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Supply chain design and operational planning models for biomass to drop-in fuel production

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ABSTRACT

Renewable fuel is playing an increasingly important role as a substitute for fossil based energy. The US Department of Energy (DOE) has identified pyrolysis based platforms as promising biofuel production pathways. In this paper, we present a general biofuel supply chain model with a Mixed Integer Linear Programming (MILP) methodology to investigate the biofuel supply chain facility location, facility capacity at strategic levels, and biofuel production decisions at operational levels. In the model, we accommodate different biomass supplies and biofuel demands with biofuel supply shortage penalty and storage cost. The model is then applied to corn stover fast pyrolysis pathway with upgrading to hydrocarbon fuel since corn stover is the main feedstock for second generation biofuel production in the US Midwestern states. Numerical results illustrate unit cost for biofuel production, biomass, and biofuel allocation. The case study demonstrates the economic feasibility of producing biofuel from biomass at a commercial scale in Iowa.

1. Introduction

Second generation biofuel is attracting increasing attention as a substitute for fossil oil from environmental, economic, and social perspectives. Second generation biofuels are made from nonfood crop or crop residues, such as corn stover, switchgrass, woody biomass, and miscanthus. Thus, the production of biofuel will not be in direct competition with food production. Biomass has different physical properties and component elements, therefore, various products yields can be seen with different thermochemical pathways [1,2]. According to the revised Renewable Fuel Standard (RFS) proposed by US Environmental Protection Agency (EPA), at least 136 Mm^3 of renewable fuels will be produced annually by 2022, and at least 60.6 Mm^3 will be from cellulosic biofuels [3].

Drop-in biofuels are hydrocarbon fuels compared to gasoline and diesel, which can be transported through the existing petroleum pipeline and are ready for vehicles to use without any modification to engines. There are two main processing platforms: thermochemical and biochemical [4]. Thermochemical processes utilize heat to facilitate the depolymerization of biomass compounds which are further processed into biofuel and co-products [5–8]. Biochemical processes involve living organisms to convert organic materials to fuels, chemicals, and other products. Thermochemical pathways are identified as promising pathways

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by the Department of Energy (DOE). This paper focuses on the thermochemical pathways. The biofuel products vary based upon the conversion configuration and reacting conditions.

The general framework for the biofuel supply chain is as follows. Biomass feedstocks are first collected and processed into bale (corn stover) or pellets (woody biomass) for easier storage and transportation [9]. For example, corn stover bales typically have a moisture mass fraction of 30%. The bales are stored on the farm before transported to preprocessing facilities. The physical and chemical properties, information related to corn stover harvesting, storage, and transportation are detailed in Refs. [10,11]. In the preprocessing facility, corn stover is chopped into size (2.5–5.0) cm, then further dried to moisture level of around 7% and grind to (1–2) mm preferably [9]. Preprocessed biomass is then sent to biorefinery facilities to be converted into raw bio-oil and other byproducts. The raw bio-oil is then sent to upgrading facilities to be refined into drop-in biofuels [12–14]. The drop-in biofuels can be transported to Metropolis Statistics Areas (MSAs) for blending or end use.

Supply chain design and operational planning is among the biggest challenges to the cellulosic biofuel industry [15–18]. Feedstock production and logistics constitute 35% or more of the total production costs of advanced biofuel [19,20], and logistics costs can make up (50–75)% of the feedstock costs [21]. To facilitate the commercialization of biofuel production, it is important to investigate the optimal number and locations for biorefinery facilities, and to find the optimal allocation of feedstock and biofuel. There has been an emerging literature in the biofuel supply chain design [15,16,22–25].

Operational planning is also essential for biofuel supply chain and network design. A stochastic multi-period model is proposed in Ref. [18] for hydrocarbon biofuel production from cellulosic biomass, and results for the optimal design of the hydrocarbon biorefinery supply chain are presented under biomass supply and biofuel demand uncertainties. Dal-Mas et al. [17] presented a dynamic multi-echelon Mixed Integer Linear Program (MILP) to assess the economic performance and risk on investment of the biomass-based ethanol plant. Zhu et al. [26] presented a multi-period MILP model to show the feasibility of commercially producing biofuel from switchgrass. Another model also presented by Zhu et al. [27] showed seasonal results for second generation biofuel from a mixture of biomass, and analyzed the effects of biomass yields on biofuel production planning and profit change. In this study, motivated by the real world scenarios, we accommodate the flexibility of fuel demand satisfaction by allowing the shortage of biofuel, which will incur a subjective penalty cost. This is similar to the concept of biofuel importation in Ref. [17].

In addition, this study considers the impact of operational constraints by incorporating the temporal inventory metrics. A multi-period optimization model is also formulated to study the detailed operational planning for biomass collection and drop-in fuel production and distribution. Sensitivity of different biofuel demand patterns is also analyzed.

The rest of the paper is organized as follows. In Section 2, model assumptions and formulation for both annual and operational planning model are presented. In Section 3, we demonstrate a case study in the state of Iowa and numerical results are presented in the same section. Results are summarized in Section 4 along with a discussion of future research directions.

2. Model formulation

This study aims to minimize total biofuel production cost using a Mixed Integer Linear Programming model (MILP). In addition to optimizing the number of biorefinery facilities and locations [23], the proposed model aims to optimize the number of biorefinery facilities, facility capacities, locations, biomass and biofuel allocations considering a variety of biofuel demand scenarios.

As illustrated in Fig. 1, biomass is collected and pretreated at farms into small particles ready for biofuel conversion. Pretreated biomass is transported to biorefinery facilities to go through conversion and upgrading processes to produce advanced biofuel. In this study, it is assumed that biofuel conversion and upgrading are conducted in the same facility, and then transported to the biofuel demand locations, which are Metropolitan Statistical Areas (MSA).

In the following sections, we present an annual based optimization model in Section 2.2 to study the strategic decisions for biofuel supply chain. Analogous to the annual based model, a more detailed operational planning model is presented in Section 2.3 to shed a light on managing the production, allocation and inventory of the biofuel.

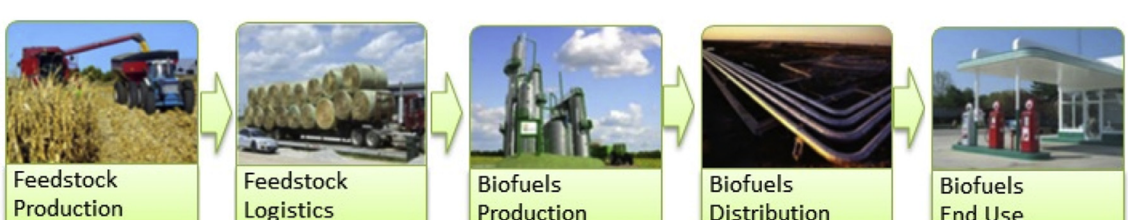

Fig. 1 – Biomass supply chain framework for biofuel production and distribution.