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An engineering approach to the optimal design of distributed energy systems in China

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ABSTRACT

China faces enormous challenges as it strives to meet its increasing energy demands. Distributed energy systems (DESs) provide a good opportunity to tackle these challenges by integrating various forms of distributed technologies, of which internal combustion engines, solar photovoltaic, and absorption chillers being the typical ones. However, fluctuation in energy demands and supplies, the large number of available distributed technologies and various possible combinations of these technologies make the design of DES a formidable task. The potential benefits of DES might be hampered by their impropriate design and operation.

This paper provides a generic energy systems engineering framework toward the optimal design of DES in China, with the purpose of obtaining optimal combination of technologies and capacity of equipment for a given area with given energy demands. A hotel in Beijing is selected as an illustrative example to demonstrate the key steps and features of the proposed approach. Results show that the optimal configuration of such a DES is a rather complex system equipped with various technologies. It is more efficient and economic than conventional centralized energy systems as well as distributed combined cooling, heating and power systems.

1. Introduction

A distributed energy system (DES) refers to an energy system where energy is produced close to end use, typically relying on a number of modular and small-scale technologies. DES has a number of advantages such as high overall efficiency, small losses on energy transmission, and small negative environmental impacts [1,2].

In recent years, China faces enormous challenges in meeting its immense and rapidly increasing energy demands under more and more stringent environmental constraints, due to the fast growth of its economy [3]. Therefore, interest has been intensifying in China in the development of DES, which is an efficient and environmental friendly alternative or complement to the conventional centralized energy system (CES). In October 2011, the National Energy Administration (NEA) issued a regulation entitled “the Guidance on the Development of Natural Gas Distributed Energy Systems”. It suggests installing up to one thousand distributed natural gas energy stations, i.e., combined heating cooling and power (CCHP), during the period of the 12th five-year plan, and the total capacity of DES is expected to reach 50,000 MW by 2020. In this context, a large number of demonstration CCHP projects have been started in different areas of China, as listed in Table 1 [4]. These CCHP projects share a similar configuration which generally includes a prime mover (gas turbine or gas engine), a waste heat boiler and an absorption chiller.

The regulation and demonstration projects indicate that Chinese government has a strong interest in promoting DESs in China. However, it can also be observed that the government is more interested in classic CCHP systems at the current stage, although possibility of integration of renewable energy with CCHP systems is also mentioned in the Guidance.

From a systems engineering viewpoint, focusing on a single or certain types of technologies, for instance, CCHP systems, may not be the best option, as there exist many other alternative energy resources and corresponding conversion technologies for various types of configurations of DES. These systems, with appropriate design and integration work, may exhibit even better performances than a classic CCHP system. For instance, integration with renewable energy resources may lead to more environmental benefits such as reduced conventional air pollutants and lower greenhouse gas (GHG) emissions.

However, optimal design of DES is not a trivial task as integration of more types of energy resources and conversion technologies

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Table 1
Demonstration projects of CCHP systems in China and their configurations.

No	Location	Main equipments
1	Pudong International Airport, Shanghai	Gas turbine, Waste heat boiler
2	Huangpu Central Hospital, Shanghai	Gas turbine, Waste heat boiler
3	Minhang Central Hospital, Shanghai	Gas turbine, Waste heat boiler
4	Shanghai Institute of Technology, Shanghai	Micro-turbine, Absorption Chiller, Waste heat boiler
5	Shuya Liangzi Ministry of Health, Shanghai	Diesel engine, Waste heat boiler
6	Zizhu Science-based Industrial Park, Shanghai	Micro-turbine, Absorption chiller
7	Shanghai Jinqiao Sports Center, Shanghai	Gas engine, Waste heat boiler
8	Shanghai Global Financial Hub, Shanghai	Gas engine, Waste heat boiler
9	Beijing Gas Group Monitoring Center, Beijing	Gas engine, Absorption Chiller
10	Ciqumen Station Building, Beijing	Micro-turbine, Absorption Chiller
11	Zhongguancun Software Square, Beijing	Gas turbine, Absorption Chiller
12	International Trade Center, Phase 3, Beijing	Gas turbine, Waste heat boiler
13	International Business Center, Beijing	Gas turbine, Waste heat boiler
14	Olympic Energy Exhibit Center, Beijing	Micro-turbine, Absorption chiller

may increase the complexity of the system, and the aforementioned benefits may be partly or even totally compensated. In this paper, we firstly present an energy systems engineering framework toward the optimal design of DES, with which energy efficiency and complexity of a system can be quantitatively evaluated. For a specific district, given its electricity, space heating, cooling and hot water loads, energy prices, and technical and financial information about optional technologies, the proposed framework helps to minimize the overall annual cost. We then illustrate the applicability of the proposed modeling and optimization framework in a case study of a hotel in Beijing. In this case study, the energy, economic and environmental performances of the optimal configuration obtained by the proposed method are evaluated and compared with those of a classic CCHP system and a conventional CES.

2. Superstructure based model for the optimal design of DES

A number of studies have been reported on the optimal design of DES, but most of them focus on distributed CCHP systems [5–18]. Ren et al. and Liu et al. developed models for optimal design of CCHP systems integrated with solar energy and biomass [19–23]. However, these models do not consider certain technologies, for instance, energy storage technologies. Moreover, National Renewable Energy Laboratory of the United States developed a design tool, namely HOMER for the optimal selection of distributed power generation technologies, which encompassed renewable energy technologies such as solar photovoltaic and wind turbines as well as energy storage technologies such as batteries [24]. However, HOMER aims for the design of distributed power generation systems, therefore heating and cooling needs are not considered in the model. In summary, most existing mathematical models for optimal design of DES cannot capture all alternative configurations due to case-by-case modeling strategy. A generic mathematical model, which can ideally include all alternative distributed generation technologies, is therefore desired to address design issues of DES.

In this paper, we propose a superstructure based model for the optimal design of DES, featuring simultaneous determination of the optimal configuration of a DES and its optimal operating conditions via mathematical programming [25]. It was firstly proposed to address process synthesis issues in heat exchanger networks [26–28], and widely used in a broad range of fields thereafter, such as process synthesis [29] and supply chain network design [30,31]. It has been proved to be an effective method to address issues associated with optimal planning of energy systems, such as bioenergy processing systems [32], polygeneration energy systems [33–35] and hydrogen infrastructure [36]. As a DES involves a variety of alternative technologies, superstructure based modeling is well suited for its optimal design.

A superstructure representation of the optimal design problem of DES is shown in Fig. 1. It consists of an energy generation section, an energy conversion section and an energy storage section. In the energy generation section, a number of technologies are considered, and via these technologies heat and electricity can be produced from various primary energy resources. The secondary energy carriers, i.e., heat and electricity, are then converted to different forms of tertiary energy carriers, i.e., heat, cooling and electricity, through different energy conversion technologies. For instance, air-source chiller is a typical energy conversion technology that can produce cooling with electricity. For a more efficient use of energy, an energy storage section comes after to shift energy generated during low usage periods for consumption during peak hours.

The framework includes six primary energy resources, namely natural gas, diesel, wind, solar energy, biomass, geothermal, four energy demands, namely electricity, space heating, cooling and hot water, and twenty types of equipments, namely internal combustion engine, gas turbine, natural gas boiler, fuel cell, diesel engine, wind turbine, solar PV, solar thermal collector, biomass boiler, biogas engine, biogas boiler, electric heater, absorption chiller/heat pump, heat exchanger, water-source chiller/heat pump, air-source chiller/heat pump, ground-source chiller/heat pump, battery, ice storage equipment and thermal storage tank. These equipments in the model constitute the most common and mature distributed energy technologies available in China, while the model can be easily extended to cover more technologies when they become commercially available.

3. Mathematical formulation

A mathematical model based on mixed-integer linear programming (MILP) optimization is illustrated in this section. We use the symbol e to represent all energy flows and its superscripts indicate its position in the superstructure while the subscripts represent the types of energy flows. With respect to superscripts, the first superscript, i.e., g, c and s, stands for the section that this energy flow belongs to, while the second one, i.e., in and out, represents whether it is an input or an output. The naming rules for the energy flows in the optimization model are shown in Fig. 2. For example, a variable named with $e^{\mathrm{c,in}}_{\mathrm{h,hct}}$ means the amount of energy carried by a heat flow coming into the energy conversion section and converted by a certain heat conversion technology. The nomenclature of all parameters, variables, superscripts and subscripts are presented in Appendix at the end of this paper.

3.1. Energy generation section

Energy generation section comes first in Fig. 1. In this section, various types of primary energy are converted to electricity and heat by different energy generation technologies. The primary energy consumptions are restrained by local resources availability at any point in time as follows: