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Integrated supply chain design for commodity chemicals production via woody biomass fast pyrolysis and upgrading

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HIGHLIGHTS

- Economic feasibility and the optimal production planning for commodity chemicals.
- Trade-off between economic and environmental metrics for chemicals is analyzed.
- Biomass availability and facility capital costs are the most important factors.

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ABSTRACT

This study investigates the optimal supply chain design for commodity chemicals (BTX, etc.) production via woody biomass fast pyrolysis and hydroprocessing pathway. The locations and capacities of distributed preprocessing hubs and integrated biorefinery facilities are optimized with a mixed integer linear programming model. In this integrated supply chain system, decisions on the biomass chipping methods (roadside chipping vs. facility chipping) are also explored. The economic objective of the supply chain model is to maximize the profit for a 20-year chemicals production system. In addition to the economic objective, the model also incorporates an environmental objective of minimizing life cycle greenhouse gas emissions, analyzing the trade-off between the economic and environmental considerations. The capital cost, operating cost, and revenues for the biorefinery facilities are based on techno-economic analysis, and the proposed approach is illustrated through a case study of Minnesota, with Minneapolis-St. Paul serving as the chemicals distribution hub.

1. Introduction

The growing interest in biofuels production has generated much related research in economic analysis, environmental assessment, and supply chain system design (An et al., 2011; Blottnitz and Curran, 2007; Bowling et al., 2011; Giarola et al., 2012; Hamelinck et al., 2005; Hess et al., 2007; Larson, 2006; Stephen et al., 2010; You et al., 2012; Zhang et al., 2013a,b,d). Biomass logistics are complicated by the bulky, distributed nature of biomass and by the high volumes of low energy density materials to be collected and transported to the conversion facilities (Tallaksen, 2011). The unique nature of biomass feedstock provides great impetus for the exploration of sustainable and robust supply chain systems.

Numerous studies have been devoted to optimal design and operational planning of the bioethanol supply chain. You et al. (2012) developed a multi-objective mixed integer linear programming (MILP) model which addressed the optimal design and planning of the cellulosic ethanol supply chain under economic, environmental, and social objectives. Dunnett et al. (2008) proposed a system model to optimize the lignocellulosic bioethanol supply chain under assumptions of energy integration. Bai et al. (2011) optimized biofuel refinery location and supply chain planning for bioethanol production, taking into account of traffic congestion issues. Giarola et al. (2012) developed a stochastic modeling framework adopting a scenario-based approach to assess the effects of trading greenhouse gas (GHG) emissions allowances under market uncertainty for bioethanol production.

Researchers have also been aggressively exploring the supply chain design for biomass-derived transportation fuels (gasoline and diesel fuel). You and Wang (2011) presented the optimal design and planning of a biomass-to-liquids (BTL) supply chain under

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economic and environmental criteria. You's design was based on a distributed preprocessing and centralized conversion network. Kim et al. (2011) designed an optimal biomass supply chain network for transportation fuels production under uncertainty and then analyzed the robust design with Monte Carlo simulation. Elia et al. (2013) developed a nationwide supply chain optimization framework for a BTL system using hardwood biomass for gasoline, diesel, and jet fuel production.

While much research is devoted to the use of biomass for fuels, there has been a concurrent growing interest in the use of biomass for the biobased products, such as renewable chemicals (Brehmer et al., 2009; Christensen et al., 2008; Dale, 2003; Gavrilescu and Chisti, 2005; Schilling, 1995). A survey on the alternative feedstocks for commodity chemicals manufacturing was conducted by Oak Ridge National Laboratory (2007) and biomass was recognized as one of the most promising alternative feedstocks for commodity chemicals production. Various production pathways, such as gasification, fermentation, and pyrolysis, were analyzed. Brehmer et al. (2009) evaluated the maximum fossil fuel replacement potential for a variety of feedstocks and reported a high potential for biomass to replace fossil fuel in the petrochemical industry. Christensen et al. (2008) discussed the possibility of establishing a renewable chemicals industry and reported that from both economic and ecological perspectives, such an industry might be most advantageous to secure the optimal use of abundant, but limited, bioresources.

Vispute et al. (2010) proposed a novel integrated catalytic thermochemical pathway to convert woody biomass to commodity chemicals, such as benzene, toluene, and xylene aromatic hydrocarbons (BTX). In this pathway, the bio-oil produced from woody biomass fast pyrolysis undergoes two-stage hydrotreatment followed by fluid catalytic cracking (FCC). Due to the high selectivity of commodity chemicals products attainable using this production pathway, the pathway has garnered significant attention and has inspired further examination of its economic feasibility and environmental effects. A techno-economic study has been conducted to examine the five commodity chemicals production scenarios, one of which was Vispute's two-stage hydrotreating followed by FCC. Vispute's pathway is found to be the most profitable among the five scenarios (Brown et al., 2012). Another techno-economic study concluded that this chemicals production pathway is economically feasible, in which the facility internal rate of return was predicted to be as high as 13% for a 20-year project (Zhang et al., 2013b). A life cycle assessment was conducted to examine the environmental performance and found that chemicals production via the integrated catalytic processing pathway could reduce GHG emissions significantly compared to the petroleum-based chemicals production (Zhang et al., 2013c).

Although there have been many studies of supply chain design and optimization for biofuel production, there have been few papers addressing supply chain design and optimization for renewable chemicals production from woody biomass via the thermochemical pathway. In this paper, a supply chain network is designed and optimized for the biobased chemical production pathway, using MILP modeling to optimize the locations and capacities of distributed preprocessing hubs and centralized biorefinery facilities. This paper examines both economic and environmental criteria in a multi-objective framework that allows analysis of trade-offs between economic feasibility and environmental impact. A case study for the state of Minnesota is presented to illustrate the integrated supply chain network design model.

2. Methods

2.1. Integrated catalytic processing pathway

Vispute et al. (2010) has proposed an integrated catalytic processing pathway for commodity chemicals production via woody biomass (Fig. 1). In this pathway, woody biomass is preprocessed (chopped, dried, and grinded) and then sent to a pyrolyzer to produce bio-oil. The bio-oil undergoes phase separations through a liquid–liquid extractor, resulting in separate water insoluble and aqueous phases. The water insoluble phase consists mainly of pyrolytic lignin, which is treated as a co-product. The aqueous phase is sent to a low temperature hydrotreating process (125 °C, 100 bar). Then the hydrotreated bio-oil is sent to a high temperature hydrotreating process for further hydrodeoxygenation (200 °C, 100 bar) over catalysts. After the two-stage hydrotreating process, FCC is performed on the hydrotreated aqueous phase to produce commodity chemicals. In addition to the primary raw material the woody biomass, hydrogen is needed for the two-stage hydrotreating process.

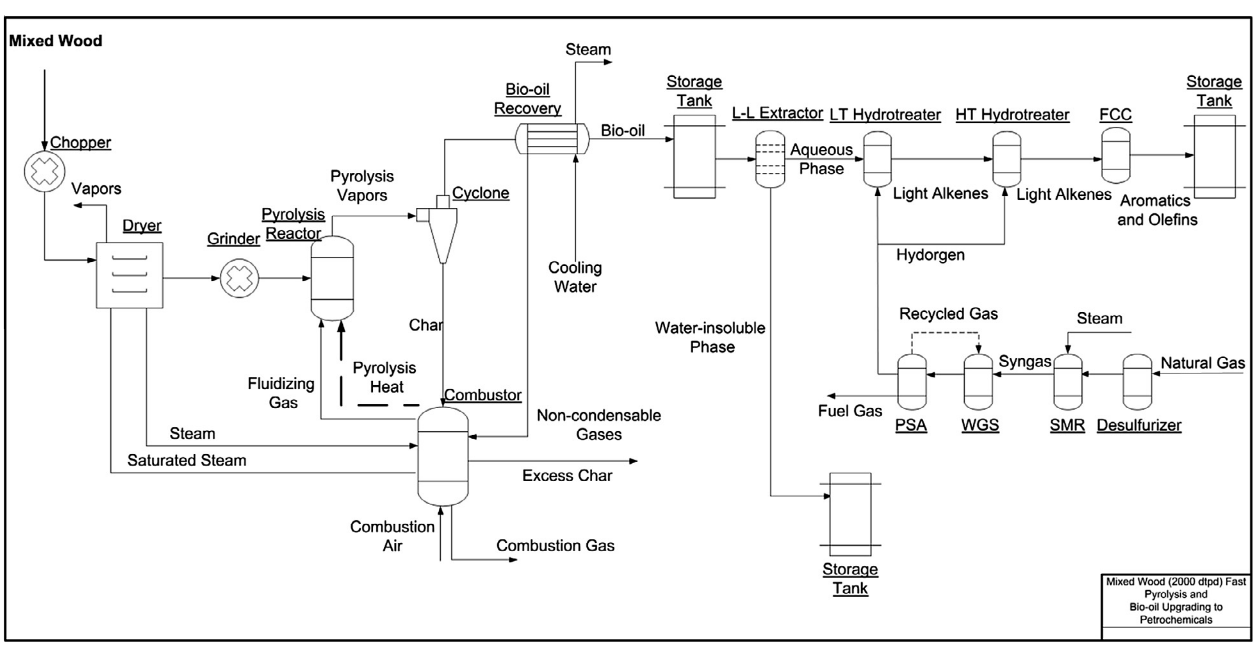

Fig. 1. Process diagram for mixed wood fast pyrolysis and bio-oil upgrading to commodity chemicals (Adapted from Zhang et al. (2013b).