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 including 1:1, 3:2, and 4:1 with feedstocks costing, and without feedstock costing. The lower heating value of the fuels, determined from a model equation was applied to estimate the annual feedstocks 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 optimum period was the 10th year. Coal + Pine saw-dust (PSD) mixed at a ratio of 1:1, was the most attractive feedstock for the energy generation. A higher profit of around 13.82 %, and 23.56 % were made from Coal + PSD compared to 100 % Matla coal with feedstock costing (WFC) and without feedstock costing (WOFC), thus; enabling a savings of about 1,868,805.41 Kg feedstock per annum. The use of 1:1 Coal + PSD mixture reduced the CO, CO_2, SO_2, and NO_X emissions by 3.4 %, 23.28 %, 22.9 %, and 0.55 %, respectively.

Key word: Co-gasification; biomass waste; coal; energy generation; Techno-economic

Nomenclature

A_{FR}	annual feedstock requirement (Kg/Yr)
BFR	bubbling fluidized bed
BFBG	bubbling fluidized bed gasifier
CC	corn cob
CHP	combined heat and power plant
$\mathrm{FR}_{\mathrm{ANNUAL}}$	annual feed rate (Kg/Yr)
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)
$\mathrm{LHV}_{\mathrm{FEEDSTOCK}}$	lower heating value of feedstock (MJ/Kg)
MC	moisture content (%)
MW	mega-watts
NPV	net present value (million ZAR/Yr)
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 (Yr)
$\mathrm{T}_{\mathrm{LPT}}$	truck load per trip (Kg)

WT	waste tyre
ZAR	South African rand
ω	CO_2 emission factor of diesel based transportation (t CO_2/Km)
ϖ	energy demand (MWh/Yr)
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/Yr)
Υ	hauling distance (Km)
IRR	internal rate of return (%)
PBP	payback period (Yr)
ξ	emission reduction by displaced energy
μ	earning after interest and tax (million ZAR)
δ	total investment (ZAR/Yr)
ε	life cycle GHG emission intensity from biomass
φ	effective emission reduction
λ	emission from transportation of biomass (eCO_2/Yr)

1.0 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 petroleum 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 climate change and global warming. 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 because coal is used for its generation. 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. Bridgwater et al. (2002) and Caputo et al. (2005) have carried out some work on pyrolysis, combustion and gasification processes, and reported that about 5MW 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 (2002); Mitchell et al. (1995); Searcy & 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 feedstocks 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 around 40 % - 50 %, and as well, reduce the cost of feedstocks used for electric and thermal power generation. The overall system efficiency of a typical co-generation system is within the range of 35 % - 40 % as affirmed by Ahmadi et al (2013).

Basically, gasification of blends of coal and biomass, and other solid wastes can minimize some of the problems earlier mentioned in this section, but most importantly, the current coal reserve in South Africa which is fast depleting, and the CO_2 emissions which South Africa is the number one emitter in Africa, could be reduced very significantly, by the application of findings from this research, thus are among the relevance of the present study. Factually, some researchers have reported on energy production via combustion, pyrolysis and gasification of biomass with reference to 5 MW, 10 MW and 20 MW CHP plants. However, their studies could not cover mixtures of biomass and other solid fuels such as coal and waste-tyre, and even of South African origin.

Consequently, there is no available data in the literature at the moment, describing the energy production in a 5MW CHP plant using blends of South African feedstocks, and with emphasis on the blending ratios, energy content of the feedstocks, feed rate and annual feedstock requirement, optimum assessment year, and the most viable feedstock for energy generation in the plant. The data is very essential, and has formed the major contribution(s) of this paper, and hence; are comprehensively developed, and discussed in the current work, under the plat-form; techno-economic analysis evaluation of electricity and heat production from co-gasification of coal, biomass, and solid waste (e.g. waste-tyre) in South Africa.

2.0. Materials and Method

2.1.Materials

The feedstocks used for the investigation are of South African origin. It includes; coal, sugarcane bagasse, corn cob, pine saw-dust and waste tyre. The biomass materials were reduced from their original size on collection of 6.0 - 10.0 mm to 0.5 – 2.0 mm with Retsch biomass cutter (SM 200 rostire), whereas the coal was milled to 0.2 – 2.0 mm using the milling machine also located at the Coal lab of the University of the Witwatersrand, Johannesburg. The waste tyre was between 0.5 - 3.0 mm as received. Physio-chemical properties of the feedstocks were checked via ultimate and proximate analysis prior to determining their heating values.

2.1.1. Blending of feedstocks and cost estimation

Matla coal (a low rank 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. Two hypothetical cases namely; “blending with feedstocks costing (WFC) and without feedstocks costing (WOFC)” was considered and studied. The WFC considers the actual costs of the feedstocks together with cost of bagging and transportation of the feedstocks, while WOFC considers only the cost of bagging and transportation of feedstocks to the plant room. The relative advantage of WFC over WOFC is to provide elaborate cost information and guidance to investors who are interested in the business area. The evaluation centered on the energy, economic, and environmental parameters of a co-gasification plant. The LHV of the fuels was estimated using an empirical model equation (shown in equation 1), and was applied to determine both the annual feedstocks requirement and the feed rate for the plant. Thereafter, some project assessment tools including the NPV, IRR, and PBP were applied to assess the viability of the power generation at the 10^{th}, 11^{th}, 17^{th} and 18^{th} year business periods.

2.2 Estimation of the LHV and annual feed rate of the feedstocks

One of the most important characteristics of biomass or other fuels used for energy conversion processes and systems is the heating value (Nhuchhen, 2009). The parameter is very useful in system's design calculations, planning, operations of the power plant, and its development. The ultimate and proximate analysis data, as well as the calorific value of the fuel, plays essential roles for efficient operations (Huang et al., 2008). Several researchers including Ahmaruzzuman, (2008); Parik, et al. (2005); Sheng, et al. (2005); & Thipkunthod, et al. (2005), Yin, et al. (2011), have studied the use of proximate and ultimate analysis data in estimating the HHV and LHV of fuels. The heating value of a fuel can also influence the amount of feedstock that required for energy production in a power plant, which in-turn affects the feed rate of the fuel. However, the LHV and the annual feed rate of the feedstock that may be used for the evaluation of the co-gasification power plant are presented in equation 1 (Cooper, et al., 1999) and equation 2 (Malek et al., 2017), respectively.

$$LHV = HHV - (0.212 \times M_H) - (0.0245 \times MC) \tag{1}$$

$$F_{R\ ANNUAL} = \frac{\gamma}{\frac{LHV_{FEEDSTOCK}}{NOH}} \tag{2}$$

2.3 Estimation of fuel requirement for the CHP plant

The LHV of the solid fuels was used to estimate the amount of feedstock required annually for the power production, and was based on the MC and the efficiency of the system. According to verma et al. (2012), the annual feedstock requirement can be determined using equation 3:

$$A_{FR} = \frac{\varpi \times 3.6}{LHV \times \eta_0} \tag{3}$$

The LHV and MC of fuels are two important parameters in thermochemical energy conversion process. Feedstocks with low or high MC can be fed in an energy conversion system, hence; offering different operational efficiencies. A low water content fuel saves the cost of feedstocks drying, improves the heating value of fuel and thus; enhances the overall efficiency of the energy production plant, whereas; a high MC fuel causes several operational difficulties such as lowering the system's heat transfer and many others (Malek et al., 2017).

2.4. Economic Analysis: Co-gasification Power Plant

2.4.1. Net Present Value (NPV)

The NPV is referred to as the sum of the present values for an investment's expected returns overtime offset by its up-front costs. It is used to identify the projects that will yield the most return over an applicable period of time, and as well, check the business options that will survive for a known period of time by meeting its target benchmark, and as well, demonstrate more viable than the other. In order to estimate the NPV, the total earnings of the consecutive number of years for the business are discounted from the Marginal Rate of Return (Malek et al., 2017). The NPV (modified) is expressed in accordance with equation 5 (Malek et al., 2017).

$$NPV = -\beta + \sum_{j=1}^{T} \frac{\phi_j}{(1+R)^j} \tag{4}$$

$$NPV = -\beta \frac{\phi_1}{(1+R)^1} + \frac{\phi_2}{(1+R)^2} + \frac{\phi_3}{(1+R)^3} + \ldots\ldots\ldots\ldots \frac{\phi}{(1+R)^T} \tag{5}$$

The β is a sensitive parameter in the NPV relation which directly is dependent on the feedstock cost; one of the factors that impacts on the investment cost (a significant variable) in the present evaluation, therefore, the profit or loss from the business is proportional to the increase or decrease in the β, and equally affects the IRR discussed in section 2.4.2.

2.4.2. Internal Rate of Return

The IRR is a metric also used in capital budgeting to measure the profitability of potential investments. It discounts all the cash back, hence; causing the NPV to become zero for the stipulated life of the business venture (Malek, et al., 2017). It is represented as shown in the equation 6.

$$NPV = -\beta + \sum_{j=1}^{T} \frac{\phi_j}{(1 + IRR)^j} = 0 \tag{6}$$

A project is more desirable to be undertaken than the other, if it generates higher IRR. At times, different types of business investments may yield uniform IRR, but the tool can be applied to rank multiple potential ventures a firm may consider as the most viable option(s).

2.4.3. Payback Period (PBP)

The time required for the amount of money invested in an asset to be repaid by the net cash flow generated by the asset is referred to as the PBP (Malek et al., 2017). An investment with shorter PBP is better because, it gives the investor a quick picture of the amount of time the initial investment will be on risk. However, the number of years it takes a project to recover its total investment (δ) by earning after interest and tax (μ) is called PBP. Kong et al. (2004) and Hasanuzzaman et al. (2011) have developed an expression for the estimation of the PBP as shown in equation 7: However, the δ is a sensitive parameter in the PBP expression, because, if the cash flows or profit made from the business is poor; then, the business status can be adjusted on the side of profit scale by changing the δ in order to shorten the PBP. Further re-adjustment can be made if economic condition appears better.

$$PBP = \frac{\delta}{\mu} \tag{7}$$

2.5. Emissions from a 5 MW co-gasification energy production plant

In order to generate energy from fuels, various forms of emissions may be accompanied with the process. Notable amongst these emissions, and which will be discussed in the current paper include; CO, CO_2, SO_2, and NO_X.

2.5.1. Emissions reduction by displaced energy

Environmental management is a worldwide issue especial as it concerns global warming caused by emissions from fossil fuels utilization. It is useful to know the amount of emissions that can be reduced if fossil fuel such as coal is replaced with renewable feed material such as biomass, or other solid waste. This can be estimated using the expression (Mahlia, 2002) shown in equation 8. If the power plant is scaled up by increasing the ϖ to either 10 MW, 15 MW or 20 MW, then the ξ will be increased, hence; increasing the amount emissions in the system.

$$\xi = \varpi \times [(\alpha^1 \times \tau^1) + (\alpha^2 \times \tau^2)] + \cdots\cdots\cdots\cdots \alpha^n \times \tau^m \tag{8}$$

In energy production or fuel processing, various emission factors are produced from the fuels. The energy mix in the current study involves coal, biomass, and tyre. Table 1 presents the emission factors of different fossil fuels.

Table 1 here

Moreover, in order to calculate the emission reduction by displaced energy from the co-gasification process, the emission factors of coal and biomass (or solid waste) are very crucial. Table 2 presents the life cycle emission factors for renewable energy sources.

Table 2 here

2.5.2. Emissions from the transportation of biomass, tyres and coals

At times, power plants are not sited together with the fuel production site. Produced fuel such as biomass is transported to the plant room with different sizes of trucks, hence; generating different amounts of emissions during the process. The emission arising from the fuel transportation is estimated from equation 9 (PDD, 2006):

$$\lambda = \left[\frac{A_{FR}\times\gamma\times\omega)}{T_{LPT}}\right] \quad (9)$$

Similarly, and according to the US EAP (2008) report, the emissions arising from different sizes of trucks in gross vehicles weight (GLT) rating for biomass transportation is presented in table 3.

Table 3 here

2.5.3. Effective Emissions Reduction: Biomass Power Plant

With regards to the life cycle GHG emission intensity from biomass (ε) as 0.045 $kgCO_2$ e/kWh, the effective emission reduction arising from a biomass energy plant is expressed as shown in equation 10 (WNA, 2011). The distance covered and type of truck used in transporting fuels has direct impact on the φ model, because if for example, the distance is decreased, and an electric powered truck is used instead of a diesel truck, then the amount of emission from λ will decrease very tremendously.

$$\varphi = \xi - \varepsilon - \lambda \quad (10)$$

3.0. Results and Discussion

3.1 Physio-chemical characterization of the feedstocks

Table 4 here

The physio-chemical properties of the feedstocks had been determined, and it has shown that the Matla coal has high ash content, whereas; the biomass samples have very low ash content as well as little or no Sulphur contents. Therefore, mixture of the two feedstocks as fuel in gasification, will limit the problems that are usually caused by ash and Sulphur from coal (Kumabe, 2006), such as; agglomeration and emissions, respectively. The volatile matter for all the biomass feedstocks and waste tyre were above 71 % and 60 %, respectively, and high volatility in fuel samples (in-organic matter) is an indication of high reactivity, that was impacted on the coal sample (with low volatile content) by the other solid samples to enhance the overall gasification reactivity of the char (Zhang et al., 2016). According to Kumabe et al (2007) & Alzate et al (2009), the co-gasification of high ash coal and biomass has the synergy for enhancing the H_2/CO in the gaseous product which for example, is required for liquid fuel synthesis. The product gas composition and quality, is dependent on several factors including but not limited to the MC of the feedstock (Kamble, 2018). More so, the heating value of the biomass and coal does not indicate a very wide range of value compare to the waste-tyre that has the highest calorific value, and which eventually may influence the energy and economic analysis of the individual feedstocks. However, the compositions of each of the fuel indicated feedstocks of better characteristics for efficient co-gasification process for energy production.

3.2 Energy analysis of the various Feedstocks and their blends

Generally, the MC of a fuel plays a major role in the electric and thermal power production, and table 5 presents the MC and LHV of the various feedstock mixtures used in the co-gasification power generation plant. The table describes the relationship between the MC and LHV of the fuels. It can be observed that the MC of the entire feedstocks except the Coal +

PSD (with the highest LHV), decreased with an increase in the LHV of the fuels, and with an increase (MC and LHV) in the blending ratio. In most cases, higher energy content fuels are more efficient in electric and thermal power production than the lower energy content fuels. Table 5 presents the results of the feedstocks at different blends.

Table 5

3.2.1. Feedstocks requirements for the different blends

Different empirical models had been developed by researcher for the estimation of the calorific values of fuels. The model presented in equation 1 was applied to determine the lower heating value (LHV) of the feedstocks, from the proximate and ultimate analysis of table 4. The HHV was experimentally determined with a bomb calorimeter. The result obtained from the model was in agreement with the range of result found in the literature (16.80 MJ/Kg – 19.50 MJ/kg), hence: was used in the current study. Table 5 presents the results of the feedstocks at different blends.

However, Figure 1a and Figure1b demonstrates the flow-chart of the proposed technical approach for the system and the schematic representation for a co-gasification electric and thermal power plant designed to generate about 5 MW (130 TJ/Yr) of electricity if operated for around 300 days per annum (7200 hr./Yr), respectively. Caputo et al (2005) has reported that the total electrical efficiency of a gasification plant with around 5 MW electric power production capacity is assumed to be 36 %. Based upon this assumption, the utilization of Matla coal and coal + PSD as feedstocks as shown in Figure 1b, generated 5 MW of electricity using 20,000,000 kg/Yr and 18,000,000 kg/Yr of Matla coal and Matla coal + PSD respectively. Furthermore, on the basis that the number of operating hours was about 7,200 h/Yr, around 2,795 kg/h of Matla coal and 2,535 kg/h of Matla Coal + PSD were converted into power by the co-gasification plant hence; producing about 5 MW (130 TJ/Yr) of electricity.

Similarly, in order to recover some costs associated with the electricity production and also maximize the heat arising from the gasification or co-gasification process, condensers or heat exchangers were installed in the form of combined heat and power (CHP) plant. Bridgwater (2004) reported that the overall thermal efficiency of a gasification plant could be assumed to be around 40 %. Under this scenario, around 5.56 MW (144 TJ/Yr) of heat power was produced from the steam-gas unit using Matla coal and Matla Coal + PSD respectively. However, the details of gasification of the Matla coal (as a control process) and Matla coal plus other solid wastes as indicated in the Figure 1b were evaluated for power production, and it can be observed the Figure 1b that the heating value (LHV); a sensitive parameter considered in the estimation, affects both the feed rate and the annual feedstock requirements of the system.

Figure 1a here

Figure 1b here

3.2.1 Relationship between the amount of feedstocks, expenditure and profit for an electric power generating co-gasification plant with 5 MW production capacity

The Matla Coal + PSD indicated the highest yield of profit and lowest expenditure compared to other feedstocks investigated, because PSD was the cheapest feedstock amongst the fuels studied. Normally, fuel with higher calorific value produces higher amount of energy. In this study, the power generating capacity of the plant is known, so the interest is on the feedstock blend that offers the highest profit and of lower emissions with 130 TJ/Yr standard targets. The energy content of Coal + WT was higher than the energy value of Coal + PSD, for this reason; higher electric and thermal power should have been generated from the blend, but was in contrary under WFC condition. Coal + WT should have yielded more profit, but more profit was obtained from Coal + WT, WOFC. It have shown that the calorific value of a fuel and the expenses incurred on the feedstocks, determines the amount of loss or profit that could be realized in a power production venture.

However, it can be observed from figure 2b that more profit was accrued, WOFC than in 2a evaluation, WFC.

Figure 2a here

Figure 2b here

3.2.2. Economic evaluation of coal gasification

The analysis involving Matla coal gasification serves as a control gasification process for the co-gasification of the Matla coal and other solid wastes as shown in figure 3. It can be observed that the amount of feedstocks used for the power production in figures 2a and 2b varied from Matla coal of figure 3 that was used for the same purpose. More fuel was consumed in the Matla coal plant, than in Matla + PSD co-gasification power plant, WFC and WOFC, and about 1,868,806.40 kg of feedstock could be saved annually by using a mixture of Coal + PSD for power production as against using 100 % Matla coal. The implication was that an annual feedstock savings has resulted to a decrease in the capital investment cost per annum; one of the significant factors considered in the assessment, and which also determined the profit and/or the feedstocks viability for energy production.

Figure 3 here

3.2.3. Co-gasification of the various feedstocks

Generally, figures 4 and 5 highlights the influence of the various feedstocks investigated and their economic parameters, WFC and WOFC, respectively. Coal + solid waste blending ratio of 1:1 was reported, because it was the optimum blending ratio. Figure 4 shows that Coal + CC blend yielded the lowest profit, because corn cob is costlier than SCB and PSD.

Figure 4 here

The heating values of the fuels are in the increasing order of Coal + CC, Coal + SCB, Coal + PSD, and Coal + WT (although they were not shown in the plot), and the profit increased with an increase in the feedstock's heating value (figure 5)

Figure 5 here

However, the ultimate analysis result (table 4) from WT has the highest amounts of carbon and hydrogen amongst the feedstocks studied. Carbon and hydrogen are the major combustible part of a fuel and hence; determines the energy content of the fuel. The energy content of WT is higher than the energy content of all other fuels studied. Thus; Coal + PSD of figure 5, was the optimum, WOFC.

3.2.4. Effect of Feedstocks blending ratios

Figures 6a and 6b present the economic evaluation of Matla Coal + PSD, WFC and WOFC at a blending ratio of 4:1 respectively. Both figures 6a and 6b (4:1) were compared to figures 2a and 2b (1:1). The result obtained from Coal + PSD mixture at a ratio of 4:1 and as shown in figure 6a, and compared to Coal + PSD mixture at a ratio of 1:1 of figure 2a, revealed that increasing the content of Matla coal in the blend, increased the expenses in the power generation by around 14.68 %. This in turn decreased the profit accrued by around 7.95 %. In this scenario also, the amount of feedstock used in the 4:1 blending ratio was increased by around 3.78 % compared to 1:1 mixture, thus amounted to a loss of about ZAR6, 461,301.771, WFC. It was considered as a loss because, the same amount of fuel from 1:1 Coal + PSD fuel mixture were used to produce the same quantity of electricity and thermal power of 5 MW and 5.56 MW, which on the utilization of the 4:1 blending ratio, increased the feedstock, hence; leading to the exorbitant loss of money.

Meanwhile, Bada et al. (2016) have reported that co-firing coal and biomass at the ratio of 1:1 will cause the reduction in the CO_2 emissions by 50 %. The current report (though not CO_2 emission per say), therefore, have also demonstrated that around ZAR6, 461,301.771 could be saved by using 1:1 coal to solid waste mixture as against 4:1 mixture, for a co-gasification plant of 5 MW electric power generation capacity. On the other hand, WOFC, and still with the same increase in the amount of fuel of 3.78 %, an increase in the expenditure by around 0.70 % was observed. This therefore led to a decrease in the profit by 0.12 % (ZAR 123,782.50).

Generally, the increase or decrease in the amount of feedstock and expenditure or profit were basically attributed to the price of South African Coal which currently is about $74.46/Ton Coal (ZAR1, 042.44/Ton Coal) compared to the solid wastes (sugarcane bagasse, corn cob, pine saw-dust, and waste-tyre) cost that are also within the range of $10.71/Ton – $42.86/Ton (ZAR149.94/Ton – ZAR600.04/Ton). Table 6 highlights the prices of the feedstocks as obtained in South Africa and some parts of the globe.

Table 6 here

Under this context, if biomass fuels (not waste biomass - e.g. miscanthus, switchgrass, beech-wood, etc.) are purchased either within or outside South Africa at the rate of around $120.00/Ton – $170.00/Ton of biomass, then it will be cheaper to generate electricity and heat from South African Matla coal than from the biomass. In overall, the analysis presented in section 3.2.1 – 3.2.4 demonstrated that the energy content of the feedstock (LHV), cost of fuel, and the blending ratio were the most significant factors influencing the estimation, although the future value of money determined in each investment year through the NPV, and reported in section 3.3, was equally a crucial influencing factor in the assessment.

Figure 6a here

Figure 6b here

3.2.5. Effects of Feedstocks on the Economic Parameters: Percentage basis

Understanding the changes in the economic parameters of feedstocks used for electric and thermal power production with regard to their percentage changes is a very important aspect of energy and economic analysis. Table 7a presents the variation in feedstocks economic parameters, WFC and WOFC, and table 7b describe (in percentage basis) the potentials of the other solid wastes studied over coal, for power generation. At this point, the analysis describes the benefits of using mixtures of coal and other solid wastes against using coal, and relative to profit making.

Table 7a here

Table 7a in real terms, describes the annual fuel savings and cost savings from the individual feedstocks, and as well, highlights how each feedstock differs from one another in terms of power production economy.

Table 7b here

Meanwhile, with reference to profit making (WFC: 1:1), Coal + PSD & Coal + CC, Coal + SCB & Coal + CC, Coal + WT & Coal + CC, Coal + SCB & Coal + PSD, Coal + WT & Coal + PSD, and Coal + WT & Coal + SCB were evaluated. Low or high profit had been described to be related to the CV of the fuel, and the investment cost. It was observed that higher profits were made from Coal + PSD, Coal + SCB, Coal + WT than the mixtures they were compared with. And more profits were equally made from Coal + PSD and Coal + WT than the blends which were compared with them, respectively. Details of the analysis at 10th year (WFC & WOFC) are presented in the **supplementary material.**

3.3. NPV, IRR and PBP Analysis

The capital cost investment here is referred to as the total expenditure incurred on the feedstocks in order to generate 5 MW of electricity, and the cash flow is regarded as the annual profit obtained by subtracting the total expenditure from the revenue generated from the sales of electricity at the rate of ZAR1.74/kWh of electric power.

The venture embarked from the 1st year to the 10th year was attractive, except 4:1 coal-to-solid waste blend, WFC. The status of the venture was shown in figures 7 – 9. The capital cost investment from Coal + CC was higher than the rest of the feedstocks studied (figure 8) hence; resulted to the lowest NPV, whereas; the NPV from the Coal + PSD was the highest out of the fuels investigated due to its lowest capital cost investment.

Figure 7 here

Figure 8 shows a significant increase in the NPV of all the feedstocks, because of the lower capital investments incurred from the individual feedstocks compared to figure 7. The price of WT (table 6) is higher than the prices of all the agro-wastes studied. Despite that, Coal + WT mixture that has the highest heating value still, produced the highest NPV (WOFC).

Figure 8 here

Figure 9 presents similar assessment using 4:1 Coal-Solid waste blending ratio, WFC.

Figure 9 here

A poor investment was indicated in figure 9, because the NPV at the end of the 10-year period were negative, and the cash returns were insufficient to encourage further investment, under the conditions and feedstocks investigated.

3.3.1. Effect of the increase in the business period on the business viability

The business life was increased from 10 to 11 years. All the fuel mixtures from the 1:1 and 3:2 ratios except the Coal + SCB from 3:2 fuel blend remained viable, whereas; all the investment made with the 4:1 fuel ratio was not viable, because of the effect of the capital cost investment and time value of money on the NPV. Similarly, all the feedstocks remained viable for the power production, WOFC, and the 1:1 Coal-to-Solid waste ratio indicated the most attractive venture. The details of the analysis WFC and WOFC at the 11th year can be found on the **supplementary data**.

3.3.2. Effect of the increase in the business period on the venture: From 11 – 17 years

The essence of this analysis was to identify when exactly the investment would become a wasteful venture. The information will be a guide both to the Energy Analysts and potential investors prior to investing in the area. Only 1:1 Coal-to-PSD was viable, and the IRR from all the feedstocks used for the venture was lower than 5 % (the initial annual interest rate) except Coal + PSD. A comprehensive result of the assessment is shown in table 8, WFC whereas; the detailed analysis WOFC is presented in the **supplementary data.**

Table 8 here

3.3.3. Extension of power production investment to check its viability: 2017 – 2035

The business period starting from 2017 and ending at the 18th year, has its period as 2017 – 2035, and none of the ventures were viable. Figure 10 highlights the viability status of the business for 1:1 coal-to-solid waste ratio, and indicated a negative NPV for all the feedstocks investigated, WFC. Similar observations were made in other blends, therefore engaging in the business with any of the feedstocks up till 2035, would be a waste of resources, whereas; WOFC was encouraging.

Figure 10 here

The results for 3:2 and 4:1 blends (WFC) are shown in the **supplementary data.**

3.4. Environmental Impact Assessment: 5 MW co-gasification power plant

A co-gasification power generation plant operating at 5MW capacity, can use Coal + SCB, Coal + CC, Coal + PSD, and Coal + WT of about 20,473,451.41 kg, 20,986,049.96 kg, 18,251,806.49 kg, and 15,276,277.85 kg respectively to produce the 5 MW of electricity annually. Coal is commonly used for power production in South Africa. If these feedstocks displace coal for the energy production, it is expected that the amount of GHG arising from the conversion process will be much reduced. Most importantly, the amount of CO_2 that will be available to be stored in the current Carbon Capture and Storage (CCS) Project taking place in South Africa, will also be reduced. However, a change in the plant's capacity such as 50 % or 100 % scale-up, will definitely increase the feed rate and annual feedstock requirements, investment cost and profit, and as well, the emissions in the plant, but may not actually disrupt the existing pattern of the results. Table 9 presents the effective emission reduction arising from the different feedstocks studied.

Table 9 here

The coal-to-solid waste ratio of 1:1 (table 9) produced the lowest amounts of CO_2 and SO_2 emissions, and the emissions increased as the amount of coal in the various mixtures increased for all the feedstocks investigated. Similarly, Coal + PSD produced the lowest amounts of CO_2 and SO_2 emission reductions, whereas; Coal + WT gave the lowest CO and NO_X emission for all the feedstocks investigated. In overall, it is possible to reduce the CO, CO_2, SO_2, and NO_X emissions by around 3.4 %, 23 .28 %, 22.97 %, and 0.55 % using the Coal-to-PSD 1:1 ratio as against the 4:1 Coal-to-PSD mixture. The CO_2 emission from the Matla coal was 5900.00 kg CO_2 ekWh whereas; the CO_2 emissions from Coal + PSD or other biomass and waste investigated at a ratio of 1:1, was 2950.00 kg CO_2 ekWh (50 % reduction). Meanwhile, Bada et al (2016) have also reported a similar trend using 1:1 coal-to-biomass mixture, thus; further information on the emission assessment by displaced energy can be found in the **supplementary data.**

3.5. Comparative Assessment of electricity and thermal power production plants

Table 10 presents a compare of the present work and other previous works. The information contained in this section are basically analysis from different researchers on studies related to electricity and thermal power generations including the technology, system capacity, feedstock and inferences from the study conducted. Malek al., 2017 used a biomass-based steam generating plant to study the energy efficiencies, cost implications, environmental effect, and the potentials of a 10 MW biomass power plant in Malaysia. Two financial cases including; with loan and without loan were tested and using MC, heating value, and investment cost as the major variables, and with an application of NPV, IRR, and PBP as the appraisal tools. Different system efficiencies namely; 20 %, 30 % and 40 % and investment years of 2015, 2020, 2030, and 2050 were reported. It was observed that savings of about MYR 0.88 – 2.43 million was made from the plant, by using raw EFB (biomass). In the current study, a 5 MW CHP plant was assessed using feedstocks originated from South Africa, and about 1,868,805.41 Kg of fuel was saved in the plant by using Coal-to-PSD ratio of 1:1, WFC, hence; making the fuel mixture the optimum amongst the feedstocks studied. Malek and group also reported that system efficiency of 25 % - 40 % could be achieved from various biomass-based steam plant, and that significant amounts of CO_2, SO_2, NO_X, and CO emissions (Table 10) were reduced in the plant compared to the existing Malaysian energy mix, whereas; the effective emission reduction of around 3.4 %, 23.28 %, 22.9 %, and 0.55 %, of CO, CO_2, SO_2 & NO_X were obtained from the 5 MW CHP assessed in the present work. The energetic efficiencies and cost of investment were the most uncertain variables reported by Voets et al (2011) during their estimations using biomass of Belgium origin, and the variables rendered the 20 MW technology option analyses unclear. However, 10th year, and Coal-to-Solid waste ratio of 1:1 were the optimum investment year, and blending ratio for the current analysis. Details of the flash Pyrolysis and gasification plants and the biomass-based Rankine Cycle steam power plant can be found on Voets et al (2011) and Malek et al (2017).

Table 10 here

3.6. Influence of Energy, Economic and Environmental Policies on the analysis results

It is expected that in the future, policy makers in energy, economic and environmental sectors could change the existing policies in order to enhance sustainability in the fields. For example, if the prices of fuel were based on the heating value of the fuel and not on the availability or production cost of the feedstock, the result of the current analysis will definitely be affected. In this work for instance, the price of PSD was cheaper than the price of WT, but the calorific value (CV) of WT was higher than the CV of the PSD, therefore if the feedstock price was based on the CV of the fuel, and would have made a serious impact on the economic (profit) assessment, thus; allowing Coal + WT to be the optimum feedstock for all the conditions investigated.

Secondly, if environment regulations and/or policy are to be promulgated, and restricting the transportation of biomass only with specific type of trucks such as electric powered trucks (batteries) and solar vehicles, emissions will be further reduced. In this case, the overall result of the present analysis will be changed.

3.7. Sensitivity of the NPV and Impact of Uncertainty

In order to evaluate the sensitivity of the NPV and impact of uncertainty on the viability of the feedstocks on energy production in the 5 MW power plant, the variance, standard deviation (SD) and standard error of the major variables in the analysis were estimated, using 2016 excel software, or manually from equations 11, 12, and 13 (Zady, 2009), respectively. and the result is shown in Table 11a. X represents the variables including amount of feedstock, capital cost investment, cash flow and net present value, while $\bar{x}$ is the mean of the variables.

$$SD = \sqrt{\frac{\Sigma(\mathrm{X} - \overline{\mathrm{X}})^2}{N-1}} \tag{11}$$

$$Variance = \frac{\Sigma(\mathrm{X} - \overline{\mathrm{X}})^2}{N-1} \tag{12}$$

$$Standard\ Error = \frac{\mathrm{SD}}{(N)^{1/2}} \tag{13}$$

Table 11a here

The standard error of the mean (SE0M) is referred to as a measure for the variance of NPV distributions (Voets et al., 2011), which is dependent on the blending ratios of the variables mentioned earlier, and their SEOM were equally estimated. Basically, to enhance the comparability of this measure for different blending ratios of the fuel, the SEOM was divided by the mean value of the NPV of the feedstocks from the various blends. The mean and relative standard (percentage) error (RSE) of all the feedstocks, and for the amount of feedstock, capital cost investment, cash flow, and net present value (NPV), that were obtained from the three different fuel blends studied in the plant (10th year), WFC are shown in Table 11b.

Table 11b here

The feedstock blending ratio and investment cost were considered as the most significant variables. Both the amount of fuel and energy content of the fuel (not shown in table 11b) has direct impact on the investment cost, as can be observed in the mean value of the RSE of Table 11b. According to the report of Australian Bureau of Statistics (ABS, 2009) on Labour Force Standard Error, a RSE of 25 % or greater is prone to high sampling error, hence; should be used with caution. Most of the RSE presented in Table 11b are less than 25 %. Meanwhile, coal-to-solid waste ratio of 1:1 was the optimum blend in terms of fuel and investment cost savings, and emission reduction. This blend has the highest mean NPV as shown in Table 11b, and the information contained in the table are among the factors that allows investors to make their decisions about an investment. In one hand, risk averse investors may embark on the energy production with the lowest RSE, or the investment that yield the highest mean NPV, in the other hand; risk seeking investors may choose the project with the highest mean NPV.

However, the sensitivity analysis was carried out using Figure 7 and Figure 8 as well as Table 9 as the base model; the optimum investment conditions in the plant. From Table 11b, the coal-to-solid waste ratio of 1:1 has the highest mean NPV, whereas; in the absent of 4:1 mixture, the lowest RSE was produced by the 3:2 feedstock blend. The 4:1 blend clearly indicated an un-attractive investment, as can be observed from the negative value of the mean NPV, thus; should not be ventured by investors. Figure 7 (base model) have demonstrated that Coal-to-PSD ratio of 1:1, WFC was the optimum feedstock and blending ratio for the energy production following the variables earlier mentioned. With reference to the value of NPV of the base model, for the most profitable condition, there was no deviation with the option of the most viable condition for the highest mean NPV.

On the basis of emission reduction in the plant, the optimal condition (1:1 blending ratio) can as well, be observed in Table 9. The Coal + PSD produced higher CO and NO_X emissions, as well as lower amounts of CO_2 and SO_2 compared to Coal + WT that yielded lower CO and NO_X, plus higher CO_2 and SO_2 emission. Under this contest therefore, at blending ratio of 1:1, the choice of feedstock for optimum emission reduction in the plant is unclear on the account of uncertainties. The two feedstocks possesses equal chance for positive NPV, but it is ambiguous stating which feedstock will yield the highest NPV, therefore, emission reduction should be a major variable for future research. However, the results of the mean of AOF, CCI, and CF variables of the 1:1 fuel mixture of Table 11b, that impacted on the NPV mean, is in affirmation with the most viable option depicted in Figure 7; the base model.

Similarly, the sensitivity analysis for the variables WOFC is presented in Table 11c. It can be observed that the mean value of the NPV of 4:1 fuel mixture, was higher than the mean value of NPV of the 1:1 fuel mixture, whereas; the RSE value of the 4:1 fuel blend was lower than the RSE value of 1:1 fuel mixture. Investors may freely decide to embark on the project (WOFC), on the grounds that the actual cost of the feedstock was discounted, thus; reducing the overall investment cost. This is contrary to the result indicated for the choice of the most profitable feedstock or condition in the plant considering the feedstock with the highest NPV of Figure 8 (the base model - 1:1 ratio, WOFC), and the choice of the most profitable feedstock or condition with regard to mean value of the NPV (1:1 ratio, WOFC of Table 9). The variance in the NPV was an indication of the high level of influence the investment cost has on the economic analysis. However, investment cost and blending ratio are the most sensitive variables in the analysis.

Table 11c here

Secondly, in the base model, Coal + WT has the highest NPV, hence; making the feedstock/blending ratio the most profitable condition (WOFC), but the result deviated from the value of the mean NPV of Table 11c, instead; the highest mean NPV value was 4:1 blending ratio. The implication was that the investment cost has a significant impact on the NPV, thus; can influence the decision of investors. Analogously, WFC Coal + PSD (1:1) was the most attractive condition, whereas; WOFC Coal + WT was the most viable condition in the energy plant due to the investment cost and feedstock blending ratio.

4.0. Conclusions

An evaluation on the economic, energy and environmental viability of a 5 MW co-gasification power plant has been carried out, using Coal blended with SCB, CC, PSD, and WT, respectively, WFC and WOFC at a ratio of 1:1, 3:2, and 4:1 respectively. The heating value, investment cost and emissions were estimated, whereas; the investment cost and feedstock blending ratio were the most significant factors considered. The NPV, IRR, and PBP tools were used to evaluate the power generation project at different business periods including; 10th, 11th, 17th and 18th year respectively. Coal + PSD mixed at a ratio of 1:1, WFC, was the most attractive feedstock for the energy generation in the power plant. The business viability order are Coal + PSD, Coal + WT, Coal + SCB, and Coal + CC, but WOFC, the order include; Coal + WT, Coal + PSD, Coal + SCB, and Coal + CC. 100 % Matla coal was not cost effective, and it produced higher emissions compared to other feedstocks investigated. A higher profit of around 13.82 % and 23.56 % were made from Coal + PSD compared to 100 % Matla coal, WFC and WOFC thus; enabling a savings of about 1,868,805.41 kg of feedstock, annually. However, the following conclusions were also drawn:

- The use of 4:1 Coal-to-PSD ratio for the power generation in the energy plant, as against 1:1 Coal-to-PSD ratio resulted to a loss of around ZAR6, 461,301.77 ($90,458,224.70) and ZAR123,782.47 ($1,732954.58), WFC and WOFC, annually.
- At the 10th year, 4:1 coal-to-solid waste blends, was not viable WFC, but Coal + PSD remained viable at the 17th year, whereas, at the 18th year, none of the feedstocks remained attractive for the business venture, WFC.

- The power plant used 20,473,451.41 kg, 20,986,049.96 kg, 18,251,806.49 kg, and 15,276,277.85 kg of Coal + SCB, Coal + CC, Coal + PSD, and Coal + WT to produce the 5 MW and 5.56 MW electric and thermal powers, annually.
- Coal-to-solid waste ratio of 1:1 produced the lowest amounts of CO_2 and SO_2 emissions, and generally, emissions increased as the amount of coal in the various mixtures increased for all the feedstocks studied.
- Emission from the energy plant was significantly reduced by the use of 1:1 Coal + PSD ratio.

4.1. Limitations and Future Work

Modelling and simulation are important aspect of the present work, but it was not carried out due to un-availability of the tool during the time of the analysis. Similarly, coal sample from Matla mine was the only feedstock used in the investigation. It is important that an extensive research and development (R&D) on the techno-economic analysis of the power plant studied in this work is further investigated using coal from different geographical locations in South Africa. Secondly, a suitable commercial predictive software such as artificial neural networks (ANNs) or Aspen Plus, should be used to predict the various parameters estimated, and make a compare of the two results. The resultant of this endeavor will widen R&D in this area of study.

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