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Techno-economic analysis of biofuel production considering logistic configurations

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HIGHLIGHTS

- Techno-economic analysis considering logistic configurations has been proposed.
- Monte-Carlo simulation considering parameter interactions has been conducted.
- Case study demonstrates the economic impact of supply chain configuration.

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ABSTRACT

In the study, a techno-economic analysis method considering logistic configurations is proposed. The economic feasibility of a low temperature biomass gasification pathway and an integrated pathway with fast pyrolysis and bio-oil gasification are evaluated and compared with the proposed method in Iowa. The results show that both pathways are profitable, biomass gasification pathway could achieve an Internal Rate of Return (IRR) of 10.00% by building a single biorefinery and integrated bio-oil gasification pathway could achieve an IRR of 3.32% by applying decentralized supply chain structure. A Monte-Carlo simulation considering interactions among parameters is also proposed and conducted, which indicates that both pathways are at high risk currently.

1. Introduction

As a renewable substitute for petroleum fuels, biofuels have attracted increasing attention for economic, environmental, and energy security considerations. First-generation biofuels could be relatively easily converted to transportation fuels but lead to food versus fuel dilemma. Cellulosic biofuel feedstock such as corn stover, switchgrass, and woody biomass does not compete with food supply but highly recalcitrant (Carriquiry et al., 2011). US Environmental Protection Agency (EPA) revised the Renewable Fuel Standard in 2007, which aims to accelerate the domestic biofuel production and consumption. The Revised Renewable Fuel Standard (RFS2) mandates that by the year 2022, at least 16 billion gallons per year of cellulosic biofuels will be produced and consumed in the US (Schnepf, 2011). However, cellulosic biofuel production has been significantly below the blending targets established by the RFS2 due to technical immaturity and feedstock availability issues (Brown, 2015).

Lignocellosic biomass could be converted into bio-oil via pyrolysis, and the biomass pyrolysis can be followed by bio-oil cracking, gasification, or hydroprocessing to produce transportation fuels (Wang et al., 2013a). The mechanism research shows that fast pyrolysis of cellulose biomass yields to products such as pyrans, furans, and linear small molecular compounds (Wang et al., 2012). The pyrolysis behaviors and structural features are significantly affected by the process conditions (Wang et al., 2015). Researchers also use thermogravimetric analysis coupled to Fourier transform infrared spectroscopy to analysis the evolution of typical pyrolysis products (Wang et al., 2013b).

The major challenge faced by the cellulosic biofuel industry is that investors are not willing to take the risk to construct commercial scale facilities, and lack of real facility cost information for the production systems prohibit the improvement of production system to reduce costs and uncertainty (Brown, 2015). Techno-economic analysis (TEA) has been widely adopted to overcome this dilemma. Process models are developed to simulate the production systems at a commercial scale. Materials and energy balances are

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developed. Cost analysis is then employed to evaluate the economic feasibility of the production system at commercial scale (Zhang et al., 2013a). TEA, as a simulation approach, is highly dependent on the model assumptions, which could lead to significant inaccuracy and even errors.

Another major barrier for commercialization of cellulosic biofuels is transporting bulky solid biomass over a long distance. This is mainly caused by the low energy density of lignocellulose biomass and a large collection radius due to the limitation of biomass availability. In general, logistics cost for transport biomass from farmland to biorefinery can make up 50–75% of the feedstock cost (Harland, 1996) and more than 35% of the total production cost of advanced biofuel is feedstock cost (Wooley et al., 1999).

TEA studies typically focus on the technical and economic performance for a single facility and neglect the upstream biomass collection and transportation as well as the downstream biofuel transportation and distribution. However, with the importance of supply chain configurations in the economic feasibility evaluation of cellulosic biofuels, TEA should incorporate the supply chain configurations explicitly rather than the simplify assumption of a flat feedstock cost and biofuel price at the facility gate. Recently, researchers have worked on incorporating pre-determined simple supply chain configurations to estimate biomass feedstock cost for integrated pathways (Manganaro and Lawal, 2012; Zhang and Wright, 2014). However, in reality, feedstock availability, logistic cost, and biofuel demands will all affect evaluation of economic feasibility (Li and Hu, 2014). This serves as the major motivation for this proposed approach to incorporate logistic settings into the techno-economic analysis.

There has been an increasing body of literature on supply chain network design for the biofuel industry (Li and Hu, 2014; Li et al., 2014; Zhang and Hu, 2013). Design and management of logistic flow includes the raw materials, work-in-process, and finished products from source of raw materials to the point of consumption (Rogers and Brammer, 2009). In order to incorporate supply chain design into TEA study, logistic information such as biomass availability, transportation cost, and demands distributions is necessary. A decision method and optimization model is necessary to determine the optimal facility locations and capacities as well as the logistic flow decisions for biomass supply and biofuel distribution.

The remainder of the paper is organized as follows: in Section 2, the proposed TEA method with logistic settings is introduced. In Section 3, we illustrate the method with a case study of comparing two competitive pathways in Iowa, namely low temperature biomass gasification pathway and fast pyrolysis (FP) integrated with bio-oil gasification pathway. Finally, the paper concludes with a summary of research findings in Section 4.

2. Methods

In this section, the proposed TEA method with logistic configurations is introduced. Materials and conversion pathways are chosen based on current technology and feedstock availability. Methods for technical and economic analysis are discussed.

2.1. TEA method with logistic settings

This proposed TEA method with logistic configurations contains three main steps: cost estimations based on traditional standalone TEA, design and evaluation of supply chain configurations, and economic feasibility assessment under realistic supply chain. In the first step, the investment for a single facility based on a traditional standalone TEA literature is evaluated. An assessment on the relationship between plant sizes and economic performance based on the rules of economies of scale and time value of money provides candidate plant sizes for the supply chain design. The second step is to design the biofuel supply chain configurations based on the conversion pathway and feedstock availability of the region under assessment. Mathematical models are formulated to provide the decision support for the supply chain design. The third step includes economic performance assessment considering the logistic configurations, and risk assessment with Monte-Carlo simulation.

The motivation of this proposed TEA method is to introduce supply chain design into traditional TEA to achieve a more comprehensive analysis and realistic economic assessment results. In the conventional TEA which has been commonly used in the literature, assumptions such as flat feedstock cost and biofuel price at the facility gate have been adopted (Li et al., 2015; Swanson et al., 2010; Wright et al., 2010). These assumptions have received significate concerns. In this proposed TEA with logistic considerations, no uniform feedstock prices at facility gates are assumed. Instead, feedstock cost is estimated by the farm gate collection cost and the shipping cost from farm to facility. The feedstock collection costs vary due to collection methods and quantities. A regression analysis is employed to estimate collection cost (Graham et al., 2007). The feedstock (crop residuals, such as corn stover) availability is assumed to be proportional to the crop yield. The feedstock shipping cost, the intermediate product shipping cost, and the biofuel shipping cost are all assumed to be proportional to the shipping distance. Biofuel market prices are based on US Energy Information Administration (EIA) projection, and the biofuel demand amounts and locations are based on the population distribution in the geographic region.

2.2. Materials and technologies

To illustrate the proposed TEA method, a case study based on Iowa is conducted. Corn stover has been chosen as the cellulosic biomass feedstock in this study due to its abundance in Iowa. The final biofuel product is assumed to a drop-in fuel which is ready for vehicle consumption.

In this study, we have thus chosen integrated pathway with fast pyrolysis and bio-oil gasification to illustrate the proposed TEA method. It has been suggested that hybrid pathways, such as integrating fast pyrolysis and downstream upgrading process such as gasification would be a viable option for commercial scale. This is due to the flexibility to accommodate a decentralized supply chain structure and also advantage of economies of scale (Li et al., 2015; Manganaro and Lawal, 2012). On the other hand, low temperature (870 °C) biomass gasification pathway has typically been brought up for comparison with the integrated bio-oil gasification pathway. Therefore, the conversion pathways under consideration in this study include low temperature biomass gasification pathway and hybrid fast pyrolysis with bio-oil gasification pathway. BMG (biomass gasification) and BOG (bio-oil gasification) are used as abbreviations for these two pathways in the following sections.

2.3. Technical analysis

The conversion process models and mass and energy balance information are based on the existing literature (Li et al., 2015; Swanson et al., 2010). Fig. 1 shows the process flow diagrams for biomass gasification pathway and integrated bio-oil gasification pathway. The main assumptions such as capital cost estimation, plant size, target IRR, and facility life are the same in both studies, while the balance of plant (BOP) and annual operating hour rate are in similar range which is typical in TEA studies (11% and 0.85 in BMG TEA while 12% and 0.9 in BOG TEA) (Wright et al., 2010;