Energy and Buildings 151 (2017) 320–331

Contents lists available at ScienceDirect

Energy and Buildings

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

A simplified estimation model for determining the optimal rooftop photovoltaic system for gable roofs

Cheolwoo Ban [a], Taehoon Hong [b,*], Kwangbok Jeong [b], Choongwan Koo [c], Jaewook Jeong [d]

[a] Republic of Korea Marine Corps., P.O. Box # 202-8, Yeonpyeong, Ongjin, Incheon, 23108, Republic of Korea
[b] Department of Architecture & Architectural Engineering, Yonsei University, Seoul, 03722, Republic of Korea
[c] Department of Building Services Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong
[d] Kolon Global Corporation, Incheon, 22001, Republic of Korea

ARTICLE INFO

Article history:
Received 21 February 2017
Received in revised form 27 May 2017
Accepted 28 June 2017
Available online 29 June 2017

Keywords:
Photovoltaic system
Gable roof
Life cycle cost
Life cycle CO_2
Net present value
Saving-to-investment ratio

ABSTRACT

This study aimed to develop a simplified estimation model for determining the optimal rooftop PV system for gable roofs that can evaluate life cycle economic and environmental assessment, by considering the type of installation to be used for such rooftop PV system. The military facilities located in three regions (i.e., Gimpo (northern part), Deajeon (middle part), and Pohang (southern part)) in South Korea were selected for the case studies. The results of this study are as follows. First, in terms of NPV_{25} (net present value in 25 years), for the roofs with a lower orientation, ToI-$2_{opt.}$ was selected as the optimal rooftop PV system, and for the roofs with a higher orientation, ToI-$2_{ext.}$ or ToI-$3_{opt.}$ was selected as the optimal rooftop PV system. Second, in terms of SIR_{25} (savings-to-investment ratio in 25 years), for the roofs with a lower orientation, ToI-$1_{ext.}$ was selected as the optimal rooftop PV system, and for the roofs with a higher orientation, ToI-$3_{opt.}$ was selected as the optimal rooftop PV system. The simplified estimation model may be useful for decision makers, including experts and non-experts (i.e., architects, owners, construction managers, etc.), or policymakers in determining the optimal rooftop PV system for a gable roof.

1. Introduction

Greenhouse gas (GHG) emissions are the main cause of global warming, and to reduce its GHG emissions by 37% below its business-as-usual level until 2030, South Korea established a national carbon emission reduction target (CERT) [1–3]. To achieve this target, the South Korean government has been implementing the Renewable Portfolio Standard since 2012, and has established the policy of obtaining 11% of the country's primary energy needs from new and renewable energy (NRE) by 2035 [4,5].

Specially, the photovoltaic (PV) system, among the various NREs, has been evaluated as the largest potential resource that can reduce GHG emissions by replacing fossil fuel [6–8]. Accordingly, the South Korean government is promoting the use of the rooftop PV system, but due to the uncertainty of the economic profitability of the said system, there is a limit to the success of such efforts. The reason for the uncertainty of the economic profitability of the rooftop PV system is that the annual electricity generation (AEG) of such system is determined according to various factors (i.e., region, PV system design, etc.) pertaining to the rooftop PV systems [7,9–11]. To improve the city landscape, it is recommended that gable roofs be installed in several cities in South Korea (i.e., Anyang, Jecheon, Incheon, etc.) based on the country's district unit plan [12,13]. The slope and orientation of a gable roof can be variously designed by region and topography. Therefore, it is necessary to develop a model for evaluating the economic profitability of the rooftop PV systems considering various factors (i.e., region and design). To address this challenge, this study aimed to develop a simplified estimation model for determining the optimal rooftop PV system for gable roofs that considers the type of installation (ToI), which can be used for life cycle economic and environmental assessment.

According to Hachem et al. [14], Hachema et al. [15], and Chiras et al. [16], the rooftop shape has a significant effect on the AEG of the rooftop PV system because various design parameters (i.e., the installation area of the rooftop PV system, the slope of the installed panel (SoP), the azimuth of the installed panel (AoP), etc.) are determined by the rooftop shape (i.e., flat roof, gable roof, etc.). The rooftop shapes of the rooftop PV system are generally categorized into (i) flat roof and (ii) gable roof.

* Corresponding author at: Yonsei University 50 Yonsei-ro, Seodaemun-gu, Seoul, 03722, Republic of Korea.
E-mail address: hong7@yonsei.ac.kr (T. Hong).

http://dx.doi.org/10.1016/j.enbuild.2017.06.069
0378-7788/

Nomenclature

Abbreviations

AEG	Annual electricity generation
AoP	Azimuth of the installed panel
BEG_t	Benefit from the electricity generation of the rooftop PV system in year t
BET_t	Benefit from the CO_2 emission reduction in year t
CER	Amount of CO_2 emission reduction
CERT	Carbon emissions reduction target
F_{CE}	CO_2 emission factor
GHG	Greenhouse gas
IIC	Initial investment cost
IIC_t	Initial investment cost in year t
LCC	Life cycle cost
$LCCO_2$	Life cycle CO_2
MADSR	Monthly average daily solar radiation
MAT	Monthly average temperature
n	Analysis period
NPV	Net present value
NPV_n	Net present value during n years
NRE	New and renewable energy
PV	Photovoltaic
r	Real discount rate
RC_t	Repair and replacement cost in year t
r_n	Nominal interest rate
r_f	One of the following elements: the inflation rate, the electricity price growth rate, or the CO_2 emission trading price growth rate
SIR	Savings-to-investment ratio
SIR_n	Savings-to-investment ratio during n years
SoP	Slope of the installed panel
ToI	Type of installation

- (i) Flat roof: Jafarkazemi and Saadabadi [17] evaluated the tilt angles and orientations of the PV panels on the flat roofs in Abu Dhabi and determined the optimum tilt angle (22°) and orientation (south direction, 0°) of the PV panels in the said country. Gopinathan et al. [18] estimated the total annual energy considering the various tilt and azimuth angles of the PV panels on the flat roofs in South Africa and found that the optimum tilt angle for maximum solar radiation collection is latitude minus 10° in summer and latitude plus 30° or 10° in winter. Park et al. [19] proposed the optimal PV system implementation strategy for reducing the carbon dioxide on the national level and analyzed the CERT achievement rate in 2030 that considered various building factors (i.e., installation area of the flat roof, SoP, AoP, etc.) and the type of PV panel (i.e., mono-Si and poly-Si).
- (ii) Gable roof: Hachem et al. [14] proposed the design methodology of the housing units' roofs that were able to not only increase the electricity generation but also decrease the heating and cooling demands by installing the building-integrated PV and thermal system in the housing units. Hachem et al. [15] evaluated the heating and cooling demands and electricity generation of the PV system according to the geometric shape of the roof, the geometric shape density in a neighborhood, and the site layout. Jeong et al. [20] conducted a life cycle economic and environmental assessment of the rooftop PV system for gable roofs and presented the optimal implementation strategies by prototype in terms of the net present value (NPV) and the savings-to-investment ratio (SIR).

As mentioned above, several studies analyzed the rooftop PV system from various view points, but such studies had the following limitations: (i) several studies were conducted to evaluate the economic profitability of the rooftop PV system on flat roofs considering various design parameters (i.e., installation area of the rooftop PV system, SoP, and AoP), and there was still a lack of study to date that evaluated the economic profitability of the rooftop PV system for gable roofs; and (ii) as gable roofs are designed considering the topography by region, the more various design parameters are considered simultaneously, the more accurately the AEG of the rooftop PV system can be estimated, but the previous studies estimated the AEG considering only the existing orientation of the gable roof, without considering various design parameters.

To address the aforementioned limitations, this study aimed to develop a simplified estimation model for determining the optimal rooftop PV system for gable roofs. Various design parameters (i.e., installation area of the rooftop PV system, SoP, and AoP) for determining the optimal rooftop PV system for gable roofs were considered in developing the simplified estimation model. The developed model can enable decision makers, including experts and non-experts (i.e., architects, owners, construction managers, etc.), or policymakers to determine the optimal rooftop PV system for gable roofs automatically, by entering input data (i.e., region, orientation, existing slope, length, and width of the gable roof).

Table 1
Physical and cost information of the PV panel and inverter.

Classification		PV panel	PV inverter
Model name		Trina TSM-240PA05-08	UNIV-30GTS
Power capacity(w)		240	3000
Module efficiency (%)		14.7	97.0
Miscellaneous losses (%)		3	3
Unit price(US$/unit)		230	525.83
Unit price per power capacity (US$/W)		0.96	0.18
Unit size	Width (mm)	1651	–
	Length (mm)	1004	–
	Thickness (mm)	46	–

2. Materials and methods

As shown in Fig. S1, this study was conducted in four steps: (i) data collection; (ii) establishment of the electricity generation using energy simulation; (iii) life cycle economic and environmental assessment; and (iv) systemization of the simplified estimation model using a Microsoft-Excel-based VBA.

2.1. Data collection

The following data were collected in this study to develop a simplified estimation model: (i) information of the PV panels and inverters; and (ii) information of the region (refer to Fig. S1).

First, the physical information (i.e., capacity, efficiency, miscellaneous losses, etc.) and cost information (i.e., unit price) of 62 PV panels and 84 inverters were collected. The products (PV panel: Trina TSM-240PA05-08, US$0.96/W; PV inverter: UNIV-30GTS, US$0.18/W) with prices most similar to the average price per unit capacity (PV panel: US$0.96/W; PV inverter: US$0.17/W) among the collected PV panels and inverters were selected as a PV panel and PV inverter for use in the simplified estimation model (refer to Table 1) [21,22].

Second, the meteorological and geographical data were collected as regional data affecting the AEG of the rooftop PV system. The monthly average daily solar radiation (MADSR) and monthly average temperature (MAT) in the 16 administrative divisions in South Korea, which are provided by National Climate Data Service System, were collected as the meteorological data [23]. The location information (i.e., latitude) where the meteorological data (i.e.,