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A finite element model for estimating the techno-economic performance of the building-integrated photovoltaic blind

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HIGHLIGHTS

- A FEM was developed to estimate the techno-economic performance of the BIPB.
- The mean absolute percentage error of the $FEM_{4\text{-}node}$BIPB was determined to be 4.54%.
- In implementing the BIPB with the $GC_{incl.SREC}$ plan, it was superior to the others.
- Users can understand the operating mechanism of the proposed model ($FEM_{4\text{-}node}$BIPB).
- The proposed model can be extended to any other country in the global environment.

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ABSTRACT

This study aims to develop the four-node-based finite element model for estimating the techno-economic performance of the building-integrated photovoltaic blind ($FEM_{4\text{-}node}$BIPB), which can be used by decision-maker in the early design phase. In developing the proposed model, this study uses various research methodologies such as energy simulation, finite element method, life cycle cost analysis, policy analysis, and visual basic application. Compared to the simulation results, the mean absolute percentage error of the proposed model was determined to be 4.54%, showing that the prediction accuracy of the proposed model was found to be excellent. Furthermore, the practical application was conducted for the 'S' elementary school facility in South Korea, which allows potential readers to easily and clearly understand the operating mechanism of the proposed model as well as its usability and extendability. The proposed model can be used to conduct the detailed analysis of the techno-economic performance of the BIPB by the type of utilization plan and to determine the optimal strategy for maximizing the value of the investment. Furthermore, the proposed research framework can be extended to any other technology, industry, and country in the global environment.

1. Introduction

The increase in the global energy demand has led to the depletion of fossil fuels and the increase in the global warming potential [1–4]. To address such a global climate change, the United Nations climate change conference was held in Paris, France on December in 2015 (i.e., the 21st Conference of the Parties) and adopted the POST-2020 climate agreement. Accordingly, the South Korean government established the *Intended Nationally Determined Contributions* to reduce the greenhouse gases emissions by 37% below the business-as-usual emission by 2030 [5]. Towards this end, it is required to take considerable effort in the building sector which accounts for about 40% of the total fossil fuels [6–9].

As one of the effective energy retrofit strategies, the photovoltaic (PV) blind can be implemented to generate the green electricity without carbon emissions from its PV panel as well as to reduce the indoor cooling demands through its shading effect [10–14]. Particularly, in a large-scale city with high-rise buildings, the PV system can be applied to the building façade as well as the building rooftop area. Such a building-integrated PV system can be linked to a grid-connected distributed generation system. Thus, if the PV system generates more electricity than the energy demands, the owner can sell the surplus energy back to the grid. In addition, installing the PV system allows the owner to receive the government subsidy and to reduce the carbon footprint from the life cycle perspective. In this context, the South Korea government initiated

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Nomenclature

Abbreviations

BEP break-even point
BIPB building-integrated photovoltaic blind
CIGS copper-indium-gallium-selenide
FEM finite element method
$FEM_{4\text{-}node}$ four-node-based *Lagrangian* finite element model
$FEM_{4\text{-}node}$BIPB four-node-based *Lagrangian* finite element model for estimating the amount of electricity generated from the BIPB
$GC_{excl.SREC}$ plan grid-connected utilization plan excluding the SREC
$GC_{incl.SREC}$ plan grid-connected utilization plan including the SREC
KCERs Korean certified emission reductions
LCC life cycle cost
MAPE mean absolute percentage error
NPV net present value
PV system photovoltaic system
SC plan self-consumed utilization plan
SIR saving-to-investment ratio
SMP system marginal price
SREC solar renewable energy certificate
VBA visual basic for applications
VT visible transmittance

Greek letters

ξ-η matrix Matrix that consists of the $x(\xi)$-axis and $y(\eta)$-axis in the finite element model
ξ ξ stands for the orientation, which is one of the independent variables, defined as $x(\xi)$-axis in the finite element model
η η stands for the visible transmittance, which is one of the independent variables, defined as $y(\eta)$-axis in the finite element model
$\phi(\xi, \eta)$ $\phi(\xi, \eta)$ stands for the amount of electricity generated from the BIPB, which is the dependent variable, defined as $z(\phi)$-axis in the FEM
α_1–α_4 coefficients of the four variables in the $FEM_{4\text{-}node}$BIPB (i.e., ξ, $\xi \cdot \eta$, η, *and constant term*)

the '*Act on the Promotion of the Development, Use, and Diffusion of New and Renewable Resources*', aiming to promote the new and renewable energy systems including the PV system. Based on the act, the various government financial supports were established for the PV system [15–17].

As shown in Table 1, several studies have been conducted to explore the applicability of the building-integrated PV system and its potential in various cases [10–11,18–38]. Even if the previous studies have not directly use the technical term, "building-integrated photovoltaic blind (BIPB)", they have made considerable efforts as follows: (i) to focus on the building façade as well as the building rooftop; (ii) to analyze the technical and economic aspects of the PV system; (iii) to consider several influencing variables affecting the PV system (e.g., architectural design elements, window design elements, and PV design elements); (iv) to use various simulation tools or methods; and (v) to conduct the design of PV system and its experimental application.

Based on the main focus of this study, the previous studies can be categorized in two ways (i.e., the technical performance and the economic performance of the PV system).

First, some of previous studies analyzed the technical performance of the PV system through the energy simulation. Bahr [10] used the '*Autodesk Ecotect Analysis*' software program to estimate the amount of electricity generated from the PV system by considering the type of PV panel, the installation area of PV system, and the slope of the installed PV panel. Hwang et al. [25] estimated the amount of electricity generated from the PV system by using the '*PV-Design*' software program. Wu et al. [38] analyzed the building attached PV system in Shanghai by using the 'PV_{SYST}' software program.

Second, other previous studies analyzed the economic performance of the PV system. Bahr [10] determined the optimal configuration for the design parameters of the PV blind through the cost-benefit approach. For this, this study conducted the comprehensive assessment by considering thermal comfort, visual comfort, and energy saving requirements. Celik et al. [19] established the best configuration of the building-integrated PV system. To do this, this study analyzed the yearly-based electricity generation and the payback period for two types of the PV electrical configuration. Jeong et al. [26] conducted the economic and environmental assessment to determine the optimal strategy in implementing the rooftop PV system, in which this study used the absolute and relative investment indices.

These previous studies have focused on one or more things among the critical factors that should be considered in implementing the PV system. Despite these efforts in the previous studies, no study has ever address all of the factors for the robust planning of the BIPB. Based on this background, the motivation of this study has been established as follows.

- While the energy simulation can be conducted with the detailed information (e.g., the drawings and specifications) available only in the detailed design phase, it cannot be conducted in the early design phase where the detailed information is not available.
- Most of the energy simulation tools (e.g., '*Autodesk Ecotect Analysis*', 'PV_{SYST}', and '*PV-Design*') are often labor-intensive and time-consuming, and they require a high level of knowledge about the building energy usage and environment. That is, it is too complex for decision-makers, such as an architect or a construction manager, to use the energy simulation tools. Thus, the simplified estimation model should be developed.
- Although there are simplified energy simulation tools such as '*RETScreen*', it just considers the total capacity of the installed PV system. Thus, it is almost impossible to consider more detailed information on the specifications of the window as well as to analyze the shading effect of the PV blind's slats depending on the solar altitude.
- In the existing energy simulation tools, the analysis results for a given project cannot be expanded to other projects because they are limited to the specific project. Thus, it is required to establish the standard database to accumulate the knowledge.
- When estimating the amount of electricity generated from the PV system in the previous studies, they have not reflected the nonlinearity relationship between the amount of electricity generation and the associated independent variables. In addition, there is a lack of fundamental understanding of the independent variables affecting the amount of electricity generated from the PV system.
- The predictive tool should be developed to determine the optimal strategy for maximizing the value of the investment for the PV system. To do this, it is necessary to analyze the economic