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Research paper

Multi-objective optimization of biomass to biomethane system

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Abstract

The superstructure optimization of biomass to biomethane system through digestion is conducted in this work. The system encompasses biofeedstock collection and transportation, anaerobic digestion, biogas upgrading, and digestate recycling. We propose a multicriteria mixed integer nonlinear programming (MINLP) model that seeks to minimize the energy consumption and maximize the green degree and the biomethane production constrained by technology selection, mass balance, energy balance, and environmental impact. A multi-objective MINLP model is proposed and solved with a fast nondominated sorting genetic algorithm II (NSGA-II). The resulting Pareto-optimal surface reveals the trade-off among the conflicting objectives. The optimal results indicate quantitatively that higher green degree and biomethane production objectives can be obtained at the expense of destroying the performance of the energy consumption objective.
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Keywords: Multiobjective optimization; Biomass to biomethane system; Green degree; Mixed-integer nonlinear programming

1. Introduction

Recently, severe fluctuations in fossil fuel prices and global environmental problems have greatly accelerated efforts to develop renewable energy. Biomass-based methane, as a reproducible and environmentally friendly fuel that can decrease greenhouse gas emissions and reduce the non-renewable energy consumption, has gotten increasing attentions. Meanwhile, the multi-objective optimization of the complex biomass to biomethane process is of great significance, which can enhance the material and energy efficiency of the biomethane production system and assist in realizing the energy saving and emission reduction.

In the last decades, considerable efforts have been made to assess and optimize digestion and upgrading units of a biomethane production system. Huang et al. [1] proposed a novel multiobjective control strategy to simultaneously optimize the biogas flow rate and the effluent chemical oxygen demand in a complex anaerobic bioreactor. The developed hybrid approach may offer a very effective and useful tool for simulation, design, operation and optimization of anaerobic digesters. Zaher et al. [2] addressed a simulation tool for the optimization and assessment of co-digestion of different solid waste streams. The integrated model could determine the feed ratio and hydraulic retention time to obtain the maximum biogas production rate. Mahanty et al. [3] developed a methodology to evaluate and optimize the co-digestion of five different industrial sludges, which can be utilized to predict the maximum possible biomethane yield. Xu et al. [4] studied and assessed three biogas upgrading techniques considering energy and environmental performance by using the process simulation and green degree (GD) method. Wu et al. [5] established a simulation model for the assessment of energy consumption of biogas upgrading process. Additionally, many

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experimental studies have been conducted to study the performance of anaerobic digestion [6—10].

Meanwhile, there have been many studies on multiobjective optimization of biomass to biofuels systems. Gebreslassie et al. [11] addressed a bi-criteria nonlinear programming (NLP) model for the optimal operation and design of hydrocarbon biorefinery that produced diesel and gasoline from hybrid poplar feedstock through fast pyrolysis, hydrotreating and hydrocracking. Then they proposed a mixed-integer nonlinear programming (MINLP) model for the rigorous optimization and operation of an algae-based biorefinery system with sequestration of carbon dioxide from power plant flue gas. The mathematical model integrates the techno-economic analysis and environmental impact assessment through a life cycle optimization framework [12]. Zhang et al. [13] proposed a comprehensive superstructure for the sustainable process design and synthesis of hydrocarbon biorefinery that included fast pyrolysis, biocrude collection, hydroprocessing and hydrogen production under economic and environmental criteria. The Pareto-optimal solutions provided optimal operation configuration, profit, and emission data for future decision-makers. Santibanez-Aguilar et al. [14] presented a mathematical model for the optimal design of a biomass conversion system considering simultaneously the total net profit maximization and the environmental impact minimization. Mian et al. [15] presented detailed thermoeconomic and environmental models for the multiobjective optimization of microalgae to synthetic natural gas (SNG) conversion system accounting for supercritical gasification. Martin and Grossmann [16] established an MINLP model for the superstructure optimization of bioethanol process from switchgrass via gasification. In addition, they optimized a process to enhance the production of biodiesel and bioethanol from algae through glycerol fermentation [17]. Wang et al. [18] proposed a superstructure model for the optimization of hydrocarbon biorefinery via gasification considering the economic and environmental performance. Gassner and Marechal [19] addressed a superstructure MINLP model for the conceptual design of thermochemical fuel production process by optimizing the exergy depletion and investment cost objectives.

However, little work concerns the rigorous optimization strategies of the complex biomethane production system, which covers the whole subsystem including collection and transportation, anaerobic digestion, biogas upgrading, and digestate utilization. In this paper, an MINLP model for the rigorous optimization of the superstructure-based biomethane production process is established. The model simultaneously considers the minimization of the energy consumption, the minimization of the total environmental impact, and maximization of the biomethane production as three objective functions by optimizing the combinations of the feedstocks, operation variables, and alternative operation technologies. The environmental performance takes into account the overall environmental impact estimated by the GD method. Meanwhile, the GD values of biomass (chicken manure, sugar cane and corn stalk, *etc.*) and digestate are developed on the basis of the GD method. Based on a real application, the description of the superstructure system is presented. Then it is optimized by a non-dominated sorting genetic algorithm II (NSGA-II). Finally, the Pareto optimization results are obtained and some typical optimal points are selected and analyzed.

2. Process description

This section provides a description of each of the four major processing steps, including biomass collection and transportation, anaerobic process, biogas upgrading, and digestate utilization shown in Fig. 1. In each processing unit, the alternative technologies (Fig. 1) considered are based on the environmental and thermodynamic performance of the system.

2.1. Collection and transportation

Distribution of biomass resources is broad and non-uniform. So collecting biomass feedstock from fields is a great challenge for biomass power plants in China. A mathematical model is addressed for the optimal design and analysis of geographic distribution of biomass power plant and satellite storages based on a square sub-collection-region [20,21]. Singh et al. [22] proposed a circular island-based mathematical model of biomass collection and transportation costs. In this article, it is assumed that all biofeedstocks collected are in centralized covered collection and all biomass transported is done by diesel trucks.

2.2. Biomass handling and anaerobic digestion

Agricultural residues should be shredded into a small particle size prior to entering into the anaerobic digestion tank, because the decomposition and methane (CH_4) potential of biomass could be considerably enhanced by pretreating for reduction of particle size [23,24]. The length of cereal residues is usually cut into the range of 2—3 cm.

The major component in this system is anaerobic digestion technique. Anaerobic digester is a sophisticated process in which insoluble organic polymers are broken down and converted into CO_2 and CH_4 by anaerobic bacteria in the absence of oxygen. Several factors within the reactor such as temperature, pH, retention time, inoculum-to-feed ratio, C/N ratio, and organic loading rate can impact the efficiency of anaerobic digester, degradation rates, biogas production, and biomethane content [25]. In this model, the influence of different temperature is taken into account in detail: mesophilic anaerobic digestion and thermophilic anaerobic digestion.

Generally, the higher operating temperature can bring higher metabolic activities. Anaerobic process can be operated at ambient temperatures exhibiting a low efficiency. So, most reactors are operated at either mesophilic conditions (30—40 °C) or thermophilic conditions (50—60 °C).

Compared to mesophilic reactor, thermophilic reactor usually possesses higher decomposition efficiency, COD

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