were employed to analyze the measured results. Fig. 1 presents the daily profile of daylight illuminance incident on and behind the PV glazing measured for a typical non-overcast sky. It can be observed that the two curves have quite similar pattern and peak at the same time indicating that the daylight illuminance data were correctly recorded. However, dissimilar trend can be noted between 14:00 and 14:30. The reason was mainly because the two sensors were not exactly mounted on the same location and only one illuminance sensor recorded the direct sunlight during this short period. With the window facing to west, the recorded daylight illuminance data were purely diffuse of low values in the morning and more direct components of high illuminance levels were obtained in the afternoon. The visible transmittance (VT) of the semi-transparent PV is an