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Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice

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HIGHLIGHTS

- Techno-economic evaluation of the jet fuel production processes from biomass.
- Comparison of 2G jet fuel production vs. 1G (vegetable oil and sugar cane juice).
- Profitability of 1G jet fuel processes are slightly better than 2G processes.
- The thermochemical and hybrid processes are the most promising 2G jet fuel options.
- Ethanol intermediate production processes result less economic viability.

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ABSTRACT

In this study, a techno-economic comparison was performed considering three processes (thermochemical, biochemical and hybrid) for production of jet fuel from lignocellulosic biomass (2G) versus two processes from first generation (1G) feedstocks, including vegetable oil and sugar cane juice. Mass and energy balances were constructed for energy self-sufficient versions of these processes, not utilising any fossil energy sources, using ASPEN Plus® simulations. All of the investigated processes obtained base minimum jet selling prices (MJSP) that is substantially higher than the market jet fuel price (2–4 fold).

The 1G process which converts vegetable oil, obtained the lowest MJSPs of $2.22/kg jet fuel while the two most promising 2G processes- the thermochemical (gasification and Fischer-Tropsch synthesis) and hybrid (gasification and biochemical upgrading) processes- reached MJSPs of $2.44/kg and $2.50/kg jet fuel, respectively. According to the economic sensitivity analysis, the feedstock cost and fixed capital investment have the most influence on the MJSP.

1. Introduction

The world consumption of jet fuel is in excess of 800 million litres per day, accounting for around 10% of global transportation energy. Although most of the world's jet fuel is produced through crude oil refineries, the necessity for sustainable jet fuel with reduced greenhouse gas (GHG) emissions, has prompted investigation of alternative jet fuel production pathways (Hemighaus et al., 2006; Mussatto, 2016).

Jet fuel produced from plant-derived sources (biojet fuel), has the potential to decrease the net GHG emissions associated with the aviation industry (Agusdinata et al., 2011; Klein-Marcuschamer et al., 2013) and increase energy security (Bond et al., 2014). The focus of biofuel production, initially was intensely on first generation (1G). 1G feedstock conversion processes include hydro-processed esters and fatty acids (HEFA process) of vegetable oil to jet fuel as well as biochemical conversion of sugars or starches to intermediates (such as alcohols, hydrocarbons and lipids), followed by upgrading to jet fuel. A promising thermochemical conversion process for the conversion of lignocellulose to jet fuel includes the gasification followed by Fischer-Tropsch (FT) synthesis process. Hybrid process pathways, such as gasification followed by syngas fermentation to ethanol, have been studied as an alternative pathway (Naik et al., 2010; Robota et al., 2013).

Fossil-derived jet fuel for commercial aviation, entails different hydrocarbons, ranging mainly between C_9 and C_{15} (Robota et al., 2013). It is desirable that biojet fuels are compatible with the existing infrastructure (Klein-Marcuschamer et al., 2011). Three biojet production processes have already been approved by the ASTM (American Society for Testing and Materials) for commercial aviation use resulting in more than 1600 commercial flights run on

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biofuels (Colket et al., 2016). These processes include the HEFA process, the FT process and the Direct-Sugar-to-Hydrocarbon process (Menetrez, 2014). A variety of other processes are still in the approval process, including the alcohol-to-jet process (Mussatto, 2016).

According to International Air Transport Association (IATA), economic viability and technology maturity is still a major hurdle for the commercial production of biojet fuel (IATA, 2014). The market price for jet fuel has undergone substantial variability in the past ten years, fluctuating between \$0.42 and \$1.28 per kg jet fuel (Colket et al., 2016; IATA, 2014).

Taking into account the commercialization status and process technology, HEFA process is considered as the most mature process for renewable jet fuel production (Mawhood et al., 2016). Although the jet fuel produced through the gasification and FT synthesis (GFT-J) process is already certified by the ASTM, the capital intensive nature and operational difficulties of the GFT-J process has delayed wide-scale commercial deployment of this process (Mawhood et al., 2016). Another pathway consists of the bioethanol production as intermediate and then ethanol upgrading to jet fuel. The bioethanol production from 1G and 2G feedstocks, through biochemical and thermochemical routes have been studied widely (Vohra et al., 2014), however the ethanol upgrading to jet fuel process is still on the laboratory and pilot plant stages of development (Mawhood et al., 2016).

This study performed techno-economic assessments on five processes that convert plant-derived sources – in particular lignocellulosic biomass and first generation feedstocks (vegetable oil and sugar cane juice) – to jet fuel. The processes considering lignocellulosic feedstock are, 1) the GFT-J (gasification and FT synthesis) process, 2) the L-ETH-J (biochemical conversion to ethanol with upgrading) process and 3) the SYN-FER-J (gasification, syngas fermentation to ethanol with upgrading) process. The processes considering 1G feedstock are 4) the HEFA (hydroprocessing of vegetable oil) process and 5) the S-ETH-J (sugar cane juice to ethanol by sucrose fermentation with upgrading) process. Since the HEFA process is the most mature technology, it is considered as baseline. The S-ETH-J process consists of a fully mature technology for production of ethanol, whilst the ethanol production sections by the L-ETH-J and SYN-FER-J processes – although having been produced commercially- is still under study (Mawhood et al., 2016). The combination of different intermediate ethanol production routes and upgrading ethanol to jet fuel is one of the promising aspects of this study.

In this study, the different feedstock and pathways for bio jet fuel production are compared through detailed techno-economic analysis of the developed processes. Mass and energy balances were constructed for all five processes based on the Aspen Plus® process simulation, whilst the economics of these processes were investigated based on cash flow analysis as well as an economic sensitivity analysis.

2. Materials and methods

Simulations were developed for the investigated processes using ASPEN Plus® (Aspen Technology Inc., USA) process simulator. A single scenario was constructed for each process, based on published experimental data. The scenarios were constructed such that the processes were steam, power and hydrogen self-sufficient, thus energy self-sufficient and independent of fossil fuel sources (Dutta et al., 2011). The heat requirements of the process were optimised using a pinch analysis, aided by ASPEN Energy Analyzer®.

For the GFT-J, SYN-FER-J and L-ETH-J processes, the feed-rate of dry, ash-free lignocellulose was fixed to 75 MT/h with a moisture content (MC) of 50 wt% and an ash fraction of 3.70 wt% (based on dry weight). The feed-rate of lignocellulose has been chosen based on previous techno-economic analysis (Bond et al., 2014; Humbird et al., 2011). The lignocellulose composition used for the process models is based on a study by Petersen et al. (2015) which aimed to represent a generic lignocellulose. It was specified using a chemical composition for the L-ETH-J process, whereas a proximate and ultimate analysis was used for the GFT-J and SYN-FER-J processes. The feed-rate of the vegetable oil to the HEFA process and wet sugar cane to the S-ETH-J process, was fixed to 14.9 MT/h, and 222.5 MT/h, respectively. The feed rate is calculated in a way to produce the same amount of jet fuel which can be obtained from lignocellulose to jet fuel processes. The composition of the vegetable oil – which is taken to be similar to jatropha oil- is based on a study by Gong et al. (2012). The wet sugar cane, contains a MC of 71.57 wt% and sucrose content of 13.30 wt% (Dias et al., 2009). For the S-ETH-J process scenario, 140 dry kg of tops and trash (MC of 15%) is assumed to be fed along with each metric ton of wet cane (Dias et al., 2009).

The developed processes can be compared based on the consumed feedstock and chemicals and also produced jet fuel. In addition, energy balance is applied to study the energy performance of the developed processes. Among the energy indicators, energy ratio and overall energy efficiency (Eqs. (1) and (2)) are well applied by researches to evaluate the biofuel processes (Leibbrandt et al., 2011; Petersen et al., 2015).

The energy ratios, is defined as the energy ratio of product (jet fuel) to feedstock which can be calculated as follows.

$$\eta_e = \frac{|m_{fuel} \cdot HHV_{fuel}|}{|m_{feedstock} \cdot HHV_{feedstock}|} \tag{1}$$

where η_e is the energy ratio of the process, m_{fuel} is the mass of the fuel produced, $m_{feedstock}$ is the mass of the feedstock input, HHV_{fuel} and $HHV_{biomass}$ are the higher heating value (HHV) of the fuel and feedstock, respectively.

The overall energy efficiency ($\eta_{overall}$) determines the efficiency of the process, considering the energy in the fuels and electrical power produced ($E_{elec.power}$) as the product, whilst taking into account the energy in the input feedstock and is calculated based on Eq. (2).

$$n_{overall} = \frac{|m_{fuel} HHV_{fuel}| + E_{elec.power}}{|m_{feedstock} \cdot HHV_{feedstock}|} \tag{2}$$

The economic investigation was performed based on the complete mass and energy balances from the ASPEN Plus® process models. The cost analysis was performed for process plants located in the USA and indexed to 2014 US dollars. In this research, equipment costs are estimated by Aspen Plus® Economic Evaluator package (Aspen Technology, Inc., USA) for: flash drums, columns, pumps, compressors, and heat-exchangers, while the special equipment such as boilers, turbo-expanders, generators, reactors, waste water treatment basins are estimated based on technical report data, using equipment-specific scaling exponents (Swanson et al., 2010; Humbird et al., 2011; Dutta et al., 2011; Jones et al., 2013; Klein-Marcuschamer et al., 2013).

Installed costs were calculated for the equipment by multiplying the purchased equipment costs by an installation factor. The fixed capital investment (FCI) and the total capital investment (TCI) were estimated from the total installed costs. The total direct cost was determined as the sum of the installed costs and the additional direct costs (10% of total installed costs). The FCI was calculated as the sum of the total direct costs and the total indirect costs (60% of total direct costs) (Humbird et al., 2011). The TCI was subsequently determined as the FCI plus the working capital (10% of the FCI) and the cost of land (Humbird et al., 2011).