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A superstructure model of an isolated power supply system using renewable energy: Development and application to Jeju Island, Korea

Sunghoon Kwon [a, 1], Wangyun Won [b, 1], Jiyong Kim [a, *]

[a] *Department of Energy & Chemical Engineering, Incheon National University, 119, Academy-ro, Yeonsu-gu, Incheon, 406-772, Republic of Korea*
[b] *Plant Research Team, GS Engineering & Construction, 33, Jong-ro, Jongno-gu, Seoul, 110-121, Republic of Korea*

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In this study, we aim to develop a superstructure-based optimization model using mixed integer linear programming (MILP) to determine the optimal combination and sizing for a hybrid renewable energy system to be used in an isolated area. The developed model has a three-layered energy structure to reflect the current reality in which energy production and consumption sites are generally separate. A variety of economic factors, including distance between facilities and an installation area, are considered for a more accurate estimation of the total annualized cost. Two types of optimization models, i.e., with and without a battery, are proposed to evaluate the economic and technical effects of a storage device to resolve operation issues caused by intermittent resources. An application case study on Jeju Island, Korea, confirms that the proposed model is suitable for decision making at the planning stage of a renewable energy system.

1. Introduction

The demand for electricity has steadily increased with the growing global economy [1]. Current power production systems rely heavily on fossil fuel, which results in air pollution problems, including greenhouse gas emissions. A wide range of studies have been conducted to address this problem [2], but for a more radical approach, it is essential to develop new energy resources as alternatives to conventional fuel sources and their corresponding energy systems. In particular, renewable energy sources (RES) such as wind and solar radiation have drawn substantial attention as viable options for power production due to their clean properties and high practicability for improving technologies [3,4].

While renewable energy systems provide various advantages, including being eco-friendly and offering a high probability for energy self-sufficiency, the current costs of such systems prevent widespread deployment and, thus, research and development efforts are concentrated on accelerated cost reductions and efficiency improvements [5]. Because the design of a RES-based power supply system involves a number of complicated parameters such as energy resources (e.g., wind, solar, biomass, geothermal), backup energy systems (e.g., fuel cell, battery, diesel generator), and power conditioning units (e.g., buck/boost converters, battery chargers), numerical modeling and optimization studies can play a crucial role in discovering a new configuration that ensures minimal cost while satisfying the electricity demand [6]. The most popular issues being investigated include integration of RES in a suitable hybrid combination [7–11], optimal selection [12–14], and sizing [15–18] of components.

The majority of research reported to-date is somewhat restricted in terms of applicability because it concerns a given location and a specific environmental condition for model development [19]. At the planning stage of RES systems, it is necessary to make an enterprise-level decision on the following important issues: (i) where to install the generation equipment, (ii) what type or what combination of RES should be adopted, and (iii) how many and how large capacity of equipment should be used. To this end, a generalized optimization model is required that can embrace a variety of RES and diverse costs occurred during power supply, including power transmission costs, land reclamation costs, as well as equipment costs. This model should be able to accommodate the fact that commercial equipment is generally provided in an off-the-shelf form.

Accordingly, the focus of this study has been devising a superstructure-based optimization model of a RES-based power supply system and investigating its performance in an application

* Corresponding author.
E-mail address: jykim77@incheon.ac.kr (J. Kim).
[1] S. Kwon and W. Won contributed equally to this work.

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on Jeju Island, Korea. The key feature is the three-layered energy structure that considers the geographical nature of an isolated area. The proposed model can embrace the various types of energy resources and is also able to consider a diversity of economic factors, including distance between production and demand sites and installation area, when calculating the total annualized cost. Two types of optimization models are devised to evaluate the energy storage device in techno-economic analysis, together with power generation equipment. The performance of the developed model is validated through application on Jeju Island. In the case study, the combination of wind turbine and battery results in the lowest cost by benefitting from centralized distribution and efficient utilization of electricity.

2. Optimal design of the power supply system

2.1. Three-layered power supply system

Because the RES potentials differ from region to region, the electricity production site may not coincide with the demand area. The three-layered power supply system is depicted in a generalized form in Fig. 1.

The supply site (SS) indicates a location with high RES potentials and is assumed to be dedicated to producing electricity without any consumption. The SS makes up an extensive area, and therefore the power generation equipment can be spatially installed throughout the site without limit. The demand site (DS) represents the major power-consuming area. The DS can also produce some electricity via self-generation, but, unlike the SS, the amount of generation is restricted due to spatial limitations. Any extra space, such as building rooftops, is assumed to be utilized for equipment installation, and hence land reclamation is not required in this area [20]. The main facility (MF) is an intermediate facility between the SS and a secondary facility (SF) and can contain energy storage devices.

The SS, MF, and SF constitute an energy network. The power shortfall of the MF and SF can be supplemented from the SS and connected MF, respectively. Because the existing power lines are used for the electricity transmission from the SS to MF, no additional cost is required. However, for electric transmission between the MF and SF, new power lines should be installed, and commensurate expenses are incurred if the additional lines are requested.

2.2. Formulation

This section provides the specific formulations of the objective function and constraints that correspond to the three-layered power supply system illustrated in Fig. 1. The developed model utilizes a mixed-integer linear programming (MILP)-based superstructure, as shown in Fig. 2, and calculates the electricity that could be provided to each region and the associated costs according to the location, type, and amount of technological equipment. The optimization model without an energy storage device is first presented, and then correction is made for the case with a storage device.

In the following equations, the set or subset for a subscript is generally omitted for simplicity except for the subscript i, which represents the equipment type as it is used for both of the general sets, i.e., $\mathbf{I}$, and its subsets, i.e. $\mathbf{I}^P$, $\mathbf{I}^B$, $\mathbf{I}^T$, and $\mathbf{I}^{PB}$. All of the symbols in the subsequent sections are defined in the Nomenclature section.

2.2.1. Objective function

The RES-based optimal power supply system can be identified by minimizing the total annual cost (*TAC*), which is defined as the sum of total investment cost (*TIC*) and total operating cost (*TOC*) for one year, such that

$$\min_{\theta} TAC = TIC + TOC \quad (1)$$

where θ is a decision variable vector that includes the type and the number of equipment installed in the considered regions as well as the connectivity between the MFs and SFs. *TIC* and *TOC* are defined in Eqs. (2) and (6), respectively.

$$TIC = ICP + ICT \quad (2)$$

ICP and *ICT* are the investment costs associated with power generation and transmission, respectively, which are written as Eqs. (3) and (4).

$$ICP = \sum_g \sum_i CRF_i \cdot N_{i,g} \cdot (EC_i + IC_i + LC_{i,g}), \quad i \in \mathbf{I}^{PB} \quad (3)$$

where CRF_i is a capital recovery factor multiplied to the expenses of power generation equipment i, and $N_{i,g}$ indicates the number of the

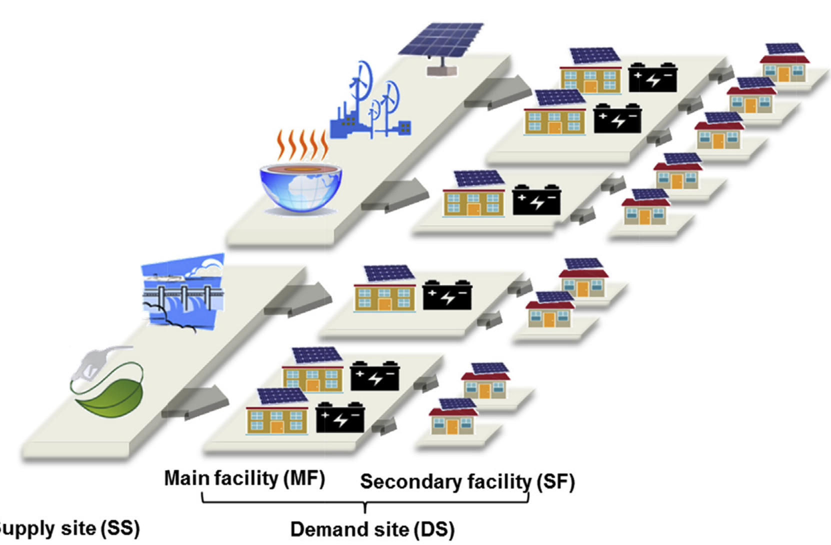

Fig. 1. Three-layered power supply system.