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Research Paper

Modeling and optimization of distributed energy supply network with power and hot water interchanges

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HIGHLIGHTS

- A MILP optimization model of a distributed energy supply network is proposed.
- The distributed energy network considers electricity and hot water interchanges.
- System size, operational strategies and energy interchanges are optimized.
- An illustrative example involving hospital and apartment in Japan is examined.
- Sensitivity analyses of various input parameters are performed.

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ABSTRACT

In this study, a mixed integer linear programming model of a distributed energy supply network integrated with electricity and hot water interchanges is presented minimizing the overall annual costs, which include annualized initial investment cost, annual operation and maintenance cost as well as annualized total infrastructure cost while guaranteeing the resilience of energy demands of various consumers. The superstructure of the energy supply system is determined. Furthermore, the system size and operational strategies including energy interchanges are optimized simultaneously. As an illustrative example, a low-carbon community located in Tokyo, Japan, has been selected for study. The robustness of the optimization model as well as the performance of distributed energy supply network have been illustrated through comparative analysis of four scenarios and multiple sensitive analyses of various uncertainty parameters including community scale, energy prices, energy policies as well as energy generation efficiency.

1. Introduction

Energy shortage has become a common problem all over the world. According to EIA's (Energy Information Administration) International Energy Outlook 2013, world energy consumption will grow by 56% between 2010 and 2040 [1]. As the main share of energy consumption, electric power industry is indispensable to solve the problem. Numerous strategies have been explored at present and one such strategy is transferring from the conventional system (centralized energy generation and long-distance energy transmission) toward decentralized energy generation through the adoption of distributed energy resource systems (DERs).

DERs are a suite of on-site, grid-connected or stand-alone technology systems and different types of DERs are available such as biomass power plants, photovoltaics (PV), wind power plants, combined cooling, heat and power (CCHP) and so on [2–4]. Such DERs offer great advantages over centralized generation by offering end users a diversified fuel supply, higher power efficiency and lower emissions [5]. However, the integration of renewable energy resources (e.g. wind turbines, PV units) which depend completely on the unsteady weather condition will increase the complexity of energy provision continuation within DERs [6]. On the other hand, the energy demands of end-consumers always fluctuate hourly which will cause energy unbalance between supply and demand sides.

Considering the above mentioned problems, the sharing and co-operative operation of the DERs which named distributed energy supply network has been proposed in recent years, in which the generated energy from each local producer may not only satisfies its self-use but also share the surplus energy with other end-consumers. Many studies have focused on the energy supply network [7–12]. Note that, before establishing an energy interchange network, the following aspects should be considered: first, from the economic viewpoint, the consumers are expected to be closed to each other to reduce the infrastructure investment especially hot water pipeline cost; second, the DERs installed at each node must be centralized

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ones for the convenience of energy interchange among the consumers; third, according to an investigation of the Ministry of Land Infrastructure and Transport in Japan, in order to maximize the benefits of the energy interchange system, the objective district is expected to have a relatively large scale (>5000 m^2). Through the construction of a district energy supply network, it would be possible to realize energy interchange by using the network pipe or wiring within or between a group of consumers, and flexible operation of the equipment can be achieved. However, this great flexibility may increase the complexity of addressing both power and heating requirements of multiple end-users. To achieve the maximum benefits of the distributed energy supply network, e.g. cost saving and environment protection, while satisfying the energy demands of each customer, the optimal design and scheduling of the system is of vital importance. Therefore, an accurate and robust mathematical model is needed.

Lots of studies have been carried out to realize the flexible interchange of electricity and heat for distributed energy networks. Mehleri et al. [9] proposed a superstructure model for the optimal design of distributed energy systems for a small neighborhood while considering the optimal selection of the system components among several candidate technologies as well as the optimal design of a hot water pipeline network, by minimizing annualized overall investment cost and annual operating cost. Wakui et al. [10] developed an optimization approach based on the mixed-integer linear programming (MILP) to investigate the energy-saving effect of power interchange operation of multiple household gas engine cogeneration systems. Haikarainen et al. [11] developed a model for structural and operational optimization of distributed energy systems considering heat interchange. Dong et al. [12] proposed an upper and lower level programming model for the DERs network planning with heat transportation. Each of the aforementioned models has its own characteristics: some of the models focus on the heating network, some refer to power network, whereas few of them refer to both heating and power networks. In addition, a comprehensive sensitivity analysis on various uncertainty parameters is escaped.

In this study, a model for optimal size and running schedule of the distributed energy supply network integrated with electricity and hot water interchanges is presented and in which the superstructure of the energy supply system has been determined beforehand. The problem is formulated as a MILP problem minimizing overall annul cost. In order to verify the feasibility of the proposed model and discuss the performance of the distributed energy network, this paper numerically analyzes the energy flow of an assumed neighborhood low-carbon community located in Tokyo, Japan. Moreover, the robustness of the optimization model as well as the performance of distributed energy supply network are shown through comparative analysis of four scenarios and multiple sensitive analyses of various uncertainty parameters including community scale, energy prices, energy policies as well as energy generation efficiency.

2. Mathematical model

2.1. Energy flows within hospital and apartment

According to an investigation on the feasibility of building energy interchanges put forward by Itabashi-ku in Japan, a local area with hospital always has more potential to establish energy interchange network for the large amount of hot water demand within the hospital. Therefore, in this study, the community is assumed to have two building categories: hospital and apartment. Fig. 1 shows the energy flow-based configuration diagram of hospital (left part) and apartment (right part). Generally, both of them are defined as grid-connected systems as grid connecting may be always necessary from the economic viewpoint, although energy can be generated on-site [13]. Besides the trade-off with the utility grid, the hospital and apartment can share their energy produced on-site via internal electricity grid and hot water pipeline.

2.2. Objective function

In a MILP model, the value of the objective function is optimized by changing the values of the decision variables, subject to constraints on the values that the variables can hold [14].

In this study, the objective function to be minimized is the overall annual cost of the whole building clusters considering annualized capital cost, annual operation and maintenance cost, annualized infrastructure cost (pipe and wire), minus the revenue through the sale of surplus electricity back to the grid. The formula can be described as follows:

$$\min\{C_{total} = C_{inv} + C_{om} + C_{pipe} + C_{wire} + C_{gas} + C_{elec} - C_{sale}\} \quad (1)$$

The annualized investment costs are determined by multiplying the capacity of each technology with its unit cost, then annualized by multiplying with the Capital Recovery Factor (CRF), which can be expressed as Eqs. (2) and (3).

$$C_{inv} = \sum_i \sum_k UCDer_{i,k} \cdot Cap_{i,k} \cdot CRF_k \quad (2)$$

$$CRF_{i,k} = IR \cdot (1+IR)^{L_{i,k}} \Big/ \left[(1+IR)^{L_{i,k}} - 1\right] \quad (3)$$

The annual operation and maintenance cost include a fixed cost (function of the unit capacity) and a variable one (function of annual generation of the unit) [14].

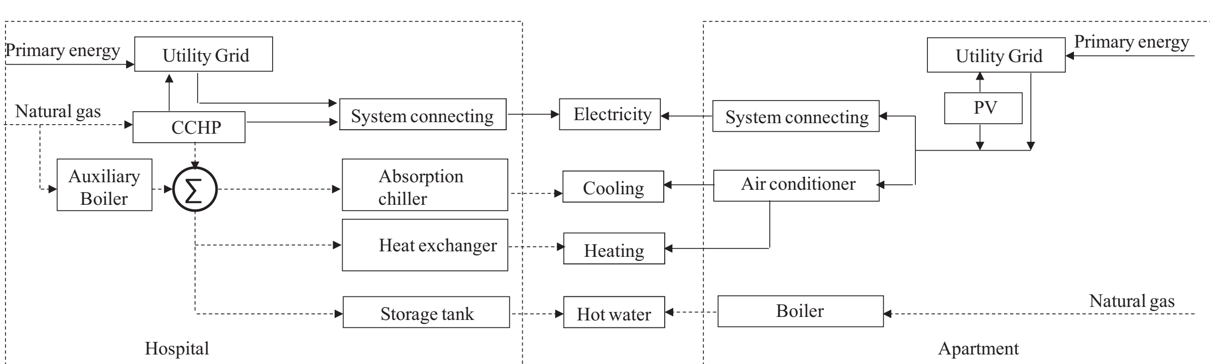

Fig. 1. Energy flow-based configuration diagram of hospital and apartment.