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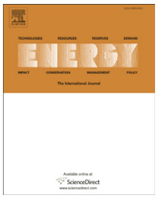

Optimal unit sizing for small-scale integrated energy systems using multi-objective interval optimization and evidential reasoning approach[☆]

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ABSTRACT

This paper proposes a comprehensive framework including a multi-objective interval optimization model and evidential reasoning (ER) approach to solve the unit sizing problem of small-scale integrated energy systems, with uncertain wind and solar energies integrated. In the multi-objective interval optimization model, interval variables are introduced to tackle the uncertainties of the optimization problem. Aiming at simultaneously considering the cost and risk of a business investment, the average and deviation of life cycle cost (LCC) of the integrated energy system are formulated. In order to solve the problem, a novel multi-objective optimization algorithm, MGSOACC (multi-objective group search optimizer with adaptive covariance matrix and chaotic search), is developed, employing adaptive covariance matrix to make the search strategy adaptive and applying chaotic search to maintain the diversity of group. Furthermore, ER approach is applied to deal with multiple interests of an investor at the business decision making stage and to determine the final unit sizing solution from the Pareto-optimal solutions. This paper reports on the simulation results obtained using a small-scale direct district heating system (DH) and a small-scale district heating and cooling system (DHC) optimized by the proposed framework. The results demonstrate the superiority of the multi-objective interval optimization model and ER approach in tackling the unit sizing problem of integrated energy systems considering the integration of uncertian wind and solar energies.

1. Introduction

Recently, due to the rising global awareness on the energy resource crisis and environmental protection, the study of integrated energy systems which make a joint use of various renewable energies such as wind and solar [1–3] has been pursued throughout the world. To take the advantage of renewable energies rationally, various operation strategies have been worked out to satisfy different objectives, e.g. cost economization and emission minimization [4–6]. In spite of that, the financial issue such as high investment but even high risk caused by improper sizing of the renewable energy supply unit is still a challenge. Hence, the unit sizing problem of a system is one of the most important problems that will govern the investor's judgement of whether such a business investment is feasible.

As the utilization of renewable energies brings about diverse benefits, the unit sizing problem of the integrated energy system is essentially a multi-objective optimization problem [7,8]. On the other hand, due to the integration of renewable energies, it is inadequate to solve the unit sizing problem in the deterministic environment [9,10]. Without considering the unpredictable characteristic of nature would ultimately depart from the original intention of developing renewable energies. To address this problem, a number of researches have been conducted on analyzing uncertain parameters via different stochastic techniques, which can be divided into two main categories including the fuzzy theory and the probability based stochastic optimizations.

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Generally, in the fuzzy theory, the uncertain variables are deemed as fuzzy numbers [11]. Then the membership function for the uncertain variable should be accurately defined. However, the membership function is usually difficult to be specified in the real world problem. In terms of the probability based stochastic optimization, uncertain variables are accounted by random numbers which are assumed to follow known probability distributions. For instance, in the case of long term programming of an integrated energy system, the two-parameter, i.e., the scale parameter c and the shape parameter k, Weilbull distribution is approved to be a suitable probability distribution function for describing the uncertainty of the wind speed [12,13]. Furthermore, Monte Carlo (MC) method is widely used to generate the random variables according to their probability characteristics [10,14]. However, a huge number of sampling required by MC technology to simulate the uncertain variables makes the probability based stochastic optimization method time-consuming [15].

The mean-variance (MV) model proposed by Markowitz [16] firstly quantified the risk of an investment. The MV model demonstrated that the anticipated return and the investment risk can be formulated as the expected value and the variance of the objective, respectively. However, as has been discussed, the low computational efficiency of the probability based stochastic optimization method used to solve the MV model makes it sometimes unpractical [12,17]. Thanks to the nonlinear interval programming model, which is proposed by Jiang et al. [18] to solve the nonlinear optimization problem with interval parameters, the uncertain variables can be treated as interval numbers represented by their lower and upper bounds. Rather than merely minizing the mean value of the objective, the interval optimization model takes both the average and deviation of the objective into consideration to make a compromise between the benefit and risk. In addtion, by transferring stochastic problems into deterministic ones, the huge computational effort as the probability based stochastic optimization method makes is no longer required in the interval method.

To the best of our knowledge, there is few researches have introduced interval optimization in the unit sizing problem of integrated energy systems. Thus, in this paper, we attempt for the first time to analyze the unit sizing problem by interval optimization. In the proposed method, the average and deviation of the life cycle cost (LCC) are formulated as a multi-objective optimization problem to represent the cost and risk of a business investment. Moreover, in order to avoid the influence of subjective factors, a multi-objective group search optimizer with adaptive covariance and chaotic search (MGSOACC) is proposed to get the Pareto-optimal solutions rather than transferring the multi-objective problem into a single objective one by the weighting factor method [18].

The MGSOACC is inspired from animal searching behavior and group living theory and consists of three types of group members: producers, scroungers and rangers. In each generation, the members corresponding to the best fitness value of each objective are conferred as the producers, and a number of members except the producers are randomly selected as scroungers, then the rest of the members are named as rangers. The producers imitate the crappies' search behavior, which is characterized by the maximum pursuit angle, maximum pursuit distance, and maximum pursuit height [19], to seek the optimal resource. The scroungers adopt the concept of adaptive covariance matrix [20] to get a reliable estimator for the paths and thus could enhance the local search ability of the proposed algorithm. The concept is based on the assumption that the successful evolutionary paths of the predators used in recent past generations may also be successful in the following generation. Gradually, the most suitable evolutionary paths can be developed automatically to guide the search behavior of each experienced predator in different evolutionary stages. Moreover, chaotic search [21,22] is employed by the rangers to explore a huge search space so as to avoid premature convergence, and obtain a well-distributed Pareto optimal front.

Afterwards, recognizing that the final unit sizing solution of the integrated energy system should be determined by the investor considering not only the economic but also environmental performances, evidential reasoning (ER) approach is utilized to conduct the multi-attribute decision making so that the optimal unit sizing solution can be obtained. Therefore, a comprehensive framework including a multi-objective interval optimization model using MGSOACC and a decision making method using ER approach for solving the unit sizing problem of the small-scale integrated energy system is developed in this paper.

The rest of the paper is organized as follows. The integrated energy systems are introduced and the optimization problem is formulated in Section 2. Section 3 describes the multi-objective interval optimization model in detail. Section 4 presents the multi-objective optimization algorithm proposed in this paper and the ER approach used for decision making. Simulation studies used to evaluate the proposed comprehensive framework are presented in Section 5. Finally, the paper is concluded in Section 6.

2. The unit sizing problem formulation

2.1. System description

In this paper, two small-scale integrated energy systems proposed in our previous works, i.e., a small-scale direct district heating system (DH) [1] and a small-scale district heating and cooling system (DHC) [2], are employed to conduct the unit sizing study. Fig. 1 shows the simplified schematic diagram of the two systems, in which the right hand side is the DH system and the left hand side is the DHC system. It should be noted that they are two separate systems working independently.

The DH system integrates wind and solar energies to supply hot water to residential consumer for space heating [1]. The energy supply units consist of a stand-alone wind turbine generator (WT), a flat-plate solar water heater with solar collectors (SC), an electric water boiler (EB) and a low temperature central gas-fired boiler (GB). The energy captured by WT is transferred to EB for hot water heating. The energies come from the wind energy system and solar water heater are given the first priority to be utilized to heat the water. If the heat generated from the renewable energies cannot meet the heating load, electricity will be imported from the utility grid to EB in order to cover the shortage. Meanwhile, GB will consume natural gas to generate heat as well. Noted that the electricity consumed by various water pumps is imported from the grid.

The DHC system makes a joint use of wind energy, solar energy and conventional fossil fuel energies to supply the residential consumer with space heating in the heating season and to provide space cooling for them in the cooling season [2]. In the heating season, the DHC system operates in the heating mode, the operation strategy of which is the same as that of the DH system. In the cooling season, the absorption chiller (AC) utilizes the thermal energy generated by EB (driven by WT), GB and the solar water heater while the reciprocating chiller (RC) is driven by the electricity directly imported from the utility grid. Considering the higher transfer efficiency of RC than that of AC, the circuit breaker CB_1 is switched on and the CB_2 is switched off in the cooling season. The detailed descriptions of the two systems can be referred to [1] and [2].