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Roadmap Towards Clean Coal Technology for Sustainable Power Sector in South Africa

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South Africa has sufficient coal resources to meet future energy demands. But reliable energy generation fleets are needed to use this local energy resource. However, the generation of energy using coal-fired power plants presents several environmental concerns. The export market's need for high-quality coal results in a decline in coal quality, which results in increased environmental regulation non-compliance. In this study, five samples of coal covering a wide range of qualities obtained from mine stockpiles supplying coal-fired power plants were collected, and standardized processes were used to prepare them for various analyses. Based on the results of coal characterization and resultant emissions, a wide range of technology options should be made available for different types of coal quality and all these technologies are presented in the current study. In order to find solutions that will satisfy the demands of coal users for dependable, tried-and-true technology while also meeting environmental regulations criteria, various limitations were used to sort through the available technologies. Although the coal roadmap proposes three possible routes, ranging from business-as-usual physical methods to chemical methods and biological methods, South Africa will likely have to take a hybrid approach to reduce emissions and address electricity supply as well as demand issues. South Africa's aging electricity generation infrastructure, sluggish economic growth and water shortages support this. Such processing methods could drastically reduce power sector SO_2 emissions if they are commercially feasible. This roadmap outlines the challenges that the power sector must overcome and provides an overview of potential treatment initiatives for the coal-fired power plants that South Africa may implement over the coming years for both newly built coal-fired plants and aging generation fleets.

Keywords: Technology; Clean coal; Roadmap; Emissions

1. Introduction

Energy drives the country's economy, therefore, meeting demand is crucial to economic growth. South Africa, like many other emerging economies, struggles to provide electricity for a growing population while reducing emissions. A high-capacity demand is placed on South Africa's aged coal-fired generation fleet. In order to meet the country's energy needs and the growing African grid, most generation facilities must operate at full capacity. Although two new coal plants are being built, delays on one of them while the other is operating at reduced capacity due to design and commissioning challenges put more pressure on the existing generation units, making it harder to take them offline for maintenance, upgrading, or retrofitting. Although there is a strong trend toward renewable energy, these technologies are not yet ready to offer baseload capacity for such a big and growing nation as the Republic of South Africa.

Global climate change is the most significant environmental problem of the 21st century worldwide. South Africa has huge wind, solar, and biomass energy potential. However, coal, a cheap but environmentally harmful fuel, is its main source. To address these serious environmental and socioeconomic challenges, the South African Ministry of Environmental Affairs (DEA) will enforce SO_2 minimum emissions standards. South Africa is now faced with the problem of high SO_2 emissions in recent years following the passing of SO_2 Minimum Emissions Standards (MES). All coal and liquid fuel-fired power stations must meet Section 21's MES under the National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004). Hence, it is necessary to promote

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efficient clean coal technologies and the utilization of coal as a source of energy to reduce emissions. Therefore, advances in clean coal technology are driven by pollution requirements. The depletion of existing coal mines along with the ageing of the existing coal-fired generation fleet, the economic drivers for exporting high-rank coal to the international market, and a 10-year lapse since the first unit of the last new power plant was commissioned provide significant challenges for scaling up to a 4.4% annual load growth (Song et al., 2017). Therefore, if coal is to remain the most important fuel for power generation in developed countries, the methods of pre-combustion, combustion, and post-combustion must advance towards zero or near-zero emissions, which is an important issue in the development of clean coal technologies.

Coal burning creates CO_2, the main greenhouse gas (GHG) in the South African power sector. the South African power sector discharged 223.4 Mt of CO_2 in 2015, down 4% from 2014 (Akinbami et al., 2021). In addition, the South African power sector emitted 2919 t of N_2O, a greenhouse gas 298 times more potent than CO_2. Coal-fired power plants emit particulates, SO_2, and NO_2 (Akinbami et al., 2021). Many researchers worldwide have established a technical method for constructing an air quality improvement roadmap, offering the scientific underpinning and technical aid for mid and long-term air quality management policy-making. Researchers have explored clean coal technologies for CO_2, NOx, and particulate matter reduction, but no detailed method has been offered for SOx technology deployments depending on coal characteristics in the power sector. The cost of any proposed technology was not considered for economic assessment. Thus, the objective of the current study is to identify the power sector roadmap to satisfy South Africa's energy-saving and emission-reduction criteria. All studies employed five power plant coal samples. Standardized procedures collected and prepared these coal samples for analysis.

2. Materials and methods

2.1 Coal samples

All studies were conducted on five coal samples collected from various stockpiles of mines supplying power plants. These coal samples were collected and prepared for different analyses using standardized procedures.

2.2 Ultimate analyses

Ultimate analyses such as Carbon, Hydrogen and Nitrogen were determined using LECO-932 CHNS Analyser following ISO 12902 standard procedure. On the other hand, the total sulphur was determined in duplicates using Leco S-628 Elemental analyzer at 1350 °C following ASTM D4239-14 standard procedure.

2.3 Proximate analyses

The proximate analyses measure moisture, volatile matter, ash, and fixed carbon (by difference). The solids remaining after the determination of the volatile matter are the whole of the mineral matter and the non-volatile matter in the coal. Fixed carbon is non-volatile organic matter. In the proximate analysis, the fixed carbon is determined by subtracting the total percentage of moisture, volatile matter and ash from a hundred. As a result, fixed carbon gathers all errors from other variables (ash, moisture, and volatile matter) measurements. Moisture content in the coal was determined by establishing the mass loss of a coal sample after drying it in an oven with a set temperature of 150 ± 5 °C and forced air circulation following the ISO 11722 (2013) standard procedure. Ash is the residue that remains after all the organic matter has been driven off during combustion. Ash is determined in a furnace maintained at a temperature of 815 °C ± 10 °C using the ISO 1171 (2010) standard procedure. Volatile matter is determined in a carbonite furnace at a temperature of 1000 °C following the ISO 562 (2010) standard procedure.

2.4 Determination of calorific value

Coal samples were burned in a bomb calorimeter and the calorific value was measured following the ISO 1928 (2009) method.

2.5 Ash oxides analysis oxides

X-ray Fluorescence (XRF) was used to determine the elemental composition of ash oxide following the ASTM D3682-13 method.

2.6 Experimental set-up

The experiment was conducted on a typical 660 MW once-through Benson type steam boiler unit of a South African coal-fired power station.

3. Results and Discussions

3.1 Coal qualities trend

In Tables 1 - 2, the values shown are of proximate analysis giving the moisture, ash and volatile matter, while the difference results in fixed carbon. Concerning coal qualities, the five coal samples may be described as follows. The hydrogen content of the coal samples is ranging from 3.02 – 3.24 wt.% which is consistent with the range of coal samples within the Republic of South Africa. Nitrogen is a major coal component inferior to sulphur in the hazard it poses to the environment. According to Krzywanski et al., (2018), coal generally contains nitrogen, and this becomes a source of NOx during combustion. All samples have a nitrogen content in the range of greater than 1.30 wt.%. A similar observation is also reported by Phiri et al. (2017) who found that nitrogen content in coal occurs in minor proportion in the order of 2% or less. Similar to fixed carbon, oxygen gathers all errors from other variables tests. The oxygen content, which is inversely proportionate to the carbon content helps with the ignition of coal samples during combustion. Hence, coal samples containing oxygen content in the range of 3.45 – 7.68 wt.% studied are more prone to spontaneous combustion. Coal stacking, compacting and spraying water on stockpiles prevent spontaneous combustion.

The coal samples have roughly the moisture contents within the range of 8.00 – 8.20 wt.%. Usually, the higher moisture content in the coal is less desirable because moisture content reduces the heating value, and its weight adds to the transportation costs of coal in case of transportation. It was also observed that the percentage sulphur content in the five coal samples studied covered a range of sulphur content ranging from less than 1 wt.% (low-sulphur coal), greater than 1 wt.% and less than 2 wt.% (medium-type coal) and to more than 2 wt.% (high sulphur coal), therefore, co-firing of these coal samples is expected to produce a range of SO_2 emissions from the coals, and the choice of the emissions reduction technology will be based on the emissions generated. Furthermore, high sulphur content also affects the heating value which is in consistent with the view of the current study (Qi et al., 2019). Low-volatile coal accounts for about 40% of the total coal used in power station boilers (Adesina et al., 2022). Because of its poor reactivity, low-volatile coal is characterized by late ignition, unstable combustion, and insufficient burnout (Song et al., 2018). On the other hand, the volatile matter content varies within the range of 20 wt.%.

In terms of calorific value, under the South African coal standard classification, the calorific values of the coal samples were determined and found to be within the range of 19.96 – 20.11 MJ/kg which is within the error of repeatability for analysis. All five coal samples are considered to have high ash contents ranging from 29.26 – 31.10 wt.% according to the ash yield classification of SANS 11760 (2007).

Table 1: Proximate analysis (wt.%, adb)

Properties	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
H_2O	8.12	8.00	8.10	8.09	8.15
Ash	29.89	30.23	30.20	29.26	30.46
FC (by diff.)	41.83	41.62	41.52	42.48	41.21
VM	20.16	20.15	20.18	20.17	20.18
Total	100.00	100.00	100.00	100.00	100.00

Table 2: Ultimate analysis (wt.%, adb)

Properties	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
H_2O	8.12	8.00	8.10	8.09	8.15
C	49.45	49.60	49.78	50.12	51.70
H	3.05	3.10	3.02	3.11	3.24
N	1.30	1.33	1.34	1.35	1.38
S	0.51	0.78	1.02	1.54	2.03
O (by diff.)	7.68	6.96	6.54	6.53	3.45
Ash	29.89	30.23	30.20	29.26	30.46
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
CV	19.96	20.03	20.11	20.07	20.05

3.2 Ash oxides analysis

Coal ash residue from burning coal contains silicon, aluminium, iron, calcium, magnesium, titanium, manganese, sodium, and potassium oxides partly mixed as silicates, sulphates, and phosphates. Ash composition helps anticipate ash and slag behaviour during the combustion process and evaluate coal combustion ash use. The results are presented as oxide basis of which the sum approximates to 100%. Table 3 shows the five coal ash samples major minerals. Table 3 shows that silica (SiO_2) and alumina (Al_2O_3) dominate at 58 and 22 wt.%, respectively. P_2O_5, Na_2O, and K_2O appear in minor proportions of 0.42, 0.60, and 0.79 wt.%, respectively. Makgato and Chirwa (2017) found comparable results.

Table 3: Ash oxides mineral analysis (wt.%, adb)

Properties	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
SiO_2	58.36	58.11	58.34	58.24	58.13
Al2O_3	22.31	22.23	22.34	22.26	22.46
Fe2O_3	4.00	4.00	4.00	4.00	4.00
TiO_2	1.30	1.30	1.30	1.30	1.30
P_2O_5	0.42	0.42	0.42	0.42	0.42
CaO	5.40	5.40	5.40	5.40	5.40
MgO	1.10	1.10	1.10	1.10	1.10
Na_2O	0.60	0.60	0.60	0.60	0.60
K_2O	0.79	0.79	0.79	0.79	0.79
SO_3	2.10	2.10	2.10	2.10	2.10

3.3 SO_2 emissions for various coal qualities

Figure 1 depicts the SO_2 emissions from the quality of coal, which vary by geographic region of coal production. It can be seen in Figure 1 that Sample 1 is 979 mg/Nm^3, Sample 2 is 1498 mg/Nm^3, Sample 3 is 2670 mg/Nm^3, Sample 4 is 4032 mg/Nm^3 and Sample 5 is 5215 mg/Nm^3. In summary, coal with a higher sulphur content of 2.03 wt.% leads to greater SO_2 emissions of 5215 mg/Nm^3 than coal with a lower sulphur content of 0.51 wt.%, leading to lower emissions of 979 mg/Nm^3. In general, the source of SO_2 emissions in the power sector originates from the sulphur content of coal. The current study agrees with Makgato and Chirwa (2017), who found that 1.37 wt.% and 0.20 wt.% sulphur content were needed to meet the minimum SO_2 emissions standards of 3500 mg/Nm^3 (Target 1) and 500 mg/Nm^3 (Target 2). Target 1 and Target 2 differ owing to 2020 and 2025 minimum emissions requirements implementation. To comply with strict environmental rules, all coal qualities must minimize sulphur content through pre-combustion, combustion or post-combustion.

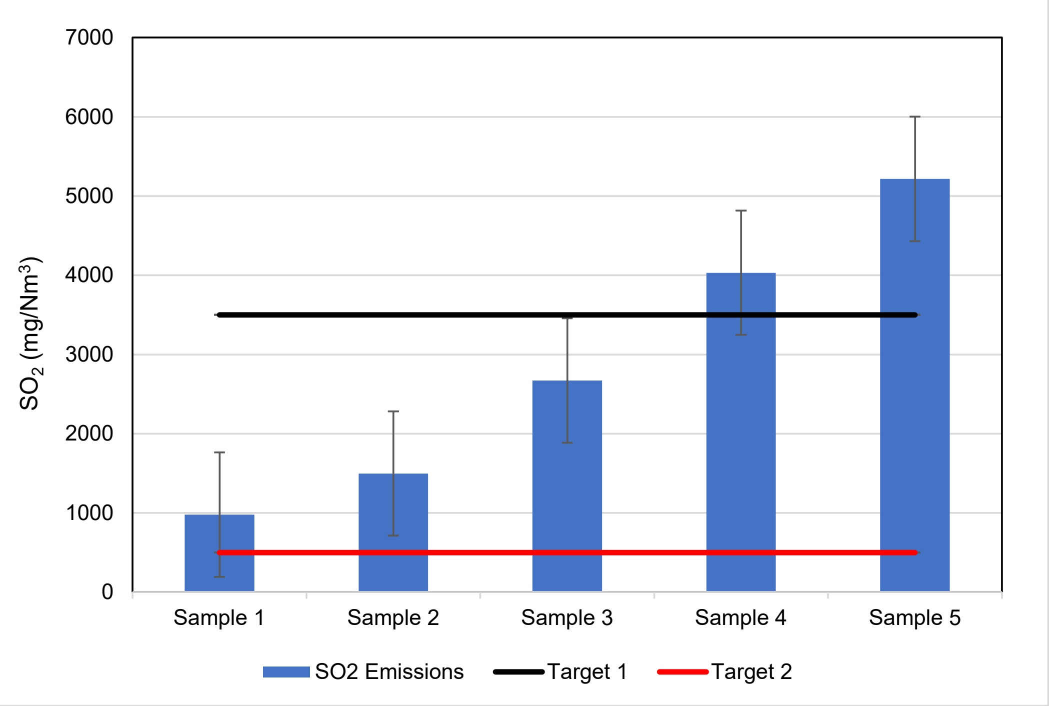

Figure 1: SO_2 Emissions resulting from five coal samples.

3.4 Clean Coal Technology Options

Sulphur forms in coal can be removed by several desulphurization technologies. This section classifies these technologies, estimates their development between now through 2050 and describes environmental compliance alternatives for each. This clean coal technology roadmap covers South Africa's limits and power generation sector possibilities today as well as over 30 years. However, clean coal technology methods depend on the coal's quality, structure and minerals makeup. Figure 2 depicts proposed South Africa-compliant clean coal technologies. Water, labour and emissions-control sorbent shortages will influence technology choice. These limits examine technologies to find ones that meet the country's environmental and reliability standards. The roadmap's worst-case scenario—rapid implementation of strict environmental criteria—would leave South Africa with few coal-fired power plant options.

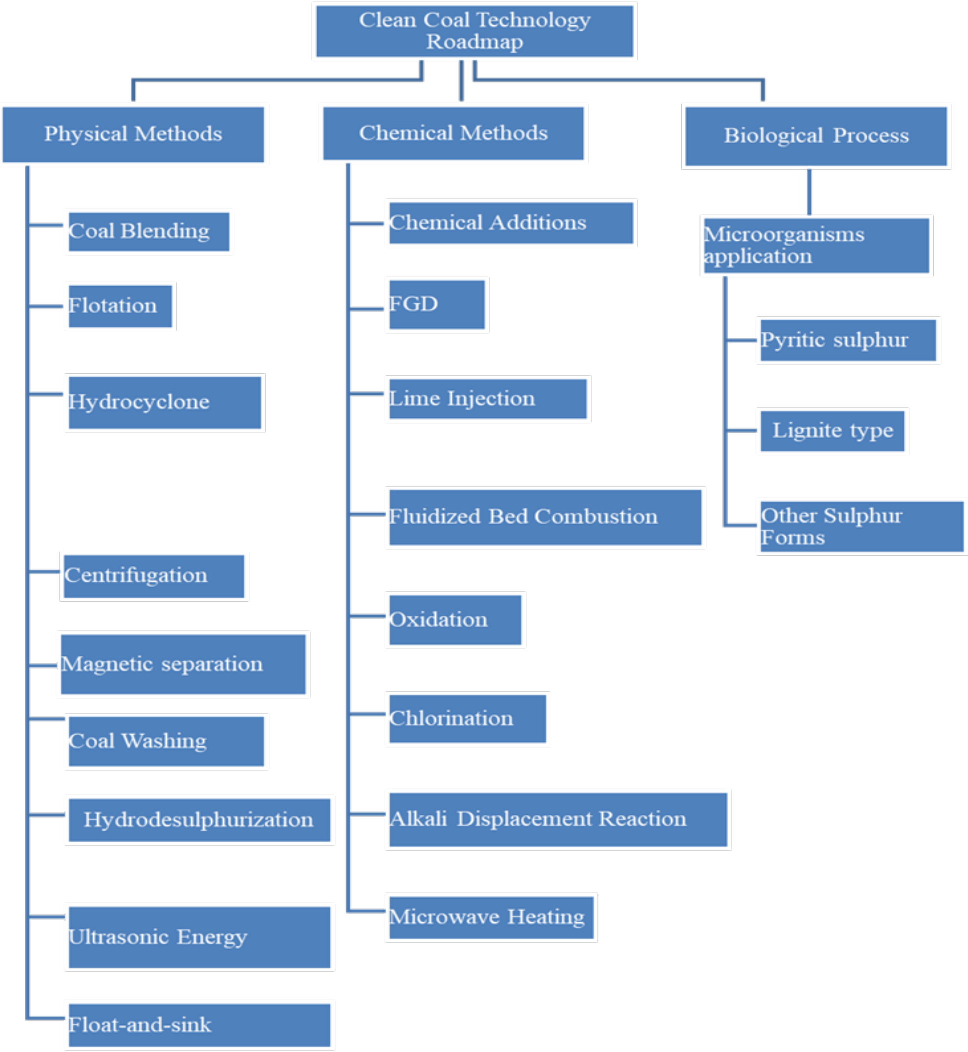

Figure 2: Clean coal technology roadmap

The clean coal technology roadmap examines local power generation industry SO_2 emission reduction strategies for aging fleets and new projects. The coal roadmap suggests these three methods: business-as-usual physical, chemical, and biological processes. Therefore, South Africa will have to combine all possibilities for various generation fleets to move toward an emissions reduction approach while addressing energy supply and demand issues. South Africa's aging electricity generation infrastructure, poor economic growth, and water limitations will determine its economic support technologies. Thus, South Africa should do multiple feasibility studies on some of Figure 2's advanced technology and water use. The feasibility studies should help South African areas choose novel coal technologies that meet their needs and reduce emissions. Therefore, new projects should utilize post-combustion procedures like flue gas desulphurization (FGD), while older fleets should use pre- and post-combustion methods like desulfurization and sorbent injection.

4. Conclusions

The current study examines clean coal technologies that can help South Africa reduce SO_2 emissions over the next 30 years. All studies were conducted on five coal samples collected from various stockpiles of mines supplying coal-fired power plants in South Africa, covering a range of coal qualities. The main conclusions are summarized as follows: Coal with a higher sulphur content of 2.03 wt.% leads to greater SO_2 emissions of 5215 mg/Nm^3 than coal with a lower sulphur content of 0.51 wt.%, leading to lower emissions of 979 mg/Nm^3. The coal roadmap proposes three possible routes, ranging from business-as-usual physical methods to chemical methods and biological methods. South Africa will likely have to take a hybrid approach to reduce emissions and address electricity supply and demand issues. The coal's quality, structure and mineral makeup affect the efficacy of physical, chemical and biological clean coal technology processes. Moreover, South Africa also has water shortages or droughts. Thus, technology selection for a specific area should cater for all these difficulties. This study establishes benchmarks for a complete assessment of various technologies and a roadmap to clean coal technology for South Africa, focusing on SO_2 emissions reduction.

Nomenclature

FC – Fixed carbon, wt.%
VM – Volatile matter, wt.%
C – Carbon, wt.%
H – Hydrogen, wt.%
N – Nitrogen, wt.%
S – Sulphur content, wt.%
O – Oxygen, wt.%
adb – Air dried basis
wt.% – Weighted percentage
FGD – Flue Gas Desulphurization
CV – Calorific Value

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