New water saving FGD technology in South Africa: CFB FGD demonstration plant

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Introduction

Environmental considerations have increased over the years in South Africa with a focus on sustainable development. Sustainable development integrates social, economic and environmental factors in planning, implementation and evaluation of decisions to ensure a sustainable life for present and future generations. Core focus areas are pollution prevention or reduction, prevention of ecological degradation and conservation of natural resources. The National Environmental Management Act (NEMA) No. 107 of 1998 governs regulations concerning the environment and is supported by other Acts. The legislative requirements provide a driver for existing and new plants to comply with the defined limits.

Kendal Power Station utilises indirect dry-cooling which consumes approximately 95% less water than the conventional method of wet cooling. This is an advantage given the recent water shortages faced in the country. South Africa is ranked as one of the 30 driest countries in the world. In order for the power station to continue to meet the more stringent future air quality requirements whilst considering the limited water availability, options that would benefit both aspects were considered. The Circulating Fluidised Bed (CFB) flue gas desulphurisation was chosen as the most viable option based on preliminary desktop assessments and a demonstration trial has been planned for to confirm the viability.

The selected power station consists of six 686 MW (total 4,116 MW) pulverised coal boiler units, each split into two flue gas streams. There is no flue gas desulphurisation in place however the station complies with existing SO2 limits which will decrease from 2025. The plant has a remaining operating life of 35 years which is the longest remaining life of the power utility’s older fleet of coal fired power stations and has been identified as the largest emitter of SO2 emissions in the Highveld Priority Area (HPA). This was considered when selecting the existing power station as the site for the desulphurisation demonstration plant.

Factors contributing to desulphurisation within the South African power generation sector

Air Quality compliance

Power generation is a large contributor to the SO2 emissions (82%) contributing 1,633,655 tons per annum. Sulphur oxide emissions are governed by the Minimum Source Emission Standards of the National Environmental Management Air Quality Act (NEMAQA) No. 39 of 2004 (Figure 1). Each Eskom generating facility has its own Emission License which will detail the compliance requirement for the facility. This varies between facilities due to ambient air quality priority area and age of the power generation facility.

The current legislation (Table 1) requires that SO2 emissions comply with a limit of 500 mg/Nm$^3$ (10% O2) for new
plants, 3,500 mg/Nm³ (10% O₂) by 2015 for existing plants and a limit of 500 mg/Nm³ (10% O₂) by 2020 for all plants. On 24th February 2015 the Department of Environmental Affairs (DEA) resolved to postpone the effective date for implementation of the 500 mg/Nm³ emissions limit for certain existing power plants. Kendal Power Station’s current emissions of SO₂ are > 2,700 mg/Nm³.

The selected power station is located in the Highveld Priority Area (HPA). The power station was identified using ambient air quality monitoring and dispersion modelling as the largest emitter in the HPAs, as seen in Figure 2.

SO₂ emissions trended over a 9-year period in the HPA indicate that although the SO₂ concentrations average below the South Africa National Ambient Air Quality Standards (SA NAAQS) these values are far above the World Health Organisation (WHO) figures, as seen in Figure 2. The associated daily averages are shown in Figure 4.

Water availability

Water restrictions in South Africa have recently become a reality in certain parts of the country due to drought and other contributing factors. Water saving initiatives are therefore gaining prominence for municipal, agricultural and industrial applications. A 2012 Water Research Commission study found that South Africa utilises 235 litres per capita per day (l/c/d) compared to the global average of approximately 175 l/c/d and a model developed by the University of Denver forecasts that the water demand will increase till 2035. Most of South Africa’s currently available water supplies have been allocated with only a small amount available to cater for additional desulphurisation demands. The selected power station is the largest indirect dry-cooled power station in the world; hence the proposed desulphurisation technology should consider this and mitigate the need for additional water resources to meet environmental limits.

Use of coal

The use of coal as a primary source for power generation is largely the case in South Africa. Approximately 95% of the sulphur in coal is released as SO₂ with the raw flue gas². Alternate methods for power production have yet to be developed to a stage where the country can drastically reduce its use of coal. On average 224 million tonnes of marketable coal is produced annually and 53% of this is utilised for power generation. The local coal reserves are estimated at 53 billion tonnes, providing an estimate of 200 years coal supply⁴.

Sorbert cost and availability

The availability and cost of sorbent is an important consideration. Wet flue gas desulphurisation utilises limestone (CaCO₃) as a sorbant and circulating fluidised bed desulphurisation utilises hydrated lime (Ca(OH)₂) or burnt lime (CaO) which is then slaked to form hydrated lime. Isolated high-grade deposits of limestone occur¹² in South Africa; the Highveld region contains Limestone deposits which are available, however the quality and purity is lower than what is conventionally required for the chemical process.

South Africa’s good limestone sources are located far from the Highveld area. The use of “dolomitic lime” as an alternative will be evaluated during the demonstration trials. Dolomitic lime is cheaper however contains a lower usable CaO content.

By-product disposal

The National Waste Management Strategy (NWMS) is a legislative requirement of the National Environmental Management Waste Act (the “Waste Act”) No. 59 of 2008. The purpose of the NWMS is to achieve the objectives of the Waste Act. Wet desulphurisation currently produces a waste stream which is further treated in a waste water treatment plant (WWTP) and is recirculated back to the process plant for further use. The WWTP mixed waste salt is disposed off-site. The WFGD gypsum by-product produced is saleable. In the Circulating Fluidised Bed option no waste water is produced so further treatment is not required. The CFB FGD by-product is composed of reaction products, unreacted sorbent and fly ash. This product is deposited in a landfill and based on its composition it can be reused in other industries.

Dolomitic lime is cheaper however contains a lower usable CaO content.
Expenditure (CAPEX), low operating expenditure (OPEX), reduced water consumption, retrofit simplicity and economic conditions: SO2 used to evaluate which technology should be used to meet environmental compliance.

Technology selection decision

Air quality control using desulphurisation technology in power plants is new within South Africa. The following criteria was used to evaluate which technology should be selected based on the South African conditions: SO2 removal efficiency, low capital expenditure (CAPEX), low operating expenditure (OPEX), reduced water consumption, retrofit simplicity and economic conditions with respect to remaining plant life.

Various technology alternatives were investigated, the alternatives can be categorised in groups of pre-combustion and post-combustion desulphurisation technology options as seen in Figure 5.

The technology evaluation was a phased approach; in the first step feasible commercial scale technologies were scanned for further evaluation. During evaluation two qualifying criteria were used to enable the arrival to a recommended FGD technology. Firstly, a qualitative criteria was defined which served as a gate keeper for all technologies identified during the scanning study. Secondly, a quantitative criteria was tabulated which was a set of technical requirements which were used to compare technologies against each other.

Qualitative Criteria

The qualitative criteria used entailed the following:

- **Level to which requirements are met**
  - Ability of the technology to meet the stakeholder’s requirements
- **Level to which design criteria are met**
  - Ability of the technology to meet the design requirements.
- **Level to which stakeholder values are met**
  - Ability of the technology to meet the strategic objectives
- **Maturity of Technology**
  - Commercial availability of the technology.

Quantitative Criteria

The quantitative criteria were made up of the following:

- **Maximum SO2 Removal Efficiency %**
  - maximum SO2 removal efficiency possible with the existing technology
- **Pressure Drop Impact**
  - level of impact to the system pressure, and requirement of additional fans to cater for the pressure drop
- **Power consumption of plant utilities**
  - maximum power consumption due to FGD technology installation (% MW impact on installed capacity)
- **Environmental Impact (Effects on Waste Water Treatment System)**
  - Number of waste streams required based on waste classification
- **Water Usage**
  - water consumption associated with the FGD technology (l/kWh gross).
- **Estimated construction time frames**
  - timelines required to construct [Target date 2025]
- **Required Footprint outside stations boundary**
  - relative footprint required in addition outside of the station boundaries (Hectares).
- **Site Arrangement**
  - ease of retrofitting the FGD technology to site.
- **Plant Operating Complexity**
  - Additional operation interventions required (linked to number of systems/unit operations).

The technology selection exercise derived two technology option which would be suited in the South African context; the WFGD and the CFB FGD. A brief summary of the major comparisons is summarised in Table 2 and Table 3; these comparisons were based on the large scale retrofit scenario.

CFB FGD has the capability to achieve the required emissions limits while operating with reduced water consumption of up to >30% less than conventional wet FGD technology. The development of CFB FGD technology could mitigate the need for additional water resources to achieve environmental compliance.

Best-fit FGD technology should have the following attributes:

- Meet emissions limits
- Fuel flexibility
- Low Capex
- Low Opex
- Reduced water consumption
- Economical with remaining operating life

Preliminary technology selection studies for the selected power station indicated that CFB FGD would be the most viable op-
tion provided that all criteria are met. A decision was made to evaluate this option further by initiating a demonstration plant project.

Various advantages of the CFB FGD technology were identified and need to be validated with the demonstration plant before full scale implementation. If one or more of the criteria are not met, the internal envisaged savings for this option will not be realised and prove more costly to operate compared to the WFGD. The sorbent cost is the largest contributor to the overall OPEX cost. An advantage of the CFB FGD is the possibility to use low quality sorbent, which could reduce the OPEX considerably. The use of “dolomitic lime” (calcination of dolomitic limestone) as a low quality sorbent has to be verified. If the lower quality lime does not prove feasible, the cost saving will not be realised and the WFGD would be the cheaper option to operate.

**CAPEX**

The overall CAPEX cost is higher for WFGD than CFB FGD for application at the selected power station. Figure 6 shows the contributing costs for the two technologies.

**OPEX**

CFB FGD has a higher operating cost that WFGD for application at the selected power station (Figure 7). Sorbent utilisation is the largest contributing factor to the high operating costs for CFB FGD. The cost of burnt lime is 3 times that of the limestone cost in South Africa.

**CFB FGD overview**

Raw flue gas containing fly ash from the upstream boiler unit enters into the CFB FGD reactor where the main desulphurisation takes place. The flue gas enters the bottom of the reactor through venturi nozzle/s. The reactor relies on turbulent mixing of the flue gas and sorbent. The sorbent particles are continuously abraded exposing the unreacted alkali surface areas of the particles. The CFB FGD process utilises hydrated lime (Ca(OH)₂) as a sorbent to bind the sulphur oxides and other gases in the flue gas as shown in the below reactions:

Hydrated lime reaction with SO₂:

\[
\text{Ca(OH)₂} + \text{SO}_2 \rightarrow \text{CaSO}_3 + \text{H}_2\text{O} \quad \text{(Eq. 1)}
\]

\[
\text{Ca(OH)₂} + \text{SO}_3 \rightarrow \text{CaSO}_4 + \text{H}_2\text{O} \quad \text{(Eq. 2)}
\]

Hydrated lime reaction with other gases eg. HF and HCl:

\[
\text{Ca(OH)₂} + 2\text{HF} \rightarrow \text{CaF}_2 + 2\text{H}_2\text{O} \quad \text{(Eq. 3)}
\]

\[
\text{Ca(OH)₂} + 2\text{HCl} \rightarrow \text{CaCl}_2 + 2\text{H}_2\text{O} \quad \text{(Eq. 4)}
\]

The hydrated lime can be bought or produced on site by the slaking process. The active pores on the hydrated lime particle influence the reactions and depend on the slaking process as well as the burnt lime used. The optimum temperature for the above reactions is 70-90°C and this can be achieved by quenching the flue gas in the reactor with water. Water is added with high pressure nozzles in the form of fine droplets. The nozzles ensure to be arranged to ensure homogenous distribution across the reactor. The process must operate above the dew point in order to prevent water from condensing out of the flue gas.

The desired absorption efficiency of 95% is achieved by choosing a stoichiometric ratio. The stoichiometry ratio is the molar ratio between Ca(OH)₂ and flue gas SO₂ and is chosen as a factor of the raw gas SO₂ concentration. The consumption of hydrated lime is dependent on the SO₂ concentration and stoichiometric factor hence the factor will influence the design of the slaking plant.

The flue gas moves up through the reactor and the height is chosen to ensure an adequate retention time is reached. A fabric filter plant (FFP) is located downstream of the reactor in which the solids from the reactor are separated. The process filter provides additional time for desulphurisation as the solids adhere to the tubes to form a filter cake as the flue gas passes through. An additional reaction efficiency of ap-
proximately 10% is achieved. The reactor and process filter can replace the upstream de-dusting system if the fly ash is not required for sale. A hopper for collection of the solids product is located at the bottom of the process filter.

**CFB FGD demonstration plant implementation**

**Justification**

Five main reasons were considered to motivate for the implementation of the demonstration plant:

- Currently one power station in the coal fired fleet is in commercial with FGD operation utilising WFGD, treating flue gas from one of six boiler units. The utility has no experience in the application of CFB FGD technology for South African and existing power station conditions. The viability and risks associated with CFB FGD technology under these conditions needs to be evaluated.

- The CFB FGD utilises burnt lime (CaO) as sorbent which is hydrated either on site to Ca(OH)₂ or is directly purchased for use in the process. A limestone source can be used as a sorbent; the limestone will be first calcinated to burnt lime and secondly hydrated to hydrated lime. The quality of limestone in the Highveld region is expected to be low (below 85% CaCO₃ content) therefore the usability of such quality needs to be investigated. In addition the possibility of using lime sources close to the power plant area could contribute to savings in transportation costs.

- Due to the current water scarcity in South Africa and since the selected power station already utilises indirect dry cooling, which contributes to significant water savings compared to wet-cooling, the actual water usage should be confirmed with further possibility for optimisations.

- Despite using less water compared to wet technologies, the CFB FGD still requires water for its process requirements. This will increase the station’s existing water requirement. Provisions have to be made for the additional water allocation and necessary infrastructure from the catchment. The demonstration plant will test if lower quality water can be used for quenching versus the raw water. A waste water stream from a nearby power station will be evaluated as a potential replacement.

- Another challenge is that South African coal typically contains high ash content. The CFB reactor has limitations for particular matter concentration and the particle size distribution. The need for fly ash pre-separation will be investigated during the demonstration plant trials.

**Objectives**

The test campaign objectives shown in **Table 4** have been outlined to prove the viability of the CFB FGD technology in South Africa:

**Feedstock limitations and optimisation**

- Sorbent

It is envisioned that the sorbent including the dolomitic limestones into the process will come from within a defined radius around the power station. The plan is to split the campaign into two phases namely phase 1 which tests the operations and performance with sorbent of good quality and phase 2 with sorbents of sub-standard quality. This should enable the test team to separate the operational from the performance issues and be able to project the requirements for the major plant’s retrofit.

**Water**

The quality of the waste water stream from an adjacent plant is known, however, the stream is a high chloride content stream. The impact of the chlorides on the mechanical design of the water distribution and on process operations need to be assessed. The stream also contains a moderate amount of abrasive solids which need to be assessed for suitability for the high pressure nozzles.

**Coal and load variations**

The power plant receives a consistent quality of coal; it is therefore expected that the flue gas stream into the demonstration plant will be consistent. On the other hand, the plant reduces its load to the minimum during certain points during the day; this transient nature of the plant will be built into the testing campaigns to test the demonstration plant’s performance in transient modes.

**Capacity considerations**

The full scale proposed CFB FGD retrofit will treat 4,700,000 m³/h (wet, actual conditions). The demonstration plant is planned to be in operation for 15 to 24 months in order to obtain sufficient data for the different variables. Three flue gas volume flow capacities were considered; 10,000, 127,000 Nm³/h and 180,000 Nm³/h. The 10,000 Nm³/h plant had the advantage of being built on a transportable framework for later use at the other power plants however the scaling up factor was large and the process equipment were not standard. The next capacity of 127,000 Nm³/h (5% of flue gas flow of one boiler) was considered as standard equipment could be used and this reduced the scaling up factor however it was found that the actual restriction on the demonstration plant sizing was the hydration plant. A minimum CFB plant size had to be considered to ensure continuous op-

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Objective</th>
</tr>
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<tbody>
<tr>
<td>Lower Burnt Lime Qualities</td>
<td>Calcination of Dolomitic Limestone</td>
<td>The capability to calcinate lower quality limestone may result in the reduction of OPEX costs and the sourcing of sorbent in closer proximity to plant.</td>
</tr>
<tr>
<td>Optimisation of Sorbent Use</td>
<td>Determine Sorbent Stoichiometry factor</td>
<td>Variation of the recirculation flow rate has an impact on the utilisation of the sorbent.</td>
</tr>
<tr>
<td>Fly Ash Concentration Limit at Reactor Inlet</td>
<td>Requirement for pre-separation</td>
<td>Operation experience based on South African coal characteristics and high ash content.</td>
</tr>
<tr>
<td>Low quality water use</td>
<td>Impact of low quality water on process design and operation</td>
<td>The use of low quality water sources for humidification may relieve the adjacent power plant of the need for a waste water treatment plant and will reduce the need for raw water.</td>
</tr>
<tr>
<td>Operation optimisation</td>
<td>• Part load variation • Ramping rate • By-product recirculation • Shutdown • Pressure drop improvements • Lime Hydration</td>
<td></td>
</tr>
<tr>
<td>Water consumption</td>
<td>• Low quality water • Hydridation requirement</td>
<td></td>
</tr>
<tr>
<td>Process efficiency</td>
<td>• Lime usage • Ash at inlet to absorber • Influence of ash and lime quality</td>
<td></td>
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<tr>
<td>Multipollutant</td>
<td>• Removal efficiency of other acids • (SO₂, CO₂, HCl, HF, Hg)</td>
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<tr>
<td>Mechanical</td>
<td>• Assessment of Materials of construction</td>
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eration of the hydration plant for a consistent quality of hydrated lime. A demonstration plant capacity of 180,000 Nm$^3$/h was chosen which met these requirements.

**Demonstration plant design concept**

**Process design**

The demonstration plant is designed to achieve 500 mg/Nm$^3$ SO$_2$ removal (10% O$_2$ reference) and a 50 mg/Nm$^3$ particulate removal. A worst case coal condition was taken as the design reference with a sulphur and ash content of 1% and 41.2% respectively (moisture free). Burnt lime quality of 90% was used as an input to the process design. To simulate real plant operation, the inlet fly ash content range of 0 to 51,000 mg/Nm$^3$ (10% O$_2$ reference) is used. The test will demonstrate if fly ash pre-separation is required based on the fly ash loading and particle size distribution.

**Equipment design**

The CFB FGD plant for one unit will consist of a reactor, a process filter, booster fan, a sorbent preparation plant (lime silo and hydrator), waste handling/recycle facilities and auxiliary equipment. The tie-in points will be downstream the existing ID fan and upstream the stack inlet. Figure 8 below illustrates the process flow of the demonstration plant.

A single reactor is required. Water for quenching is added to the reactor via high pressure nozzles installed around the reactor cross section.

A booster fan is installed downstream of the process filter to compensate for the pressure drop from the reactor, ductwork and FFP.

Burnt lime is delivered onsite by trucks. The burnt lime is stored in a burnt lime silo. Hydrated lime will be produced onsite in a hydrator. The hydrated lime produced will be stored in a hydrated lime silo until use and will be pneumatically conveyed from the hydrated lime silo and injected directly into the reactor.

By-product collected from the process filter hopper will be sent to the by-product silo for storage. The silo will store the by-product until disposal by truck to the dedicated disposal facility.

**Arrangement design**

As shown in Figure 9 and Figure 10, the ideal location for the demonstration plant is downstream the induced draft fan as it provides sufficient space. A slip stream is taken from the “clean gas duct” after the existing ESPs and returned into the same duct after the CFB FGD plant for discharge via the stack. Two dampers at the inlet and outlet of the slip stream are provided to control the flue gas flow and to isolate the demonstration plant.

No material modifications are envisioned for the existing ductwork since at 85°C the flue gas exiting the CFB FGD plant is above the saturation temperature. The demonstration plant has been designed to avoid any clashes with existing plant.

**By-product handling and disposal**

Currently the selected power station for the CFB FGD retrofit sells 23,000 tons of fly ash per month to commercial users; this reduces the burden on the station’s ash dams lightly. However, if a CFB-FGD is installed, it would likely replace the current ESPs and if the campaigns prove that the CFB-FGD can operate with higher ash load at inlet, this will require a business case to source saleable ash at a nearby power plant or elsewhere. This is because a typical CFB by-product consists of fly ash, unreacted sorbent, CaSO$_3$, CaSO$_4$, CaCO$_3$, CaCl$_2$ and CaF$_2$ thereby modifying the quality of the ash being sold currently.

The demonstration plant will also address the classification of the by-product. The South African waste legislation recognises wastes of various classes according to the wastes’ hazardous nature which imposes where and how the wastes are disposed. The classification from the demonstration plant waste will then be used as a reference for the full scale retrofit if the demonstration plant proves successful. Waste generated during the trials will be temporarily stored in a silo and transported to a hazardous waste disposal facility until classified.

**Demonstration implementation challenges and risks – Retrofit and arrangement**

The requirement for the demonstration plant by the host plant was that there should be least disruptions to the operations. The host plant is a 6 unit plant with

![Fig. 8. CFB FGD Demonstration Plant Main Equipment.](image-url)
substantial infrastructure around the plant stacks and identifying the host unit was subject to several iterations. The ideal slip stream would have been from air heater outlet but this was deemed disruptive to draught group balance since the station is a parallel twin gas flow draught system.

**Sorbent sourcing**

The calcination of dolomitic limestones for the demonstration plant is by far the largest risk for the project. The project will need to partner with local calcination plants to enable calcination and therefore the success of a large portion of the project.

**Conclusion**

Stricter air quality requirements in South Africa has prompted an investigation into possible SO\textsubscript{2} reduction measures at existing coal fired power. The selected power station for the retrofit has been chosen due to the longest remaining operating life and has been identified as the largest SO\textsubscript{2} emitter in the Highveld Priority Area.

Two technologies were compared for implementation: wet and semi-dry circulating fluidised bed flue gas desulphurisation. The CFB FGD was chosen due to its potentially lower lifecycle costs and retrofit benefits. A demonstration plant project is in progress to validate the successful implementation of the technology with respect to achieving SO\textsubscript{2} emission limits, multi-pollutant removal, process flexibility in relation to feedstock availability and characterisation of by-products.

A demonstration plant is of important interest to the FGD body of knowledge. The demonstration plant will verify and validate unconventional CFB FGD operation. There is high motivation in the direction of lower water FGD technologies in South Africa. The project benefits the country through local skills development and local resources utilisation potential.

**Acknowledgements**

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**Abbreviations**

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<tr>
<th>CFB –</th>
<th>Circulating Fluidised Bed</th>
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<tr>
<td>FGD –</td>
<td>Flue Gas Desulphurisation</td>
</tr>
<tr>
<td>l/kWh –</td>
<td>Litres Per Kilowatt Hour</td>
</tr>
<tr>
<td>MW –</td>
<td>Megawatt</td>
</tr>
<tr>
<td>NAAQS –</td>
<td>National Ambient Air Quality Standards</td>
</tr>
<tr>
<td>Nm\textsuperscript{3}/h –</td>
<td>Normal Cubic Meters Per Hour</td>
</tr>
<tr>
<td>NEMA –</td>
<td>National Environmental Management Act</td>
</tr>
<tr>
<td>NWMS –</td>
<td>National Waste Management Strategy</td>
</tr>
<tr>
<td>SA –</td>
<td>South Africa</td>
</tr>
<tr>
<td>SO\textsubscript{2} –</td>
<td>Sulphur Dioxide</td>
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<td>WFGD –</td>
<td>Wet FGD</td>
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**References**

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