BIOMASS AND BIOENERGY 35 (2011) 608–616

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Effect of multiple-feedstock strategy on the economic and environmental performance of thermochemical ethanol production under extreme weather conditions

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ARTICLE INFO

Article history:
Received 11 June 2010
Received in revised form
31 August 2010
Accepted 18 October 2010
Available online 12 November 2010

Keywords:
Biofuel production
Extreme weather
Multiple-feedstock
Economic performance
GHG emission

ABSTRACT

Current US transportation sector mainly relies on liquid hydrocarbons derived from petroleum and about 60% of the petroleum consumed is from areas where supply may be disturbed by regional instability. This has led to serious concerns on energy security and global warming. To address these issues, numerous alternative energy carriers have been proposed. Among them, second generation biofuel is one of the most promising technologies. Gasification-based thermochemical conversion will bring flexibility to both feedstock and production sides of a plant, thus presents an attractive technical route to address both the energy security and global warming concerns. In this paper, thermochemical ethanol production using multiple-feedstock (corn stover, municipal solid waste, and wood chips) is simulated using Aspen Plus and compared with the single-feedstock scenario, in terms of economic performances, life cycle greenhouse gas (GHG) emissions and survivability under extreme weather conditions. For a hypothetical facility in southwest Indiana it is found that multiple-feedstock strategy improves the net present value by 18% compared to single-feedstock strategy. This margin is increased to 57% when effects of extreme weather conditions on feedstock supply are considered. Moreover, multiple-feedstock fuel plant has no potential risk of bankruptcy during the payback period, while single-feedstock fuel plant has a 75% chance of bankruptcy. Although the multiple-feedstock strategy has 26% more GHG emission per liter of ethanol produced than the single-feedstock strategy, the trend is reversed if feedstock supply disruption is taken into account. Thus the idea of multiple-feedstock strategy is proposed to the future thermo chemical biofuel plants.

1. Introduction

27,925 trillion Btu of energy was consumed in the transportation sector in 2008, 94.3% (or 26,332 trillion Btu) of which was derived from petroleum, with only 2.98% from biomass [1]. According to U.S. Energy Information Administration (EIA), this leads to emission of 1917 million MT of carbon dioxide, accounting for 27.55% of total U.S. greenhouse gas (GHG) emission [2]. About 60% of petroleum consumed is from areas where supply may be disturbed by regional instability, and roughly one third of the gasoline produced in the U.S is produced along the hurricane-prone gulf coast from Corpus Christi, Texas to New Orleans, Louisiana [3]. The current US transportation energy system is facing two challenges: energy security and climate change due to GHG emission [4].

Various technologies are currently being developed to enhance energy security while reduce GHG emission of transportation fuel systems [5,6]. Biomass-derived liquid fuels

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0961-9534/$ – see front matter
doi:10.1016/j.biombioe.2010.10.023

(i.e. biofuels) represent promising candidates due to their high energy density and compatibility with the existing infrastructure for distribution and delivery. However, Hedegaard K et al. and Roberts KG et al. found out that first generation biofuels, which are mainly produced from traditional food crops, are limited in their ability to achieve targets for petroleum substitution and climate change mitigation [7,8]. In addition, the diversion of food crops to biofuels has already raised concerns about food prices [9], and has exacerbated food security to poor people in developing countries [10]. In response to these concerns, research attention has shifted to second generation biofuels derived from non-food feedstocks. Second generation biofuels have significantly larger GHG emission reduction potential than first generation biofuels and they only use agricultural wastes and forest residues. However production of second generation biofuels remains vulnerable to crop hazards such as drought, plagues and storms. This is especially true if the fuel production exploits a single crop/feedstock as energy source. Thus an economically and environmentally sustainable biofuel plant should have the following features: (1) profitable, both in the short- and long-term; (2) robust, to use diverse feedstocks; (3) low life cycle greenhouse gas emission.

Gasification technologies represent a promising route to convert different kinds of feedstocks into a wide range of fuel products, such as ethanol, gasoline, diesel and aviation fuel [11,12]. One of the main features of gasification technology is that it could tolerate a large variation in feedstock characteristics, allowing a gasification-based biofuel plant to use alternative feedstocks when the supply of one is disrupted, minimizing production losses. However, to date the strategy of biofuel production via utilizing multiple-feedstock has not been explored quantitatively. It is not clear that to what extent the multiple-feedstock strategy will improve economic performance in the long term. Specifically, it is not clear how a multiple-feedstock strategy will decrease the probability of biofuel plant bankruptcy during its life span. Similarly, it is unknown whether a multiple-feedstock strategy may have a different environmental impact than a single-feedstock strategy. A number of previous studies have carried out life cycle assessment of thermochemical biofuel production [7,8,13–17]. However, none examined the effect of feedstock supply variation on the relative environmental performance of multiple and single-feedstock strategies. This paper will address these gaps using a gasification-based ethanol plant located in the Midwestern U.S. as a case study. Results from this research are expected to help relevant biofuel stakeholders i.e. investors, plant managers, and government agencies to make decision with regard to investment, plant operation, and policy.

2. Methodology

2.1. Plant simulation model

To date there is no commercial thermochemical ethanol plant in operation. Therefore, analysis here will be based on plant level process simulation. The Aspen Plus model developed by Department of Energy National Renewable Energy Laboratory (DOE NREL) simulates a thermochemical alcohol production plant with capacity of 2000 MT biomass per day [16], which provides the basis for this study. In the NREL study, maple wood chips were selected as the only feedstock. The model predicts yield of methanol, ethanol and higher molecular weight alcohols while conducts economic analysis. The plant was designed to be energy self-sufficient i.e. all power and steam required are generated inside the plant using the biomass feedstock.

The plant simulated includes seven sub-systems: feedstock drying and handling, gasification, syngas conditioning, ethanol synthesis, ethanol separation, steam and electricity generation, and water management. The gasification subsystem consists of a dual-bed, indirect heating reactor. Steam acts as fluidizing medium in the gasification reactor, while the char produced as the byproduct of syngas is combusted to support endothermic pyrolysis and gasification reactions in the gasifier. After being cleaned and conditioned, syngas is synthesized into ethanol in a fixed bed reactor.

The NREL model utilizes an empirical correlation to calculate syngas yield and composition. For other feedstocks considered in this paper, similar correlations will be developed by using steam gasification data from literature:

$$X_i = A_i + B_i T + C_i T^2 \tag{1}$$

where X_i stands for different syngas components; A_i, B_i and C_i are the corresponding quadratic coefficients. The yield of char and tar are calculated using ultimate analysis and proximate analysis by element mass balance. For simplicity, it is assumed that when different kinds of biomass are mixed together, syngas flow rate, char yield and tar yield could be averaged based on their weight contents [18].

2.2. Feedstock management strategies

There are many kinds of biomass feedstock that are widely available in Midwest [19,20]. Gasification data is readily available for corn stover, wood chips and municipal solid waste (MSW), which were selected for this study. Table 1 lists the proximate and ultimate analyses of these feedstocks.

Table 1 – Proximate and ultimate analysis of feedstocks considered (FC = fixed carbon; VM = volatile material; HHV = higher heating value; MSW = municipal solid waste).

	MSW [21]	Corn stover [22]	Wood chips [11]
Proximate analysis (dry basis)			
FC	11.79	16.7	18.36
VM	82.28	71.8	80.77
Ash	5.93	11.4	0.87
HHV (kJ/kg)	20,284	17,201	20,136
Ultimate analysis			
C	51.81	43.3	47.99
H	5.76	5	5.97
N	0.26	0.8	0.41
S	0.36	0.06	0.11
O	35.88	39.44	42.73
Ash	5.93	11.4	2.79