Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Nonlinearity analysis of the shading effect on the technical–economic performance of the building-integrated photovoltaic blind

Taehoon Hong [a], Choongwan Koo [b,a,*], Jeongyoon Oh [a], Kwangbok Jeong [a]

[a] Department of Architectural Engineering, Yonsei University, Seoul 03722, Republic of Korea
[b] Division of Construction Engineering and Management, Purdue University, West Lafayette, IN 47907, USA

HIGHLIGHTS

- The shading effect can affect the technical–economic performance of the BIPB.
- The shading effect depends on the complexity among design variables of the BIPB.
- This study focused on the width of the PV panel installed on the blind's slats.
- The nonlinearity of the shading effect on the AEG_{unit} from the BIPB was analyzed.
- The LCC analysis was conducted for the preliminary feasibility study of the BIPB.

ARTICLE INFO

Article history:
Received 10 March 2016
Received in revised form 15 April 2016
Accepted 3 May 2016
Available online xxxx

Keywords:
Building-integrated photovoltaic blind
Nonlinearity
Shading effect
Electricity generation
Life cycle cost analysis

ABSTRACT

This study aims to conduct the nonlinearity analysis of the shading effect on the technical–economic performance of the building-integrated photovoltaic blind (BIPB), which is designed as a preliminary study to evaluate the feasibility of the BIPB before its implementation. First, in terms of the technical performance of the BIPB, the shading effect due to the blind's slat in the BIPB can have a nonlinear effect on the amount of electricity generation per unit area (AEG_{unit}) from the BIPB. Particularly, as the width of the PV panel increases, the AEG_{unit} from the BIPB tends to decrease. Second, in terms of the economic performance of the BIPB, the feasibility of the BIPB depends on the type of investment values. Specifically, as the width of the PV panel increases, the NPV_{25} (net present value at year 25) tends to increase; however, the SIR_{25} (saving-to-investment ratio at year 25) tends to decrease. That is, while the NPV_{25} is determined to be highest at US$82,869 when the width of the PV panel is 50 mm, the SIR_{25} is determined to be highest at 2.90 times when the width of the PV panel is 10 mm. The main findings of this study can be used to clearly define the design specifications of the BIPB before its implementation, which ensure to meet the client expectations on various objectives, such as technical performance (e.g., the AEG_{unit} from the BIPB) and economic performance (e.g., NPV_{25} and SIR_{25}).

1. Introduction

Despite the rapid increase in global population and energy usage, it is widely assumed that coal has a reserves-to-production ratio of about 112 years; natural gas, 63.6 years; and oil, 54.2 years [1,2]. In this context, new and renewable energy (NRE) is expected to address the challenges due to the energy depletion and climate change. The developed countries are promoting a variety of government policies, such as financial support for NRE projects [3–5]. Keeping pace with the global trend, the South Korean government plans to increase the installation capacity of NRE systems up to 11% in 2035. In addition, the comprehensive assessment of the potential for NRE systems is being actively conducted to expand the support policies for NRE projects [6–9]. Particularly, solar photovoltaic (PV) energy, a sustainable clean energy resource, is considered to be an attractive technology that can realize the distributed energy generation systems and more innovative electrical infrastructure. Furthermore, in complex urban environments, such as urban areas with high population density, the building integrated PV (BIPV) systems are more attractive to end-users who plans to achieve zero energy buildings [10].

As a part of the BIPV, the building-integrated photovoltaic blind (BIPB) is considered to be one of the effective technologies that can provide the electricity generated from the PV system, as well as reduce the cooling demand in buildings by blocking the solar

* Corresponding author at: Purdue University, West Lafayette, IN 47907, USA.
E-mail addresses: koo15@purdue.edu, cwkoo@yonsei.ac.kr (C. Koo).

http://dx.doi.org/10.1016/j.apenergy.2016.05.027
0306-2619/

Nomenclature

Abbreviations

AEG_{unit}	amount of electricity generation per unit area
AEG	amount of electricity generation
BEP	break-even point
BIPB	building-integrated photovoltaic blind
BIPV	building-integrated photovoltaic
CIGS	copper–indium–gallium–selenide
EBS	electricity bill saving
IIC	initial investment cost
KCERs	Korean certified emission reductions
LCC	life cycle cost
NPV_{25}	net present value at year 25
NRE	new and renewable energy
PV	photovoltaic
SIR_{25}	saving-to-investment ratio at year 25

radiation [11,12]. In order to ensure that the BIPB is effectively implemented to the building façade, it is necessary to consider the nonlinearity of the shading effect on the technical and economic performance of the BIPB. This nonlinearity emerges from the complex relationship among the design variables of the BIPB. As shown in Table 1, previous studies have considered lots of design variables affecting the technical and economic performance of the PV system (which can be categorized into architectural, window, and the PV system design variables). However, there is a lack of studies on the nonlinearity of the shading effect due to the blind's slat in the BIPB. Previous studies can be summarized as follows.

First, some of the previous studies considered the design variables for the rooftop PV system [13–30]. For example, Drury et al. [15] analyzed the technical–economic performance of the rooftop PV system with the consideration of the architectural design variables (i.e., orientation and region) and the PV design variables (i.e., solar tracking type). Kacira et al. [18] assessed the technical performance of the rooftop PV system by considering the architectural design variables (i.e. orientation) and the PV design variables (i.e., type of PV module, tilt angle, and tracking type). Wu et al. [26] analyzed the technical performance of the rooftop PV system based on the meteorological data (i.e., global horizontal solar radiation and ambient temperature). While some of these studies have considered the shading effect on the technical or economic performance of the rooftop PV system, in others, the shading effect remains unaddressed.

Second, other studies considered the design variables for the PV system applied to the building façade [30–40]. For instance, Bahr [30] analyzed the technical–economic performance of the PV system by considering various BIPB design variables, such as blind's tilt angle, proportion of blind's installation distance to module depth, and panel type. Hwang et al. [33] predicted the amount of electricity generated from the PV system implemented to the building façade, which depended on the architectural design variables (i.e., wall orientation) and the PV design variables (i.e., inclined angle, and ratio of distance between panels to length of panel). Masa-Bote and Caamaño-Martín [35] conducted the technical performance analysis for the exterior shading type of the PV system by considering the architectural design variables (i.e., orientation), window design variables (i.e., size), and the PV design variables (i.e., slope, peak power, and module in series/parallel). Even if some of these studies on the façade type of the PV system have slightly considered the shading effect, they have not address the nonlinearity due to the complex relationship among the design variables of the BIPB (such as the orientation, the width of PV panel, and the season).

Third, another studies conducted the experimental investigation to evaluate the impact of partial shading conditions, different irradiance conditions, and different incident angle on the PV modules operation and the PV array performance in terms of maximum power point tracking [41–43]. While these studies have explored the shading effect on the technical performance of the PV system through the experimental approach, they have not considered a variety of design variables of the BIPB, but just investigated the shading effect on the PV array performance.

Despite these efforts in previous studies, the fundamental understanding of the nonlinearity of the shading effect on the technical–economic performance of the BIPB is limited. Namely, although the shading effect can have a nonlinear effect on the technical–economic performance of the BIPB, previous studies have not addressed these challenges. Thus, this study is designed to fill the research gap as follows.

- In terms of the technical analysis, some of the previous studies have a bit considered the shading effect of the BIPB applied to the building façade. However, it is not enough to conduct the nonlinearity analysis of the shading effect due to the complex relationship among the design variables of the BIPB (i.e., the orientation, the width of PV panel, and the season).
- Furthermore, it is necessary to analyze the economic performance of the BIPB as well as its technical performance before its implementation in order to ensure that all of the features of the BIPB will meet the client expectations on various project objectives, which includes the amount of electricity generation per unit area (AEG_{unit}) from the BIPB, as well as the net present value (NPV) and the saving-to-investment ratio (SIR) from the life cycle perspective.

Therefore, this study aims to conduct the nonlinearity analysis of the shading effect on the technical–economic performance of the BIPB, which is designed as a preliminary study to evaluate the feasibility of the BIPB before its implementation. This study was conducted in three steps: (i) definition of the design variables of the BIPB; (ii) technical performance analysis of the BIPB; and (iii) economic performance analysis of the BIPB.

2. Materials and methods

2.1. Definition of the design variables of the BIPB

2.1.1. Design variables affecting the AEG_{unit} from the BIPB

Park et al. [11] categorized the design variables affecting the amount of electricity generated from the BIPB into three groups: (i) architectural design variables; (ii) window design variables; and (iii) BIPB design variables.

- *Architectural design variables:* These variables can be divided into two factors (i.e., region and orientation). First, region can affect the amount of solar radiation, which is one of the most critical factors that can have an effect on the AEG_{unit} from the BIPB. In addition, the geographical factors and meteorological factors depend on the region variable [44–47]. Second, orientation can affect both the amount of solar radiation and the shad-