Renewable and Sustainable Energy Reviews 57 (2016) 822–837

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

An integrated multi-objective optimization model for determining the optimal solution in implementing the rooftop photovoltaic system

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ARTICLE INFO

Article history:
Received 29 May 2014
Received in revised form
7 September 2015
Accepted 18 December 2015

Keywords:
Rooftop photovoltaic system
Existing building
Integrated multi-objective optimization
Trade-off problem
Genetic algorithm
Economic and environmental assessment

ABSTRACT

The photovoltaic (PV) system has been highlighted as a sustainable clean energy source. To successfully implement the PV system in a real project, several impact factors should be simultaneously considered. This study aimed to develop an integrated multi-objective optimization (iMOO) model for determining the optimal solution in implementing the rooftop PV system. This study was conducted in six steps: (i) establishment of database; (ii) generation of the installation scenarios in the rooftop PV system; (iii) energy simulation using the software program '*RETScreen*'; (iv) economic and environmental assessment from the life cycle perspective; (v) establishment of the iMOO process using a genetic algorithm; and (vi) systemization of the iMOO model using a *Microsoft-Excel-based VBA*. Two criteria were used to assess the robustness and reliability of the developed model. In terms of effectiveness, the optimal solution was determined from a total of 399,883,120 ($=91\times49\times19\times80\times59$) possible scenarios by comprehensively considering various factors. In terms of efficiency, it was concluded that the time required for determining the optimal solution was 150 s. The developed model makes it possible for final decision-maker such as construction managers or contractors to determine the optimal solution in implementing the rooftop PV system in the early design phase.

Contents

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http://dx.doi.org/10.1016/j.rser.2015.12.205
1364-0321/

1. Introduction

The rapid increase in the use of fossil fuels has caused energy depletion and environmental pollution. World primary energy consumption in 2010 registered a 5.6% increase, which was the highest rate since 1973. If the annual increase rate of energy consumption is assumed to be 1.4% from 2008 to 2035, some experts estimate that fossil fuel reserves will be fully depleted within 50 years [1–8]. To overcome this challenge, the interests in new renewable energy (NRE) have increased [9–12]. According to a press release, renewable energy power plants accounted for about 60% of newly installed power plants in the European Union and more than 50% in the United States [13–17]. In particular, a photovoltaic (PV) energy is expected to play an important role in renewable and sustainable energy development [18–22]. The interests in PV energy have rapidly increased in the wake of the nuclear-power-plant accident in Fukushima, Japan [23]. The PV market was only 7.2 GW in 2009, but it has 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 [24–27].

In South Korea, various energy policies (such as *Renewable Portfolio Standard* and *Renewable Energy Certificates*) have been promoted to activate the distribution of the PV system [28–31]. In addition, PV system has greater potential in South Korea because South Korea is one of the leading countries in a semiconductor technology (which is related to crystalline silicon used in 94% of PV modules) [32]. Even if the PV system has several advantages (such as governmental financial support, the decreases in the unit cost of the PV system, and high potential as a sustainable clean energy source), its initial investment cost is still high, which has been an obstacle to its continuous growth. To overcome this challenge, it is required to analyze the whole life-cycle cost of a potential PV system before its implementation. That is, based on the holistic analysis from the life-cycle perspective, a final decision-maker (e.g., owner, construction manager, designer, and contractor) should be able to determine whether or not the economic feasibility of the PV system can be achieved. To do this, one of the most significant steps is to estimate the amount of electricity generation from the PV system. There are several impact factors that should be considered in estimating the amount of electricity generation from the PV system, which include (i) the regional climates (i.e., the geographical factors such as latitude and monthly meridian altitude, and the meteorological factors such as monthly average daily solar radiation (MADSR) and monthly average temperature) and (ii) the building characteristics (i.e., the azimuth of the installed panel (AoP), the slope of the installed panel (SoP), and the rooftop area limit). In addition, it is required to take into account the regulation such as the *Mandatory Renewable Energy Installation Program* (which makes it compulsory to supply over 10% of energy consumptions in a public building as the minimum electricity generation limit).

As mentioned above, in order to determine the economic feasibility of the PV system before its implementation, it is necessary to consider the various impact factors affecting the amount of annual electricity generation (AEG) from the PV system as well as its initial investment cost (IIC) with government subsidy. In addition, in order to conduct the whole life-cycle cost analysis on the PV system from the various perspectives, it is required to analyze the net present value (NPV) as an absolute index and the saving-to-investment ratio (SIR) as a relative index. As such, there are several objectives that should be considered in implementing the PV system (i.e., the IIC, the AEG, the NPV, the SIR, and the AEG per unit panel (AEG/EA)), which have the trade-off relationships.

In order to analyze the complex relationships among the several objectives, the research team has conducted a series of studies. First, Hong et al. [33] developed a GIS (geographic information system)-based optimization model for estimating the amount of electricity generation from the rooftop PV System. This study conducted a comprehensive sensitivity analysis on how the AEG/EA in the rooftop PV system depended on the complex correlations among the impact factors. Based the results, this study finally developed a GIS-based optimization model for estimating the AEG/EA in the rooftop PV system. The results showed that (i) a 1.12-fold difference in the AEG depended on the regional climates; (ii) a 1.62-fold difference in the AEG depended on the AoP; and (iii) a 1.37-fold difference in the AEG depended on the SoP. Second, Koo et al. [34] developed an economic and environmental optimization model for a rooftop PV system by implementing various processes and the associated equations. The results showed that as follows: (i) the number of the installed panels (NoP) depended on the type of the panel (ToP) and the SoP, which resulted in the different the IIC, the AEG, the NPV, the SIR, and the AEG/EA; (ii) a trade-off relationship between the NPV and the SIR occurred in the specific zone.

Based on the previous studies conducted by the research team, it can be concluded that several types of parameters should be simultaneously considered to analyze the economic feasibility of the PV system. That is, a multi-objective optimization problem should be well defined in a dynamic, complex, and multi-dimensional decision space. Therefore, this study aimed to develop an integrated multi-objective optimization (iMOO) model for solving the aforementioned trade-off problems, which makes it possible to determine the optimal solution in implementing the PV system. Using the optimal solution, this study can achieve the five objectives: (i) minimization of the IIC (with government subsidy); (ii) maximization of the AEG; (iii) maximization of the NPV; (iv) maximization of the SIR; and (v) maximization of the AEG/EA.

2. Literature review

2.1. Reviews on the impact factors of the rooftop PV system

There are a lot of impact factors affecting the amount of electricity generation from the PV system, which should be considered to determine the optimal solution in implementing the rooftop PV system. Many previous studies on the PV system considered these impact factors [33–62], which can be categorized into two parts: (i) the regional climates (i.e., the geographical factors and the meteorological factors) and (ii) the building characteristics (i.e., the on-site installation factors, the rooftop area limit, and the budget limit). In particular, the previous studies have mainly focused on the building characteristics (e.g., the AoP and the SoP)