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A comprehensive model for design and analysis of bioethanol production and supply strategies from lignocellulosic biomass

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ABSTRACT

This study aims to present a comprehensive decision model for design of the integrated bioethanol supply chain (IBSC). In achieving this goal, we developed a new optimization model using mixed integer linear programming. The model consists of the objective function to minimize the required cost to establish the IBSC along with practical constraints including the limit of biomass, the capacity of technologies, and the land availability. This model is capable of identifying a wide range of solutions for the economically viable IBSC: biomass as a feedstock, technical configuration of the biorefinery, and supply chain solutions. We then analyze the impact of the policies to the bioethanol production and supply strategies by implementing the different scenarios of the bioethanol-gasoline blending policy. To illustrate the capability of the proposed model, we applied the model to the biomass-derived liquid fuel supply system of Jeju Island, Korea. As a result, the total supply cost was estimated to range from 0.83 to 0.88 $/liter according the blending policies. We also analyzed the preferable options to build the IBSC of Jeju Island: woody biomass to agricultural residues, gasification to fermentation as the main conversion technology, and regions with high biomass availability to high-demand regions.

1. Introduction

The development of biofuels can reduce fossil fuel consumption, thereby mitigating climate change and enhancing energy security. Biofuels are compatible with existing vehicles and corresponding infrastructure [1]. Thus, many countries have encouraged the use of biofuels to overcome energy vulnerability in the transportation sector by diversifying energy sources [2–4]. In particular, bioethanol can be utilized for various applications such as fuels, fuel cells, and industrial ingredients. As a substitution for conventional fuels, bioethanol is already utilized in low 5%–10% blends with gasoline (called E5 and E10, respectively). Furthermore, all gasoline-ethanol blends from 0% to 85% ethanol can be used in flexible-fuel vehicles (FFVs), thereby bioethanol consumption is expected to steadily increase [5].

A wide range of research has been attempted regarding the research and development of bioethanol production and economy, from discovery of biological property to establishment of enterprise business and national policy. In particular, numerous studies for development of bioethanol production technologies can be found in the literature on catalytic and chemical conversion [6–10], enzymatic fermentation [11–14] and thermochemical decomposition [15–20] technologies, which utilize existing resources [21,22], and new dedicated energy crops [23].

Recently, systematic approaches such as supply chain optimization, logistics management, and business decision support system have been spotlighted to bring bioethanol into a real energy economy. Huang et al. [24] developed the bioethanol supply chain model that includes biomass collection, biomass delivery, biomass-to-ethanol conversion, and ethanol distribution, considering spatial and temporal dimensions. Zhang et al. [25] proposed a new optimization model for the bioethanol supply chain that considers the life cycles in biomass supply as well as fuels supply chain. Marvin et al. [26] proposed the bioethanol supply system, which utilizes multiple types of lignocellulosic biomass resources using real data and an optimization technique. You et al. [27] designed a decision support model using a multi-objective optimization technique for the bioethanol supply chain to analyze the economics and environmental impacts of bioethanol.

Whereas a literature review reveals that many issues regarding the realization of bioethanol have been dealt with and resolved, challenges remain about how to facilitate and commercialize

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bioethanol along with its infrastructure. One of these challenges may be the integration of the emerging infrastructure (new flows, facilities, and business model) to the existing, fossil-fuel-based and well-structured system. For example, Andersen et al. [28] proposed a supply chain optimization model that determines economically suitable locations of terminals where blending of bioethanol and gasoline takes place and other essential facilities to the biomass-derived energy supply system. Whereas they dealt with the logistics of the downstream bioethanol supply system, the upstream activities such as harvesting, collecting, and supplying of biomass have not been discussed in detail.

Using information about bioethanol technologies, we propose a new optimization model to support the comprehensive decision-making on the design of bioethanol-blended liquid fuels supply system, which includes the selection of types and amount of biomass; the technology configuration of biorefineries; and the types, capacities, and locations of major facilities. The optimization model minimizes the entire cost of the *integrated bioethanol supply chain* (IBSC) system and is capable of i) identifying the optimal supply chain of the IBSC and ii) providing flow information and the optimal solution for operation schedules of the involved facilities. We also developed practical strategies using different ethanol-gasoline blending policies to evaluate the impact of the blend policy on the configuration and the cost structure of the IBSC system.

2. The integrated bioethanol supply chain (IBSC) system

2.1. System boundary and assumption

The objective of this study was to develop an optimization model to design the IBSC system. The overall network of the IBSC system is illustrated in Fig. 1(a). The IBSC system is largely divided into two parts: the biomass supply chain and the liquid fuel supply chain. The biomass supply chain refers to the flows of biomass resources from farm to biorefinery, which is the bioethanol production facility. The liquid fuel supply chain is defined as the flows of ethanol, gasoline, and blended fuel from biorefinery to gas station.

The biomass supply chain includes three sources of biomass supply: existing biomass (i.e., agricultural and forest residues), newly cultivated biomass, and imported biomass. Here the newly cultivated biomass refers to *energy crops*, which are plants specifically grown for the purpose of energy production at the marginal land. Imported biomass refers to the agricultural and forest residues imported from overseas. All types of biomass are transported to biorefineries for ethanol production or to warehouses where they are stored to balance the lack of biomass in any following periods.

Biorefineries convert biomass into bioethanol. We considered several types of biomass conversion technologies as a biorefinery such as thermochemical, chemical, and biochemical technologies;

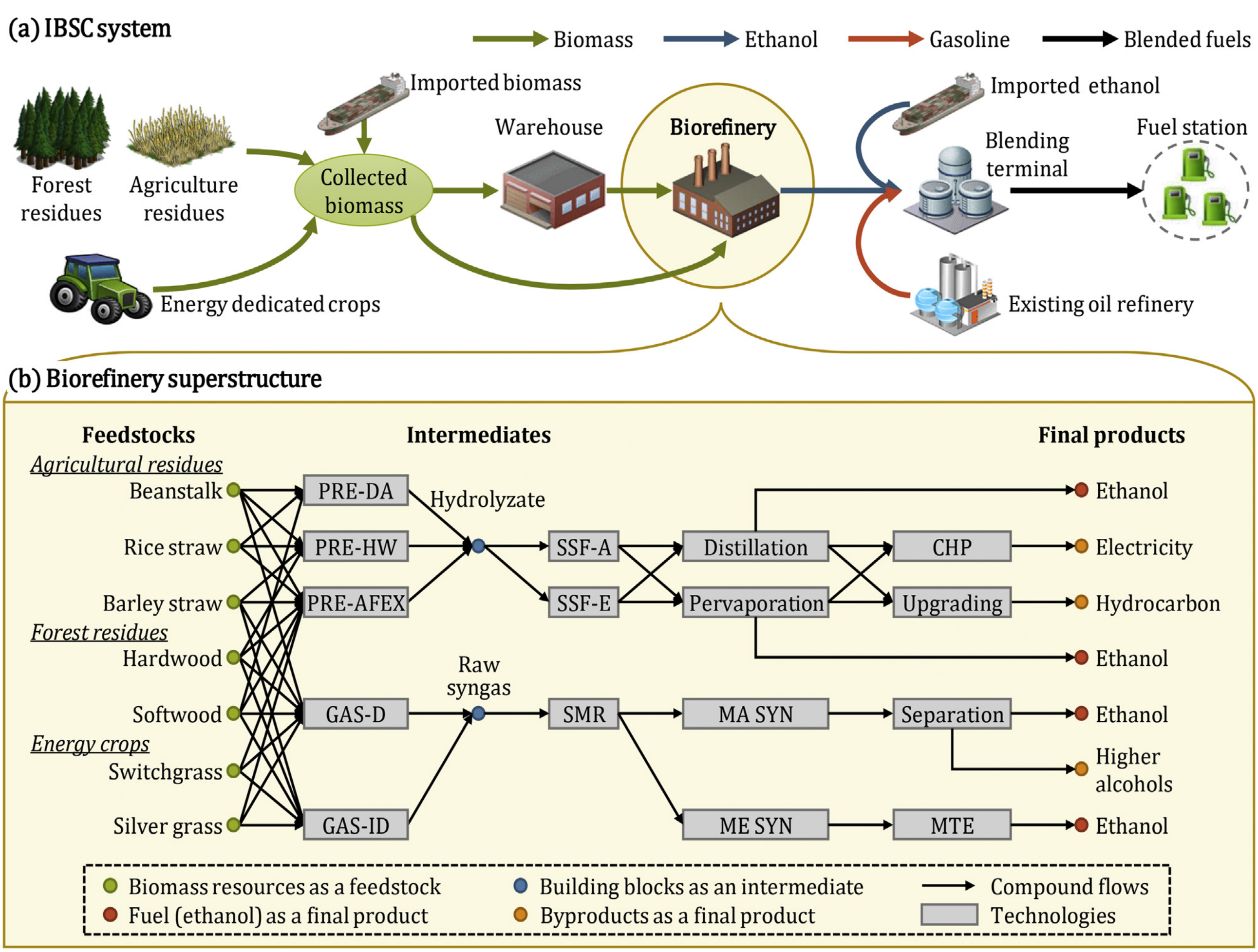

Fig. 1. (a) Schematic representation of the IBSC system and (b) the network of technologies and materials in the biorefinery. Abbreviation: PRE-DA (-HW, -AFEX): dilute acid (how water, ammonia fiber expansion) based pretreatment, GAS-D (-ID): direct (indirect) gasification, SSF-A (-E): acidic (enzymatic) simultaneous saccharification and fermentation, MA (ME) SYN: mixed alcohols (methanol) synthesis, SMR: steam methane reforming, MTE: methanol to ethanol conversion, CHP: combined heat and power generation.