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Comparison of second-generation processes for the conversion of sugarcane bagasse to liquid biofuels in terms of energy efficiency, pinch point analysis and Life Cycle Analysis

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ABSTRACT

Three alternative processes for the production of liquid transportation biofuels from sugar cane bagasse were compared, on the perspective of energy efficiencies using process modelling, Process Environmental Assessments and Life Cycle Assessment. Bio-ethanol via two biological processes was considered, i.e. Separate Hydrolysis and Fermentation (Process 1) and Simultaneous Saccharification and Fermentation (Process 2), in comparison to Gasification and Fischer Tropsch synthesis for the production of synthetic fuels (Process 3). The energy efficiency of each process scenario was maximised by pinch point analysis for heat integration. The more advanced bio-ethanol process was Process 2 and it had a higher energy efficiency at 42.3%. Heat integration was critical for the Process 3, whereby the energy efficiency was increased from 51.6% to 55.7%. For both the Process Environmental and Life Cycle Assessment, Process 3 had the least potential for detrimental environmental impacts, due to its relatively high energy efficiency. Process 2 had the greatest Process Environmental Impact due to the intensive use of processing chemicals. Regarding the Life Cycle Assessments, Process 1 was the most severe due to its low energy efficiency.

1. Introduction

There is a global interest in producing biofuels from a range of energy crops, with sugarcane being one of the primary candidates since it produces one of the highest yields of biomass from sunlight [1]. Thus, the South African government [2] has a vested interest in producing biofuels from of energy crops, with sugarcane being the primary candidate in country's subtropical regions [2]. The use of agricultural land for biofuel production is severely criticised, due to the potential impact it poses on the food industry [3,4]. Additionally, there are sustainability issues such as water usage and a sudden potential of high greenhouse gas emissions associated with the preparation of land for energy crop growth [5–7]. Thus, an alternative strategy to bypass those concerns is to consider lignocellulosic feed such as sugarcane bagasse for second generation biofuels [5,6]. The sugar industry of South Africa produces about 8 million tons of bagasse per annum, all of which is inefficiently burnt to supply the energy needs for the mills [8]. If the boilers could be replaced with highly efficient boilers, up to 52% of the bagasse would become available for other renewable uses, such as biofuel production [8]. Thus, there would be adequate supplies for a centrally located facility with a capacity of 600 MW [9,10], which would require 909,474 tons of dry bagasse per annum. It has previously been shown that such a scale might be profitable, while a smaller scale will not to be economically viable [9].

Biological conversion to ethanol and thermochemical conversion to Fischer–Tropsch (FT) fuels (diesel and gasoline) are competing processing routes for second generation biofuel production [4,11]. The energy efficiencies of these processes have been previously compared [9,12] and the thermochemical routes have typically shown a higher efficiency (51.7 ± 0.8% vs. 43 ± 1.1%). The environmental impacts associated with biological and thermochemical scenarios were not compared in either study, though it is expected that thermochemical process have lower environmental burdens [11]. While Mu et al. [13] compared them for fuel production from wood chips, corn stover, waste paper, and wheat straw, the result is not indicative of the FT scenario in question, since the FT scenario of Mu et al. [13] produced alcohol-fuel rather than gasoline and diesel. Otherwise, the integration of techno-environmental evaluations could also be viewed as part of an iterative design or research procedure that evaluates the environmental

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impacts of the decisions that is being proposed or investigated [14]. This has been observed in Life Cycle Assessment (LCA) studies [15] that sought to search for the optimal economic and most environmentally sustainable use of excess sugarcane bagasse between electricity and second generation ethanol production.

Variants in the design strategies of the thermochemical conversion in the respective studies (examples see [11,18,19]) tended to encompass alternative technologies for all the major conversion processes, whereas variants on the biological routes [9,18] only focused on the pre-treatment step, since it is the most economically intensive step in the process [19]. Separate Hydrolysis and Fermentation (SHF) was the only configuration for the central processing step in the biological scenarios, since it allows each process stage to operated optimally [20]. The competing technology, Simultaneous Saccharification and Fermentation (SSF), was not considered in the biological process models, probably due to its comparative technological immaturity [21]. Experimental yields of ethanol from C5 and C6 sugars for SSF have generally been higher than that of the SHF [22]. Additionally, an SSF setup would theoretically reduce the cost of capital, since the SSF configuration combines the fermentation an hydrolysis reactions, there would only be capital expenditure for one set of reactors instead of two [23,24].

Thus, in this paper, the technical comparison between detailed simulations of biological SHF and SSF processes to a Gasification and Fischer–Tropsch (GFT) synthesis process in terms of the energy efficiency is considered. A pinch point analysis was performed for each process scenario, to ensure that the maximum energy efficiency is obtained without excessive capital requirements. Assessments on the applications of pinch point analysis for a second generation ethanol facility [25] have shown that heating and cooling requirements of 23.6% and 38.7% could be achieved respectively, while Dias et al. [26] achieved reductions of 30.8% and 33.7% on high and low pressure steam respectively. The environmental impact assessment will also be compared using both Process Environmental Assessment (PEA) and LCA. The methods used in the various stages of the Life Cycle Assessment methodology would be those that have been established from literature as being the most reliable and transparent.

2. Development of theoretical processes for simulations

2.1. Ethanol production through pre-treatment, bio-processing and purification

Adapting the flow sheet developed in the National Renewable Energy Laboratory (NREL) Design Report [27,28] for corn-stover to sugarcane bagasse (Fig. 1) was carried out by establishing the process conditions and conversions of the major units on data obtained from experimental literature on bagasse [9,10]. The biomass is pre-treated with steam-explosion to improve digestibility of cellulose and hydrolyse xylan [19,27]. Data from Martin et al. [29] was used to affect the pre-treatment of the bagasse that is catalysed with sulphuric acid. SO_2 impregnation has been shown to be advantageous over sulphuric acid since it has shown to have similar potential to solubilise hemicelluloses, but with less formation of inhibitory products [30,31]. Furthermore, higher yields of glucose had been attained from the enzymatic hydrolysis of the substrates that were pre-treated with SO_2 impregnated pulp [32]. The highest yield of xylose from xylan by SO_2 catalysed pre-treatment currently reported in the literature is 80.9% [33], which would therefore be the design case.

With regards to the conversion of the pre-treated material through enzymatic hydrolysis and fermentation, it can either be separate (SHF) or simultaneous (SSF) processes. The SHF configuration has an advantage in the kinetics [11,21], since the reactions can proceed at their optimum temperatures, while the SSF has a fundamental advantage in equilibrium yields, since end product inhibition effects are diminished [21,23]. Experimental literature on SSF and SHF on the cellulose fraction only has shown though that yields of the SHF were higher [34,35]. Thus, the primary advantage of SSF is that selectivity towards xylose fermentation is improved, as previously experimentally demonstrated [19,22]. Albeit, the former studies [34,35] had clearly demonstrated that the production rate of SSF was much higher, since the combined time of hydrolysis and fermentation for SHF was more than three times greater in either study. Experimental data shown in Table 1 validates that the SSF configuration is superior to SHF when xylose co-fermentation is considered. These values also serve as a summary of the design specifications of each scenario.

Pilot operations at the NREL have confirmed that SHF processes can tolerate a total solids content of up to 20% [23], which corresponds to a water insoluble solids content (WIS) of about 15–17% [37]. Thus, experimental data obtained for a SHF experiments for bagasse on a bench scale operating at a WIS of 9% [36] were scaled to 17.5% for the simulation of the full scale operation [10]. Such high WIS contents were also used for the specifications in the NREL design [27] and other studies that were based on that design [18]. However, pilot data is not available to prove that the high solids loadings could be tolerated by a continuous SSF configuration. For the purposes of this study, it would be assumed that the solids loadings for the SSF scenario are high enough to achieve similar ethanol concentrations in the beer products of the SHF process counterparts.

The beer product from the fermentation is sent for purification, initially through carbon dioxide removal and a beer column [38]. The distillate of the beer column is sent to the rectifier, and the distillate of the rectifier is purified to >99.5% through molecular sieves [38]. The still of the beer column is filtered to produce a filter cake for the boiler feed. From the filtrate, a portion is recycled to the ethanol production phase (hydrolysis and fermentation) and the rest is concentrated in a 3 phase evaporating step to supplement the boiler feed [27]. The steam generated by the boiler is used to satisfy the heating and steam requirements of the plant; and to generate electricity by expansion in a four stage Condensing-Extracting-Steam-Turbine (CEST) [27]. The parameters describing the simulation of separation, evaporation and energy production is detailed in Leibbrandt et al. [10].

2.2. Gasification–synthesis–purification of synthetic fuels

Bagasse is dried to a moisture content of 5% with excess process heat [39], such as the stack gas, before it is gasified in a fluidised bed gasifier that is oxygen blown (Fig. 2). The adaption of this process for a bagasse feedstock was achieved by optimising the process parameters by equilibrium modelling over the gasification section [9]. The optimum conditions were a gasifying temperature of 1100 K, an equivalence ratio (supplied oxygen to stoichiometric oxygen) of 0.25 and steam to biomass ratio of 0.75. Steam requirements for the gasification are generated from the cooling of the crude syngas. The crude syngas is cooled further to 40 °C for acid gas removal in a Rectisol unit [9,16]. Alternatively hot gas cleaning could be employed, but this technology has not yet achieved commercial status and it has not shown any noticeable benefits on the overall energy efficiency [17].

Clean syngas undergoes Fischer–Tropsch synthesis to produce a syn-crude that is refined and upgraded into gasoline and diesel [40]. Since the refinery section was not modelled in Aspen Plus® [41] , the overall conversion of CO to gasoline and diesel fractions was specified at 20.56% and 32.44% respectively [9] to reflect the overall conversion of the synthesis loop and refinery [16], From