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Techno-economic analysis of electricity and heat production by co-gasification of coal, biomass and waste tyre in South Africa

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ABSTRACT

South Africa has large deposit of coal that supports about 95% of electric power generation in the country. The fuel is fast depleting, though the current reserve may serve for the next century. However, the emissions from the coal projects huge threat to the environment. Similarly, the country has abundant solid wastes that can be co-gasified with coal to H_2 enriched syngas for clean energy production. A 5 MW combined heat and power plant was studied using different coal-to-solid waste ratios of 1:1, 3:2, and 4:1 and economy of the plant was evaluated with feedstock costing (WFC) and without feedstock costing (WOFC). The lower heating value of the fuels, determined from a model equation was applied to estimate the annual feedstock requirement and the feed rate. Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP) were used to evaluate the viability of the power generation at the 10th, 11th, 17th and 18th year business periods. The predicted optimum period of the plant is the 10th year. The use of Coal + Pine saw-dust (PSD) blend of blend ratio 1:1, is the most attractive feedstock for the energy generation. A higher profit of about 13.82%, and 23.56% were estimated for the use of Coal + PSD as compared to the use of 100% Matla coal at WFC and WOFC, thus; enabling a savings of about 1,**868.81 t** feedstock per annum. The use of Coal + PSD blend of blend ratio 1:1 reduces the CO, CO_2, SO_2, and NO_X emissions by 3.4%, 23.28%, 22.9%, and 0.55%, respectively.

1. Introduction

Currently, global energy consumption is rising very rapidly, and amounting to the fast depletion of the available source of fuel. Fossil fuels such as coal and crude oil are the two major fuels used for energy generation in the world. The emissions arising from both fuels raise huge concern to the society at large, because of their contributions in global warming that result in climate change. In South Africa, coal is the major source of fuel for power production, and around 95% of the electric power generation in the country comes from coal. At the moment, the estimated coal reserve in the country is about 32 million tons, and it may last for about a century (Stats SA, 2015).

The local availability of coal in South Africa has also contributed so immensely in the low electricity tariff in the country of about $0.1408 c/kWh (SA Power Networks, 2017), and the tariff is one of the lowest around the world. It is true that the cost of electricity supply to consumers in South Africa is low, but at the same time, the emissions associated with the production is equally very high. Similarly, power production from biomass is not cost effective; if waste biomass is not used, and besides, biomass feedstock produces high amounts of tar that causes operational difficulties in the gasifiers and end use facilities. Biomass fuels (e.g. agro-waste) and other solid waste are in abundant in South Africa, and can be co-gasified with coal to produce electricity. Co-gasification has higher efficiency than the solitary coal gasification because the cellulose, hemicellulose and lignin content of biomass help to ignite and enhance the rate of gasification (Kamble et al., 2018). The process will also reduce emissions, cost of feedstock, tar production, and as well be instrumental to waste management in South Africa.

Some researchers have investigated the use of coal, biomass, solid wastes or mixture of them in electric and thermal power production. Understanding the physio-chemical and gasification characteristics of coal that can be blended with any of these solid fuels to produce energy is very essential. Oboirien et al. (2011) have

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Nomenclature

A_{FR}	annual feedstock requirement (t/y)
BFR	bubbling fluidized bed
BFBG	bubbling fluidized bed gasifier
CC	corn cob
CHP	combined heat and power plant
FR_{ANNUAL}	annual feed rate (t/y)
G_E	electric power efficiency (%)
GHG	greenhouse gas
G_Q	thermal power efficiency
HHV	higher heating value (MJ/kg)
IGCC	integrated gasification gas stream combined cycle
LHV	lower heating value (MJ/kg)
$LHV_{FEEDSTOCK}$	lower heating value of feedstock (MJ/kg)
MC	moisture content (%) MW mega-watts
M	million
NPV	net present value (million ZAR/y)
NOH	number of hours
PSD	pine saw-dust
R	annual rate of return (%)
SCB	sugarcane bagasse
SA	South Africa
T	economic life of the plant or business period (y)
t	ton
T_{LPT}	truck load per trip (t)
WT	waste tyre
ZAR	South African rand
Y	year
ω	CO_2 emission factor of diesel based transportation (t CO_2/Km)
ϖ	energy demand (MWh/y)
ϕ	cash flow (million ZAR)
$\eta_{TeGasi.}$	overall electrical efficiency of a gasification plant (%)
$\eta_{TQGasi.}$	overall thermal efficiency of a gasification plant (%)
η_o	operating efficiency of the plant (%)
β	capital investment (ZAR/y)
Υ	hauling distance (Km)
IRR	internal rate of return (%)
PBP	payback period (y)
ξ	emission reduction by displaced energy
μ	earning after interest and tax (million ZAR)
δ	total investment (ZAR/y)
ε	life cycle GHG emission intensity from biomass
φ	effective emission reduction
λ	emission from transportation of biomass (eCO_2/y)

studied the structure and gasification characteristics of selected South African bituminous coals using a bubbling fluidized bed reactor. Bridgwater et al. (2002) and Caputo et al. (2005) have equally carried out some work on pyrolysis, combustion and gasification processes, and reported that about **5 MW** of electrical power capacity are feasible for most fluidized bed systems. The authors were also able to determine the most viable technology amongst the conversion technologies investigated, but could not report on the optimum feedstock for the power production with reference to both profit and emission reduction. Malek et al. (2017), carried out the techno-economic analysis of electricity production in 10 MW biomass-based steam power plant to identify the order of viability of the various feedstocks for power production, but blends of the feedstocks were not used to evaluate the same goal aimed in the study.

Other researchers including; Bridgwater et al., 2002; Mitchell et al. (1995); Searcy and Flynm (2010) have also indicated that biomass integrated gasification and combined gas-steam power cycle (IGCC) is an attractive technology providing about 40%–50% total conversion efficiency, whereas; Demirbas (2001) argued that a biomass integrated gasification combined cycle (BIGCC) plant of around 20 MWe capacity may be as high as about 40%. The IGCC technology as reported by the above authors is quite promising, although the feedstock that could remain viable for a known period of investment was not determined, and the information is considered very useful for investors. However, the Co-gasification process in a fluidized bed system is expected to support an overall conversion efficiency of about 40%–50%, reduce the cost of feedstocks used for electric and thermal power generation as well. The overall system efficiency of a typical co-generation system is within the range of 35%–40% as reported by Ahmad et al. (2013).

Gasification of blends of coal and biomass, and other solid wastes can minimize some of the problems earlier mentioned. Although some researchers have reported on the energy production via combustion, pyrolysis and gasification of biomass with reference to 5 MW, 10 MW, and 20 MW CHP plants, but their studies did not consider blends of biomass and other solid fuels such as coal and waste-tyre, available in south Africa. Consequently, there is no available data in the literature describing the energy production in a 5 MW CHP plant using blends of South African feedstocks, and with emphasis on the blending ratios, energy content of the feedstock, feed-rate and annual feedstock requirement, optimum assessment year, and the most viable feedstock for energy generation in the plant. The findings of this study could pave way to elongate the consumption period of coal reserve that is fast depleting in the South African and the CO_2 emissions for which South Africa is the number one emitter in Africa. In addition, the availability of data on techno-economic analysis of electricity and heat production from co-gasification of coal, biomass and solid waste (e.g. waste-tyre) could be instrumental to decision-making by the government and the key players in energy sector in South Africa and Africa at large.

2. Materials and method

2.1. Materials

Feedstocks used for the investigation in this study were coal, sugarcane bagasse, corn cob, pine saw-dust and waste tyre, obtained in South Africa The biomass materials were reduced from their original size of 6.0–10.0 mm to 0.5–2.0 mm with Retsch biomass cutter (SM 200 Rostire), and the coal (Matla coal) was milled to 0.2–2.0 mm using the milling machine located at the Coal Lab of the University of the Witwatersrand, Johannesburg. The waste tyre was shredded to 0.5–3.0 mm and the re-enforced materials removed. Physio-chemical properties of the feedstocks were checked through ultimate and proximate analysis prior to determining their heating values.

2.2. Blending of feedstocks and cost estimation

The coal and other solid wastes of South African origin were blended in the ratio of 1:1, 3:2, and 4:1, respectively to examine their potentials for electric and thermal power production. The feedstocks and their blends are shown in Table 1, but the estimated results from the blends is presented in Table 5.