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Techno-economic and uncertainty analysis of Biomass to Liquid (BTL) systems for transport fuel production

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ABSTRACT

This work examines the technical and economic feasibility of Biomass-To-Liquid (BTL) processes for the manufacture of liquid hydrocarbon fuels. Six BTL systems are modelled and evaluated which are based on pressurised oxygen gasification of woody biomass, and specifically on circulating fluidised bed and entrained flow gasification systems. Three fuel synthesis technologies are considered: Fischer-Tropsch synthesis, methanol conversion followed by Methanol to Gasoline (MTG) and the Topsoe Integrated Gasoline (TIGAS) synthesis.

Published modelling studies of BTL systems based on gasification have only used deterministic estimates of fuel production costs to assess economic viability without accounting for uncertainties of their model parameters. Unlike other studies, the present techno-economic assessment examines and quantifies the effect of uncertainty of key parameters on the fuel production costs. The results of this analysis show that there is a realistic chance (8–14%) of concepts based on Fischer-Tropsch synthesis meeting the cost of conventional fuels; that this probability could be increased to 50% with moderate tax incentives (an 8% reduction in the tax rate); but that deterministic estimates may be systematically underestimating likely production costs.

The overall energy efficiency and production costs of the BTL designs evaluated range from 37.9% to 47.6% LHV and €17.88–25.41 per GJ of produced fuels, respectively. The BTL concept with the lowest production costs incorporates CFB gasification and FT synthesis. The model deterministic estimates of production costs of this design indicate that a BTL process is not yet competitive with conventional refineries since the biofuel production costs are approximately 8% higher than current market prices. Large scale biofuel production may be possible in the long term through subsidies, crude oil price rises and legislation.

1. Introduction

For the last four decades there has been a considerable interest in producing liquid transportation fuels from biomass as costs of petroleum continue to rise, which has been reinforced by subsequent environmental concerns. Since the Industrial Revolution, humans have significantly added to the amount of heat-trapping greenhouse gases in the atmosphere by burning fossil fuels that emit CO_2, cutting down forests that reduces CO_2 absorption and other activities (e.g. transporting goods and people, waste disposal). It is believed that the significant increase in anthropogenic greenhouse gas emissions since the beginning of industrial revolution (e.g. 40% increase for CO_2) is the main reason behind the observed rise in average global temperatures [1].

In addition to environmental concerns and according to the current facts, energy experts predict a 35% increase in worldwide petroleum demand by 2025 [2]. This will increase dependency on a relatively limited number of oil producing countries with serious risks for energy security and global social stability. Regarding the oil market, it is predicted that the Middle East will continue to be in dominant position as it has the greatest proven oil reserves in the world. Conversely, nations with less petroleum resources will be vulnerable to energy shortages unless they develop alternative sources of energy. Such alternatives include nuclear, wind, solar, hydroelectricity, wave, tidal, geothermal and energy from biomass.

Biomass derived transport fuels (biofuels) can play an important role in reducing greenhouse gas emissions and dependency on fossil fuels by limiting or reducing consumption and combustion of fossil fuels [3]. This is also why the European Union has set ambitious targets for the application of biofuels through EU Biofuels Directive 2009/28/EC. According to the directive, 10% of all transport fossil fuels sold in EU countries, calculated on the basis of energy content, should be replaced

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with biofuels by 2020 [4].

Nowadays, the substitution of transport fossil fuels with biofuels is already feasible by state-of-the-art renewable liquid fuels, such as bioethanol for gasoline engines, produced by fermentation of sugar or starch and biodiesel for diesel engines produced via transesterification of vegetable oils or animal fats [5]. These so-called “first generation biofuels” are characterised by an unexpected growth following government subsidies and legislative pressures, however there are some serious problems associated with their application with respect to feedstock requirements and land availability – the food vs fuel debate. In addition to the consequences on economy and land competition, net carbon savings from first generation biofuels are questionable due to the clearance of virgin land (e.g. rain forests) for cultivation, high fertilizer requirement and low productivity per hectare [6].

In order to overcome the above mentioned shortages, the so-called “second generation biofuels” have been introduced. Unlike first generation biofuels, they avoid using food resources and also make use of a wider range of biomass feedstocks than just plant oils and sugar/starch components. These sources include non-food biomass, dedicated energy crops and biomass co-products and waste from many different sectors such as agriculture, horticulture, forestry, paper and pulp processing and wastes, such as MSW. [7].

This study examines the technical and economic feasibility of processes that manufacture second generation liquid fuels from non-food crops and wastes which are referred to as Biomass-To-Liquid (BTL) processes. The term “BTL” is only applied to thermo-chemical processes, such as pyrolysis and gasification, and thus it is not used for biochemical routes (e.g. fermentation) to biofuel production. The scope was limited to synthetic liquid hydrocarbons (diesel, gasoline and kerosene) as these can be readily incorporated and integrated with conventional markets and supply chains while alcohols (e.g. ethanol, methanol, mixed alcohols) and ethers (e.g. DME – dimethyl ether) have more limited short term prospects in the UK and European transport fuel infrastructures [8].

Large scale coal-to-liquid (CTL) and gas-to-liquid (GTL) processes have been commercialised for decades (e.g. Sasol and Shell plants). This is not the case with BTL processes with only a few plants built to date on pilot and demonstration scale: In the late nineties, Choren started operating a 1 MW_{th} BTL plant in Freiberg, Germany and planned to build a commercial plant with a capacity of 15,000 t/yr of fuel products before filing for insolvency in July 2011 [9]. NSE Biofuels Oy operated a 12 MW_{th} (656 t/yr of fuels) BTL demonstration plant in Finland from 2009 to 2011 which employed a circulating fluidised bed (CFB) gasifier developed by Foster Wheeler [10]. Plans were made to build a commercial plant with a projected output capacity of 100,000 t/yr but it was never constructed due to lack of public funding [11]. In 2010, five French partners and Uhde launched BioTfueL with two pilot plants currently on operation in France: a biomass pretreatment plant with a torrefaction unit in Venette and an entrained flow gasification and Fischer-Tropsch (FT) synthesis plant near Dinkirk [12]. It is currently planned to validate the techno-economic feasibility of the whole process chain by 2020 before moving on to industrial scale production. The Karlsruhe Institute of Technology (KIT) bioliq pilot plant with a capacity of 1 t/day has been in operation since 2014 and produces gasoline via DME using a process similar to the Topsoe Integrated Gasoline Synthesis (TIGAS) process. More information on the Choren and KIT Bioliq processes is provided in Section 2.4.

The environmental and socio-economic impacts of large scale BTL projects are not known with certainty as there is not an industrial plant currently on operation. BTL plants consume biomass as feedstock and thus it is expected to reduce GHG emissions with respect to fossil fuel processes, especially if forest waste is used [13]. Energy crops, like miscanthus, are typically grown close to the conversion plant to reduce transportation costs. This prompts the development of associated industries for biomass growing, collecting and transporting and thus large BTL facilities could significantly enhance the local economy [14].

The techno-economics of BTL processes is a heavily researched topic with the main aim being to support policy makers and businesses in their decision making by identifying the most economic process designs and the parameters (e.g. biomass price) that significantly affect the economic competitiveness of these technologies. Tijmensen et al. [15] evaluated the co-production of transport fuels and power from integrated biomass CFB gasification and FT synthesis. The cost of fuel products was estimated at 19.6 €$_{2014}$ per GJ at a co-production efficiency of 45% (LHV) for oxygen blown pressurised gasification (2000 dry t/d plant capacity). Swanson et al. [16] modelled and compared two BTL process concepts based on entrained flow and CFB gasification. Both concepts included FT synthesis for the production of liquid fuels and electricity as a co-product. The entrained flow gasification concept resulted in higher biomass to fuel efficiencies and lower production costs compared to the CFB gasification design at 53% (LHV) and 27.1 €$_{2014}$ per GJ, respectively. Boerrigter [17] also examined the economic competitiveness of entrained flow gasification for BTL production. The production cost was estimated at approximately 15.8 €$_{2014}$ per GJ when the plant was scaled up to 9100 MW_{th}. Baliban et al. [13] evaluated BTL concepts based on other fuel synthesis options in addition to FT synthesis: the methanol-to-Gasoline (MTG) and the Mobil-Olefins-to-Gasoline/Distillate (MOGD) processes. The authors developed an optimization framework for the process synthesis of a BTL refinery and the economic feasibility of 24 BTL process designs was investigated. Production costs ranged from 11.56 to 24.55 €$_{2014}$ per GJ for woody biomass (forest residues). All BTL concepts were claimed to be economically viable for crude oil prices above $80 per bbl and for a biomass feedstock price below $120 per dry tonne. Researchers from KIT [18–20] have carried out BTL techno-economic studies focusing on the KIT bioliq process. Production costs ranged from 25 (3.3 GW_{th} plant capacity) to 35 €$_{2014}$ per GJ (1 GW_{th} plant capacity) which were higher than those reported by most studies discussed above. As a reference, the market price (without taxes) of conventional diesel and gasoline in 2014 was €16.2 and €16.6 per GJ, respectively [21].

In techno-economic feasibility studies of BTL plants, production costs are estimated using a number of technical and economic parameters which, among others, include product yields, capital costs and raw material costs. The values used for these parameters have a degree of uncertainty and thus are not known with absolute accuracy. This results in uncertainty in the model's output (i.e. production costs) and can be reduced through acquiring more data. However, even then, the modeller can never be entirely certain of their models’ estimates particularly in the case of new plant projects and technologies, such as a BTL plant, as there is no experience of a real life plant. The above studies typically assess uncertainty using sensitivity analysis where the effect on biofuel production costs of changing key model parameters is determined.

While sensitivity analysis can show how variation in a single parameter can affect production cost, it does not take into account the effect of simultaneous variation of parameters. This lack can lead to a systematic bias in the estimation of costs. For example if two quantities can each independently vary by ± 50%, their product can be between 75% lower and 125% higher than an estimate based on the product mean values of the variables. As this range isn’t symmetric, an estimate based on varying one parameter at a time would underestimate the likely value.

Even where a deterministic estimate of production cost is not systematically biased, it does not give us any information about the probability with which a particular cost level will be met. Baker & Shittu argue [28] that knowledge of the probability distributions underlying estimates are "particularly important for determining near term optimal technology policy" and that, in the context of climate change damage, such knowledge can have a major impact on climate change technology policy, in some cases justifying significantly higher levels of R&D investment [29]. Similarly, Mills et al. argue [30] that investors are unwilling to make energy-related investments because of a

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