



# Techno-economic assessment of integrating methanol or Fischer–Tropsch synthesis in a South African sugar mill



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## HIGHLIGHTS

- Integration of synthetic fuel production into sugar mills.
- Optimising syngas generation from biomass for cost and efficiency.
- Allothermal syngas production advantageous over autothermal.
- Conventional and advanced synthesis of Fischer Tropsch and methanol.
- Advanced methanol synthesis is the most favourable.

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## ABSTRACT

This study considered an average-sized sugar mill in South Africa that crushes 300 wet tonnes per hour of cane, as a host for integrating methanol and Fischer–Tropsch synthesis, through gasification of a combined flow of sugarcane trash and bagasse. Initially, it was shown that the conversion of biomass to syngas is preferably done by catalytic allothermal gasification instead of catalytic autothermal gasification. Thereafter, conventional and advanced synthesis routes for both Methanol and Fischer–Tropsch products were simulated with Aspen Plus® software and compared by technical and economic feasibility. Advanced FT synthesis satisfied the overall energy demands, but was not economically viable for a private investment. Advanced methanol synthesis is also not viable for private investment since the internal rate of return was 21.1%, because it could not provide the steam that the sugar mill required. The conventional synthesis routes had less viability than the corresponding advanced synthesis routes.

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## 1. Introduction

Lignocellulosic plant biomass can replace non-renewable carbon resources in numerous applications and has the potential to reduce greenhouse gas (GHG) emissions associated with present use of fossil fuels (Kreutz et al., 2008; Tijmensen et al., 2002). However, the conversion of lignocellulose into second generation biofuels comes at a significant cost of production, which has hindered its economic viability and prevented wide-scale commercial implementation (Sims et al., 2010). Bio-residues such as sugarcane bagasse and post-harvesting residues (“trash”) in particular, are

lignocellulosic materials generated in large quantities by the raw sugar industries (RSI) (Petersen et al., 2014; Leibbrandt et al., 2013). Thus, integrating biofuel production into this industry by converting lignocelluloses into biofuels and process energy could be economically attractive due to reduced costs of utilising residues onsite (Petersen et al., 2014), since the only costs associated with the bagasse is the amortised capital requirements for improving the mill efficiency while the costs of trash is associated with the collection from the field (Macrelli et al., 2012). As the export of energy products from a sugar requires an operating efficiency that is reflective of a steam demand of 0.4 tonnes per tonne of cane, the cost calculated for availing bagasse for such purposes was at 6 US\$ per dry tonne (Petersen et al., 2014), which basically reflects the capital required to upgrade a typical South African mill that operates at a specific steam demand of 0.55 tonne/tonne cane. Thus, the installation of an integrated fuel co-production and energy cogeneration system would only be viable if it can meet the demands of the upgraded mill in a feasible manner (Macrelli et al., 2012).

*Abbreviations:* RSI, raw sugar industry; ALO-G, allothermal gasification; DFB, dual fluidised bed gasifier; ACE, amortised capital expenditure; CSP, cost of syngas production; HRSG, heat recovery steam generator; AUT-G, autothermal gasification; OOC, operational opportunity cost; SIF, supplementary information file; CE, conversion efficiency; FT, Fischer–Tropsch; IRR, internal rate of return.

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The integration of biofuel production in the RSI has primarily been investigated for biological routes, where either the entire fraction of the lignocellulosic carbohydrates (cellulose and hemicellulose) is converted to biofuel, or just the hemicellulose fraction (Petersen et al., 2014; Macrelli et al., 2012). Where the cellulose and hemicellulose are converted, possible drawbacks include the high costs of the enzymes required to hydrolyse cellulose (Macrelli et al., 2012), where as using hemicellulose only results in a lower fuel yield (Petersen et al., 2014). Thermochemical conversion of lignocellulose to biofuels through gasification-synthesis is an alternative to biological conversion (Consonni et al., 2009). Gasification-synthesis would utilise both carbohydrates and lignin in the biomass feedstock for biofuel production and has shown to be more energy efficient (Leibbrandt, 2010). Intermediate liquid fuel products such as bio-methanol and bio-synchrude can take advantage of existing fuel production infrastructures, by processing with fossil based fuels at existing refineries, to produce Fischer-Tropsch (FT) liquids or biodiesel (Consonni et al., 2009). Previous investigations on the feasibility of finished FT liquids (i.e. gasoline and diesel) from biomass have shown that scales in excess of 110 dry tonnes per hour of feed are required for economic feasibility, due to the high capital investments (Leibbrandt, 2010). Such scales would not be attainable in the RSI of South Africa, since the average scale is at 300 tons per hour of wet sugar cane, which results in a combined amount of trash and bagasse at 60 dry tonnes per hour (Petersen et al., 2014). Thus, the production of intermediate fuels may be an option for integrated biofuels scenarios using thermochemical pathways, since they are less capital intensive than facilities generating finished products (Ekboom et al., 2009).

The viability of integrating gasification-synthesis into an existing sugar mill is largely dependent (i) on the requirement for the gasification-synthesis process to meet the steam and electrical demands of the sugar mill, since this processing plant will replace the existing steam-electricity supply in the mill (Petersen et al., 2014), and (ii) the efficient conversion of lignocellulose into synthesis gas by gasification and conditioning, since this is where the primary capital and energy costs in a thermochemical process lie (Leibbrandt et al., 2013). As such, previous studies have analysed the effects of the gasification operating parameters (moisture content, pressure, temperature, steam-to-biomass ratio (SBR) and equivalence ratio (ER)) on the syngas composition and the gasification efficiency (Leibbrandt et al., 2013; Baratieri et al., 2008; Silva and Rouboa, 2014; Schuster et al., 2001) at thermodynamic equilibrium. The gasification efficiency measures the performance by relating the amount of input energy captured in the syngas while the syngas composition is important because the ratio of carbon monoxide and hydrogen determines the efficiency of methanol and FT synchrude synthesis (Leibbrandt et al., 2013; Phillips et al., 2011). Predictions made with thermodynamic equilibrium calculations (Schuster et al., 2001; Baratieri et al., 2008; Silva and Rouboa, 2014; Leibbrandt et al., 2013) have shown acceptable accuracy for biomass gasification at temperatures of 800–1000 °C, in the presence of a gasification or steam reforming catalyst (such as dolomite or nickel-based), which also reduces tar formation to an acceptable level (Filippis et al., 2004; Rapagna et al., 1998).

Coupling the measurement of gasification efficiency with equilibrium models, has been used in statistical models to optimize the operating parameters of syngas production for applications such as Fischer Tropsch synthesis and H<sub>2</sub> production (Leibbrandt et al., 2013; Silva and Rouboa, 2014). These studies however, have not considered the impact of downstream syngas conditioning units on the overall efficiency and furthermore, have not quantified the associated costs of producing syngas. As examples, the capacity of the heat recovery steam generator on the syngas stream and the energy demands of the Rectisol unit to remove the acids from syngas are directly dependent on the enthalpy and properties of

the product gas (Kreutz et al., 2008; Leibbrandt, 2010), and thus – the efficiency and cost of conditioning syngas is dependent on the operating conditions of gasification. Otherwise, in terms of cost and efficiency, more efficient process technologies are often characterised by greater capital and operational expenses (Ryan and Campbell, 2012) in a general sense. With particular reference to syngas production, the combined gasification-conditioning processes can be configured for steam-blown or oxygen-blown gasification, with the latter having higher efficiency (Puig-arnavat et al., 2010), while being considerably more costly (Baratieri et al., 2008).

Thus, the present study assessed the techno-economic feasibility of methanol and FT bio-synchrude synthesis as alternative options for integrating biofuel processes into the RSI of South Africa. Operational conditions for gasification-conditioning to produce cleaned-compressed syngas were first simulated in Aspen Plus<sup>®</sup>, to minimise the overall production costs while maintaining an acceptable conversion of biomass to synthesis gas. The preferred gasification-conditioning approach was subsequently combined with methanol or FT synthesis flow-sheets through Aspen Plus<sup>®</sup> simulation (version 7.1) (Aspen Technology Inc., 2008). All Aspen simulations were based on published technical data and technologies. For both FT and methanol production, conventional and advanced synthesis technologies were compared on the basis of energy efficiency and economics. Generally, conventional synthesis technologies employs gas-phase reactors with recycle loops, while advanced synthesis technologies employs liquid-phase reactors that potentially operates on a once through basis. Financial risk assessments of the alternative flowsheets were completed with Monte Carlo (stochastic) methods, using Simetar™ (Richardson et al., 2008) software.

## 2. Methods

### 2.1. Technological overview

#### 2.1.1. Lignocellulosic biomass gasification

Equipment designs for the gasification of lignocellulosic biomass tend to focus on fluidised bed gasifiers (Tijmensen et al., 2002), which can be based on autothermal gasification (AUT-G) or allothermal gasification (ALO-G). During AUT-G, the gasification medium includes both steam and an oxidant in sub-stoichiometric proportions, to initiate the combustion reactions and to supply the reaction heat required by the endothermic gasification (reduction) reactions (Filippis et al., 2004). A high calorific value of the syngas, as is desired for Fischer-Tropsch synthesis, requires the oxidation medium as pure oxygen. The pure oxygen is obtained by an Air Separation Unit, which typically bears substantial energy and capital costs (Kreutz et al., 2008; Schuster et al., 2001). AUT-G systems can also be done under pressure to avoid costly syngas compression for downstream synthesis applications (Larson et al., 2009). However, a pressurised system requires high capital cost and also reduces the content of hydrogen and carbon monoxide in the syngas (Holmgren et al., 2012).

Regarding ALO-G, a syngas with a calorific value similar to that of the oxygen-fed autothermal systems (Schuster et al., 2001) is produced by reforming with steam. The energy required for the endothermic steam gasification reactions is supplied by a heat transfer medium (bed material) that is circulated between combustion and gasification chambers in the setup of a dual fluidised bed gasifier (DFBG) (Schuster et al., 2001; Baratieri et al., 2008). The bed material containing the gasification catalyst is separated from the gasification chamber effluent (i.e. syngas) with unconverted char and enters the combustion chamber with additional fuel to heat the bed material that is returned to the gasifier. Un-reacted char, however, only occurs if the gasification conditions

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