Available online at www.sciencedirect.com

ScienceDirect

http://www.elsevier.com/locate/biombioe

BIOMASS & BIOENERGY

Optimal design of advanced drop-in hydrocarbon biofuel supply chain integrating with existing petroleum refineries under uncertainty

Kailiang Tong [a], *Michael Joseph Gleeson* [a], *Gang Rong* [b], *Fengqi You* [a,*]

[a] *Department of Chemical and Biological Engineering, Northwestern University, Evanston, IL 60208-3120, USA*
[b] *Department of Control Science and Engineering, Zhejiang University, Hangzhou 310027, China*

ARTICLE INFO

Article history:
Received 11 May 2013
Received in revised form
12 October 2013
Accepted 20 October 2013
Available online 17 December 2013

Keywords:
Biofuel supply chain
Petroleum refinery integration
Fuzzy possibilistic programming
Modeling
Optimization

ABSTRACT

This paper addresses the optimal design of an advanced hydrocarbon biofuel supply chain integrated with existing petroleum refineries. Three major insertion points from the biofuel supply chain to the petroleum refineries are investigated and analyzed, including bio-intermediates co-processed with crude oil, bio-intermediates co-processed with refinery intermediates, and finished biofuels blended with conventional petroleum products. A multiperiod, mixed-integer linear programming model is proposed that accounts for diverse conversion pathway, technology, and insertion point selections, biomass seasonality, geographical diversity, biomass degradation, demand distribution and government incentives. This model simultaneously optimizes the supply chain design, insertion point selection, and production planning. In addition, the conversion rate, operation cost associated with insertion points in petroleum refinery, as well as the biomass availability and product demand are modeled as fuzzy numbers to account for the data uncertainty. A fuzzy possibilistic programming approach is applied to this model, where possibility, necessity and credibility measures are adopted according to the decision makers' preference. This model is illustrated by the county level case study of Illinois. Compared to traditional biofuel supply chains, advanced hydrocarbon biofuel supply chain integrating with existing petroleum refinery infrastructure significantly reduces capital cost and total annualized cost.

1. Introduction

Biofuels have been shown to be a promising future fuel source, capable of both reducing dependence on fossil fuels and slowing climate change. They can be produced domestically from a wide variety of biomass sources. Moreover, biofuels can reduce overall greenhouse gas emissions (GHG), because the carbon dioxide produced from their consumption is partially recaptured by additional biomass feedstocks. According to the strategy goal set by the Biomass Program under the U.S. Department of Energy, there is a great need to *develop commercially viable biomass utilization technologies to enable the sustainable, nationwide production of biofuels that are compatible with today's transportation infrastructure and can displace a share of petroleum-derived fuels to reduce U.S. dependence on oil and encourage the creation of a new domestic bioenergy industry, supporting the Energy Independence and Security Act of 2007 goal of 136 hm^3 per year of renewable transportation fuels by*

* *Corresponding author*. Tel.: +1 847 467 2943; fax: +1 847 491 3728.
E-mail address: you@northwestern.edu (F. You).
0961-9534/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biombioe.2013.10.023

2022 [1]. With the development of the third generation biofuel technologies, advanced biofuels can now be produced from cellulosic biomass such as crop residues, wood residues or dedicated energy crops [2]. Moreover, advanced hydrocarbon biofuel products (e.g., cellulosic-biomass-derived gasoline, diesel and aviation fuel) are functionally identical to their petroleum counterpart. Because of these advantages, according to the U.S Department of Energy, advanced hydrocarbon biofuels are likely to replace the first and traditional second generations of biofuels [3,4].

Many studies have been done on the design and planning of traditional biofuel supply chains from diverse aspects, for instance, feedstock selection [5,6], facility location and capacity design [7–9], technology selection [10,11], feedstock seasonality [12,13], multiobjective model considering economics, financial risk [14], sustainability [13,15], and social impact [11]. Also, these models were applied to various countries, such as the US [6,13], the UK [8,16], Italy [9], etc. However, these models neglected to make full use of the existing petroleum infrastructure so their results were less than promising.

Researchers are investigating the possibility of converting biomass into biofuel in the traditional refinery. Huber and Corma [17] summarize the techniques for converting biomass into biofuel in existing petroleum refineries. They note that catalytic cracking, hydrotreating, and hydrocracking are the three main techniques for converting biomass to biofuels. They also note that biomass should be converted to bio-oil through fast pyrolysis first before sent to the upgrading units. U.S. Department of Energy [4] is investigating three possible insertion points into the traditional refinery. They note that after converting the biomass into liquid bio-intermediate, it can be mixed with crude oil that feed the Crude Distillation Units (CDU), or sent directly to upgrading units to produce gasoline and diesel. Baliban et al. [18]proposed an optimization framework for the synthesis of a thermochemical biomass and natural gas to liquids refinery. However, the studies on explicitly economic evaluation of the integration possibility from the supply chain point of view are limited. Elia et al. [19] proposed an optimization framework for a nationwide energy supply chain network using hybrid coal, biomass, and natural gas to liquids (CBGTL) facilities. In order to lower the cost of advanced hydrocarbon biofuels to a level comparative to conventional fuels, a sophisticated supply chain model, which considers designing, logistics and planning decisions, is urgently needed to take the advantage of the existing petroleum refinery infrastructures.

As a matter of fact, the feasibility of the supply chain is subject to various sources of uncertainties, such as seasonal and geographical fluctuation of biomass supply, variability of biofuel demand due to unstable economic situations, and imprecise processing data due to the process fluctuation and immature technologies. The inability to handle these uncertainties may lead to either an infeasible supply chain design or suboptimal performance. Some works have been done to incorporate the uncertainties with the biofuel supply chain design. Stochastic programming [14], robust optimization [21], and sensitive analysis [20] are often used to deal with demand and supply uncertainties [14,22], as well as cost fluctuation [20,23]. However, few works have been done considering the production uncertainty, such as conversion rate and product yield [24,25]. As pointed out by Tong et al. [25], the uncertainty of conversion rate greatly influence the supply chain decision making, especially the product inventory.

Uncertainties can be described as either "probability" or "possibility". The former maybe measured by repetition of experiments and the latter is employed to measure the truth or possibility of the event [26]. To the problem in which the distribution of uncertainty can be obtained from historical data, the stochastic programming is a good choice, as it leads to a more detailed and quantitative representation of different options. However, stochastic programming may fail due to the lack of uncertainty information. The recently proposed stochastic inventory approach [48–51] can be an efficient approach to address the issues on uncertainty information and computational performance, but its current capability is limited to handling supply and demand uncertainty. On the other side, fuzzy programming can provide a good alternative by using fuzzy logic to represent the truth of the uncertainty values. Although the choice of parameter values in fuzzy logic is often quite subjective and depends on the user's preference, it reduces the computational burden significantly and is suitable for the uncertainty that lacks information. For instance, the conversion rate and capital cost for integration in our model is hard to obtain due to the immaturity of the technology. It is better to use fuzzy programming dealing with such uncertainties.

Since the publication of Zadeh's work [27], fuzzy set theory has become a powerful means for dealing with non-stochastic impression and vagueness. Two types of fuzzy programming are commonly used, flexibility programming and possibilistic programming [28]. Flexibility programming treats constraints as fuzzy set and allows violation in constraints, while possibilistic programming deals with uncertain coefficients on objective functions as well as constraints. Following the idea of chance constraint programming with stochastic parameters developed by Charnes and Cooper [29], in a fuzzy decision system we assume that the fuzzy constraints will hold with at least a possibility α called the confidence level [30]. This is the central idea behind possibilistic programming. Possibilistic programming uses possibility and necessity measure to model the likely degree or certainty degree of constraints. However, to the best of our knowledge, applications of fuzzy theory in biofuel supply chain optimization are limited, especially for fuzzy possibilistic programming. The work from Tan et al. [31,32] and Tay et al. [33] are the only ones that are related to bioenergy optimization, but they used the fuzzy flexible programming.

In this work, we address the optimal design and operation of advanced hydrocarbon biofuel supply chain under various types of uncertainties. A multiperiod mixed-integer linear programming model is proposed to take account of main characters of advanced hydrocarbon biofuel supply chain, such as integration with petroleum refineries, "drop in" fuels blending with crude derivatives, and use of pipelines to distribute products. Additionally, typical features of biofuel supply chain are also considered, such as biomass seasonality, deterioration, geographical distribution of biomass, moisture content, diverse conversion pathway selection, product distribution, and government incentives. We consider biomass availability, product demand, conversion rate and corresponding cost for insertion points in the petroleum refinery as the fuzzy numbers in our model. Possibility, necessity and