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A bottom-up approach for estimating the economic potential of the rooftop solar photovoltaic system considering the spatial and temporal diversity

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HIGHLIGHTS

- The economic potential of the rooftop solar PV system was estimated in South Korea.
- The spatial and temporal diversity of the solar PV technology were considered.
- The rooftop solar PV profitability was calculated based on a bottom-up approach.
- The economic potential was 36-fold the installed capacity of the study area in 2016.
- This study took one step farther towards the rooftop solar PV potential estimation.

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ABSTRACT

To successfully deploy distributed solar generation in urban environments, it is essential to investigate the potential to generate electricity from the rooftop solar photovoltaic (PV) system within a region. While various interpretations are possible for the rooftop solar PV potential, most of the previous studies focused on estimating the technical potential, not considering the economic viability and market dynamics. Therefore, it is necessary to estimate the economic potential of the rooftop solar PV system to quantify the amount of economically viable solar PV energy within a region and to evaluate the impact of the various factors affecting market access. Towards this end, this study proposed a bottom-up approach for estimating the economic potential of the rooftop solar PV system considering the market dynamics by adoption year. Accordingly, the economic potential of the rooftop solar PV system was estimated for the Gangnam district in Seoul, South Korea from 2008 to 2016. In terms of power capacity, it was analyzed that as of 2016, the actual installed capacity of the solar PV system in the Gangnam district was only 3% of the maximum economic potential of the rooftop solar PV system (i.e., economic potential for electricity business purposes), showing a high potential for additional rooftop solar PV adoption. In terms of electricity generation, it was shown that as of 2016, the annual economic potential of the rooftop solar PV system could supply up to 4.48% of the annual electricity consumption in the Gangnam district, while only 0.12% could be supplied from the annual electricity generation of the actual installed solar PV system. This study has significant contributions in that it took one step farther towards the rooftop solar PV potential estimation process, from the technical potential to the economic potential, considering the spatial and temporal diversity of the solar PV technology.

1. Introduction

Recent concerns on climate change and resource depletion have brought about a demand for alternative energy sources and strategies, which highly contributed to the new energy paradigm shift from centralized to decentralized electricity generation with renewable energy, the so-called "distributed generation (DG)" [1]. DG allows onsite electricity generation through renewable energy for nearby end users with small capacities, often with the solar photovoltaic (PV) system, instead of supplying electricity in a conventional manner, with large and centralized power plants [2]. In this regard, abundant rooftops and plenty of sunlight play a significant role in promoting distributed solar generation (DSG) in the building sector [3].

To successfully implement DSG by utilizing plenty of rooftops in

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urban environments, it is essential to investigate the potential of generating electricity from the rooftop solar PV system (i.e., rooftop solar PV potential) within an urban boundary [4]. In general, the rooftop solar PV potential can be categorized into five different hierarchical levels: (i) physical potential; (ii) geographic potential; (iii) technical potential; (iv) economic potential; and (v) market potential [5–7]. While various definitions and interpretations of the aforementioned rooftop solar PV potential are available, most of the previous studies focused on estimating the technical potential, the amount of energy that can be converted from solar radiation considering the geographic constraints (i.e., available rooftop area) and system performance (i.e., module efficiency) [7–10]. Early studies estimated the technical potential of the rooftop solar PV system of a region using relatively simplified methods, usually by approximating the available rooftop area with multipliers [3,11,12]. A study by Byrne et al. [3] used census data with certain factors that adopts an approximation of the available rooftop area, to estimate the rooftop solar PV potential in South Korea. Recent studies estimated the technical potential of the rooftop solar PV system of a region by integrating the geographic information system (GIS) technology [4,8,13–20]. Typically, studies by Buffat et al. [17] and Margolis et al. [18] utilized the satellite image data, Light Detection And Ranging (LiDAR) data in particular, to accurately estimate the rooftop solar PV potential in Switzerland and the United States (U.S.), respectively. A series of studies by Assouline et al. [19,20] used machine learning algorithms such as support vector machine and random forests, a relatively new approaches for estimating the rooftop solar PV potential, to estimate the rooftop solar PV potential in Switzerland.

There is a dearth of studies, however, that attempted to investigate the economic and market potentials of the rooftop solar PV system worldwide. The economic potential is the subset of the technical potential, where the rooftop solar PV system is economically viable within a region. That is, the economic potential can explain how much energy is available with the economically viable rooftop solar PV system within a region. Meanwhile, the market potential refers to the amount of energy that can be expected from the market adoption of the rooftop solar PV system considering the market factors other than the economic aspects. Despite the significance of the economic and market potentials for promoting DSG, there have almost been no studies dealing with such potentials except for few researches done by *National Renewable Energy Laboratory (NREL)*, a government-owned research center under the *U.S. Department of Energy (DOE)* specialized in renewable energy and energy efficiency. *NREL* estimated the economic potentials of various renewable energy sources in the U.S. considering the levelized cost of energy and levelized avoided cost of energy at the national level as of 2014 [6]. It was shown that the sum of the economic potentials of the different renewable technologies estimated in this study (i.e., wind energy, utility PV, DSG, hydropower, geothermal, and biopower) varied from one-third to over ten times the 2013 total U.S. generation from all energy sources, depending on the three distinct formulations defined in this study. *NREL* also estimated the market potentials of distributed energy resources for the residential, commercial, and industrial sectors in the U.S. through 2050 by developing the Distributed Generation Market Demand (dGen) model, a geospatially rich, bottom-up, market-penetration model that simulates the potential adoption of various distributed energy resources (e.g. the dSolar module for DSG) [21,22]. Besides the U.S., the national level solar PV potential in South Korea has been estimated by *Korea New & Renewable Energy Center (KNREC)* under *Korea Energy Agency (KEA)*, but only three hierarchical levels of the rooftop solar PV system (i.e., the physical, geographic, and technical potentials) were considered for analysis [5]. Therefore, to understand the economic viability of the rooftop solar PV system in a detailed way, and to evaluate the impact of various factors affecting market access (e.g., installation prices and policies), it is necessary to develop a method of estimating the economic potential and to conduct relevant studies in various regions.

To address this challenge, this study aimed to develop a novel bottom-up approach for estimating the economic potential of the rooftop solar PV system in a region. Using the developed method, the economic potential of the rooftop solar PV system was estimated for the Gangnam district, which consumes the most electricity (i.e., a total of 4,698,163 MWh in 2016) among the 25 local government districts of the city of Seoul in South Korea [23]. Towards this end, the following were mainly considered in this study, which differenciates it from other previous studies: (i) as a follow-up study, this study considered the technical potential of the rooftop solar PV system calculated for each building in the Gangnam district using the method developed by Hong et al. [8]; (ii) this study considered the rooftop solar PV profitability of each building in the Gangnam district based on the bottom-up approach to estimate the economic potential; (iii) this study considered the different installation purposes and subsidy payments to calculate the rooftop solar PV profitability and to estimate the economic potential; and (iv) this study considered the changes in the market conditions (i.e., installation cost, policies and support schemes, and electricity price) from 2008 to 2016 to calculate the rooftop solar PV profitability and to estimate the economic potential.

First, this study calculated the technical potential of the rooftop solar PV system for each building in the Gangnam district using the method developed by Hong et al. [8]. As urban areas are not always suitable for installing the rooftop solar PV system due to the shadows on the rooftop from the surrounding buildings, Hong et al. [8] focused on calculating the available rooftop area by considering such shadows using Hillshade analysis to develop a method for estimating the technical potential. By using this method, each building in the Gangnam district would show a different technical potential, which would ultimately lead to different economic profitability for the rooftop solar PV system [24,25]. These differences in the technical and economic performance among the buildings were reflected to calculate the economic potential of the rooftop solar PV system within the Gangnam district. Second, this study calculated the rooftop solar PV profitability of each building in the Gangnam district based on the bottom-up approach for estimating the economic potential of the rooftop solar PV system. To calculate the rooftop solar PV profitability of each building in the Gangnam district, this study used life cycle cost (LCC) analysis based on the discounted cash inflows and outflows. Third, this study estimated the economic potential of the rooftop solar PV system for the different installation purposes and subsidy payments. In South Korea, the rooftop solar PV system can be installed for the following two purposes: (i) self-consumption, and (ii) electricity business. When the rooftop solar PV system is installed for self-consumption purposes, the electricity generated from the system is primarily used for the building's consumption. The surplus electricity generated from the rooftop solar PV system installed for self-consumption purposes can also sold to the grid depending on the selected business model. Meanwhile, when the rooftop solar PV system is installed for electricity business purposes, all the electricity generated from the system is sold to the grid. As the electricity generated from the installed rooftop solar PV system can be used for two different purposes, the profit structure also varies depending on the installation purpose. Therefore, this study considered the two different installation purposes, (i) self-consumption, and (ii) electricity business, to calculate the rooftop solar PV profitability, and ultimately, to estimate the economic potential. Furthermore, this study also considered the two different subsidy payments for self-consumption purposes, (i) without subsidy (i.e., baseline scenario), and (ii) with subsidy, to investigate the impact of subsidy payments, because there is always a possibility of not receiving such subsidy. Fourth, this study estimated the economic potential of the rooftop solar PV system from 2008 to 2016 to consider the changes in the market conditions (i.e., installation cost, policies and support schemes, and electricity price). As the market conditions of the solar PV industry, including the installation cost, policies and support schemes, and electricity price, vary significantly by year, the rooftop solar PV economic viability and profitability can be considerably different each year. Therefore, this study was conducted