Woody biomass-based transportation fuels – A comparative techno-economic study

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HIGHLIGHTS

- Evaluation of several biomass based vehicle fuels including thermochemical and biochemical conversion.
- Mass and energy balances for the systems from feedstock to product.
- Economic assessment on investment and production cost.
- The cost of travel and the travel distance for a specific amount of feedstock is estimated for each fuel.

ARTICLE INFO

ABSTRACT

Production of synthetic vehicle fuels from biomass is a hot topic. There are several alternative fuels to consider when evaluating properties such as cost of production and energy efficiency to both product and final use in a road vehicle. Thermochemical conversion via gasification and downstream synthesis of fuels as well as biochemical conversion of woody biomass to ethanol is considered in this paper. The vehicle fuels considered in this paper include methanol, ethanol, synthetic natural gas, Fischer–Tropsch diesel, dimethyl ether and synthetic gasoline from the methanol-to-gasoline process. The aim of the study is to evaluate all the different fuels on the same basis. The production cost of the various fuels is estimated as well as the overall investment cost. Well-to-wheel energy efficiency calculations were performed to evaluate how far a vehicle can travel on the fuel produced from a specific amount of feedstock. The production cost of the fuel as a function of distance travelled is also presented. Of the fuels considered in this study, dimethyl ether manages the highest efficiency from feedstock to travelled distance and manages to do so at the lowest cost. Ethanol produced from woody biomass is the most inefficient and expensive fuel, when considering biomass harvesting and transport, the production and road use (ignoring fuel distribution), in this study due to low yields in fuel production. Total investment cost for ethanol is considerably lower at MM$ 281 compared to the thermochemical fuels that ranges from MM$ 580 to MM$ 760. The production costs of the various fuels range from $79.9/MW h for synthetic natural gas to 139.6 $/MW h for Fischer–Tropsch diesel. The production cost translates to a travel cost ranging from $4.98/100 km for dimethyl ether to $8.51/100 km for ethanol.

1. Introduction

The era of cheap crude is behind us, and at the same time, the need for transportation is increasing. There is also a growing demand for fossil-free and sustainable vehicle fuels to mitigate the increased carbon dioxide levels in the atmosphere. The conventional bio fuels, ethanol and bio-diesel from oil containing crops, are also heavily debated as the primary feedstock for those fuels are food crops. The advanced bio fuels are fuels that utilize other feedstocks such as woody biomass, sewage sludge and municipal waste. There are primarily two routes for conversion of the feedstock into a usable fuel – thermo-chemical and biological conversion. For biological conversion, the feedstock must contain cellulose and/or hemicelluloses. If the target product is ethanol, the cellulose-rich feedstock is pre-treated and hydrolysed into a solution with a high glucose content that is fermented into ethanol. If the desired product is methane the feedstock is anaerobically digested into a methane rich gas known as biogas which contains around 60% methane (CH_4) and 40% carbon dioxide (CO_2). The biogas needs to be upgraded by removing the CO_2 in order to meet specifications of energy density and CO_2 levels. Biogas is not considered in this study as woody biomass is not the typical feedstock for biogas. The thermo-chemical conversion utilizes gasification to produce an energy-rich gas containing carbon monoxide (CO) and hydrogen (H_2). Gas mixtures containing CO and H_2 are commonly

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known as synthesis gas or syngas as it is used to produce fuels and chemicals through chemical synthesis. The gas produced in a gasifier (producer gas) contains, in addition to CO and H_2, CO_2, CH_4 and lower hydrocarbons (C_{2+}), tars and other contaminants. The gas needs a thorough cleaning and conditioning before it can be used in chemical synthesis to produce synthetic fuels.

It is advantageous for synthetic fuels to be as similar to the conventional fuels as possible to ease the transformation towards the synthetic fuels. First of all, low blending of the synthetic fuels is possible if the fuels have similar in chemical properties. Secondly, the whole infrastructure for the fuel handling such as filling stations, storage etc. is already in place. A totally different fuel from what is traditionally used, such as hydrogen, would require a completely new fuel infrastructure which would likely be expensive to implement.

This paper covers the production of renewable vehicle fuels from woody biomass. The fuels produced by thermo-chemical conversion are synthetic natural gas (SNG), methanol (MeOH), dimethyl ether (DME), Fischer–Tropsch diesel (FT) and methanol-to-gasoline (MTG). Flow sheeting calculations are performed in Aspen Plus to solve the material and energy balances. For comparison of thermo-chemical conversion and biological conversion, expected production of lignocellulosic ethanol plants is used.

The literature on the subject of system studies on synthetic vehicle fuels consists of a large quantity of papers. The comparison between the different studies is not always straightforward as the respective authors chose to emphasize different aspects of the purpose of their study. Some papers (e.g. [1–5] contain detailed economic assessments while others focus on CO_2 abatement and energy efficiency [6]. Furthermore, some papers include district heating as a means to decrease fuel production cost. District heating is not available in most regions of the world and is therefore not considered in this study. For comparison with the purpose of this work, only papers including techno economic evaluation not utilising district heating revenues will be considered. Among these is an investigation on woody biomass to gasoline (MTG) via gasification and downstream synthesis by Phillips et al. [1] that established a gasoline production price of $57/MW h ($0.52/L gasoline) and a total plant investment cost of $199.6 MM. Trippe et al. estimated the MTG production cost using a direct DME synthesis to $160/MW h ($1.47/L gasoline). The total plant investment cost was estimated to $270–280 MM depending on plant configuration [2].

Furthermore, the study on SNG production by Gassner et al. resulted in a SNG production price of $80–125/MW h for a plant size of 150 MWth and above [3]. Energy efficiency for the process were similar to those presented by Juraščík et al. [5] at around 55–70% thermal. Among the studies on biomass-to-Fischer Tropsch liquids, the report by Boerrigter [4] found that the production cost for a 400 MWth input plant would be roughly $75/MW h ($1.2/L diesel). Boerrigter considered an entrained flow gasifier which has, among others, higher investment costs than other gasifier types. Thermodynamic efficiency was reported to 55% from wood to FT diesel [4]. Hamelinck et al. calculated the production cost of FT-diesel for a 400 MWth (HHV) to $60/MW h ($0.9/L diesel) [7]. In a similar study by Tijmensen el al. the production price of FT diesel ranged from $50–110/MW h ($0.75–1.75/L diesel) for a plant investment cost ranging from $281–338 MM [8]. Furthermore, Trippe et al. estimated the production cost of FT diesel to $170/MW h ($1.7/L diesel). For methanol Leduc et al. reported production cost of $140/MW h ($0.85/L methanol) [9]. In a report by Altener the production cost of methanol was estimated to $63/MW h ($0.28/L methanol). Total plant investment cost was estimated to $417 MM [10]. In a paper by Huisman et al. the production cost of DME was estimated to $100/MW h, only slightly more expensive than the estimated methanol production cost of $95/MW h. Total capital investment was reported to $310 MM [11].

2. Method

The gasifer chosen for the liquid fuels and DME is a Carbona/Andritz type gasifier. For SNG production, a gasifier with higher methane content in the producer gas is desirable. For all cases studied, including lignocellulosic bioethanol, the energy input is 400 MWth woody biomass. The MILENA type gasifier is a pressurized allothermal gasifier with high methane and lower hydrocarbons in the producer gas. Unfortunately, it also produces high levels of benzene and tars. The OLGA oil-scrubber is used downstream of the gasifier to produce a gas with low tar content. The OLGA does not remove benzene and lower hydrocarbons and a pre-reformer is still necessary to convert the hydrocarbons except methane into synthesis gas and methane. In Table 1 is presented the composition of the producer gases used as input to the Aspen Plus model. The outlet pressure of the Carbona/Andritz gasifier is 10 bar(a) and the pressure after the OLGA gas cleaning is 6 bar(a).The Carbona type gasifier requires both pre-reforming of the tars and lower hydrocarbons and methane reforming to maximize the output of synthetic fuels. The process configuration can be seen in Fig. 1 for all thermochemical fuels in this study.

The unit operations depicted in Fig. 1 is used during simulations and a more descriptive schematic over the methanol/DME/MTG processes are depicted in Figs. 3–5. Operating parameters for the unit operations are summarised in Table 2.

2.1. Detailed model description

2.1.1. Fischer–Tropsch

The Fischer–Tropsch reactor was modelled as an isothermal plug reactor with varying length. The reaction kinetics was modelled as power law reactions following the Anderson–Schulz–Flory distribution (1) with α-value chosen ($\alpha = 0.85$) to yield as much diesel fuels (C_{10}–C_{15}) as possible, see Fig. 2.

$$Wn = n \cdot (1 - \alpha)^2 \cdot \alpha(n - 1) \tag{1}$$

The hydrocarbons that are heavier than diesel fuels would be a good feedstock for a cracker to produce more vehicle fuels. The length of the reactor is varied to achieve a once-through conversion of 80% of the ingoing CO. The hydrocarbons produced in the reactor contain alkanes and alkenes from methane to C_{20}. The separation of useful fuels and tail-gases is around C_6, with the most part of the C_6 ending up in the tail-gas and most of the C_7 in the

Table 1
Gasifier producer gas composition [18,32].

Component	MILENA (vol-%)	MILENA + OLGA (vol-%)	Carbona/andritz (vol-%)
CO	21.4	21.6	27.3
H_2	16.8	16.9	28.8
CO_2	9.9	10.0	16.9
O_2	0.0	0.0	0.0
H_2O	37.6	37.6	22.7
CH_4	8.8	8.9	3.8
N_2	0.8	0.8	0.0
Ar	0.0	0.0	0.0
C_2H_2	0.2	0.2	0.0
C_2H_4	2.9	2.9	1.1
C_2H_6	0.2	0.2	0.0
C_3H_6	0.0	0.0	0.0
C_6H_6	0.7	0.5	0.2
C_7H_8	0.1	0.0	0.0
H_2S (vppm)	150	150	150
NH_3 (vppm)	2000	2000	2000
Tars (mg/N m^3)	20,000	<40	500