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Utilization of eucalyptus for electricity production in Brazil via fast pyrolysis: A techno-economic analysis

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ABSTRACT

A process model of a 2000 metric ton per day eucalyptus Tail Gas Reactive Pyrolysis (TGRP) and electricity generation plant was developed and simulated in Pro/II software for the purpose of evaluating its techno-economic viability in Brazil. Two scenarios were compared based on operational conditions in the country: a single biomass to bio-oil TGRP production facility and a distributed/satellite processing that consists of several small TGRP production facilities with aggregate capacity similar to the single one, both feeding into one centralized electricity generation plant. The selling price at the breakeven point of the electricity generated via TGRP was estimated to be US$0.34 and US$0.62 per kWh for the single and the distributed scenarios respectively, considering a 10-year payback period. The single capacity pyrolysis and electricity generation facility is found to have better economic benefits over the distributed plants of small sizes under the current conditions in Brazil. The results therefore indicate that pyrolysis of eucalyptus wood for electricity in a single facility cannot be competitive with the current electricity cost in Brazil (US$0.08–0.13/kWh) at present time. Considering auxiliary benefits such as climate change and carbon credits, plus the continuous increasing in the electricity market price in Brazil, both scenarios could be competitive in the future.

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1. Introduction

The environmental degradation coupled with energy resource depletion in recent years has led to the emergence of alternative energy sources such as bio-oil derived from biomass. While fossil fuels are presently the prevalent and least expensive energy sources, energy derived from biomass, the largest renewable carbon resource, is considered sustainable in the long term. Electricity generation is regarded as one of the most promising possibilities for reaching commercial scale production [1] when considering biomass as a resource.

The installed capacity in Brazil based on renewable sources was 140 GW representing 76% of the total electricity generated in 2015. The main renewable source is the hydroelectric power plant that contributes 64% of the total electricity generated in Brazil; the biomass has a share of 8% [2]. However the hydroelectric power generation in Brazil has proven to be vulnerable to extraneous scenarios leading to unpredictability since 2015, the year in which a severe drought affected the populated states of Sao Paulo and Rio de Janeiro, reducing the efficiency of hydroelectric power plants. As an alternative, thermoelectric plant operations increased to fill the gap, further expanding the use of fossil fuels thereby increasing greenhouse gas (GHG) emissions and the price of electricity [3]. According to the Brazilian Electricity Regulatory Agency (ANEEL), the industrial price of electricity in the Southeast region increased from 80.94 to 131.25 US$/MWh during 2012–2016 [4].

Brazil is well known for its abundance of sugarcane bagasse. However, other potential biomass resources, such as eucalyptus, have proven to be a feasible resource for energy production via fast pyrolysis [5] and integrated gasification [6] due to its increased bulk density and higher calorific value compared to other woody biomass.

The pulp and paper industries have played an important role in the Brazilian economy and have encouraged farmers to grow eucalyptus on their arable lands. Although pulp and paper is an important market, there is a lot of volatility in the sector. The

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eucalyptus tree takes about 7 years to mature and during this period changes in the economy can negatively impact the supply chain, leaving growers with an unmarketable product. In the state of Goias alone, many areas with 10-year old eucalyptus trees have found no potential buyers. In 2011, the total eucalyptus planted area was 4,873,952 ha with Minas Gerais and Sao Paulo as the leading producers [7].

Although biomass could be used directly for the production of electricity similar to coal combustion, it would be more expedient when the biomass handling and pretreatment processes are de-coupled from the actual electricity generation facility due to the low bulk density of the biomass. Considering the various thermo-chemical biomass conversion technologies, combustion and gasification included, fast pyrolysis is perhaps the best-suited technology to efficiently decouple biomass-to-electricity via the conversion of biomass into bio-oil and subsequently into electricity using turbines or compression ignition engines. Converting the biomass into intermediate liquids at several satellite sites before its use for electricity generation at a centralized location has the potential to increase efficiency and decrease capital costs [8].

Our group has expended much effort in investigating the behavior of bio-oil in thermal systems [9–11] and has moved beyond bench-scale bio-oil production with the development of the patented Combustion Reduction Integrated Pyrolysis System (CRIPS) [12] a 2 MTPD system demonstrated at up to 1 MTPD and having a DOE Technology Readiness Level of 6–7.

The location of the pyrolysis plant is an important decision in order to minimize the transportation costs of the feedstock. The electricity generation plant should be equally well located, since the electricity distribution point should be close to customers. Wright et al. [13] studied the logistics related to the distribution of the biomass and bio-oil processing unit in the United States of America. According to their concept, the ideal distribution is to have a central bio-oil processing unit surrounded by several pyrolysis plants, so that the high energy-dense material (bio-oil) is shipped instead of the low energy-dense material (wood), to reduce logistics costs.

Process modeling and simulation present essential tools for the critical technical and economic review of process performances. Techno-economic analyses (TEA) of electricity generation from fast pyrolysis oil using process models and simulation software have not been studied extensively in the literature. Nonetheless, several authors [14–16] have used TEA to evaluate the minimum selling price (MSP) of pyrolysis oil and upgraded bio-oil based on different biomass capacities ranging from 10 to 2000 MTPD (metric ton per day). Based on different assumptions made by these authors, the MSP of bio-oil has been estimated to be between US$0.20/kg to US$0.50/kg.

The objective of this paper is to evaluate the economic viability of electricity production from fast pyrolysis oil with eucalyptus as the main feedstock. A 2000 MTPD (distributed) and a single 2000 MTPD pyrolysis and power generation facilities are modeled and the total capital investment and unit production cost of electricity are estimated. The effect of critical factors on the cost of electricity production for the proposed plant is also evaluated through sensitivity analyses.

2. Material and methods

2.1. Process description, modeling and simulation

The generation of electricity from pyrolysis oil proposed in this study consists of four sectors (Fig. 1): (1) biomass cultivation, U1; (2) biomass pretreatment, U2; (3) biomass fast pyrolysis, U3 and (4) electricity generation, U4; from pyrolysis oil. U3 was developed and simulated in the SimSci PRO/II® software. With the technical parameters from the basic design of the plant and input assumptions specified, the software was used to generate the mass and energy balances that were further used as basis for the techno-economic analysis.

2.1.1. Feedstock cultivation, transportation and pretreatment

About 10–40% of total production cost is usually incurred during biomass cultivation, harvesting, shredding, compacting, collection [17] and for that reason these factors must be evaluated for their economic impact. The pre-treatment of woody biomass is a set of unit operations that are mandatory in order to enable the feedstock amenable to pyrolysis conversion: reception, grinding, screening, drying and storage. Feedstock logistics are necessary to guarantee a continuous supply to the industry [18]. Eucalyptus trees were mechanically harvested (cut and debarked) and allowed to dry on the field for 180 days until their moisture content was around 30% before use. The debarked trunks were road transported to the biomass pre-treatment area (i.e. U1, Fig. 1). In this area, wood trunks were chopped into smaller pieces, dried to about 10 wt% moisture content, and milled to 2 mm particle size. The pre-treated biomass was transported to section 2 (i.e. U2, Fig. 1), to be converted via fast pyrolysis. A 2–3 mm particle size range is consistent with fluidized-bed pyrolysis where high specific surface area of the feedstock is necessary to achieve the heat rate associated with fast pyrolysis. While sawdust fits this particle size range and could reduce the production costs if used, our goal in this paper was to present the processing of eucalyptus by producers within the biorefinery concept. For that reason, our starting feedstock comprises eucalyptus trees and not sawdust.

However these feedstock pretreatment unit operations were not sized by in PRO/II modeling, rather, the capital and operating costs of vendor suggested units were considered. Power requirements for biomass grinding were calculated based on average specific energy consumption presented by Mani et al. [19]. For drying operations, it was assumed that 5 MJ per kg of water is evaporated [14].

2.1.2. Tail gas reactive pyrolysis (TGRP)

TGRP is a fluidized-bed pyrolysis process developed at the Agricultural Research Service (ARS) laboratory of U.S. Department of Agriculture (USDA), Wyndmoor, PA. The patented process uses a reactive atmosphere created by a fluidizing medium recycled from the tail gas of the fluidized-bed reactor instead of an inert gas medium [20]. An on-farm/in-forest autogenic pyrolysis system is selected based on the patented Combustion Reduction Integrated Pyrolysis System (CRIPS) [12] developed by the USDA and the University of Pretoria (South Africa) that uses part of the system's own energy generated in an external combustor to provide for the endothermic pyrolysis reactions of the TGRP. The system comprises two reactors: a pyrolysis reactor fluidized with the tail gas (reduction bed) integrated with a combustion reactor fluidized with air (oxidizing bed). After the pyrolysis reaction the spent sand and residual char is introduced into the combustion bed where the sand is reheated by combustion of the residual char and returned to the pyrolysis reactor. A detailed explanation about the integrated CRIPS-TGRP process description and its modeling using PRO/II software is presented in the Electronic Supplementary Material. In this paper, bio-oil refers to the fraction collected in the electrostatic separator (ESP).

2.1.3. Electricity production

The bio-oil (S15, Fig. S1) is transported from the pyrolysis section to the power generation unit where it fuels a steam boiler that drives a steam turbine for electricity generation. For ease of