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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 demand. However, using this local energy resource presents several environmental compliance 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 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, and all these technologies are presented in the current study. Therefore, South Africa will likely have to take a hybrid approach to reduce emissions and address electricity supply and demand issues. South Africa's ageing electricity generation infrastructure, sluggish economic development, and water shortages support this. In order to find solutions that will satisfy the demands of coal users for dependable, tried-and-true technology while also meeting environmental criteria, various limitations were used to sort through the available technologies. The coal roadmap proposes three possible routes, ranging from business-as-usual physical methods to chemical methods and biological methods. Such processing methods could drastically reduce power sector SO2 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 power sector that South Africa may implement over the coming years.

**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 SO2 minimum emissions standards. South Africa is now faced with the problem of high SO2 emissions in recent years following the passing of SO2 Minimum Emissions Standards. All coal and liquid fuel-fired power stations must meet Section 21's Minimum Emission Standards (MES) under the National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004). Hence, it is necessary to promote 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 CO2, the main greenhouse gas (GHG) in the South African power sector. the South African power sector discharged 223.4 Mt of CO2 in 2015, down 4% from 2014 (Akinbami et al., 2021). In addition, the South African power sector emitted 2919 t of N2O, a greenhouse gas 298 times more potent than CO2. Coal-fired power plants emit particulates, SO2, and NO2 (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 CO2, 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 in 20 years. All studies employed five power plant coal samples. Standardized procedures collected and prepared these coal samples for analysis.

* 1. **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.

* 1. **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 SO2 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 |
| H2OAshFC (by diff.)VMTotal | 8.1229.8941.8320.16100.00 | 8.0030.2341.6220.15100.00 | 8.1030.2041.5220.18100.00 | 8.0929.2642.4820.17100.00 | 8.1530.4641.2120.18100.00 |

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

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Properties | Sample 1 | Sample 2 | Sample 3 | Sample 4  | Sample 5 |
| H2OCHNSO (by diff.)AshTotalCV | 8.1249.453.051.300.517.6829.89**100.00**19.96 | 8.0049.603.101.330.786.9630.23**100.00**20.03 | 8.1049.783.021.341.026.5430.20**100.00**20.11 | 8.0950.123.111.351.546.5329.26**100.00**20.07 | 8.1551.703.241.382.033.4530.46**100.00**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 (SiO2) and alumina (Al2O3) dominate at 58 and 22 wt.%, respectively. P2O5, Na2O, and K2O 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 |
| SiO2Al2O3Fe2O3TiO2P2O5CaOMgONa2OK2OSO3 | 58.3622.314.001.300.425.401.100.600.792.10 | 58.1122.234.001.300.425.401.100.600.792.10 | 58.3422.344.001.300.425.401.100.600.792.10 | 58.2422.264.001.300.425.401.100.600.792.10 | 58.1322.464.001.300.425.401.100.600.792.10 |
|  |  |  |  |  |  |

**3.3 SO2 emissions for various coal qualities**

Figure 1 depicts the SO2 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/Nm3, Sample 2 is 1498 mg/Nm3, Sample 3 is 2670 mg/Nm3, Sample 4 is 4032 mg/Nm3, and Sample 5 is 5215 mg/Nm3. In summary, coal with a higher sulfur content of 2.03 wt.% leads to greater SO2 emissions of 5215 mg/Nm3 than coal with a lower sulfur content of 0.51 wt.%, leading to lower emissions of 979 mg/Nm3. In general, the source of SO2 emissions in the power sector originates from the sulfur content of coal. The current study agrees with Makgato and Chirwa (2017), who found that 1.37 wt.% and 0.20 wt.% sulfur content were needed to meet the minimum SO2 emissions standards of 3500 mg/Nm3



Figure 1: SO2 Emissions resulting from five coal samples.

(Target 1) and 500 mg/Nm3 (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.

**3.4 Clean Coal Technology Options**

Coal sulphur compounds can be removed by several desulphurization methods. This section categorizes these technologies, predicts advances between now and 2050, and describes environmental management options for each. This clean coal technology roadmap discusses South Africa's restrictions and coal power options accessible today or in the next 30 years. The coal's quality, structure, and mineral makeup affect the efficacy of physical, chemical, and biological clean coal technology processes. Figure 2 demonstrates clean coal technologies that meet economic and environmental emissions restrictions for South Africa. Water, labour, and emissions-control sorbent shortages will also drive technology selection. These restrictions are used to screen technologies to locate ones that suit the country's demand for reliable, proven technology and environmental criteria. The roadmap's worst-case scenario—rapid implementation of severe environmental criteria—would leave South Africa with few if any, coal power plant alternatives.



*Figure 2: Clean coal technology roadmap*

The Clean Coal Technology Roadmap provides a multi-scenario examination of local coal sector SO2 emission reduction options. The coal roadmap recommends three methods: business-as-usual physical, chemical, and biological. South Africa will have to combine all possibilities to move toward a less coal-intensive society while addressing supply and demand issues. South Africa's aging electricity generation infrastructure, sluggish economic development, and water shortages support this. Thus, South Africa should conduct several feasibility studies on some of Figure 2's sophisticated technologies' water consumption aspects. According to feasibility studies, South African water availability regions should stimulate innovative coal technologies that reduce water usage and emissions. New projects should use emission reduction techniques like flue gas desulfurization, while older infrastructure should use pre-combustion and combustion methods like sorbent injection.

* 1. **Conclusions**

The current study examines clean coal technologies that can help South Africa reduce SO2 emissions over the next 30 years. All studies were conducted on five coal samples collected from various stockpiles of mines supplying 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 SO2 emissions of 5215 mg/Nm3 than coal with a lower sulphur content of 0.51 wt.%, leading to lower emissions of 979 mg/Nm3. 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. South Africa also has water shortages or droughts. Thus, technology applications for an area should address 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 SO2 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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