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An optimization model for economic feasibility analysis and design of decentralized waste-to-energy systems

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ABSTRACT

This paper considers a methodology for economic feasibility analysis of a decentralized hybrid WTE (waste-to-energy) system, when input waste streams and technical parameters can be uncertain. A hybrid WTE system is decentralized when there are possibly different owners of the waste treatment units. A two-stage stochastic programming model is proposed to evaluate and optimize the joint probability that each installed unit is able to achieve its own financial target, while adhering to stipulated environmental requirements. A case study is performed based on the city state of Singapore. The results show that, the proposed model can help provide the effective decision support for policy-makers in evaluating the appropriate technological mix of WTE alternatives. Furthermore, the designs generated by the proposed model can significantly improve the economic feasibility of the overall system without sacrificing certain installed unit's financial position. Finally, the optimized hybrid WTE system obtained by the proposed model achieves an optimal mix and balance of implemented treatment technologies, which is more practical than the current incineration only design in the MSW (municipal solid waste) management future in Singapore.

1. Introduction

MSW (Municipal solid waste) generation in many countries and cities continues to rise in the face of industrialization, urbanization and population expansion. For example, the annual disposed MSW in Singapore had been increased from 0.74 million tons in 1972 to 2.80 million tons in 2000 [1]. Diminishing landfill space availability, increasing population density, risks of contamination of surface and ground water, air and soil pollution are among the important waste management issues for policy makers in any modern municipality. In the recent years, rapid advances in waste treatment technologies has made possible the efficient recovery of useful energy from waste in the forms of primary fuels. For example, AD (anaerobic digestion) technology recovers biogas from organic waste. Gasification and highly-enhanced incineration are now able to recover significant yields of syngas, electricity, and useful heat from MSW combustion. These treatment technologies are now commercially available in various scales, and offers a promising solution to alleviate high volume MSW disposal problems and as a source of renewable energy simultaneously. In this work, they are collectively termed as WTE (waste-to-energy) technologies. However, most of the above-mentioned technologies are capable of only treating a specific subset of waste streams effectively. Also, although most WTE technologies can reduce the volume of the input waste streams, they may still generate various solid residues and emissions post-treatment, which will still require further processing and final disposal.

Hybrid WTE systems that couple inputs and outputs of different WTE units operating as a single system have been studied and proposed as an effective solution for modern sustainable MSW management practices. In contrast to single-unit WTE systems, studies on hybrid system design emphasize on the appropriate choice of technological portfolio for the treatment of all input MSWs and residues in a sustainable manner. Such a system can

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effectively help to balance treatment unit utilizations by effectively distributing waste flows, and improve achievement of multiple sustainability targets such as emission and landfill volume reduction, energy recovery and economic performance targets. On the other hand, due to the high capital investment costs of new treatment technologies, there is a significant financial risk for the WTE operators. Hence, a careful environmental-economic feasibility analysis need to be performed before embarking on the acquisition of such systems. Some relevant work has been proposed in the literature. For example, Ref. [2] presented a technical and economic feasibility study for the hybrid WTE system based on the integration of gas turbines to MSW incinerator for disposing solid waste in medium-sized cities. Ref. [3] proposed a linear programming model to identify feasible WTE technologies for treating different waste streams in a medium term future energy system with the objective of minimizing system cost. Ref. [4] developed a mixed-integer linear programming model to minimize the total cost of regional energy system, and found that the construction of new WTE plants can help achieve a regional fossil fuel-free energy system. Ref. [5] adopted the fuzzy optimization method to simultaneously consider economic performance, waste volume reduction, and energy recovery for optimizing the WTE network synthesis.

In practice, many system parameters can be uncertain at the early stage of feasibility study of the WTE system. For example, accurate projections of individual waste stream volumes may not be available. Also, technological coefficients such as energy recovery efficiency of an AD unit may be highly uncertain, since it can be sensitive to operating conditions (such as ambient temperature, pH level of the digestate, etc). Hence, making feasibility evaluations without carefully accounting for such uncertainties have the danger of arriving at incorrect or highly inaccurate conclusions. This can have significant consequences since the installation of new WTE units are extremely expensive. Two-stage stochastic programming modeling is a popular approach for handling decision problems with uncertainties in MSW management studies. All such models use a single expected utility function, including total system life cycle costs, profits and net present value as a performance criteria to rank the WTE systems from the perspective of a centralized operator. For instance, Ref. [6] formulated a two-stage interval-stochastic programming model aiming at minimizing the expected system costs by incorporating the idea of two-stage stochastic programming within the interval programming framework for planning solid waste streams under uncertainty. And Ref. [7] integrated the robust programming and two-stage stochastic programming within a mixed integer linear programming framework to develop a two-stage fuzzy robust integer programming model for waste flow allocation and facility capacity planning with the objective of minimizing the sum of first-stage cost and second-stage capacity shortage penalty. However, in most existing practice, individual MSW treatment units can operate as independent entities, for example they can be different operators contracted to provide waste management services, and are interested in their own financial positions. This practice is referred as a *decentralized* WTE system. That is, the decentralization concept in this paper emphasizes on the *ownership* rather than the physical location of the installed MSW treatment units. Hence, a design solution that performs well under a total profits criteria may not be sustainable in a decentralized setting since such a system may ignore or compromise the economic feasibility of some units. However, none of the prior works using two-stage stochastic programming models have addressed this issue.

In this work, a two-stage mixed-integer stochastic programming model for the evaluation and design a decentralized WTE system is proposed. The main feature of the proposed model is that it imposes an objective to maximize the economic feasibility of the system under uncertainty. In the first stage, capacity investment decisions are made, to choose treatment units to implement. In the second stage, when parameter values are assumed to be more accurately known, the waste flow distribution is made to maximize the benefit of the system. The criteria implemented is the joint probability that each installed treatment unit is able to achieve its own financial target. An implication of such an objective is that, if a treatment unit cannot meet its financial target in many uncertainty outcome scenarios, then including the unit in the design is very undesirable, regardless of how high the total system profits are. A feasible design must also comply to stipulated environmental requirements, such as greenhouse gas emission limits [8] and landfilling capacity constraints [9]. Such a model is useful for policy-makers at the local government level, who often require a quick first-cut evaluation of the economic feasibility of a hybrid WTE system implemented in a decentralized setting.

The rest of this paper is organized as follows. Section 2 presents the problem statement and assumption to give an overview of the WTE system design problem. Section 3 describes the details of the proposed model and its solution approach. Section 4 presents a computational case study based on the solid waste management system in Singapore. The case study shows how the proposed model can be used to analyze WTE options under various scenarios. It also provides the main insight of why it is necessary to balance WTE units with a AC (aerobic composting) unit in order to manage both financial performance and landfilling requirements, the conclusions of which are qualitatively similar to the real-life situation in Singapore. Section 5 concludes this paper.

2. Problem statement and assumption

The complete life cycle of a MSW handling process includes collection, presorting, recycling, treatment, energy recovery, and final (landfill) disposal processes. The collection and presorting processes segregate mixed MSW into several categories with similar physical and chemical characteristics. The recycling process follows to recover re-usable materials for various applications and re-manufacturing. Waste treatment and energy recovery processes, which are collectively termed as the WTE system boundary, handle the remaining un-recyclable MSW and include activities such as volume reduction, energy products recovery and residuals treatment. The WTE system can comprise of a portfolio of different treatment and energy recovery technologies (units) suitable for treating different categories of waste in parallel. The solid residuals generated from various WTE units are referred to as a type of “process-generated feedstock” since they are produced within the waste treatment units. The collected, presorted, or unrecyclable MSWs are referred to as “input feedstock” since they originate outside the boundary of the WTE system. This paper focuses on the WTE system, and assumes that the collection, presorting and recycling stages serves as inputs to its scope. Fig. 1 illustrates the topology diagram of the MSW management system.

This work considers the hybrid WTE system design problem that selects the appropriate WTE units and their capacity levels for treating input feedstock. During system operation, input and process-generated feedstock is distributed across the implemented processes to best achieve different requirements, including local government environmental regulations. The objective of this model is to maximize the joint success probability of achieving financial (profit) targets for all selected facilities over the design horizon of the system. It is also referred as the probability of achieving economic feasibility. Some modeling assumptions are listed below: