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Comparison of combustion and pyrolysis for energy generation in a sugarcane mill

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ABSTRACT

The study focusses on the comparison of biomass to energy conversion process (BMECP) models to convert sugar mill biomass (bagasse) into energy products via combustion and pyrolysis as thermochemical pathways. Bagasse was converted to steam and electricity via combustion using 40 bar, 63 bar and 82 bar Condensing Extraction Steam Turbines (CEST) systems and a 30 bar back pressure steam turbine (BPST) system. Two BMECPs, namely partial fast pyrolysis and pure fast pyrolysis systems, were modeled for the pyrolysis pathway. In the Pure Fast Pyrolysis BMECP all the input bagasse stream was converted to pyrolysis products, with subsequent combustion of some of these products to generate steam and electricity for sugar mill operations. In the partial fast pyrolysis BMECP, a fraction of the bagasse is combusted directly to supply steam and electricity to the sugar mill, while the remaining fraction is pyrolyzed to generate pyrolysis products. All process models were simulated in AspenPlus® and were assessed on their ability to supply the energy requirement of to two sugar mill scenarios: More efficient mill and less efficient mill. The economic viability of BMECPs was determined using Aspen Process Economic Analyzer. Both combustion based and pyrolysis based BMECPs were capable of meeting the energy requirement of the sugar mill, although the pyrolysis based BMECP had limited steam and electricity production rates due to the accumulation of energy in pyrolysis products. High energy valued pyrolysis products resulted in higher overall process efficiencies of 85.09% and 87.65% for partial fast pyrolysis and Pure Fast Pyrolysis BMECPs respectively compared to 77.48% for the most efficient combustion BMECP (82 bar CEST). CO_2 savings were higher for the pyrolysis based BMECPs due to the sequestration of carbon in pyrolysis products. The 63 bar CEST combustion system was the most economic viable option, while the Pure Fast Pyrolysis BMECP was the least viable. The increased energy efficiency and environmental benefits of pyrolysis-based processes are therefore off-set by increases in production costs.

1. Introduction

The increase in the demand for energy caused by the increase in global industrialization and the rapid rate at which fossil oil reserves are depleting, as well as issues of environmental concern with regards to greenhouse gas emissions, have encouraged the search for alternative energy sources, mainly from renewable resources such as biomass [1–6]. Biomass provides a clean and renewable source of energy. Converting biomass to energy rich products has the potential to be CO_2 neutral, as any CO_2 produced during the conversion process is reabsorbed from the atmosphere by plants [7]. Also the emission level of NO_x and SO_x from biomass compared to that of fossil based fuels is almost zero, since biomass contains very low percentages of N and S [8]. Biomass has been successfully converted to energy sources such as heat, electricity and even transportation-grade fuels through both thermochemical and biological processes [9–11].

Sugar production from sugarcane remains as one of the predominant agro-industrial activities in South Africa, producing sugar as the main product and in some instances excess of electricity after meeting the industry's energy demand. A substantial amount of bagasse is generated in this industry during the milling process (270 kg bagasse/ton of cane milled) according to Garcia-Perez et al. [12]. Bagasse is the fibrous material that remains after juice is extracted from sugarcane during the sugar manufacturing process. It is made up mainly of cellulose, hemicelluloses, lignin and some small fraction of extractives [2,6,13–16]. Currently bagasse in South Africa just as in many other sugar producing countries is inefficiently combusted as solid fuel in cogeneration systems attached to sugar mills to raise steam and generate electricity to provide the energy demand of the industry [17–19] leaving very little or no surplus bagasse after meeting mill energy demand due to the energy intensive nature of the sugar manufacturing process as well as inefficiencies within the manufacturing

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process. According to Smith et al. [20] about 297 kg bagasse/ton of cane (50% average moisture content) was generated by the South African sugar industry during the 2010/2011 milling season. Based on 50% steam on cane mill efficiency which is the average for South African mill [20], only about 15% of this is made available per ton of cane crushed assuming the rule of thumb of the sugar industry that 2 kg of steam is generated per each kg of bagasse burned [21].

Given the rapidly changing market for sugar and the instability and uncertainties in the price of sugar, it has become important for sugar factories to introduce some form of product diversification in the industry [22,23]. The production of valuable products from bagasse is one way in which sugar factories can bring in added benefits. Bagasse has significant potential as energy source, which has not been fully exploited by the sugar industry [18]. Among the diversification that can be introduced into the sugar industry are the generation of excess power through improvement in efficiency of biomass combustion process and the production of fuels and specialty chemicals from bagasse by pyrolysis. Exploring the potential of bagasse, however, requires the availability of a sufficient amount of bagasse and this in turn calls for improvement in process efficiencies and the optimal use of energy in sugar mills.

Energy integration in the sugar industry has been identified as a way of minimizing the waste of energy and ensuring the proper use of energy [19,22]. The implementation of such measures within the sugarcane milling process will thus make sufficient bagasse available, since the external thermal energy demand of the mill will be reduced drastically, implying less bagasse needed for steam generation. However, storing large quantities of bagasse for future use is not beneficial to the sugar industry in financial terms. Bagasse has low bulk density [18,21,24], hence requiring large volume for storage, which is very expensive. Moreover, stockpiling bagasse and other sugarcane residues poses an environmental threat to sugar mills and their surroundings because bagasse is self-combustible and may spontaneously combust if stockpiled for longer periods [18,25]. This means that bagasse must be readily converted to valuable energy sources such as electricity in highly efficient cogeneration systems for sale to the grid as, is been done in Mauritius and Reunion [17]. The one-time use of bagasse implies that the sugar mills will have to depend on fossil based fuel for energy generation during off-season. Thus the need arises to search for alternative ways of converting bagasse.

Fast pyrolysis, a thermochemical process, has been used to convert biomass such as bagasse into products (bio-oil and char) with a high energy density [13]. Unlike other thermochemical processes such as gasification and combustion where the generated syngas and heat have to be used immediately on site, the products of pyrolysis can be stored and used later when the need arises [9,10,21]. The bio-oil and biochar produced can be used for electricity and steam production during both in-season and off-season [21], hence ensuring all year round electricity production of which surplus can be offered for sale to the grid to generate extra income for the sugar industry. Bio-oil can be used for specialty chemical production or upgraded to transport-grade fuels [9–11] thus introducing product diversification in the sugar industry. Also, char can be upgraded to activated carbon which can be used in the sugar refinery process to remove color [26]. Char can also be used as soil amendment agent/soil additive alongside fertilizers on sugarcane plantations to improve the fertility of the soil [27,28], which subsequently will lead to increased sugar cane yields. Studies have shown that soils that receive a combined application of fertilizer and char exhibit better plant growth resulting in yields of as high as 50% over and above that which can be obtained from soils that are given only fertilizer [29,30]. Aside these benefits, pyrolysis also has the ability to supply the thermal and electrical energy needed to run the sugarcane milling/sugar production process. Due to the high temperatures at which the technology of fast pyrolysis operates, as much energy as possible can be harnessed in the form of high pressure steam during pyrolysis products recovery, to provide steam and electricity for the sugar mill plant. Thus through the implementation of efficient and effective energy integration networks within the sugar mill, the sugar industry can benefit from producing valuable products (bio-oil and char) from fast pyrolysis, while also meeting its thermal and electrical needs from the heat recovered from the pyrolysis plant and even generating surplus electricity for sale.

This work therefore seeks to develop process models (using Aspen Plus® simulation software) for the efficient conversion of sugar mill biomass to energy (steam and electricity) and/or energy products. Notably, models are developed for combustion (the current technology used in the sugar industry) and pyrolysis process technologies, with the aim of investigating the possible introduction of pyrolysis into the sugar mill to convert sugar mill biomass (bagasse) into energy dense products, while also meeting the electricity and steam demand of the mill. Though research into pyrolysis has received significant attention in recent times, most studies have only concentrated on the use of pyrolysis as a stand-alone process solely for the production of bio-oil and biochar from biomass and the application of the technology as an integral part of the sugar mill to simultaneously supply the energy (steam and electricity) requirement of the sugar mill and to generate pyrolysis products from sugar cane bagasse has not received much attention especially in the context of South Africa. On the basis of process modeling, the combustion and pyrolysis processes will be compared in terms of provision of the required process steam and electricity for low- and high-efficiency sugar mill scenarios, the environmental impact in terms of CO_2 savings and reduction in greenhouse gas emissions, the energy efficiency of the conversions, as well as the economic viability as an investment case.

2. Materials and methods

For the conceptual design and the analysis of the biomass-to-energy conversion processes (BMECP) modeled in this study, the following steps were followed: (i) selection of process design scenarios; (ii) process flow sheet development and generation of mass and energy balances using Aspen Plus®; (iii) sizing of equipment and economic evaluation of process scenarios by use of Aspen Icarus® and cost data from literature and vendor quotations.

The block flow diagram (BFD) of the BMECP plant as depicted in Fig. 1 was assumed in this study to be a single power plant that provides all of the steam and electricity requirements of the sugar mill. The energy demands (steam and electricity) are met by the BMECP, while excess energy is offered for sale. The sugar mill in turn supplies the BMECP plant with bagasse and condensate for its operation.

2.1. Choice of scenarios

Three main scenarios of the BMECP were selected in this study as the technological pathways for the conversion of sugar mill biomass into energy and energy and energy products. The first scenario referred herein as combustion BMECP (Fig. 2), models the current technological pathway used in the sugar industry for the generation of electricity and steam to run the sugar milling process. Here sugar cane bagasse from the sugar mill is fed to a biomass combustor/steam-turbine cycle to cogenerate electricity and low pressure (LP) steam for the sugar mill.

In the second scenario all of the bagasse from the sugar milling process is fed to a fast pyrolysis plant, where it is converted into pyrolysis products (bio-oil and biochar). Part of the pyrolysis products is combusted to supply the energy for pyrolysis and also to