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Comparing alternative cellulosic biomass biorefining systems: Centralized versus distributed processing systems

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ABSTRACT

This study explores how two different cellulosic ethanol production system configurations (distributed versus centralized processing) affect some aspects of the economic and environmental performance of cellulosic ethanol, measured as minimum ethanol selling price (MESP) and various environmental impact categories. The eco-efficiency indicator, which simultaneously accounts for economic and environmental features, is also calculated. The centralized configuration offers better economic performance for small-scale biorefineries, while the distributed configuration is economically superior for large-scale biorefineries. The MESP of the centralized configuration declines with increased biorefinery size up to a point and then rises due to the cost of trucking biomass to the biorefinery. In contrast, the MESP in the distributed configuration continuously declines with increasing biorefinery size due to the lower costs of railroad transportation and the greater economies of scale achieved at much larger biorefinery sizes, including biorefineries that reach the size of an average oil refinery—about 30,000 tons per day of feedstock. The centralized system yields lower environmental impacts for most impact categories than does the distributed system regardless of the biorefinery size. Eco-efficiency analysis shows that the centralized configuration is more sustainable for small-scale biorefineries, while the distributed configuration with railroad transport is more sustainable for large-scale biorefineries. Compared with gasoline from petroleum, cellulosic ethanol fuel offers sustainability advantages for the following environmental impact categories: fossil energy consumption, global warming, human health impacts by particulate matter, ozone layer depletion, ecotoxicity, human health cancer, and human health non-cancer, depending somewhat on the biorefinery sizes and the system configurations.

Abbreviations: ACID, acidification; AFEX, ammonia fiber expansion; DCFROR, discounted cash flow rate of return; ECOT, ecotoxicity; EISA, Energy Independence and Security Act; EUTR, eutrophication; FSE, fossil energy consumption; GE, gasoline equivalent; GHG, greenhouse gas; GREET, greenhouse gases, regulated emissions, and energy use in transportation model; GWI, global warming; HHC, human health cancer; HHNC, human health non-cancer; HHP, Human health impacts are measured by particulate matter; IPCC, Intergovernmental Panel on Climate Change; MESP, minimum ethanol selling price; NREL, National Renewable Energy Laboratory; OLD, ozone layer depletion; PDF, potentially disappeared fraction; SMG, smog formation.

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1. Introduction

Ethanol is a renewable liquid transportation fuel. Global ethanol fuel production in 2013 is about 89 hm^3 (23 billion gallon) [1]. Ethanol production in the United States accounts for about 57% of global ethanol production and is almost completely derived from corn grain. The second largest ethanol producing country is Brazil, accounting for 27% of global ethanol production. Sugar from sugar cane is the major feedstock for ethanol fuel in Brazil. Ethanol fuel from cellulosic biomass is also of great interest because of the potentially much larger volumes obtained with little impact on the food system. Unlike corn or cane ethanol, however, the cellulosic ethanol industry is in its infancy, and the preferred production systems are still being developed. This paper analyzes two very different potential system configurations for cellulosic ethanol: distributed versus centralized processing.

Feedstocks for cellulosic ethanol fuel include crop residues (e.g., corn stover, wheat straw, etc.), energy crops (e.g., switchgrass, miscanthus, willow, etc.), wood residues and wastes. Unlike starch (or sugar) based feedstocks (e.g., corn, cane sugar), cellulosic feedstocks require a pretreatment process to help convert cellulose and hemicellulose to fermentable sugars. There are numerous available pretreatment technologies – e.g., ammonia fiber expansion (AFEX™[1]), dilute acid, hot water, steam explosion, and so on [2–5]. Despite the requirement for a pretreatment process, cellulosic biofuels are very attractive in terms of potential sustainability and economic features. A cellulosic biorefinery facility can operate without external energy sources [6–9]. In some projected cellulosic biorefinery system designs, excess electricity can be exported to the electric grid.

Under the Energy Independence and Security Act (EISA) of 2007, the United States will produce 61 hm^3 (16 billion gallon) of cellulosic biofuel by 2022. Currently several commercial cellulosic biorefinery facilities are operating or under construction. The average size of the proposed commercial cellulosic biorefinery at this point is about 700 dry Mg of feedstock per day [10]. Larger biorefinery facilities are expected in the future.

However, cellulosic biomass is bulky, geographically dispersed and prone to decomposition and combustion – making it expensive and difficult to store and transport. Until now, the cost of transporting and storing cellulosic biomass has severely limited the size of biorefineries and prevented them from achieving the economies of scale necessary to significantly reduce biofuel prices. In particular, modeling studies have shown that biorefineries producing cellulosic ethanol from biomass sugars are limited to processing less than about 5000 dry Mg biomass per day because the cost of transporting the low density biomass outweighs the greater economies of scale for larger biorefineries. In addition to the logistics cost, the relative costs of contracts (“transaction costs”) with farmers/biomass producers will increase with the biorefinery size [11,12]. A distributed biomass processing system might reduce these limitations [11–14]. Two types of distributed systems are conceptually available thus far: the Advanced Uniform Design system [14] and the Local Biomass Processing Depots system [11,12].

The advanced uniform design system is located near feedstock production areas and processes biomass to a higher-density, aerobically stable, easily transportable formatted feedstock [14]. Due to these properties of preprocessed feedstock, the advanced uniform design system can cost-effectively utilize biomass from isolated and low yield areas (so-called “stranded biomass”). For large-scale biorefineries, the advanced uniform design system can result in a Minimum Ethanol Selling Price (MESP) that is lower than those of the centralized system. Greenhouse gas (GHG) emissions of the advanced uniform design system are slightly higher than those of the centralized system due to the additional transportation requirements, but are still significantly less than the corresponding petroleum fuel system.

The local biomass processing depot (referred to in this study as a ‘depot’) is a facility that first pretreats cellulosic feedstock and then densifies (pelletizes) the pretreated feedstock. The pretreatment process is therefore geographically isolated from the biorefinery and is located near feedstock production areas. This local network system consists of a number of small depots which supply the much larger biorefinery. The depot system can also reduce the logistics and contracting costs of cellulosic biofuels [11,12]. Egbendewe-Mondzozo et al. [15] show that the depot system has better environmental performance at a biorefinery size of 2000 dry Mg per day in terms of GHG emissions despite lower profitability at that scale.

Most previous analyses of biorefinery systems were restricted by either constant feedstock collection radius or constant biorefinery size or both. Obviously, the required feedstock collection radius increases with increased biorefinery size. This study therefore investigates the effects of different biorefinery system configurations and biorefinery size on economic performance and environmental impacts in order to determine better system configurations with respect to biorefinery size. To achieve the objectives of this study, the MESP and environmental impacts are quantified for different system configurations with respect to the biorefinery size. A discounted cash flow rate of return analysis is used to determine the MESP. The environmental impacts are estimated via life cycle assessment and quantified by the TRACI model version 2.1 that is specific to US conditions [16]. To balance economic performance and environmental impacts, eco-efficiency indicators, which simultaneously account for economic and environmental features of a given system, are also estimated. The eco-efficiency indicator may be useful in decision making processes, particularly for systems that exhibit trade-offs between economic values and environmental impacts. In general, the eco-efficiency indicator is defined as a ratio of product (or service) economic value to its environmental impact [17]. High eco-efficiency indicators are obviously preferred to lower ones.

2. Methods

2.1. System configuration

The system configurations are illustrated in Fig. 1. The distributed and centralized configurations are referred to as

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[1] AFEX™ is a registered trademark of MBI International, Lansing, MI USA.