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A fuzzy multiobjective linear programming model for design and management of anaerobic digestion based bioenergy supply chains

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ABSTRACT

The purpose of this study is to develop a decision support system (DSS) for design and management of anaerobic digestion based biomass to energy supply chains in a cost effective and environment friendly manner by tackling inherent uncertainties. To this aim, a fuzzy multiobjective mixed integer linear programming (MILP) model is constructed. To explore the viability of the proposed model, computational experiments are performed on a real world problem. The results reveal that the proposed model can effectively be used in practice.

1. Introduction

To compete with fossil fuel sourced energy production systems in today's highly global and competitive markets, decision models for bioenergy supply chain planning should be developed to represent the real world problem precisely. Unfortunately, in real world, most of the energy system structures and parameters to be included in the models are not exactly known and do not represent definitely the real problem. Uncertainty may be related to target values of objectives, supply and demand, costs, prices etc. Incomplete, imprecise and/or uncertain parameter values should be incorporated into the modeling approach to represent the energy systems more realistically. Bioenergy supply chain models proposed so far, except a few ones, either used traditional crisp modeling approaches that ignore uncertainty or consider it with additional analyses (i.e. sensitivity and scenario analyses) or with stochastic modeling approaches that depends on probability distributions governing the data.

Linear programming (LP) with scenario generation and sensitivity analyses are used to monitor and analyze the impacts of different system states and fluctuations in system parameters on the supply chain performance. Ekşioğlu et al. [1] propose an MILP (multiobjective mixed integer linear programming) model with scenario generation that can be used to design the supply chain and manage the logistics of a biorefinery. Pérez-Fortes et al. [2] developed a multiobjective MILP model to support designing and planning of biomass based supply chains. They performed sensitivity analyses to show how optimum scenarios can vary if some key parameters are changed. Foo et al. [3] utilized LP to minimize the environmental impact of a palm oil based regional supply chain. Multiple biomass supply scenarios are considered in the study to exhibit operational flexibility such as closure or expansion of mills.

Stochastic programming and simulation are also employed to solve bioenergy supply chain problems with uncertainty. Osmani and Zhang [4] developed a two-stage stochastic MILP for strategic and tactical decision making in a multi-feedstock bioethanol supply chain. Kim et al. [5] propose an integer stochastic programming model for a biorefinery network structure for single and multiple design scenarios. Sodhi and Tang [6] introduce a two-stage stochastic model for supply chain management under uncertainty by applying a stochastic mixed integer non-linear programming to determine the production topology, plant sizing, product selection and allocation and vendor selection. Simulation methods are important tools to monitor the behavior of complex real world systems. They are also useful to analyze the impact of variations in system parameters. Sokhansanj et al. [7] developed a dynamic integrated biomass supply analysis and logistics model to simulate the flow of biomass from field to biorefinery. Climatic and operational constraints that have influence on the availability of biomass to a biorefinery are modeled using the proposed approach.

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The real world is complex; complexity in the world generally arises from uncertainty in the form of ambiguity. For systems with little complexity, hence little uncertainty, closed-form mathematical expressions provide precise descriptions of the systems. For the most complex systems where few numerical data exist and where only ambiguous or imprecise information may be available, Fuzzy set theory (FST) provides a way to understand system behavior. Fuzzy modeling approaches provides the appropriate framework to describe and treat uncertainty when there is lack of evidence available or lack of certainty in evidence, that the standard probabilistic reasoning methods are not appropriate. FST was developed by Zadeh [8], since then it has been applied to the fields of operations research, management science, artificial intelligence/expert systems, statistics and many other fields. In 1976, Zimmermann [9] first introduced FST into conventional LP problems. He considered LP problems with a fuzzy goal and fuzzy constraints. Since then, fuzzy linear programming has been developed in a number of directions.

In the light of our literature review about decision making in biomass to energy supply chains, we can conclude that there is scarcely any research on biomass to energy supply chain planning models that employs fuzzy modeling approach. Among them, Aviso et al. [10] developed an LP model with fuzzy input output analysis to optimize supply chains under water footprint constraints. Tong et al. [11] developed a multiperiod MILP model for optimal design and planning of a hydrocarbon biofuel supply chain integrated with existing petroleum refineries. They applied fuzzy possibilistic programming to their model.

Most of the models applied for the energy systems design work for different objectives such as satisfying minimum system costs and minimum level of harmful gas emissions, and a set of technological, economic, environmental and social constraints. Multi dimensionality of the sustainability goal and complexity of energy systems make multicriteria and multiobjective decision making (MODM) methods increasingly popular for sustainable energy systems. Although goal programming (GP) is one of the most powerful MODM approaches in practical decision making it is rarely used in biomass to energy conversion systems design.

Modeling and optimization approaches for biomass to energy supply chain network design of increasing scope and sophistication have been devised recently. However, network design models for the bioenergy supply chains including anaerobic digestion facilities have not been dealt with in the previous research although it is one of the most efficient and environment friendly energy production systems. Also, the vast majority of the related studies consider only energy crops as biomass resource. As improper disposal or storage of organic wastes causes pollution in underground and surface waters and environmental problems that threat human health, constructing waste biomass to energy conversion plants is vital in decreasing such problems besides gaining economical benefits.

Since integrating FST with multiobjective optimization techniques provides the real system to be modeled more realistically and closer to the decision maker's needs, fuzzy modeling approaches become prominent in decision making for preference modeling and multi criteria/objective evaluation. We propound that fuzzy multiobjective decision making (FMODM) approach can effectively be used in design and management of bioenergy supply chains. Considering these facts and the gaps in the literature, this study aims to develop a fuzzy multiobjective MILP based DSS (decision support system) for design and management of biomass to energy supply chains that include anaerobic digestion facilities.

The proposed model includes environmental and economic objectives and it is structured as multiperiod to incorporate variation and seasonality in feedstock supply and cost parameters. In addition, multiple types of biomass and products are incorporated in the model. To provide the decision makers for a more confident solution set for policy decision making, the model is solved by using different FGP (fuzzy goal programming) approaches and the results are evaluated. To explore the viability of the proposed DSS, applications of the model with different FGP approaches are performed on a real world problem.

2. Methodology

2.1. Anaerobic digestion based biomass to energy supply chains

In anaerobic digestion systems, biomass is fed into a digester that produces biogas through an anaerobic fermentation process. As biomass feedstock is fermented through wet digestion process, water has to be added to the digester to adjust the total solid content of the feedstock mixture. Subsequently, biogas is treated, stored and converted into heat and power by combined heat and power (CHP) unit. In modern power stations, approximately 40% of the energy potential in biogas is converted into electrical energy, the remainder is being discharged as waste heat. It is possible to make use of the waste heat. Depending on the decision maker's preference the waste heat can be used to meet the internal heat requirement of the plant or for district heating with additional investment cost. The generated electrical energy is usually fed into the national electricity grid. Residue of the fermentation process which is high-quality organic nutrient source that feeds the plants and soil, can be used as organic fertilizer in agricultural activities.

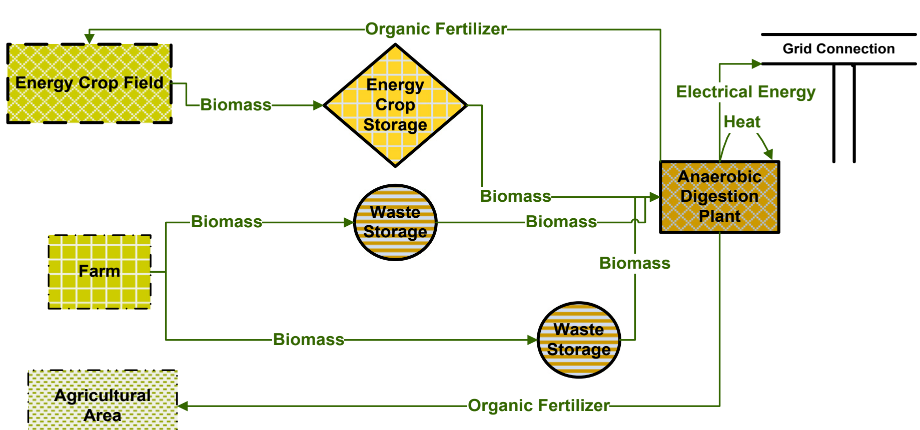

Fig. 1. Biomass to energy supply chain considered in this study.