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Short Communication

Size optimization for a hybrid photovoltaic–wind energy system

Zong Woo Geem *

Gachon University, Department of Energy IT, 1342 Seongnam Daero, Seongnam 461-701, South Korea
Johns Hopkins University, Environmental Planning and Management Program, 11833 Skylark Road, Clarksburg, MD 20871, United States

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A B S T R A C T

Because photovoltaic (PV) and wind energies are renewable and free from greenhouse gas, they can be alternatives to fossil fuels. So far, many researchers have cost-optimally designed hybrid PV-wind systems. However, they have seldom provided whole datasets for other researchers to fully understand their approaches and to tackle the same problem with their novel techniques. Thus, this study shows one example of the optimal design of a hybrid PV-wind system by providing (1) regular optimization formulation, (2) full dataset, and (3) computing results with various design constraints. Hopefully many researchers will apply various optimization techniques to the problem in the future.

1. Introduction

Sun and wind have powers which can be converted into energy (electricity) generated by solar panels and wind turbines. Because photovoltaic (PV) and wind energies are abundant, renewable, and clean without causing greenhouse gas, they can be alternatives to fossil fuels [1]. Also, these renewable energies can significantly contribute on reducing the electricity generation cost in off-the-grid remote places such as islands [2].

So far various researches have been performed for the optimal design of hybrid PV and wind power generating systems [3–8]. However, they have seldom provided full datasets for other researchers to replicate and to apply existing and novel algorithms [9–12]. Actually, so many novel methods for optimal design problems have been developed during last decade or two, and researchers want to test the performance of those techniques by applying them to renewable energy problems. The design of hybrid solar-wind systems can be a good example for those demands, however, the examples in previous literature are too large-sized to become bench-mark problems, or they do not provide detailed numerical datasets.

Thus, the objective of this paper is to provide a full dataset for the design of a basic PV-wind system. In addition, this study intends to provide a better optimization formulation and solving technique for the design.

* Address at: Gachon University, Department of Energy IT, 1342 Seongnam Daero, Seongnam 461-701, South Korea. Tel.: +82 31 750 5586, +1 301 251 2646.
E-mail addresses: geem@gachon.ac.kr, geem@jhu.edu

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2. Optimization formulation

The objective function of the PV-wind system design is the total design cost C_T which consists of total capital cost C_{Cpt} and total maintenance cost C_{Mtn} as follows:

$$\text{Minimize } C_T = C_{Cpt} + C_{Mtn} \tag{1}$$

Here, it should be noted that while the capital cost occurs in the beginning of a project, the maintenance cost occurs along the project life. Consequently, costs at different times cannot be directly compared, but should first be made equivalent through the use of discount factors that convert a monetary value at one time to an equivalent value at another time [13,14]. In this study, the initial capital cost P is converted into annual capital cost A using the following capital-recovery factor:

$$\frac{A}{P} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

where i is annual interest rate; and n is life span of the system (in years). Thus, total annual capital cost C_{Cpt} can be:

$$C_{Cpt} = \frac{A}{P}\,[N_{Sol}C_{Sol} + N_{Wind}C_{Wind} + N_{Batt}C_{Batt} + C_{Backup}] \tag{3}$$

where N_{Sol} is number of solar panels, which is decision variable; C_{Sol} is unit cost of solar panel; N_{Wind} is number of wind turbines, which is decision variable; C_{Wind} is unit cost of wind turbine; N_{Batt} is number of batteries; C_{Batt} is unit cost of battery; and C_{Bachup} is cost of backup generator for the use when solar and wind energies are not sufficient and storage batteries are low. The unit cost of solar panel C_{Sol} consists of panel price and installation fee; and the unit cost of wind turbine C_{Wind} consists of turbine price and installation fee. The number of batteries N_{Batt} is determined by the following function:

$$N_{Batt}(N_{Sol},\ N_{Wind}) = Roundup\left[\frac{S_{Req}}{\eta \cdot S_{Batt}}\right] \quad (4)$$

where $Roundup(\cdot)$ is a function which returns a number rounded up to an integer number; S_{Req} is required storage capacity; η is usage% of rated capacity which guarantees battery's life span; and S_{Batt} is rated capacity of each battery. The required storage capacity S_{Req} is the function of number of solar panels N_{Sol} and number of wind turbines N_{Wind} as follows:

$$S_{Req}(N_{Sol},\ N_{Wind}) = \sum_{t=1}^{Max\ t}(P_{Sol}^t + P_{Wind}^t - P_{Dmd}^t)\Delta t - \sum_{t=1}^{Min\ t}(P_{Sol}^t + P_{Wind}^t - P_{Dmd}^t)\Delta t \quad (5)$$

where $Max\ t$ is the time when cumulative energy (kW h) is highest; $Min\ t$ is the time when cumulative energy (kW h) is lowest; Δt is unit time; P_{Sol}^t is the power (kW) generated by solar panels at time t; P_{Wind}^t is the power (kW) generated by wind turbines at time t; and P_{Dmd}^t is the power (kW) demanded at time t. Here, the power generated by solar panels can be calculated as follows:

$$P_{Sol}^t = N_{Sol} \times P_{Sol\_Each}^t \quad (6)$$

where $P_{Sol\_Each}^t$ is the power (kW) generated by each solar panel at time t. $P_{Sol\_Each}^t$ can be obtained using insolation data and insolation-power characteristic curve. The power generated by wind turbines can be calculated as follows:

$$P_{Wind}^t = N_{Wind} \times P_{Wind\_Each}^t \quad (7)$$

where $P_{Wind\_Each}^t$ is the power (kW) generated by each wind turbine at time t. $P_{Wind\_Each}^t$ can be obtained using wind speed data, turbine hub height correction function, and wind speed-power characteristic curve.

Total annual maintenance cost C_{Mtn} in Eq. (1) can be:

$$C_{Mtn} = \left[C_{Mnt}^{Sol} \times \sum_{t=1}^{24}(P_{Sol}^t \cdot \Delta t) + C_{Mnt}^{Wind} \times \sum_{t=1}^{24}(P_{Wind}^t \cdot \Delta t)\right] \times 365 \quad (8)$$

where C_{Mnt}^{Sol} is maintenance cost per kW h for PV array; and C_{Mnt}^{Wind} is maintenance cost per kW h for wind turbine. Here, it should be noted that because the battery is vulnerable in the renewable power generation system, the replacement cost of the battery may be also included in the objective function of the total design cost. While this numerical example, which is basically based on Kellogg et al.'s system [6], does not provide any realistic value for the battery replacement cost, this cost will be considered in future research where a more complex renewable system is optimally designed.

In addition to the above-mentioned objective function as described in Eqs. (1)–(8), the major constraint in this optimization problem is that total energy amount generated by solar panels and wind turbines should be greater than or equal to total energy amount required by users as follows:

$$\sum_{t=1}^{24}(P_{Sol}^t \cdot \Delta t) + \sum_{t=1}^{24}(P_{Wind}^t \cdot \Delta t) \geqslant \sum_{t=1}^{24}(P_{Dmd}^t \cdot \Delta t) \quad (9)$$

The numbers of solar panels and turbines should be non-negative integer variables as follows:

$$N_{Sol} = Integer, \quad N_{Sol} \geqslant 0 \quad (10)$$

$$N_{Wind} = Integer, \quad N_{Wind} \geqslant 0 \quad (11)$$

The problem can have optional constraints of resource limitation as follows:

$$N_{Sol} \leqslant N_{Sol}^{Max} \quad (12)$$

$$N_{Wind} \leqslant N_{Wind}^{Max} \quad (13)$$

$$N_{Batt} \leqslant N_{Batt}^{Max} \quad (14)$$

where N_{Sol}^{Max} is maximum available number of solar panels; N_{Wind}^{Max} is maximum available number of wind turbines; and N_{Batt}^{Max} is maximum available number of storage batteries.

3. Numerical example

A hybrid PV-wind system, which is to be designed based on the optimization formulation as described in Eqs. (1)–(14), is given here. The numerical example proposed in this paper is similar to that proposed by Kellogg et al. [6]. However, because they did not provide whole dataset, this study complements it so as to provide a complete dataset and for other researchers to tackle it using their own mathematical or meta-heuristic techniques.

Table 1 provides the values of design variables used for the numerical example. Here, because the life span of each battery is 4 years, five times of N_{Batt} is required to satisfy the life span of the PV-wind system.

Table 2 provides the values of annual average hourly demand P_{Dmd}^t and generated powers by each solar panel ($P_{Sol\_Each}^t$) and each wind turbine ($P_{Wind\_Each}^t$). Fig. 1 shows the annual average hourly demand; Fig. 2 shows the annual average solar power generated by each solar panel; Fig. 3 shows the annual average wind power generated by each wind turbine; and Fig. 4 shows the power difference between generated and required powers ($\Delta P^t = P_{Sol}^t + P_{Wind}^t - P_{Dmd}^t$) when N_{Sol} = 158 for solar alone system; N_{Wind} = 2 for wind alone system; and N_{Sol} = 72 and N_{Wind} = 1 for hybrid PV/wind system.

Here, it should be noted that although Kellogg et al. [6] provided insolation data observed by a pyranometer, they did not provide the insolation-power characteristic curve. Thus, P_{Sol}^t (and $P_{Sol\_Each}^t$) was restored by the two steps: (1) manually read ΔP^t for solar alone system in Fig. 4; and (2) calculate $P_{Sol}^t = \Delta P^t + P_{Dmd}^t$. They also did not provide wind speed-power characteristic curve while providing wind speed data and turbine hub height correction function. Thus, P_{Wind}^t (and $P_{Wind\_Each}^t$) was restored by the two steps: (1) manually read ΔP^t for wind alone system in Fig. 4; and (2) calculate $P_{Wind}^t = \Delta P^t + P_{Dmd}^t$.

4. Methods and computational results

The numerical example was originally solved by tedious trial and error approach [6]. However, this study applied Branch-and-Bound

Table 1
Design variables used for a PV-wind system.

Variable	Value
Annual interest rate (i)	6%
Life span of the system (n)	20 years
Solar panel price	$350/panel
Solar panel installation fee	50% of the price
Wind turbine price	$20,000/turbine
Wind turbine installation fee	25% of the price
Unit cost of battery (C_{Batt})	$170
Backup generator cost (C_{Bachup})	$2000
Usage% of battery's rated capacity (η)	80%
Battery's rated capacity (S_{Batt})	2.1 kW h
Battery's life span	1500 cycles (≈4 years)
Unit time (Δt)	1 h
Maintenance cost for PV array (C_{Mnt}^{Sol})	0.5 cent/kW h
Maintenance cost for wind turbine (C_{Mnt}^{Wind})	2 cents/kW h