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Optimization-based approach for strategic design and operation of a biomass-to-hydrogen supply chain

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ABSTRACT

We present a new optimization-based approach for design and operation of a renewable hydrogen system from various types of biomass. To achieve this goal, we develop an optimization model (mixed integer linear programming) which determines the optimal logistics decision-making to minimize the total annual cost for a comprehensive biomass-to-hydrogen (B2H2) supply chain with import and inventory strategies. With the proposed approach we can identify the optimal design of the supply chain and main cost-drivers, manage logistics operations against fluctuations of biomass availability and hydrogen demand, and make strategic decisions for planning the B2H2 system such as capital investment and energy import planning. To validate the model, a case study of an upcoming B2H2 supply chain for the transportation sector at Jeju Island, Korea, is analyzed. Finally, a sensitivity analysis is conducted to provide insights into the efficient management of the B2H2 supply chain.

Introduction

Recent research in the area of alternative energy sources has been spurred by a combination of complex problems such as decreasing reserves of nonrenewable fossil fuels, increasing volatility of oil prices, and growing environmental damage caused by the industrialization and use of nonrenewable fossil fuels and their resulting carbon dioxide (CO_2) emissions. Biomass is a promising alternative to fossil fuels. Alternative biomass fuels can be generated from a variety of sources like agricultural residues, industrial residues, and forestry residues, and they can be cultivated and/or collected at various sites [1–3]. While the biomass can be transformed to various types of energy carriers (e.g., ethanol [4] and hydrogen [5–14], electricity [15], etc.), hydrogen is one of the major gaseous energy carriers that can be used as a fuel for vehicles (i.e., hydrogen fuel cell vehicles or HFCV) due to its environmental merits [5–11]. Berry et al. [5] studied the advantage of hydrogen as a future transportation fuel from the political, environmental, and scientific aspects and described the techniques and facilities required for the same. Many other

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researchers have focused on using hydrogen as an alternative fuel for vehicles. Kim et al. [6] presented a sustainable hydrogen energy system as an alternative to fossil fuels and conducted case studies in the context of South Korea's energy policy (e.g., reducing carbon emissions) and the effect of rising oil prices on the country. Elia et al. [7] considered a hydrogen production plant and developed a model to predict hydrogen demand, determine its market price, and the extent of carbon emission reductions due to fossil fuel substitution by hydrogen fuel. Stephens-Romero et al. [8] optimized the location of refueling station by considering the existing gasoline station in a local. Ball et al. [9] developed the model for optimization of regional hydrogen supply based on the (Baltic model of regional energy market liberalization) BALMOREL tool and analyzed different infrastructure scenarios and energy price scenarios. Parker [10] designed the biomass-to-hydrogen (B2H2) supply chain and developed a model basis on geographic information system to demonstrate biomass economic as a feedstock. Sabio et al. [11] developed spatio-temporal model to design the optimal hydrogen supply chain in Spain and performed analysis on their model to identify the trade-off between cost and risk.

Research in the area of alternative eco-friendly and sustainable energies can be subdivided into three categories: development of alternative energy pathway technologies, development of alternative energy supply chain models, and practical strategies of energy supply. Mckendry [16–18] conducted a review on the status and availability of technologies for converting biomass into renewable fuel as an alternative source of energy production. Hawkes et al. [19] focused on hydrogen as an alternative fuel and presented a continuous hydrogen production process with fermentation of carbon-based material. Hwang [20] studied hydrogen production pathways and conducted life-cycle analysis of energy consumption and greenhouse gas emission for transportation fuels. Boalt and Thiel [21] designed delivery pathways of hydrogen passed production activity, transportation activity, storage activity and a refueling station and analyzed the pathways to find the least cost configuration of the hydrogen supply chain.

Dunnett et al. [15] proposed a schedule for harvesting biomass, processing it, and producing alternative fuel for a 12-month cycle. Ekşioğlu et al. [22] studied the potential of bio-refinery to replace fossil fuels using a model to determine the specifics (number, size, and location) for such a refinery, and suggested ways to modify the biomass energy supply chain of the State of Mississippi. Rentizela et al. [23] considered a variety of energy generation technologies using various types of biomass to study the demand-driven problem. Kim et al. [24] attempted to provide the best strategy to practically resolve the problems posed by different biomass-to-fuel conversion technologies.

To the best of our knowledge, even though the reviewed literature has analyzed optimization models for biomass-based supply chains, none of these studies present an integrated optimization model for a multiple biomass-based hydrogen supply chain considering import and inventory strategies. In this article, we develop a mixed integer linear programming (MILP) model with import and inventory strategies to minimize the total annual cost (TAC) of such a supply chain by considering existing constraints. The proposed model provides the optimal decisions for a comprehensive B2H2 supply chain/logistics infrastructure while simultaneously determining the locations and sizes of such facilities, their transportation flows, the needed quantities of biomass–hydrogen, and the quantities to be imported under the import and inventory strategies. Then, the model is tested on an upcoming B2H2 supply chain for HFCVs at Jeju Island, South Korea by estimating the expected hydrogen demand in 2040.

The remainder of this article is organized as follows. Section 2 provides the problem statement and lists the assumptions employed in the article. Section 3 presents the MILP. Section 4 presents preliminary data on biomass potential and other parameters of the proposed model for the B2H2 supply chain for HFCVs at Jeju Island. Section 5 presents the best possible configuration and planning using the optimal solution of the MILP model. Computation results from the sensitivity analysis are discussed in Section 6. Finally, Section 7 summarizes the contribution and research findings with providing suggestions for future studies.

Problem statement

The three main objectives of this study are to develop an optimization model to integrate biomass supply chain into the B2H2 supply chain, manage the logistics operation against fluctuations in biomass yields and demand, and make strategic decisions for planning the B2H2 system such as capital investment and energy import planning. Fig. 1 shows the schematic structure of the multiple B2H2 supply chain in this study. The structure is divided into the biomass and hydrogen supply chains. The biomass supply chain includes four types of regional suppliers and one overseas supplier for import. The regional suppliers consist of a supplier each of industrial residues, agricultural residues, forest residues, and energy crops. Two biomass tower silos with different sizes are used to store the residues and energy crops from the regional and overseas suppliers. Then, the collected biomass is transported to gasification plants to transform it into hydrogen, or the biomass is held in tower silos of a limited capacity to meet future demand. In the hydrogen supply chain, the facilities comprise two biomass gasification plants, two hydrogen storage systems, and two hydrogen refueling stations with different capacities. This problem utilizes a single technology called *biomass gasification* to convert multiple biomass materials (industrial, agricultural, and forest residues, and energy crops) into biofuel energy (hydrogen). The biomass gasification plants receive the biomass from the tower silos and transform it into hydrogen. As the name implies, the hydrogen storage systems store the hydrogen produced from the gasification plants or that imported from overseas. Finally, the refueling stations fuel the HFCVs using this hydrogen to satisfy market demand.

The following assumptions are used to establish the proposed B2H2 supply chain:

- Four types of biomass (energy crops, forest residues, industrial residues, and agricultural residues) are considered in the biomass supply chain.