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# An integrated model for estimating the techno-economic performance of the distributed solar generation system on building façades: Focused on energy demand and supply

Jeongyoon Oh[a], Choongwan Koo[b,*], Taehoon Hong[a], Seung Hyun Cha[c]

[a] Department of Architecture and Architectural Engineering, Yonsei University, Seoul 03722, Republic of Korea
[b] Department of Architectural Engineering, Kyonggi University, Suwon 16227, Republic of Korea
[c] Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

## HIGHLIGHTS

- A novel approach was developed for analyzing the building energy demand and supply.
- The techno-economic performance of the DSG system on building façades was estimated.
- The finite element method was used to simplify the complex conventional approach.
- The effectiveness and efficiency of the integrated model (i-FEM) were validated.
- The usability, integrity, and practicality of the novel approach were enhanced.

## ARTICLE INFO

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Integrated model
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Life-cycle cost analysis

## ABSTRACT

There has been growing interest in the distributed solar generation (DSG) system in accordance with the 'Post-2020 Climate Change Agreement', especially for the reduction of greenhouse gas emissions from buildings. In this respect, this study aimed to develop an integrated model for estimating the techno-economic performance of the DSG system on building façades, with a focus on energy demand and supply. The integrated model was developed in five stages: (i) definition of design variables affecting the DSG system on building façades; (ii) establishment of a standard database for the DSG system on building façades using energy simulation; (iii) technical analysis of the DSG system on building façades using the finite element method; (iv) economic analysis of the DSG system on building façades through life-cycle cost analysis; and (v) systemization. Detailed analyses were conducted in three aspects: (i) nonlinearity analysis; (ii) validation of the developed model; and (iii) practical application (to the 'S' apartment block in South Korea). With the newly developed integrated model (i-FEM), it was found that the technical performance of the DSG system could be accurately estimated in only 6 s: (i) heating energy demand (1.01%); (ii) cooling energy demand (9.27%); and (iii) building energy supply (3.55%). It is expected that decision-makers (e.g. construction managers or facility managers) can use the newly developed integrated model (i-FEM) to evaluate the potential impact of the DSG system on building façades in a timely and accurate manner.

## 1. Introduction

At the 21st session of the Conference of Parties (COP 21) of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris, France, on 9 December 2015, the United Nations (UN) sought to get agreement on a new international framework following the Kyoto Protocol. Accordingly, the '*Post-2020 Climate Change Agreement*' was launched and endorsed by 196 countries around the world [1].

The South Korean government targeted a greenhouse gas (GHG) emissions reduction of 37% by 2030, compared to business as usual (BAU). On 6 December 2016, '*The 1st Basic Plan for Response to Climate Change*' and the '*Basic National Roadmap for GHG Reductions by 2030*' were established to allocate the amount of reduction by industry. In addition, the government plans to reduce 219 million tons of GHG emissions by 2030 (i.e. 25.7% of 2030 BAU) from eight main sectors, including the reduction of 35.8 million tons from buildings [2].

* Corresponding author.
*E-mail addresses:* omk1500@yonsei.ac.kr (J. Oh), cwkoo@kgu.ac.kr (C. Koo), hong7@yonsei.ac.kr (T. Hong), seung-hyun.cha@polyu.edu.hk (S.H. Cha).

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**Nomenclature**

*Abbreviations*

| | |
|---|---|
| BAU | business as usual |
| BED | building energy demand |
| BEDS | building energy demand and supply |
| BEP | break-even point |
| BES | building energy supply |
| BIPBs | building-integrated photovoltaic blinds |
| CIGS | copper indium gallium selenide |
| ESB | electricity-saving benefit |
| FEM | finite element method |
| GC plan | grid-connected utilization plan |
| $GC_{incl.SREC}$ plan | grid-connected utilization plan including the SREC |
| $GC_{excl.SREC}$ plan | grid-connected utilization plan excluding the SREC |
| GHG | greenhouse gas |
| i-FEM | integrated finite element model |
| IIC | initial investment cost |
| KCERs | Korean certified emissions reductions |
| KPX | Korea power exchange |
| LCC analysis | life cycle cost analysis |
| NPV | net present value |
| MOLIT | Ministry of Land, Infrastructure and Transport |
| PV | photovoltaic |
| SC plan | self-consumed utilization plan |
| SIR | saving-to-investment ratio |
| SMP | system marginal price |
| SREC | solar renewable energy certificate |
| UNFCCC | the united nations framework convention on climate change |
| VBA | visual basic for application |
| VT | visible transmittance |
| WWR | window-to-wall ratio |

With respect to residential buildings in South Korea, the annual 5.8 million tons of GHG emissions derive from energy consumption during operation and maintenance, of which 58% is a consequence of the heating and cooling energy demand. This demand is closely related to building envelope design [3–6]. Accordingly, the government has proposed energy policies and design standards for systematic building envelope design: (i) '*Energy-saving design criteria for buildings*'; (ii) '*Low-carbon, green-energy building design guidelines*'; and (iii) '*Standard for the design and performance evaluation of residential green buildings*' [7–9].

To achieve the targeted reduction by 2030, it will be essential to adopt a more proactive strategy (such as new and renewable energy) along with systematic building envelope design. In particular, there has been growing interest in the distributed solar generation (DSG) system, which is easy to implement, as an alternative to existing centralized power plants [10]. The DSG system could reduce the loss of power entailed by delivering electricity generated in the centralized power plants. If the DSG system is introduced as part of the systematic building envelope design, it could become a way to realize net-zero-energy buildings. In addition, since it is required to install the new and renewable energy systems for public buildings over the minimum requirement (e.g. 18% of total energy demand in 2018, South Korea), it is inevitable to utilize the building façade as well as the rooftop when introducing the photovoltaic (PV) system to meet the requirement. In particular, it is strongly recommended by the government to install the PV system in the south facing façades of high-rise buildings in a big city (e.g. Seoul, Hong Kong) [11–15]. In order to promote the business, the Korean government provides the subsidy for the initial investment as an incentive. In this regard, this study aimed to investigate the potential impact of the DSG system on building façades (i.e., a building-integrated photovoltaic blind (BIPB) system) from the perspective of the building energy demand and supply.

Previous studies have analyzed the building energy demand and supply with difference envelope design, which can be categorized into three aspects: (i) building energy demand (BED); (ii) building energy supply (BES); and (iii) building energy demand and supply (BEDS) (see Table 1) [16–33].

First, some previous studies analyzed the techno-economic performance of different building envelope design in terms of the BED through energy simulation tools and multiple calculations. Lam et al. [16] used climate data to analyze the relationship between the overall thermal transfer value of building skins, and evaluated energy performance through the '*DOE-2*' software program. Huang et al. [17] focused on the effect of the building envelope (i.e. the insulation material and high-reflectivity coating) on cooling demand via the '*EnergyPlus*' software program. Koo et al. [18] proposed a model for predicting the BED (i.e., heating and cooling load) using the architectural and window design variables via the '*DesignBuilder v3.0*' software program. Hong et al. [19] sought to identify the optimal energy-saving technology (e.g. insulation on window frames) in terms of energy efficiency, reduction of $CO_2$ emissions and life-cycle cost (LCC), by using the '*DesignBuilder v2.2*' software program.

Second, other previous studies used various methods to conduct the techno-economic analysis of different building envelope design in terms of the BES through energy simulation tools and multiple calculations. Hong et al. [20] sought to visualize the optimal amount of electricity generated by the PV system and the corresponding optimal PV panel's installation angle by region, using the Geographic Information System (GIS) and genetic algorithm. Koo et al. [21] developed a model for predicting the amount of electricity generated from distributed solar generation system via the 9-node-based finite element model. Kang et al. [22] used the mathematical model to analyze the technical performance of BIPBs by considering several design variables (e.g. orientation, blind-slat angle, and standard of PV panel). Bahr [23] proposed an optimal design of BIPBs by considering the estimated amount of electricity generated from BIPBs through the '*Autodesk Ecotect analysis*' software program and the relevant results from the cost-benefit analysis.

Finally, other studies focused on the technical analysis of different building envelope design in terms of the BEDS through energy simulation tools and multiple calculations. Hachem et al. [24] analyzed the BEDS via the '*EnergyPlus*' software program by considering various design variable (e.g. density of buildings and floorplan.). Hwang et al. [25] presented the optimal design of PV systems by simultaneously considering the amount of electricity generated from PV systems and the electricity consumption through the '*e-QUEST*' and '*PV-DesignPro*' software programs. Chae et al. [26] analyzed the thermal-optical properties of commercial buildings with building-integrated PV window systems in terms of the heating and cooling energy demand and the amount of electricity generated by PV systems via the '*EnergyPlus 6.0*' and '*Equivalent one-diode*' software programs.

The limitations of the previous studies on the techno-economic performance of different building envelope design in terms of the BEDS (especially, for the DSG system) can be explained in three aspects: (i) usability; (ii) integrity; and (iii) practicality.

- *Usability:* The conventional methods (e.g., energy simulation modeling and mathematical formulas) cannot be used for a decision-maker (such as a construction manager or facility manager) to carry out the quick review of design alternatives at the early design stage. This is because the conventional methods require the detailed information (e.g., building's physical characteristics, operational schedule, equipment capacity) that can be obtained from design