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A multi-fuel management model for a community-level district heating system under multiple uncertainties

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ABSTRACT

In this study, an interval two-stage double-stochastic single-sided fuzzy chance-constrained programming model is developed for supporting fuel management of a community-level district heating system (DHS) fed with both traditional fossil fuels and renewable biofuels under multiple uncertainties. The proposed model is based on the integration of interval parameter programming and single-sided fuzzy chance-constrained programming within an improved stochastic programming framework to tackle the uncertainties expressed as crisp intervals, fuzzy relationship, and probability distributions. Through transforming and solving the model, the related fuzzy and stochastic information can be effectively reflected in the generated solutions. A real fuel management case of a DHS located in Junpu New District of Dalian is utilized to demonstrate the model applicability. The obtained solutions provides an effective linkage in terms of both “quality” and “quantity” aspects for fuel management under various scenarios associated with multiple factors, and thus can help the decision makers to identify desired fuel allotment patterns. Moreover, this study is also useful for decision makers to address the other challenges (e.g. the imbalance between fuel supply and demand, the contradiction between air-pollution emission and environmental protection, as well as the tradeoff between the total heating cost and system satisfaction degree) generated in the fuel management processes.

1. Introduction

With the acceleration of urbanization process, the district heating system (DHS) is expanding at a phenomenal rate in China due to the merits of energy conservation and emission reduction. In 2014, the district heating area has been up to 6.11 billion square meters, and increased by nearly 50% when compared to the area in 2010 [1]. Despite this, the use of fuel and the control of air-pollutant are continuing to be challenges faced by decision makers of DHSs since the coal-fired heating technique with the relatively high air-pollutant emission intensity still plays a leading role in China's DHSs, and exacerbates the problems including energy crisis, environmental pollution, and greenhouse effect [2]. In the last two decades, Chinese government has promulgated a series of policies to encourage utilizing renewable energy sources, especially the biofuels, to partly substitute the fossil fuel for cleaner heating. That is mainly due to the fact that biofuels are not only a type of clean energy to reduce the dependence on fossil fuels for space heating, but also can be stored and utilized on demand [3–6]. Therefore, with the utilization and promotion of the biofuel-based heat source (BHS) on a global scale, this clean heating technique is gradually penetrating into the traditional coal-fired DHSs in northern China, especially in the regions with rich biomass resources, such as Liaoning, Jilin and Shandong provinces, leading to the occurrence of a new-type DHS named the hybrid-fuel-based multi-source district heating system (HMDHS). Such a HMDHS is typically composed of

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one or several coal-fired heat sources (CHSs) to cover the basic space-heating demand and a few BHSs to compensate the peak heat load during the on-peak period [7]. Nevertheless, the conversion from the single-fuel (i.e. coal) fueling mode to the multi-fuel (i.e. biofuel and different coals) fueling mode presents a considerable challenge to the fuel management (FM) since the penetration of BHSs may add extra complexities to the HMDHS, including the fluctuations of fuel quality and availability, the heating load distribution among heat sources, and the matching between heat demand and fuel supply. In other words, the material flows, energy flows as well as their interactions during the entire FM process in a HMDHS are more complicated than those in a single-fuel DHS.

The FM decisions with rational design and planning cannot only effectively improve the cost-effectiveness and stability of the energy conversion systems (e.g. power generation or heating systems), but also significantly mitigate the burden on the environment. Previously, a number of research works were conducted on the basis of various system analysis and optimization techniques to support FM decisions in energy conversion systems [8–16]. For example, Yin et al. proposed a nonlinear-based coal blending technology based on neural network models for power plants in the City of Hangzhou, China [17]. Akhtari et al. developed a linear programming model to the optimal flow of biomass between nodes of the supply network including biomass source points, terminal storages, and heating plants [18]. Rentizelas et al. used an optimization model for multi-biomass tri-generation energy supply. The result showed the multi-biomass supply chain may have significant impact on the system cost [19]. Schlünz et al. proposed a unified methodology for the modeling and solution of single- and multi-objective in-core fuel management optimization problems, providing cycle-to-cycle optimization capabilities for nuclear reactor [20]. Guo et al. applied adaptive simulated annealing genetic algorithm into the coal blending optimization process with raw coal of different grades to satisfy the requirements of the end users [21]. Minas et al. developed an integer programming model that incorporates both fuel management and suppression preparedness decisions, providing decision supports for forest fire management [22]. From the above FM-related research works, it can be seen that most studies mainly focused on either the “quality” (e.g. fuel treatment and quality improvement) or the “quantity” aspect (e.g. fuel supply chain and fuel reloading operation) to some extent, but few were found to address both aspects of FM in a HMDHS simultaneously. Actually, there are complicated interactions existing between the FM “quality” and “quantity”, and they are also interplayed with other system factors, such as heat-supply satisfaction degree, cost control and clean production. For instance, the variation of emission limitations may change the fuel selection and utilization, which potentially affects the economic efficiency; the fluctuation of the local biomass (e.g. straw, bark and logging residues) availability may influence the security of heat supply to residents, which causes the managers to turn to other high-priced alternative biofuels outside the local region or other high-polluting heating sources. Generally, the interactive complexities make the proper FM planning difficult, which in turn makes the HMDHS volatile and risk vulnerable. Beyond that, FM in a HMDHS is rather difficult since different uncertainties, such as residents' heat demands, the fuel quality, fuel availability and the associated economic implications, exist in the HMDHS, and most of these uncertainties are linked to the fuel utilization process (e.g. fuel-availability estimation, fuel processing, energy conversion and transmission) [23,24]. Moreover, when designing FM optimization models, more than one type of uncertainties can exist in the modeling system, and even be concurrently embedded within one model parameter due to the penetration of BHSs. For example, it is better to use interval parameter to express the uncertainty lying in the biofuel property, since the biofuel property is fundamentally affected by the biomass's non-homogeneous nature and irregular variations in yearly meteorological condition. In the meanwhile, due to a number of uncertain factors (e.g. farmers' enthusiasm, local crop and forest residue accessibility, market situation and biofuel production capacity), the amount of available biofuels cannot be measured correctly, and would be subject to the estimation by the experts, managers and/or stakeholders under different scenarios (e.g. good, normal and poor levels of biomass availability), which results in the stochastic-fuzzy property existing in the biofuel availability. If the above uncertainties are ignored or simplified and expressed by only one type of uncertainty, the solutions of the optimization models may be unreliable or suboptimal [25], and even infeasible [24]. That is mainly because the oversimplification of the uncertain parameters may loss the valuable information inputs and cannot reflect the real system situation. Therefore, effectively reflecting and handling multiple uncertainties are also important to support the formulation of sound FM decisions and analyze the corresponding economic and environmental impacts associated with the different fuel selection and allotment alternatives.

To address the uncertainties within the FM process, a few techniques based on stochastic theory (e.g. scenario analysis and stochastic programming) have been employed, especially in the field of fuel supply-chain management [11,26–33]. Among them, a two-stage stochastic programming (TSP) has been adopted in the past few years since they are effective to define potential scenarios when the probability distributions of uncertain parameters on the right-side are known [34,35]. For example, Nunes et al. applied a two-stage stochastic mixed-integer programming to the design of Great Britain's liquid hydrogen supply chain, providing the operation mode of the methane-reforming hydrogen plants, and the most suitable storage size under different scenarios [36]. Zhou et al. integrated TSP, a genetic algorithm, as well as Monte Carlo method into a framework to cope with the optimal design problem of a distributed energy system with multi-fuel-based energy conversion facilities [37]. To deal with the stochastic uncertainty in monthly available biomass, Shabani et al. developed a TSP model for optimizing the supply chain of a forest biomass power plant at the tactical level [38]. Using TSP together with mixed integer programming, Kim et al. explored the designs of a biofuel supply network in the Southeastern region of the United States, which enabled decision making for the infrastructure of biofuel conversion processing [39]. From the previous studies, it is revealed that the core running mechanism of TSP lies in the concept of “recourse”, in which the first stage decisions should be made ‘‘here-and-now’’ prior to the occurrence of random events, and after the random events have happened, the “wait-and-see” variables (i.e. the corrective variables) need to be determined in the second stage in order to minimize ‘‘penalties’’ that may appear due to any infeasibility. However, in some real-life cases, the “here-and-now” decisions should depend on the system situations affected by uncertainties. For instance, as the common first-stage decisions, the heat demand corresponding to the normal meteorological condition during the heating season may be unsuited to the cold or mild heating season. Such unfixed scenarios may cause the randomness penetrating into the first-stage decisions. If these first-stage decisions are made arbitrarily, the biased solutions or high system costs could be generated due to ignoring the fluctuation of economic penalties. In addition to the uncertainty embedded within the first stage decisions, TSP may encounter other technical difficulties for FM in a HMDHS, although it can handle stochastic parameters on the right-side effectively. Specifically, it can hardly cope with discrete intervals associated with the model objective