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A GIS (geographic information system)-based optimization model for estimating the electricity generation of the rooftop PV (photovoltaic) system

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ABSTRACT

The global PV (photovoltaic) generation market has been rapidly growing. In the introduction of a PV system, the electricity generation efficiency of the PV system depends on regional factors and on-site installation factors. It has a significant effect on the returns on investment. Therefore, this study conducted a sensitivity analysis on how the impact factors of the rooftop PV system affect its electricity generation. Based on the results of the sensitivity analysis, this study aimed to ultimately develop a GIS-based optimization model for estimating the electricity generation of the rooftop PV system.

Several impact factors were used in the sensitivity analysis. The result of this study showed that there were 1.12-, 1.62-, and 1.37-fold differences in the annual electricity generation of the rooftop PV system in South Korea due to the regional factor, the azimuth of the installed panel, and the slope of the installed panel, respectively. Using a GIS-based optimization model, final decision-maker could easily and accurately estimate the electricity generation of the rooftop PV system in a preliminary feasibility study.

1. Introduction

The global use of fossil fuels has caused grave environmental crises including energy depletion and pollution and is projected to increase by more than one-third by 2035. Despite this rapid increase in energy usage, coal has a reserves-to-production ratio of about 128 years, natural gas 54 years, and oil 41 years, according to the '*2010 Survey of Energy Resources*.' Given this background, if the annual increase rate of energy consumption from 2008 to 2035 is assumed to be 1.4%, fossil fuel reserves will be fully depleted within 50 years [1–8].

To overcome such a crisis, there has been growing interest in NRE (new renewable energy) [9–12]. As of 2009, NRE accounted for about 18% of global electricity generation and 25% of the world's electricity generation facilities (1230 GW of 4800 GW). According to the '*Medium-Term Renewable Energy Market Report 2012*,' global renewable energy generation will increase by 40% over the period from 2011 to 2017 [13]. Since 2008, the U.S. and the EU have been establishing more renewable energy power plants than conventional fossil energy power plants. According to a press release, renewable energy power plants accounted for about 60% of newly installed power plants in the EU and more than 50% in the U.S [14–17]. Also, the International Energy Agency expects to double the share of renewable energy by 2035, compared to in 2008. In other words, it is forecast to increase from 19% in 2008 to almost 33% by 2035, which means renewable energy could catch up with coal [18].

Regarding the global energy and environmental issue, solar energy (including PV (photovoltaic) energy) is recognized to play an important role in the renewable and sustainable development [19–25]. The interest in PV energy has been rapidly increased as the radioactive pollution and energy storage issues were raised in the wake of the nuclear-power-plant accident in Fukushima, Japan [26]. The PV market was only 7.2 GW in 2009, but it was increased more than twofold to 16.6 GW in 2010. As of 2011, the installation capacity of global PV system went up to 40 GW. Especially, with the continuous downward trend in the cost of the PV system, it is expected that the PV market would be expanded to achieve the net-zero energy buildings and the carbon emissions reduction target [27–31].

Keeping pace with such global trend, the South Korean government is promoting various incentive policies such as financial support for NRE projects, the 1 Million Green Homes Project, and the Feed-in-Tariff [32–35]. Among NREs, the PV system has the highest potential as a sustainable energy source. Particularly, crystalline silicon, commonly used by the semiconductor industry, is the material used in 94% of all PV modules today. Thus, it is

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considered that the PV system has great potential in the export market since South Korea is one of leading countries in semiconductor technology [36].

In spite of the various advantages of the PV system including the government's financial support, the decrease in the systems' unit cost, and their high potentials, one major obstacle remains: the high initial investment cost. Therefore, it is crucial to assess the ROI (return on investment) in introducing the PV system by accurately estimating its electricity generation. The electricity generation of the PV system is affected by various impact factors such as (i) regional geographical information; (ii) regional meteorological information; and (iii) on-site installation information. Therefore, a sensitivity analysis should be conducted on how the impact factors of the rooftop PV system affect its electricity generation.

In previous studies, various analyses have been conducted on the impact factors of the PV system [37–60]. Zhao et al. [37] analyzed that the optimal installation angle of a PV panel depended on the installation location. Dincer and Meral [38] analyzed the temperature as a factor that impacts the efficiency of a PV solar cell. It was concluded that the temperature of a solar cell should be kept in a lower temperature as the optimal condition. Hwang et al. [39] also conducted an optimization analysis of the building integrated PV system in office buildings. To generate the maximum amount of electricity, they analyzed various factors, including the azimuth and slope of the installed panel, and the installation distance to the module length ratio. Siraki and Pillay [40] focused on the change of the azimuth and slope of the installed panel depending on both the regional latitude and the surrounding buildings.

While these previous studies individually analyzed the impact factors of the PV system, they failed to comprehensively analyze them. Therefore, the objective of this study is to conduct a comprehensive sensitivity analysis of how the electricity generation of the PV system would change from the complex interaction of the aforementioned impact factors. Based on the results of the sensitivity analysis, this study aims to ultimately develop a GIS-based optimization model for estimating the electricity generation of the rooftop PV system. Using a GIS-based optimization model, final decision-maker could easily and accurately estimate the electricity generation of the rooftop PV system in a preliminary feasibility study.

This study was conducted in three steps: (i) the key factors affecting the electricity generation of the rooftop PV system were selected through an extensive literature review and interviews with experts; (ii) a sensitivity analysis on how the impact factors of the rooftop PV system affect its electricity generation was conducted through an energy simulation; and (iii) using the GIS (geographic information system) and genetic algorithm, the optimal annual electricity generation of the rooftop PV system and the corresponding optimal SoP were visually proposed by region in South Korea.

2. Materials and methods

2.1. Definition of the impact factors of the rooftop PV system

The following impact factors of the rooftop PV system were derived from an extensive literature review and interviews with experts (i.e., solar photovoltaic staff of Parsons Brinckerhoff, Oerlikon Solar, and Hilti Corporation): (i) regional geographical information; (ii) regional meteorological information; and (iii) on-site installation information. As shown in Table 1, the regional geographical information is classified by latitude and monthly meridian altitude; the regional meteorological information is classified by the MADSR (monthly average daily solar radiation) and the monthly average temperature; and the on-site installation information is classified by the AoP (azimuth of the installed panel), the SoP (slope of the installed panel), and the type of the panel and inverter.

The data on the impact factors were collected in 78 regions in South Korea. However, the MADSR data were measured at 24 of the 78 weather stations nationwide (refer to Table S1). The MADSR data at the 54 other weather stations were gleaned from the results of previous studies (refer to Table S2). Koo et al. [61], as in previous research, developed an A-CBR (advanced Case-Based Reasoning) model for MADSR estimation using the monthly geographic and

Table 1
Reviews of previous studies on the impact factors of the rooftop PV system.

Variables	Attributes			Detailed description	Reference
Independent variable	Regional factors	Geographical information	Latitude	( ) °N	Crook et al. [42], Hummon et al. [56], Levinson et al. [43], Liu et al. [44], Siraki and Pillay [40], Tang and Wu [51], Tiris and Tiris [52], Zhao et al. [37]
			Monthly meridian altitude	( ) °	Kaldellis and Zafirakis [54], Li and Lam [48], Zhao et al. [37]
		Meteorological information	Monthly average daily solar radiation	( ) kWh/m^2/day	Crook et al. [42], Kaldellis and Zafirakis [54], Li and Lam [48], Siraki and Pillay [40],
			Monthly average temperature	( ) °C	Braun et al. [57], Dincer and Meral [38], Green [59], Hoffmann and Koehl [58]
	On-site installation factor	On-site installation information	The azimuth of the installed panel (AoP)	( ) °	Asowata et al. [53], Gopinathan et al. [50], Gunerhan and Hepbasli [49], Hummon et al. [56], Hussein et al. [46], Jafarkazemi and Saadabadi [47], Kaldellis and Zafirakis [54], Levinson et al. [43], Li and Lam [48], Siraki and Pillay [40], Tang and Wu [51], Ubertini and Desideri [45]
			The slope of the installed panel (SoP)	( ) °	Asowata et al. [53], Bojić et al. [55], Gunerhan and Hepbasli [49], Huld et al. [60], Hummon et al. [56], Hussein et al. [46], Hwang et al. [39], Jafarkazemi and Saadabadi [47], Kaldellis and Zafirakis [54], Li and Lam [48], Liu et al. [44], Siraki and Pillay [40], Tang and Wu [51], Tiris and Tiris [52], Ubertini and Desideri [45], Zhao et al. [37]
			Type of the panel	( )	Li and Lam [48], Ordóñez et al. [41]
			Type of the inverter	( )	Li and Lam [48], Ordóñez et al. [41]
Target variable	–	–	Electricity generation	( ) kWh	–