Applied Energy 229 (2018) 1–17

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Transition of a South African sugar mill towards a biorefinery. A feasibility assessment

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HIGHLIGHTS

- Two energy self-sufficient scenarios producing chemicals from bagasse are proposed.
- The proposed scenarios display better economic performances than the baseline case.
- The most profitable option includes furfural, lactic acid and electricity production.
- The scenarios show potential environmental benefits against their reference systems.
- Transition of sugar mill towards a biorefinery is a promising option in South Africa.

ARTICLE INFO

Keywords:
Sugarcane
Furfural
Lactic acid
LCA
South Africa

ABSTRACT

The survival of the sugar industry in South Africa is under threat due to an unstable and low sugar price, high production cost and old infrastructure. At present, coal and sugarcane bagasse are used as fuels in an inefficient boiler to generate the heat and electricity required by the plant. Moreover, the residues produced during the sugarcane agriculture stage are burnt in the field causing serious concerns in the nearby rural areas. The progress in the conversion of lignocellulosic residues to valuable chemicals in the South African sugar mills would bring benefits in sustainability and both rural and industrial economic development. Sugarcane bagasse and green harvesting residues are the largest lignocellulosic wastes in the production of sugar from sugar cane. They are seen as promising feedstock to improve the long-term sustainability of the local sugar mill. Integrated biorefinery-sugar mill scenarios using sugarcane harvesting residues, bagasse and molasses as feedstock to co-produce chemicals and electricity are evaluated in this work for the first time. The integration of plants was designed in a way to provide both economic and environmental benefits. The following lignocellulose biorefineries were simulated in Aspen Plus V8.8: (SM LE) Co-production of sugar and lactic acid, and (SM LF) co-production of sugar, lactic acid, and furfural. Surplus power was produced in both scenarios for export. Both scenarios were simulated based on literature and experiment data presented in this work. Experiments were conducted on the bagasse pretreatment using dilute acid, and the conversion of hemicellulose into furfural product. The results of techno-economic assessment showed that both scenarios are economically feasible under the considered conditions and provide strong economic benefits in comparison with an existing sugar mill. Among the biorefinery scenarios, the SM LF scenario has better economic performance than SM LE. In terms of environmental assessment, both scenarios demonstrate a significant reduction in climate change, fossil fuel depletion, freshwater ecotoxicity and eutrophication and human toxicity impacts in the South African context. In a nutshell, biorefineries demonstrate potential to be a feasible and more sustainable alternative to the existing sugar mills in the South African context.

Abbreviations: 2G, second generation; CHP, combined heat and power; d.b., dry basis; DBRP, dollar-based reference price; EPFL, école polytechnique fédérale de Lausanne; GHG, greenhouse gas; GHR, green harvesting residues; HEN, heat exchanger network; HMF, hydroxymethylfurfural; HP, high pressure; HPLC, high performance liquid chromatography; IRR, internal rate of return; LA, lactic acid; LCA, life cycle assessment; LCIA, life cycle impact assessment; LP, low pressure; MPP, maximum purchasing price; MSP, minimum selling price; NPV, net present value; PEP, prospective economic performance; PLA, polylactic acid; RID, refractive index detector; RS, reference system; RV, recoverable value; SA, South Africa; SACU, South African Customs Union; SD, standard deviation; SM, sugar mill; TEA, techno-economic assessment; THF, tetrahydrofuran; WWT, wastewater treatment

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https://doi.org/10.1016/j.apenergy.2018.07.104
Received 11 December 2017; Received in revised form 13 June 2018; Accepted 22 July 2018
0306-2619/

1. Introduction

Interest in the sustainable and secure supply of resources has increased worldwide in the last decades [1]. Agreement regarding the use of limited resources and the greenhouse gas (GHG) releases was stated at the United Nations Climate Change Conference (COP21) in Paris 2015. Biomass conversion processes can gather a large reduction of GHG emissions [2]. Biomass most often refers to lignocellulosic biomass, involving residues from the agricultural (e.g., corn stover and sugarcane bagasse) or forest products industries, and 'energy crops'. Lignocellulosic wastes are a potential feedstock for second generation (2G) fuel and chemical products [3]. In order to meet policies related to the reduction of GHG emissions and taking into account the oil depletion, non-petroleum based products are gaining much attention [4].

The survival of the sugar industry in South Africa (SA) is threatened by the unstable and lowering sugar price, the increasing energy cost, an aging infrastructure and the competition with low-cost sellers. However, the sugar industry directly or indirectly affects the livelihood of nearly 1 million people in SA. At the same time, South Africa is a signatory to the Paris Agreement, and it is the government's stated intention to mitigate GHG emissions. In the COP21 conference, SA set a target of 4.5% CO_2 annual reduction by 2030 [5]. A revitalized South African effort involving research, development, demonstration, and commercialization in the biomass conversion field would provide benefits in sustainability and both rural and industrial economic development.

A typical South African sugar mill, uses sugarcane as feedstock. The main steps taking place at the plant are: (1) *milling and sugarcane juice extraction*, where sugarcane bagasse is disposed after the cane pressing (2) *clarification* of the sugarcane juice in order to remove impurities, (3) *evaporation* of the clarified juice to obtain concentrated syrup; and (4) *crystallization*, where the syrup is saturated with sugar and the sugar crystals are finally produced. The blend of sugar crystals and syrup is separated producing C molasses and raw sugar. These are the saleable goods of a common sugar mill in SA. Currently, the sugarcane bagasse remaining after cane pressing is burnt to generate some of the heat and electricity used at the mill. An inefficient boiler is fueled with coal and sugarcane bagasse to satisfy the plant energy requirements.

Due to the extensive practices in sugar industries in SA, sugarcane bagasse is one of the largest flows of lignocellulosic residues in the country. Regarding the agriculture practices, the sugarcane green harvesting residues (GHR) comprise a major agricultural residue too. In the South African context, at present, GHRs are burnt in the field causing health problems for workers and those who live nearby [6]. Bagasse is seen as budding 2G feedstock to improve the long-term sustainability of the South African sugar mill. In tropical and sub-tropical regions where the climate favors sugarcane growth, C molasses are being evaluated for conversion to valuable products due to its high content of fermentable sugars [7]. The GHRs are also seen as potential feedstock [8]. Increasing the efficiency of steam and power generation, bagasse could be used as feedstock for non-petroleum based products (such as fuels or chemicals) while still meeting the plant energy demand [9]. Using GHR for steam and power generation would decrease the contamination of the harvesting environment while increasing the amount of bagasse for conversion into bioproducts. The change in harvesting practices would also encourage the job creation and rural development of SA.

Biorefineries are considered as potential industries to produce biofuels and/or added-value chemicals using low-cost lignocellulosic biomass as feedstock [3]. An emblematic biorefinery is based on the conversion of extracted sugars into cellulosic ethanol by using the residues as fuel for steam and electricity cogeneration [10]. The interest in bioproducts in South Africa is already in progress. The Tongaat Hulett South African sugar company and the Addax and Oryx Group energy companies have initiated a project known as "Makeni ethanol and power project" in Sierra Leone to produce bioethanol from sugarcane [11]. The South African company, Sasol (the largest non-petroleum hydrocarbon industry in the world) is evaluating a shift to the biotechnology arena [12]. Sasol technology orientated to the production of commodities was developed for coal, but it can readily be adapted to biomass feedstock. However, the techno-economic analysis carried out in the South African context showed that the economic benefits of an ethanol biorefinery annexed to an upgraded South African sugar mill are not significant [13]. The average scale of a typical sugar mill in SA challenges the profitability of an integrated sugar mill-biorefinery plant.

Significant volumes of industrial bio-based chemicals can be commercially manufactured using less feedstock than the required to meet energy needs while offering substantial benefits [14–16]. Among the different fine chemicals derived from fermentation of sugars (amino acids, enzymes, vitamins, antibiotics, etc.), lactic acid is one of the major contributors to the global trade with mature market in place. Lactic acid (LA) is an organic acid. It has been commonly used in the food and non-food industries, comprising the pharmaceutical and cosmetic ones [17], and the production of oxygenated chemicals, plant growth regulators, and special chemical intermediates [18]. LA can be polymerized into polylactic acid (PLA), which is a promising biodegradable and biocompatible plastic [19]. LA has two optically active enantiomers: D(−) and L(+). Pure isomers can be obtained through fermentation by selecting an appropriate strain. Most of the bio-based LA produced globally is obtained by fermentation of hexoses, but there are also some strains able to ferment pentose sugars [20,21]. Lactic acid is also produced from petrochemical resources by chemical synthesis. However, this route produces an optically inactive racemic mixture of DL-lactic acid [22] consuming more energy than the biological route [23]. The demand for lactic acid has increased considerably due to its wide range of applications, so the interest in the use of low-cost non-food materials for LA production is increasing. Even though technologies for LA production from lignocellulose-derived sugars are not advanced yet, some industrial biotechnology companies have already fermented LA on a pilot scale from lignocellulose [24,25].

Besides fermentation, bagasse sugars can also undergo chemical transformation to marketable biochemicals such as sorbitol, furfural, glucaric acid, hydroxymethylfurfural or levulinic acid [26]. Furfural is considered a promising bio-based chemical that can be commercially produced from the pentose sugars of biomass [27,28]. It involves a wide range of industrial applications in plastic, agrochemicals and pharmaceuticals. Furfural is needed to produce fungicide, adhesives, flavor compounds [29] or it can be used as a precursor for furfuryl alcohol or tetrahydrofuran [30]. Sugarcane bagasse is the most suitable feedstock to produce furfural due to its high content of xylan in the hemicellulose [10,31]. South Africa is currently one of the largest producers of bio-based furfural in the world [32]. The South African Illovo group produces and markets high-value chemicals (such as furfural or furfuryl alcohol) from the sugarcane bagasse. These chemicals produced downstream in the sugar manufacture are worldwide sold into niche markets.

Producing chemicals from renewable materials also fits current plans by the South African government to move towards a greener economy or bioeconomy. Nonetheless, the life cycle assessment (LCA) of a production system has to be evaluated prior to any commercial implementation [33]. The LCA of a biorefinery enables to determine the environmental impact of a product (good or service) from production of raw materials, transport of inputs and feedstock to industrial processing [34]. De Jong and Marcotullio [32] proposed the conversion of the cellulosic fraction to ethanol, the hemicellulosic fraction to furfural, and the combustion of lignin to provide process heat and electricity for the plant. The LCA performed by Daful et al. [35] indicated that the LA produced from sugarcane had considerably reduced environmental impacts. Results showed 80–99% environmental saving in the production of bio-based LA in comparison with that produced from fossil fuels. In the context of SA, Daful and Görgens [36] showed that the lactic acid production from the cellulose-based sugars in bagasse presented an