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Biomass-to-bioenergy and biofuel supply chain optimization: Overview, key issues and challenges

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ABSTRACT

This article describes the key challenges and opportunities in modeling and optimization of biomass-to-bioenergy supply chains. It reviews the major energy pathways from terrestrial and aquatic biomass to bioenergy/biofuel products as well as power and heat with an emphasis on "drop-in" liquid hydrocarbon fuels. Key components of the bioenergy supply chains are then presented, along with a comprehensive overview and classification of the existing contributions on biofuel/bioenergy supply chain optimization. This paper identifies fertile avenues for future research that focuses on multi-scale modeling and optimization, which allows the integration across spatial scales from unit operations to biorefinery processes and to biofuel value chains, as well as across temporal scales from operational level to strategic level. Perspectives on future biofuel supply chains that integrate with petroleum refinery supply chains and/or carbon capture and sequestration systems are presented. Issues on modeling of sustainability and the treatment of uncertainties in bioenergy supply chain optimization are also discussed.

1. Introduction

Biomass-derived liquid transportation fuels and energy products have been proposed as part of the solution to climate change and our heavy dependence on fossil fuels, because the biomass feedstock can be produced renewably from a variety of domestic sources, and the production and use of bioenergy/biofuel products have potentially lower environmental impacts than their petroleum counterparts (An, Wilhelm, & Searcy, 2011a; Gold & Seuring, 2011; Marquardt et al., 2010). Consequently, many countries have set national biofuels targets and provide incentives and supports to accelerate the growth of bioenergy industry. For example, in the U.S. the Renewable Fuels Standard (RFS), part of the Energy Independence and Security Act (EISA) of 2007, establishes an annual production target of 36 billion gallons of biofuels by 2022 (EISA, 2007). Currently most biofuels in the U.S. are made from corn starch that might have negative implications in terms of both food prices and production (McNew & Griffith, 2005; Rajagapol, Sexton, Hochman, Roland-Holst, & Zilberman, 2009). To avoid adverse impacts on food supply, EISA further specifies that 16 out of the 36 billion gallons of renewable fuels produced in 2022 should be advanced biofuels made from non-starch feedstocks, such as cellulosic or algal biomass. Yet, the current annual production capacity of advanced biofuels is less than 1 billion gallon worldwide. It is foreseeable that the bioenergy industry will be undergoing a rapid expansion in the coming decade. Many sustainable and robust biomass-to-bioenergy supply chains, which link the sustainable biomass feedstock and the final fuel/energy products, need to be designed and developed for lower costs, less environmental impacts and more social benefits (Elia, Baliban, & Floudas, 2012; Hosseini & Shah, 2011; Sharma, Ingalls, Jones, & Khanchi, 2013). To accelerate the transition towards the large-scale and sustainable production and use of biofuels and bioenergy products, a significant challenge in research is to systematically design and optimize the entire bioenergy supply chains from the biomass feedstock production to the biofuel/bioenergy end-use across multiple spatial scales, from unit operations to biorefinery processes and to the entire value chain, as well as across multiple temporal scales, from strategic to operational levels, in a cost-effective, robust and sustainable manner (Daoutidis, Marvin, Rangarajan, & Torres, 2013; Marquardt et al., 2010). It is the objective of this paper to identify the key research challenges and opportunities in modeling and optimization of biomass-to-bioenergy supply chains using Process Systems Engineering (PSE) tools and methods, and to chart a path for addressing these challenges.

In this paper, we classify the existing contributions on bioenergy supply chain optimization, elucidate the research challenges, and demonstrate that multi-scale modeling and optimization approach can play a leading role to address these challenges. We first review the major biomass-to-biofuels pathways, with a specific emphasis

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on producing "drop-in" liquid hydrocarbon fuels from terrestrial and aquatic biomass, which may blend with or displace gasoline, diesel, jet fuel, kerosene or home heating oil. We then describe the key components of the biomass-to-biofuels supply chains and their major characteristics, along with a comprehensive overview and classification of the existing contributions on bioenergy supply chain optimization. We further demonstrate the important role of multi-scale modeling and optimization, which allows the integration across multiple temporal and spatial scales. The potential research vistas on future bioenergy supply chains that integrate with petroleum refinery supply chains and/or carbon capture and sequestration systems are presented next. Key issues on modeling of sustainability and the treatment of uncertainties in bioenergy supply chain optimization are also discussed. Although the focus of this paper is on biofuels supply chains, at the end of this paper we discuss the modeling and optimization for supply chains with non-fuel end-uses of biomass derivatives, including biopower and biomass-to-heat supply chains and biomass-to-chemicals supply chains, which represent other products from biomass and will impact the supply chain.

2. Biomass-to-biofuels pathways

Biomass is unique among renewable energy sources in that it can be easily stored until needed and provides a liquid fuel alternative for use in today's transportation system. In the short term, biofuels are the only renewable resources that can address the transportation sector's heavy dependence on foreign oil without replacing the vehicle fleet (DOE/EERE, 2013d). In this section, we review the major pathways from biomass to biofuels, and discuss the main properties of the feedstocks, fuel products and intermediates. Fig. 1 shows a number of major conversion pathways from terrestrial and aquatic biomass to intermediates and to final biofuel products (DOE/EERE, 2010b, 2011a, 2011b).

2.1. Terrestrial and aquatic biomass feedstocks

Biomass is a renewable resource that acquiries carbon by carbon dioxide fixation during their growing cycles. In comparison to fossil fuels such as natural gas and coal, which take millions of years to form, biomass is easy to grow, collect, utilize and replace quickly without depleting natural resources.

2.1.1. Terrestrial feedstocks

Many types of abundantly available biomass on the land can be utilized as feedstocks for biofuel production. The 2011 report released by U.S. Department of Energy (DOE) and Oak Ridge National Laboratory (ORNL) titled "U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry", details biomass feedstock potential throughout the contiguous United States at a county level of resolution (DOE/EERE, 2011c). The report examines the U.S. capacity to sustainably produce over 1.6 billion dry tons of terrestrial biomass annually for conversion to bioenergy and bioproducts, while continuing to meet existing demand for food, feed, and fiber. The report estimates that the United States could potentially produce approximately 85 billion gallons of biofuels annually—enough to replace approximately 30% of the nation's current petroleum consumption.

The terrestrial biomass feedstock can be generally categorized into two groups. The first group includes corn grain, sugarcane, soy bean, oil seed, etc. These feedstocks are rich in sugar or lipids, and have high yields after converted into bioethanol or biodiesel. Currently, most biofuels are made from these feedstocks, due to the maturity in technologies and lower unit production cost. However, the use of these feedstocks for biofuel production might have implications both in terms of world food prices and production.

The second group of terrestrial biomass feedstocks, the cellulosic biomass, can avoid adverse impacts on food supply, because they are non-starch, non-edible and non-food feedstocks. Cellulosic biomass feedstocks can be obtained from a number of sources, such as agricultural residues, forest residues and energy crops. Agricultural residues are typically plant parts left in the field after harvest (e.g., corn stover), as well as the secondary residues like manure and food processing wastes. Forest residues are leftover wood or plant material from logging operations, forest management, and land-clearing, as well as secondary residues like mill wastes. Dedicated energy crops (e.g., poplar, switchgrass, Miscanthus) are typically fast-growing trees and perennial grasses specifically grown for energy uses.

2.1.2. Aquatic feedstocks

Aquatic biomass includes a diverse group of primarily aquatic, photosynthetic algae and cyanobacteria ranging from the microscopic (microalgae and cyanobacteria) to large seaweeds (macroalgae) (DOE/EERE, 2010b).

Many macroalgae, microalgae, and cyanobacteria carry out photosynthesis to drive rapid biomass growth. Certain strains of microalgae make extremely efficient use of light and nutrients. As they do not have to produce structural compounds such as cellulose for leaves, stems, or roots, and because they can be grown floating in a rich nutritional medium, microalgae can have faster growth rates than terrestrial crops. In some cases, algae growth rates can be an order of magnitude faster than those of terrestrial crop plants. As algae have a harvesting cycle of 1–10 days, their cultivation permits several harvests in a very short time-frame, a strategy differing from that associated with yearly crops. Algae naturally remove and recycle nutrients (e.g., nitrogen and phosphorous) from water and wastewater, and can be used to sequester carbon dioxide from the flue gases emitted from fossil fuel-fired power plants. Adding to the appeal, some strains of microalgae can grow on land unsuitable for other established crops, for instance: arid land, land with excessively saline soil, and drought-stricken land. This minimizes the competition on arable land with the cultivation of food crops. More importantly, algae biomass can contain high levels of oil (lipids or triacylglycerides), making it a promising feedstock for the production of renewable gasoline, diesel, and jet fuel. Algae can produce one or even two orders of magnitude more oil per unit area than conventional crops such as rapeseed, palms, soybeans, or jatropha (DOE/EERE, 2010b; Hasan & Chakrabarti, 2009).

The cultivation of macroalgae (e.g., seaweed) is similar to that of terrestrial plants but in aquatic environment. In practice, macroalgae are cultivated in large offshore farms, near-shore coastal zones, or open pond facilities. In contrast, depending on the type of microalgae and cyanobacteria, there are various cultivation methods, varying both in their advantages and challenges. Broadly speaking, algae can be cultivated via photoautotrophic or heterotrophic methods. The former requires light and carbon dioxide for photosynthesis while the latter requires suitable feedstocks such as lignocellulosic sugars for growth. The cultivation system for microalgae and cyanobacteria is either closed bioreactor or open pond. Closed bioreactor yields less loss of water and better biomass quality, but has scalability problems. Open pond requires lower capital costs and take advantage of evaporative cooling, but it is subject to weather and condition changes and inherently difficult to avoid contamination and foreign algae (DOE/EERE, 2010b).

2.2. Types and major properties of biofuels

2.2.1. Ethanol and other alcohols

As the first generation biofuel technology, biomass-derived ethanol and other alcohols were largely produced from starch- or sugar-based biomass, such as corn and sugarcane. Due to the