ⓡ Eskom

	Report	Technology

Title: **Medupi Power Station Direct Sorbent Injection Feasibility Study**

Unique Identifier: **348-9953598**

Alternative Reference Number: **N/A**

Area of Applicability: **Engineering**

Documentation Type: **Report**

Revision: **1**

Total Pages: **27**

Next Review Date: **N/A**

Disclosure Classification: **CONTROLLED DISCLOSURE**

Compiled by

Jeanne Fourie

Engineer: Boiler Auxiliary CoE

Date: 27 /01 /2020

Functional Responsibility

Annikie Moganelwa

Senior Engineer: Boiler Auxiliary CoE

Date: 28 /01 /2020

Authorised by

Viren Heera

Senior Manager: Power Plant (acting)

Date: 28 /01 / 2020

Supported by

Prof. Saneshan Govender

General Manager: Plant Engineering (acting)

Date: 30 /01 /2020

Supported by

Dr Titus Mathe

General Manager: Group Technology

Do further test studies & look at line cost reduction

Date: 30 /1 /2020

CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Medupi Power Station currently experiences sporadic SO_2 emission exceedances above the existing emissions license limit of 3500 mg/Nm^3 (valid until 2025). As a measure to address these intermittent exceedances, direct sorbent injection has been considered as an interim, low efficiency measure to assist in meeting the current SO_2 emissions limit until such time as the Wet Flue Gas Desulphurisation (WFGD) plant is installed. The WFGD plant will be capable of meeting the future SO_2 emissions limit of 500 mg/Nm^3, to come into effect in 2025. Direct sorbent injection is a low efficiency technology and is not capable of meeting 500 mg/Nm^3 limit.

Of the commercially available FGD technologies, direct sorbent injection was selected for consideration as an interim measure due to its relatively low capital cost and short implementation timelines when compared to FGD technologies with higher SO_2 removal efficiencies. This study explores various options; including 'hot' and 'cold' direct sorbent injection. It is concluded that duct sorbent injection (DSI) using hydrated lime upstream of the gas airheater (GAH) is the most suitable direct sorbent injection option considered for Medupi Power Station to achieve SO_2 removal efficiency of up to 25%, as required to maintain the existing SO_2 emissions limit. Sodium based sorbents are not feasible due to the high leachability of their waste products and consequent environmental concerns and higher cost.

Despite DSI being the most appropriate direct sorbent injection option, it is concluded that it is technically unfeasible for implementation at the existing Medupi Power Station. This is due to a number of technical concerns, including the uncertainty regarding sorbent quality and availability, the configuration of the existing Medupi Power Station plant systems, specifically the fabric filter plant (FFP) and dust handling plant (DHP) as well as waste management concerns. Furthermore, DSI will exacerbate the current underperformance of the FFP. In order to allow acceptable operation with DSI major plant modification would be required, which is unfeasible for short-term implementation.

Further to the technical concerns, the extended implementation timelines owing to environmental requirements and necessary sorbent testing will result in the direct sorbent injection system being operational for less than a year at the best case. The high capital cost for implementation for the brief operational period is thus not warranted. The total cost for one year's operation, including capex for the process equipment, opex and decommissioning for all six boiler units is R4.93 billion. This does not include the costs associated with the significant modifications to existing plant required.

Although the intention of this feasibility study is to assess the practicality of the short-term application of direct sorbent injection only, it must be noted that extended operation of the direct sorbent injection system, should the long-term WFGD system be deferred, will result in significant operational costs due to the large quantity of high cost sorbent required.

A summary of the unfeasibility of direct sorbent injection at Medupi Power Station is presented in Table 1-1 on the following page.

Table 1-1: Summary of concerns regarding direct sorbent injection

Concern	Consequence
Interim Implementation for Low Efficiency SO$_2$ Reduction	
Sorbent characteristics uncertain	Unknown whether suitable SO$_2$ reduction efficiency is achievable. By-product characteristics unknown.
FFP design unsuitable for direct sorbent injection	Major FFP modification required to achieve optimal operation (casing enlargement for >50% additional bag area required and pulsing system replacement needed). This is costly and will require significant outage time. If FFP is not modified, unacceptably high dP and early bag failure will be experienced
DHP and waste handling infrastructure does not allow for direct sorbent injection	DHP pneumatic capacity increase required to convey additional particulate loading Waste handling infrastructure not designed for additional particulate loading
Environmental management	Amended waste management license will be required for disposing of the ash, sorbent and by-product mix. The characteristics of this mixed product (leachability, stackability) are not yet known.
Long development schedule	Due to required pre-concept testing required to define sorbent and by-product characteristics, as well as EIA requirements, the implementation schedule is extended. Consequently, the direct sorbent injection system will be operational for approximately one year only.
High implementation cost	CAPEX investment of R222.6 million per unit (excluding modification to existing plant and decommissioning costs) required for short operational period and low SO$_2$ removal efficiency
Sorbent cost and availability	High sorbent cost of R532.30 million annually per unit will be incurred to achieve low (up to 25%) SO$_2$ removal. Suitable sorbent is not currently available near Medupi – significant transport costs will be incurred. Logistic for sorbent delivery may interfere with current operations.
Long Term Implementation	
Low SO$_2$ reduction efficiency	Will not meet future emissions limits
High sorbent costs	Significant OPEX (life cycle costing greater than WFGD)

1. INTRODUCTION

Medupi Power Station, which is currently in various stages of execution, has been designed and constructed to be 'Wet Flue Gas Desulphurisation (WFGD) ready'. The multi-package Medupi Flue Gas Desulphurisation (FGD) Retrofit Project is presently under development to realise the installation of WFGD technology at Medupi Power Station. The objective is to reduce sulphurous flue gas emissions to within legislated limits.

The FGD Retrofit Project is required to meet commitments made to the Department of Environment, Forestry and Fisheries (DEFF) (previously the Department of Environmental Affairs (DEA)) and the Medupi Power Station project funders (the World Bank and African Development Bank).

It was originally intended that the WFGD technology would be retrofitted during each unit's first general overhaul outage six years after commissioning with complete installation finalised in 2025. However, the project delivery time frame has been extended due to various factors, including: availability of funding, commercial processes, governance considerations, environmental licencing requirements (including the new requirement for separate gypsum and ash disposal facilities), existing plant process issues at Medupi Power Station and lessons learnt regarding more realistic project schedules and ensuring critical hold points. It is therefore currently anticipated that the WFGD plant for all units will be operational by 2030.

In the interim, Medupi Power Station experiences sporadic sulphur dioxide (SO_2) emissions excursions during periods when the station receives high sulphur coal. The current Medupi Power Station emissions license is for a SO_2 limit of 3500 mg/Nm^3 and will reduce to 500 mg/Nm^3 from 1 April 2025. An application for alternative limits in the minimum emissions standard (MES) applicable to Medupi Power Station has been made in November 2019. It is requested that a limit of 4000 mg/Nm^3 be applicable from 1 April 2020 and 1000 mg/Nm^3 from 1 April 2030. A response to this application is not yet available at the time of this document's compilation. A solution is thus being sought to address the intermittent SO_2 exceedances above 3500 mg/Nm^3 until such time as the WFGD is installed.

In order to assess whether direct sorbent injection is suitable as a short-term solution to address SO_2 emissions excursions above the existing 3500 mg/Nm^3 limit, a feasibility study considering various forms of direct sorbent injection has been completed.

2. SUPPORTING CLAUSES

2.1 SCOPE

The scope of this document includes direct sorbent injection only. Other FGD technologies are not considered in this document. Direct sorbent injection is considered only as a short-term, low efficiency desulphurisation solution.

This document is limited to a feasibility study and extensive conceptual development is not included.

2.1.1 Purpose

The purpose of this document is to establish whether direct sorbent injection is feasible at Medupi Power Station as an interim measure for SO_2 emissions reduction to below the current station limit of 3500 mg/Nm^3 until the WFGD system is installed.

2.1.2 Applicability

This document shall apply throughout Eskom Holdings Limited Divisions.

2.2 NORMATIVE / INFORMATIVE REFERENCES

A complete list of literature referenced in this study is included in Section 15. Internal Eskom documentation is listed below.

2.2.1 Normative

[1]   Briefing Note titled *Interim SO$_2$ mitigation for Medupi Power Station – Duct Sorbent Injection*, 16 November 2017

[2]   Memorandum titled *Potential interim solution for Medupi SO$_x$ reduction*, 11 October 2019

[3]   474-10175: Medupi Flue Gas Desulphurisation: Technology Selection Study Report

[4]   323-09: Economic Evaluation Parameters

2.2.2 Informative

[5]   ENV19-R235: Application for alternative limits in terms of the minimum emissions standard for the Medupi Power Station

[6]   363-SOx-BBBB-D00139-140: Fleet SO$_x$ Emissions Reduction Project, Tutuka Power Station Concept Design Report

[7]   363-SOx-BDDD-D00185-7: Fleet SO$_x$ Emissions Reduction Project, Majuba Power Station Concept Design Report

2.3 DEFINITIONS

Term	Definition
Calcination	*Calcination* is a process whereby limestone (or other mineral deposits containing calcium carbonate) is heated to high temperature in a kiln to produce quicklime with carbon dioxide as a by-product.
Direct Sorbent Injection	*Direct (or dry) Sorbent Injection* is a method of reducing SO$_2$ in flue gas by injecting dry sorbent at a chosen location within the flue gas stream.
Duct Sorbent Injection	*Duct* sorbent injection typically refers to direct dry sorbent injection upstream or downstream of the gas airheater.
Normalised	*Normalised/Normal Conditions* are at 273 K, 101.3 kPa, dry and 10% O$_2$

2.3.1 DISCLOSURE CLASSIFICATION

Controlled Disclosure: Controlled Disclosure to external parties (either enforced by law, or discretionary).

2.4 ABBREVIATIONS

Abbreviation	Description
AD	Air Dried
Ca(OH)$_2$	Calcium Hydroxide (hydrated lime/slaked lime)

Abbreviation	Description
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide (quicklime/burnt lime)
CAPEX	Capital Expenditure
CDS	Circulating Dry Scrubber
CFB	Circulating Fluidised Bed
DEA	Department of Environmental Affairs
DEFF	Department of Environment, Forestry and Fisheries
DSI	Duct Sorbent Injection
EIA	Environmental Impact Assessment
EPA	United States Environmental Protection Agency
ESI	Economiser Sorbent Injection
ESP	Electrostatic Precipitator
FFP	Fabric Filter Plant
FGD	Flue Gas Desulphurisation
FSI	Furnace Sorbent Injection
GAH	Gas Airheater
HCl	Hydrochloric acid
HF	Hydrofluoric acid
LIMB	Limestone Injection Multi-stage Burner Technology
MES	Minimum Emissions Standard
mg/Nm^3	Milligram per Normalised cubic metre
$NaHCO_3$	Sodium Bicarbonate
NSR	Nett Stoichiometric Ratio
O_2	Oxygen
OPEX	Operational Expenditure
R	Rand
SO_2	Sulphur Dioxide
SO_3	Sulphur Trioxide
SO_x	Sulphur Oxides
SSA	Specific Surface Area
WFGD	Wet Flue Gas Desulphurisation

2.5 ROLES AND RESPONSIBILITIES

Not Applicable

2.6 PROCESS FOR MONITORING

Not Applicable

2.7 RELATED / SUPPORTING DOCUMENTS

Briefing Note titled *Interim SO_2 mitigation for Medupi Power Station – Duct Sorbent Injection*, 16 November 2017

Memorandum titled *Potential interim solution for Medupi SO_x reduction*, 11 October 2019

3. BACKGROUND

A detailed technology selection was completed for the Medupi FGD Retrofit Project, focusing on the selection of a technology to suitably reduce SO_2 emissions to below the future limit of 500 mg/Nm^3 for the remaining life of the plant. Details are available in [3]. However, as a short term interim solution to mitigate minor exceedances of the current station limit of 3500 mg/Nm^3, a cost effective and easily implementable technology must be considered.

Medupi Power Station currently experiences sporadic SO_2 emissions spikes above the 3500 mg/Nm^3 limit in instances when poor quality coal with sulphur content above the specified rejection limit is received. In order to curb the interim emissions limit exceedances, SO_2 reduction of between approximately 4% and 25% must be achieved to meet the station's current limit. Deviations from this range may be experienced in some instances as it depends on the quality, specifically sulphur content, of coal being burned. When coal with 2.2% sulphur is received, process modelling indicates that an SO_2 reduction efficiency of 20% is required.

Therefore, of the commercially available FGD technologies, direct or dry sorbent injection[1] was selected for consideration as an interim measure until such time as the WFGD is installed. This is due to the relatively low capital cost and short implementation timelines associated with direct sorbent injection technology when compared to FGD technologies with higher SO_2 removal efficiencies. Due to the low efficiency of direct sorbent injection, as well as significant sorbent costs to achieve this low reduction of SO_2, it is not suitable as a permanent SO_2 reduction solution to achieve the future emissions limit.

4. TECHNOLOGY OVERVIEW

Direct sorbent injection is an emissions, or pollution, control technology that falls under the dry FGD technology category. It was originally developed to reduce acidic gases such as sulphur trioxide (SO_3), hydrochloric acid (HCl) and hydrofluoric acid (HF). SO_2 was secondarily reduced in this process. However, due to the evolution of regulatory and compliance requirements as well as site specific constraints, this technology is now considered for low efficiency reduction of SO_2.

Although direct sorbent injection achieves reduction of SO_2, its reaction is in competition with the other acidic flue gas constituents. Furthermore, the residence time of sorbent in flue gas is less for direct sorbent injection than with other, higher efficiency FGD technologies. Consequently, only low efficiency SO_2 reduction is possible. Direct sorbent injection very rarely yields SO_2 removal efficiencies up to 90% as is typically required in order to comply with emissions regulations; therefore, direct sorbent injection is usually implemented in utilities and industrial applications that require low removal efficiencies and/or with a short remaining plant life. The potential advantages include relative ease of retrofit if the existing plant infrastructure is suitable and low associated capital investment in comparison with more efficient FGD technologies.

Direct sorbent injection is compared to selected, more efficient FGD technologies (WFGD as well as the semi-dry spray dryer absorber (SDA) FGD and circulating fluidised bed (CFB) FGD) in Table 4-1. It can be seen that direct sorbent injection is most suited to power stations with low SO_2 removal requirements, short remaining life (since operational costs will outweigh capital costs after a certain lifetime) and small boiler units where building the complex, capital intensive systems required for WFGD and the semi-dry FGD applications are not warranted.

---

[1] *Direct/dry sorbent injection* refers to the technology whereby sodium or calcium based sorbent is directly injected into the flue gas stream. *Duct sorbent injection* is a subset of this technology and refers to the injection location upstream or downstream of the gas airheater (GAH). For purposes of this document, the abbreviation *DSI* is used to refer specifically to *duct* sorbent injection.

Table 4-1: Comparison of Direct Sorbent Injection Capabilities with Selected FGD Technologies

	WFGD	SDA	CFB	Direct Sorbent Injection
SO_2 removal efficiency	High	Medium - high	Medium - high	Low
Capital Cost	High	Medium - high	Medium - high	Low
Operational Cost	Medium	High	High	High
Water Consumption	High	Medium	Medium	Low

Direct sorbent injection involves the pneumatic injection of an alkaline sorbent, typically calcium or sodium based, directly into the flue gas path. The sorbent reacts with the target acidic gas and competing acidic gases via adsorption. The acidic gas content in the flue gas is reduced and a solid waste is produced as a by-product. The solid waste product is removed via the particulate control system (the electrostatic precipitator (ESP) or fabric filter plant (FFP)).

Due to the competing reactions with the other acidic flue gas constituents, relatively high sorbent injection rates are required for sufficient SO_2 removal when compared with the removal of other acidic gases from the flue gas stream. The most commonly used sorbents include hydrated lime ($Ca(OH)_2$), calcium carbonate ($CaCO_3$) typically obtained from limestone, sodium bicarbonate ($NaHCO_3$) and sodium sesquicarbonate known as trona, a sodium based sorbent mainly mined in the United States of America.

In general, sodium based sorbents can yield better SO_2 reduction efficiencies when compared to calcium based sorbents (Sargent & Lundy , 2017); this implies that higher volumes of calcium based sorbent is required for similar removal efficiencies compared to sodium based sorbents. However, the addition of sodium based sorbent may increase NO_2 emissions and significantly alters the ash properties once combined. This increases the leachability of components like selenium and arsenic, which holds environmental concerns. Environmental and site specific constraints, such as local sorbent availability and disposal options, are thus significant items to consider beyond SO_2 reduction efficiency when sorbent is selected.
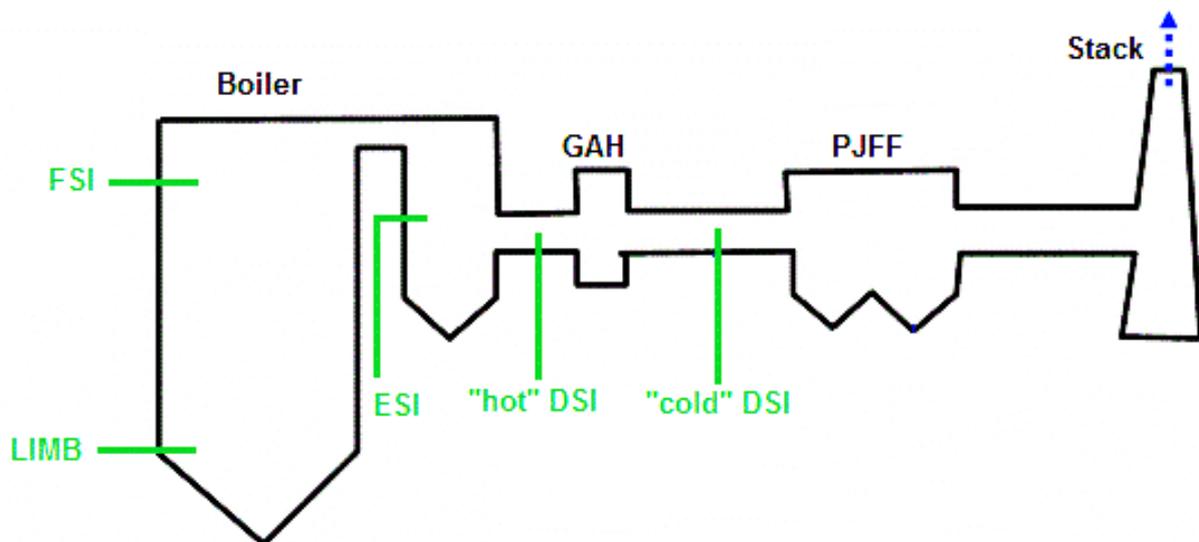

**Figure 4-1: Schematic of direct sorbent injection variations**

The sorbent can be pneumatically injected at various points in the flue gas path from the furnace to the stack, as can be seen in Figure 4-1. Elevated temperatures are, however, more favourable for SO_2 control. Each injection location has associated advantages and disadvantages. The following points are typically used and are discussed further:

- Injection through the burner system (limestone injection multi-stage burner technology (LIMB))
- Furnace sorbent injection (FSI)
- Economiser sorbent injection (ESI)
- Injection upstream/downstream of the gas airheater (GAH) (duct sorbent injection (DSI))

4.1 LIMESTONE INJECTION MULTI-STAGE BURNER TECHNOLOGY (LIMB)

Calcium based sorbent, typically limestone, is injected directly into the furnace through the low NO_x burner system. It can be injected with the pulverised fuel or through the tertiary or overfire air ports in order to reduce the incidence of sorbent sintering (Mongeon, Mustonen, & Lachapelle, 1984), which reduces SO_2 reduction efficiency (Sargent & Lundy , 2017). LIMB is designed for sorbent reactivity at temperatures of 871°C to 1200 °C. Where limestone is employed, calcination of the limestone to quicklime is facilitated at the high temperatures (above 950°C) followed by partial removal of SO_2 via sulphation in accordance with the basic chemical reactions in Equation (1 (Mongeon, Mustonen, & Lachapelle, 1984)

$$CaCO_3 \rightarrow CaO + CO_2 \dots Calcination$$

$$CaO + SO_2 + \frac{1}{2}O_2 \rightarrow CaSO_4 \dots Sulphation$$

(1)
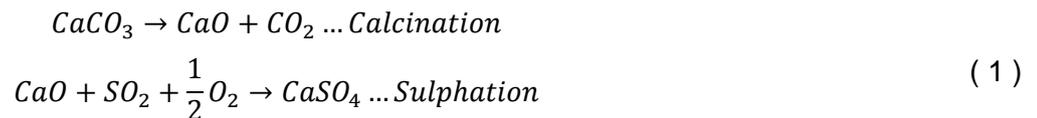
Although limestone is typically used, alternative, more costly, sorbents such as calcitic and dolomitic hydrated lime and hydrated lime enriched with calcium lignosulfonate have been successfully employed (U.S Department of Energy, 2000).

SO_2 removal efficiencies of between 15% and 50% can be achieved at ideal conditions with 20% SO_2 reduction typically achievable (Mongeon, Mustonen, & Lachapelle, 1984).

4.2 FURNACE SORBENT INJECTION (FSI)

In FSI the dry sorbent, typically hydrated lime or sodium based sorbent although limestone is occasionally used, is injected in the upper part of the furnace above the flame where the temperature is in the range of 950°C to 1000°C. The same basic calcination and sulphation reactions described in Equation(1 occur if limestone is used. The injection location must be carefully selected as the sulphation reaction ceases at temperatures below 750°C, while the sorbent active surface area is reduced at high temperatures due to pore blockage by the by-product produced (Haji-Sulaiman, Scaroni, & Yavuzkurt, 1990)

For hydrated lime, the basic chemical reaction for SO_2 removal is described by (2 (Schantz, et al., 2016):

$$Ca(OH)_2 + SO_2 + \frac{1}{2}O_2 \rightarrow CaSO_4 + H_2O$$

(2)
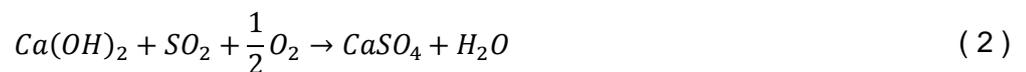
SO_2 removal efficiencies of up to 60% can be achieved at ideal conditions (U.S Department of Energy, 2000). The critical parameters that affect the efficiency are the injection temperature and the residence time of the sorbent in the furnace.

4.3 ECONOMISER SORBENT INJECTION (ESI) AND DUCT SORBENT INJECTION (DSI)

Sorbent can either be injected into the flue gas stream near the economizer zone or upstream of the GAH where the temperature is in a range of 300°C to 650°C (classified as "hot" sorbent injection) or into the duct after the 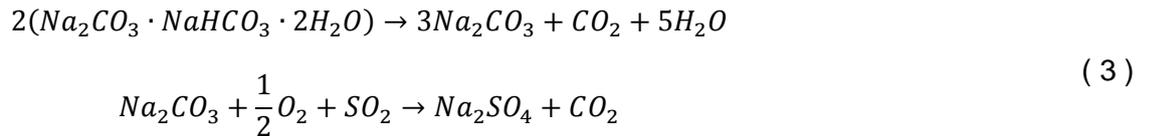GAH where the temperature is below 150°C (referred to as "cold" sorbent injection). In this application, hydrated lime or sodium based sorbents are used.

For hydrated lime, the chemical reaction described by (2 applies. For trona, the basic chemical reaction is described by Equation(3 (Schantz, et al., 2016):

$$2(Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O) \rightarrow 3Na_2CO_3 + CO_2 + 5H_2O$$

$$Na_2CO_3 + \frac{1}{2}O_2 + SO_2 \rightarrow Na_2SO_4 + CO_2$$

(3)

SO$_2$ removal efficiencies of up to 50% to 60% can be achieved at ideal conditions using hydrated lime. Removal efficiencies of up to 80% can be achieved using sodium based sorbents such as trona or sodium bicarbonate (Srivastava & Jozewicz, 2001).

Humidification of the flue gas can occur before or after the injection point and improves SO$_2$ reduction efficiency and particulate capture where an ESP is employed (U.S Department of Energy, 2000). Humidification is not recommended where FFPs are employed for particulate capture due to the adverse effects on bag life and pressure drop when moisture is introduced into a FFP.

5. FACTORS THAT IMPACT DIRECT SORBENT INJECTION EFFECTIVENESS

The properties of the flue gas and sorbent as well as the configuration and design of the system significantly influence the effectiveness and efficiency of the direct sorbent injection technology. Ultimately, site-specific factors, constraints and requirements will inform the application. Extensive testing and demonstration is thus required prior to full-scale implementation (Sargent & Lundy , 2017). Selected parameters with significant bearing on direct sorbent injection effectiveness are further discussed below.

5.1 FLUE GAS PROPERTIES

The raw flue gas properties that affect the efficacy of LIMB, FSI, ESI and DSI include (Schantz, et al., 2016):

- The temperature profile of the flue gas.

  The temperature of the flue gas will directly impact the reaction kinetics of the system and injection location must be carefully chosen to consider the average temperature and temperature profile in order to allow adequate SO$_2$ reduction.

- The concentration of competing acidic gases.

  The following order of reactivity is generally accepted SO$_3$ > HCL/HF > SO$_2$; consequently the presence of SO$_3$ and other acidic gases in the flue gas stream will reduce the efficiency of SO$_2$ removal and significant additional sorbent may be required

- The flue gas moisture content, flow distribution and velocities as well as carbon dioxide concentration.

Generally, temperatures over 580°C are required to ensure pure thermal dissociation of calcium hydrate for removal efficiencies higher than 60%. Below 580°C, the reaction depends on the amount of moisture in the flue gas since the reaction with SO$_2$ takes place in the liquid phase and not the gas phase.

Therefore, further conditioning of the flue gas is required to obtain higher removal efficiencies at temperatures below 580°C, as would be experienced in ESI and DSI. Water can be injected onto the hydrated lime prior to injection into the duct as a thin mist to create a hydration layer around the particles. Below 150°C, a significant quantity of water is required to aid the reaction and removal efficiencies of less than 20% can be expected. Thus, in the case of cold DSI where temperatures below 150°C are experienced, better suited technologies such as CFB FGD and SDA technology have been developed.

Furthermore, at low temperatures (around 150°C) hydrated lime has increased affinity to react more quickly with SO_3, HF and HCl than with SO_2. In this case the hydrated lime would react with all the SO_3, HF and HCl before it reacts with the SO_2, thereby limiting the possible SO_2 removal efficiencies and increasing the sorbent requirements.

5.2 .REAGENT PROPERTIES

Properties of the selected reagent (sorbent) which affect the efficacy of LIMB, FSI, ESI and DSI include:

- Reagent type.
- Specific surfaces area (SSA) and particle size.

  Smaller particle sizes increase the SSA of the reagent and consequently the reactivity. The drawback, however, is that smaller particle sizes with higher surface area require more processing which comes at additional cost

- Porosity and pore size distribution.
- Purity.

Theoretically, SO_2 removal efficiencies of between 20% and 30% may be achieved with the use of normal hydrated lime with an excess Ca/S nett stoichiometric ratio (NSR) of between 2 and 4, a SSA of 20 m^2/g and a porosity of approximately 0.7 cm^3/g; assuming the other conditions (flue gas temperature and moisture content, reagent mixing and residence time) are favourable. The removal efficiency can be increased through the utilisation of an optimised technical hydrated lime sorbent (e.g. SORBACAL) with a SSA greater than 40 m^2/g and porosity of ~0.23 cm^3/g. The production of such technical hydrated lime sorbents involves a specific and proprietary slaking process which increases the cost of the reagent and is not currently available in South Africa.

Direct sorbent injection with the use of sodium based sorbents, such as sodium bicarbonate or trona, can achieve removal efficiencies of up to 80% with similar NSR as hydrated lime. However, the environmental implications associated with the high leachability of harmful elements and the consequent cost implications to the ash disposal facilities must be considered.

5.3 SYSTEM CONFIGURATION

Direct sorbent injection SO_2 removal efficiency can be improved by ensuring that the system configuration is optimised to allow the following:

- Longer sorbent particle residence time.
- Favourable distribution of sorbent particles over the cross-section of the duct.

- Further reaction of the unreacted sorbent collected on the FFP bags with the remaining SO_2 in the flue gas by employing an appropriate FFP filtration velocity[2].

- Sorbent and target gas mixing and dispersion of sorbent in flue gas.

- Sorbent flow rates and quantity to achieve optimal NSR.

Multiple injection trains with strategically positioned nozzles based on flow conditions, longer duct length post sorbent injection in order to extend sorbent residence time and the presence of a FFP for particulate emissions reduction (as opposed to an ESP) are beneficial for the reduction of SO_2.

6. PRACTICAL IMPLICATIONS AND RISKS FOR APPLICATION AT MEDUPI POWER STATION

6.1 SO_2 REDUCTION REQUIREMENTS AT MEDUPI POWER STATION

As discussed previously, direct sorbent injection is best suited to small boiler units with low sulphur coal where low SO_2 reduction efficiency is required. Medupi Power Station is therefore not an ideal candidate, since boiler units are large (800 MW) and high sulphur coal is burnt. Direct sorbent injection is considered only as an interim, low efficiency SO_2 reduction measure to achieve SO_2 removal efficiency of up to 25%, depending on the coal quality received.

Table 6-1: Selected Medupi Process Temperatures and Coal Constituents

Parameter	Design Value	Comment
Flue gas temperature at furnace outlet (°C)	1180	This temperature varies based on evaporator performance and temperatures can exceed 1350°C
Flue gas temperature leaving economiser (°C)	391	-
Flue gas temperature at GAH outlet (°C)	125	Due to poor GAH performance this temperature varies from 110°C to 190°C but averages around 137°C to 140°C
Medupi coal sulphur content (%, air dried (AD))	1.2	The specification for the sulphur content of Medupi coal is 0.8% to 1.8% (AD), however sulphur excursions above 1.8% are received approximately 10% of the time
Medupi coal moisture content (%, AD)	10.5	The specification for the moisture content of Medupi coal is 5% to 12% (AD)
Chlorine (%, AD)	<0.1	-
Fluorine (%, AD)	<0.005	-

A high level process calculation (summarised in Appendix A) predicts that when coal with 2.2% sulphur is received, 4381 mg/Nm^3 (dry, at 10% O_2) SO_2 will be emitted should no FGD process be present. Therefore, SO_2 reduction of 20% is required to meet the 3500 mg/Nm^3 limit. The optimal Ca/S NSR to

---

[2] *Filtration velocity*, otherwise referred to as the *air-to-cloth ratio*, is a key design consideration in the sizing of FFPs. For high particulate loading applications such as when direct sorbent injection is employed, larger cloth area is required for similar flue gas volumes in order to maintain adequate pressure drop and aid SO_2 reaction. Consequently, a lower filtration velocity is required. This equates to larger FFP casings.

achieve the required efficiency must be defined through pilot testing. The impact of the Ca/S NSR on sorbent requirements is shown for the typical range (2 to 4) in Figure 6-1. For an optimistic Ca/S NSR of 2, 1094 tons per day of 87% purity hydrated lime is required. This corresponds with 720 tons of quicklime per day. In instances where coal with higher sulphur content is received, the sorbent requirement will be greater.
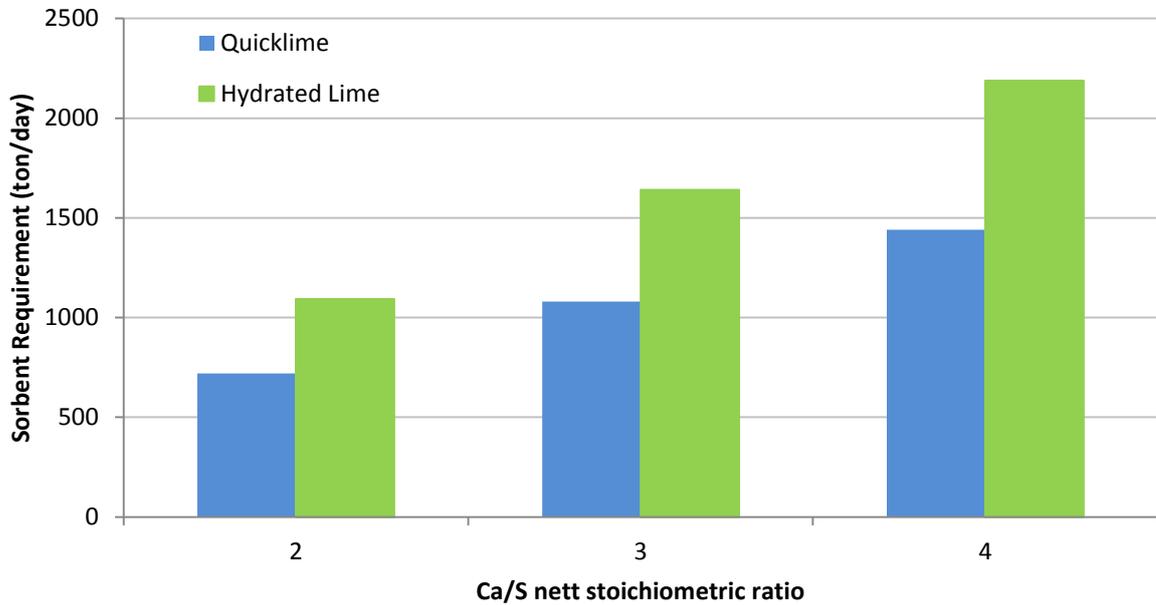

Figure 6-1: Impact of Ca/S NSR on sorbent requirements

Medupi specific concerns, taking into account design and current plant operation, are further discussed below.

6.2 DIRECT SORBENT INJECTION LOCATION: EROSION, FOULING AND BLOCKAGE CONCERNS

LIMB offers the advantage of being able to use limestone as sorbent, which is less costly than other sorbents considered. Should limestone be introduced directly with the pulverised fuel, plant modification to the milling system will be required since the capacity and operability of the milling system do not make provision for the addition of limestone. In order to avoid limestone sintering at high temperature which reduces SO_2 removal efficiency as occurs when the limestone particles are injected directly with the pulverised fuel, it is preferable to inject the limestone particles through the tertiary or overfire air. This will however, require the installation of a new limestone milling, storage and delivery system. Conceptual designs would inform whether portions of this system could be reused in the WFGD plant. Although the existing multistage burners could be used to implement LIMB, their design does not cater for the addition of sorbent and modification as well as optimisation will be required to ensure that combustion and NO_x levels are not affected. Furthermore, the introduction of LIMB technology will result in more alkaline slags. This will significantly increase the slagging ratio of the ash in the radiant furnace section.

The implementation of FSI will result in a significant increase in entrained solids throughout the boiler due to the NSR required for SO_2 neutralisation. Since injection will take place before the boiler convective sections in order to achieve the temperature requirements, this will increase the fly-ash erosion rate as well as the slagging propensity and boiler fouling. Increased particulate build-up on convective surfaces can be expected, for which the existing sootblowing system is not designed. The

efficacy of boiler heat transfer may therefore be affected. More frequent sootblowing may increase boiler tube erosion and corrosion.

The Medupi boilers are currently experiencing high erosion rates and the increase in solids associated with LIMB and FSI therefore poses a significant erosion risk. The Medupi boilers are further experiencing high furnace exit gas temperatures which increase the probability of slagging. Increased slagging propensity resulting from the introduction of sorbent in the furnace is therefore undesirable.

ESI or DSI upstream of the GAH increase the likelihood of abrasion of the ducting and GAH as well as by-product solid deposits and GAH blockage over time. However, neutralisation of SO_3 due to the sorbent injection may be beneficial for low temperature acid condensation plugging of the GAH.

For DSI at low temperatures downstream of the GAH where further conditioning of the flue gas using moisture is required in order to achieve suitable SO_2 removal efficiency, liquid water carryover to the FFP, which would cause blinding of the filter bags, is a significant risk.

6.3 WASTE CAPTURE, MANAGEMENT AND DISPOSAL

Implementation of any of the direct sorbent injection variations will increase the solids loading through the FFP which captures the particulates in the flue gas. Although the presence of a purpose designed FFP is beneficial for direct sorbent injection SO_2 removal efficiency as it increases the reaction time due to the build-up of the ash cake on the bag surface, the existing FFP at Medupi Power Station has not been designed with adequate air-to-cloth ratio to enable this while maintaining suitable pressure drop. Since sorbent is added in excess to ensure adequate reaction with the SO_2, the solids loading to the FFP will increase significantly. The current FFP system suffers severe underperformance and will not be able to handle the additional solids loading.

Should direct sorbent injection be installed, the FFP pulsing system will require replacement to ensure adequate bag cleaning is possible. Furthermore, due to the poor flow distribution of the existing FFP, flow modifications will be necessary to minimise bag and structural abrasion in high velocity zones and solids fall out in low velocity zones. Extending the FFP to increase the bag cloth area will be necessary to achieve optimal sorbent residence time while ensuring that the differential pressure across the FFP is maintainable within operational limits. According to typical air-to-cloth values, an increase in cloth area of 54% will be required, which will entail major FFP casing modification and extension. Sufficient space for lateral casing extension is not available. Increasing the casing height is costly due to structural stiffening required for the additional wind loading. Furthermore, the existing foundations may not be able to manage the additional weight.

The existing DHP plant does not have the capacity to transport the additional solids after capture by the FFP. The current pneumatic handling systems will have to be increased by approximately 35% in order to be capable of removing the additional solids introduced by direct sorbent injection. Adequate DHP backlog recovery should also be considered. Furthermore, the existing ash handling infrastructure after the DHP which conveys the particulate to the ash dumps has not been sized to handle the additional loading and capacity increase may thus be required.

Furthermore, the composition of the particulates will be altered and will include the by-product from SO_2 removal as well as a significant amount of unused sorbent (since it is added in excess to meet the Ca/S NSR requirements). The flow characteristics of the mixed particulate material is not yet understood and the impact to the conditioning plant, transport to the silos and the impact on the rest of the materials handling value chain up to the current ash dump cannot be quantified until testing is completed to characterise the sorbent, the by-product and its interaction with Medupi fly ash.

The current ash dump was designed to cater for fly ash for the first 20 years of the station life. The available space is, however, constrained due to the excess coal stock yard on the same footprint. The ash dump lifetime will be reduced due to the increase in solids loading. This poses a significant risk to the continued operation of Medupi Power Station since a location for a future waste disposal facility has not yet been identified. Furthermore, the ash dump is currently lined with a Class C liner. The direct sorbent injection waste (i.e. fly ash, sorbent and by-products) would require an environmental classification which cannot be completed until testing to characterise the sorbent and its waste is concluded. The licensing authorities have indicated that co-disposal of gypsum (the by-product from the WFGD process) and ash is not preferred; it is thus anticipated that extensive testing will be required in order to obtain approval for the mixed disposal of the direct sorbent injection waste with fly ash. It is likely that the existing ash dump will require upgrading to a Class A liner, which is approximately double the price of the current Cass C liner.

6.4 SORBENT SOURCING

Due to the environmental concerns, cost and unavailability of locally sourced purpose developed sodium based sorbents hydrated lime is considered to be the most viable sorbent option for Medupi Power Station's application.

Hydrated lime is produced by first calcining limestone to quicklime[3], a process which produces carbon dioxide, and subsequently slaking it through the addition of water to produce hydrated lime[4].
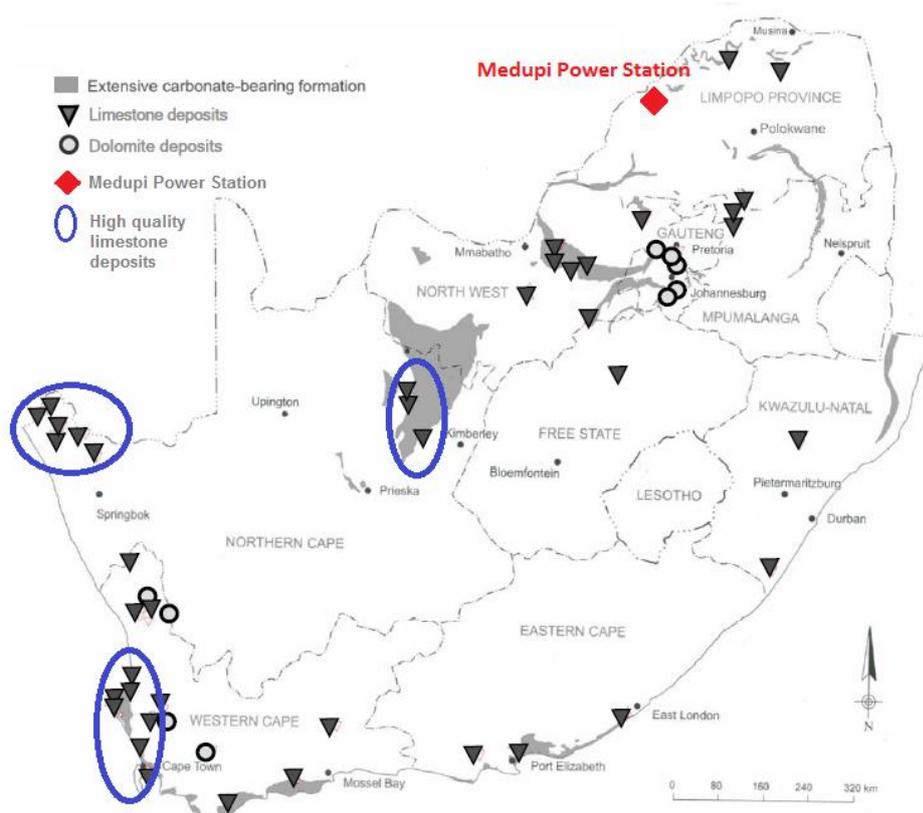

Figure 6-2: Limestone and dolomite deposits in South Africa

---

[3] *Quicklime* is also known as burnt lime. Its chemical compound is calcium oxide (CaO).

[4] *Hydrated lime's* chemical compound is calcium hydroxide ($Ca(OH)_2$).

Although South Africa has large limestone deposits, the majority is of highly variable, low grade limestone (Directorate: Mineral Economics, 2003) with mineralogy unsuitable for calcination. While high quality limestone deposits favourable for calcination do exist, the commercially exploited deposits of suitable quality are predominantly in the Northern and Western Cape (Ramane & Modiselle, 2010), as can be seen in Figure 6-2, and transport costs to Medupi Power Station are therefore significant.

Note that Figure 6-2 indicates only the presence of mineral deposits and all deposits are not necessarily mined. The low quality limestone deposits located nearer Medupi Power Station are not extensively commercialised and it is not known whether this poor grade limestone would be suitable for calcination or whether the hydrated lime produced would be sufficiently reactive to achieve suitable SO_2 reduction.

Hydrated lime with the maximum specific surface area and porosity that can be achieved with conventional slaking may be acceptable to achieve the low removal efficiency (<25%) required for interim reduction of Medupi's periodic SO_2 emissions exceedances. However, the SO_2 reduction efficiency of South African hydrated lime has not yet been established. Pilot scale evaluation of the characteristics of South African hydrated lime is required in order to establish whether it is suitable for SO_2 reduction at the efficiency required.

There is thus uncertainty regarding the characteristics of the available South African quicklime and hydrated lime and its suitability for the direct sorbent injection process. Proprietary sorbents sourced internationally may be required if the desired removal efficiency cannot be achieved with local hydrated lime, which would significantly increase the sorbent cost.

Assumptions regarding the sorbent quality and reactivity were made to calculate an expected sorbent utilisation rate, described in Appendix A. These assumptions can only be confirmed during a concept design and once pilot testing characterising sorbent behaviour has taken place. Based on these initial calculations, the expected hydrated lime requirement for a 20% SO_2 reduction is approximately 1094 tons per day per unit at a Ca/S NSR of 2 if the direct sorbent injection unit is running on a continuous basis. The sorbent requirement will increase if higher sulphur coal is received. A significant amount of sorbent will thus be required for limited abatement of SO_2. This equates to approximately 20 to 30 truckloads of sorbent per unit per day (total of 120 to 180 truckloads per day for all units) for continuous operation. If testing and conceptual design concludes that a higher Ca/S NSR is needed, this quantity will increase (refer to Figure 6-1). Although the trucking requirements can be optimised during a conceptual design for batch-wise operation, the figure is not expected to reduce significantly. This poses a significant logistical challenge. Storage of large volumes of sorbent on site must also be considered. Current knowledge suggests that quicklime of sufficient quality is only available from the Northern Cape area near Kimberley and will therefore have to be delivered to Medupi Power Station via truck or rail, where available, over extended distances. This holds significant transport cost implications.

Should normal hydrated lime sourced in South Africa be proven acceptable, cursory market research shows that it would be simpler to source quicklime and hydrate it on site at Medupi Power Station in a slaking plant. This is due to the cost and logistical considerations associated with transporting hydrated lime which is heavier due to its water content as opposed to the lower bulk of non-hydrated quicklime. The future WFGD waste water treatment plant will require hydrated lime for pH control. An opportunity thus exists to potentially reuse the slaking plant in the future system, although the quantity of hydrated lime required for the future waste water plant is significantly lower than that required for direct sorbent injection. The slaking plant could also potentially be used to fill Matimba's chemical requirements for hydrated lime, although the current requirement is lower than that needed for direct sorbent injection.

6.5 CONTINUOUS VERSUS BATCH-WISE OPERATION

The SO_2 emissions at Medupi should be within the existing plant emissions license when operating with design coal. Operation of the direct sorbent injection system would thus only be required when receiving coal quality between the worst case and rejection point for sulphur or out of specification. Additional instrumentation would be required to monitor the SO_2 emissions in real time to ensure timeous starting of the injection process. If operated continuously, large quantities of sorbent will be wasted.

6.6 ENVIRONMENTAL REQUIREMENTS

An environmental impact assessment (EIA) will be required due to the construction of new plant, processing of chemical sorbents, and change in quantity and quality of the FFP waste stream and the handling and disposal thereof. Furthermore, the implementation of direct sorbent injection will require an amendment to the current Water Use License due to the additional water requirements for the slaking plant, should hydrated lime be used as sorbent. The slaking process requires potable water; hence the quantity of water requiring treatment by the existing water treatment plant will increase.

6.7 INFRASTRUCTURE REQUIREMENTS

For LIMB, the following new plant and modification to the existing plant would be required:

- Limestone off-loading facilities
- Limestone silo/s
- Limestone milling system/modification to coal mills
- Pneumatic pipelines for transportation of limestone
- Modification to burners
- Modifications to FFP and DHP
- Waste management systems including modifications to the existing ash dams
- Additional control & instrumentation for real time SO_2 monitoring and direct sorbent injection system activation

In order to allow operation of a direct sorbent injection system (FSI, ESI or DSI), the following new plant and modification to the existing plant would be required:

- Sorbent off-loading facilities
- Quicklime silo/s for the storage of quicklime
- Lime slaker to hydrate the quicklime
- Hydrated lime silo/s to store hydrated lime
- Pneumatic pipelines for transportation of hydrated lime
- Sorbent injection ports
- Flue gas conditioning/additional water before hydrated lime injection into the duct
- Bulk Materials Handling infrastructure
- Modifications to FFP and DHP
- Waste management systems including modifications to the existing ash dams
- Additional control & instrumentation for real time SO_2 monitoring and direct sorbent injection system activation

Due to the planned addition of the WFGD plant at Medupi Power Station, space for the additional infrastructure for interim direct sorbent injection is limited. The cost and time associated with the significant modifications required to the FFP must not be underestimated. Although modifications to the existing FFP are currently under consideration to improve its performance, the modifications required for direct sorbent injection will result in an over-designed FFP once the direct sorbent injection system is no longer in use.

Furthermore, the addition of a slaking plant at Medupi Power Station holds additional operational and maintenance implications. Since only Matimba Power Station is located in the vicinity, there is no benefit offered by a central slaking facility, as may be realised in Mpumalanga should sufficient stations make use of the sorbent. Since direct sorbent injection is being considered as an interim measure only, the slaking plant would be operational for only a short period before decommissioning if it cannot be reused for the WFGD waste water treatment plant.

6.8 DIRECT SORBENT INJECTION FOR MEDUPI POWER STATION

Based on the Medupi specific considerations discussed above, specifically relating to the significantly increased risk of boiler tube erosion and consequent tube leaks associated with LIMB and FSI, ESI or DSI are deemed most appropriate. Due to the existing plant configuration as well as concerns relating to the FFP should low temperature DSI be employed, high temperature DSI upstream of the GAH is the most appropriate direct sorbent injection variation considered.

Due to the local unavailability and, pertinently, the significant environmental concerns associated with sodium-base sorbents, hydrated lime is the most appropriate sorbent for use in a Medupi DSI system. The uncertainty regarding achievable SO_2 reduction efficiency with locally available hydrated lime as well as the associated sorbent and transport costs are however highlighted.

Implementation of DSI without the extensive plant modifications discussed above is, however, unfeasible due to the technical concerns relating to the FFP and waste handling and management systems.

7. SCHEDULE

Due to the uncertainty regarding the suitability of locally available sorbents for direct sorbent injection, research is required to establish sorbent characteristics. This must be completed prior to concept design development. Two scenarios considered for this are described below. Note that neither scenario includes piloting of a slaking plant, a technology with which Eskom does not have experience on the scale required.

- Scenario 1: Laboratory Testing

  Scenario 1 involves laboratory testing of sorbent characteristics. A scale test apparatus can be developed to determine expected efficiencies, particle fall out and behaviour at Medupi Power Station. Although this scenario has the benefit of shorter duration, it must be noted that results will be indicative only: scalability of laboratory models is problematic.

- Scenario 2: Pilot Testing

  Scenario 2 involves using the results from the planned Kendal CFB FGD demonstration plant which will characterise local sorbents. Although insight into sorbent behaviour will be obtained, this scenario has a long duration and will provide no appreciation of the application of direct sorbent injection at Medupi Power Station.

  A pilot test of direct sorbent injection at one unit at Medupi Power Station would be most appropriate for establishing the suitability of direct sorbent injection for interim SO_2 reduction at Medupi Power Station, however such a demonstration is unfeasible due to the FFP and waste handling concerns discussed in the preceding section and the EIA requirements for such an on-site pilot. Such a pilot would consequently have an implementation timeline similar to full scale implementation.

Figure 7-1 shows the indicative, high-level schedules for both scenarios discussed above as well as the most recent dates at which WFGD operation is expected per unit (based on the FGD Retrofit Project Schedule dated 31 December 2019). Note that an optimistic procurement duration of 1 year is assumed. The time required for modification of existing plant is not included. It is clear that Scenario 2 is unfeasible since direct sorbent injection will be implemented after the WFGD plant is operational on all units. Scenario 1 shows operation of direct sorbent injection on all units for only 9 months. The short operation of the direct sorbent injection system does not warrant the associated cost and significant plant modifications required.

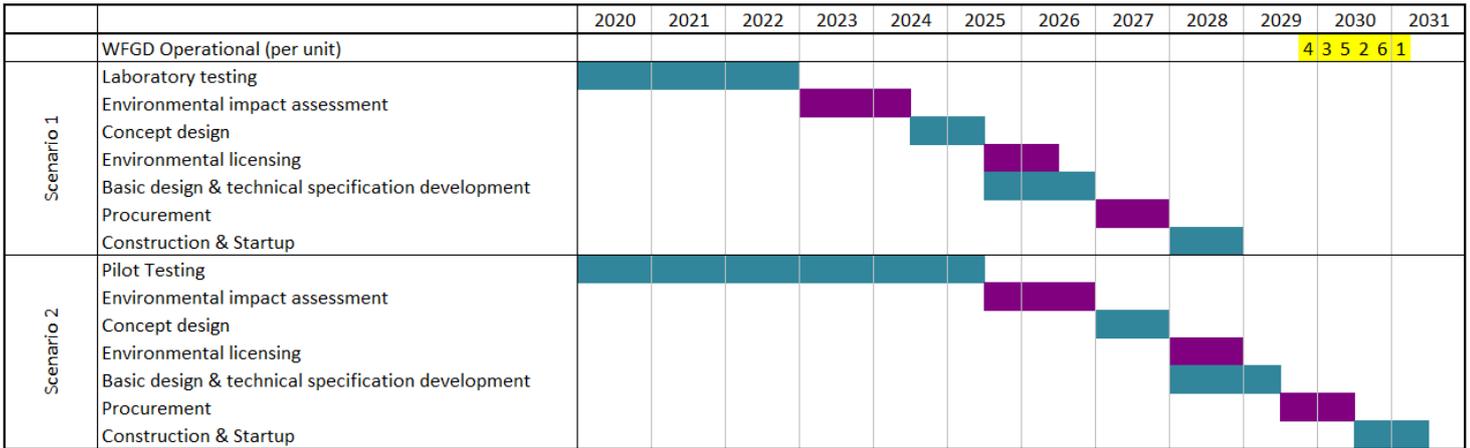|		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
	WFGD Operational (per unit)										4 3	5 2 6	1
Scenario 1	Laboratory testing												
	Environmental impact assessment												
	Concept design												
	Environmental licensing												
	Basic design & technical specification development												
	Procurement												
	Construction & Startup												
Scenario 2	Pilot Testing												
	Environmental impact assessment												
	Concept design												
	Environmental licensing												
	Basic design & technical specification development												
	Procurement												
	Construction & Startup												

Figure 7-1: Indicative schedule scenarios for direct sorbent injection implementation

8. COSTS

High level costing for DSI has been developed and is presented in Table 8-1. This costing is indicative only and considers purely the process system and sorbent.

The total cost of a DSI system is estimated at approximately R821.68 million per unit (R4.93 billion for all six boiler units) for one year's operation to achieve an SO_2 reduction efficiency of 20% when coal with 2.2% sulphur is continuously received. The operation for one year only is based on the schedule discussed in the preceding section of this document. Should poorer quality coal be received and SO_2 reduction of up to 25% be required, this cost will increase due to the significant sorbent cost.

CAPEX of R222.6 million is required for the direct sorbent injection system only (costs for FFP and DHP modifications as well as waste handling and disposal are not included). Significant OPEX of R1.62 million per day (R532.30 million annual cost) is required for sorbent.

Table 8-1: Direct sorbent injection implementation costs: DSI Costs per Unit

Parameter	Unit	Value for One Boiler Unit	Assumption
Capital Cost			
Sorbent Process Equipment	R million	55.65	2017 B&W Estimate, escalated to 2020 cost using 2018/2019 CPI (5.4%) and 2019/2020 CPI (5.6%)
Total Implementation Cost	R million	222.60	Typical factor of 4 for chemical process equipment applied
Variable Cost			
Decommissioning Cost	R million	44.52	20% of Capital Cost
Operating Cost (Annual)			
Lime Sorbent Cost	R/ton	2250.00	Estimated 2020 escalated cost, delivered to site
Quantity of Lime Sorbent Required (ton/day)	ton/day	720.18	2017 DIMBO mass balance at 2.2% sulphur for reduction to 3500 mg/Nm^3 SO_2 (dry, at 10% O_2)
Lime Sorbent Annual Cost	R million	532.30	90% unit load factor assumed
Maintenance	R million	22.26	10% of Capital Cost
Total annual opex	R million	554.56	
TOTAL COST	R million	**821.68**	

The following explanation describes how the cost was obtained:

- In 2017, Eskom received a cost estimate of R50 million for the sorbent process equipment. This was escalated to present value using the Eskom approved Economic Evaluation Parameters [4].

- A cost factor of 4 was used to provide for the Engineering work, procurement, shipping, construction, etc. associated with the sorbent process equipment.

- The Capital Cost excludes costs associated with the FFP, DHP and the waste handling.

- Decommissioning was estimated at 20% of the capital cost.

- Lime delivered to site was estimated at a cost of R2250/ton.

- In 2017, a DIMBO mass balance was performed by Steinmüller Engineering and it was found that 720.18 tons/day of lime is required to reduce the 2.2% sulphur to 3500 mg/Nm^3 SO$_2$ (dry, at 10% O$_2$)

- The maintenance associated with the plant is estimated at 10% of the capital cost.

This costing is indicative only and full concept design development, including consideration of the modifications required to the FFP, DHP, waste handling and disposal plants will be required to arrive at a complete cost for implementation, which should include costs associated with outage duration.

Note that due to the high sorbent cost, the overall plant cost will increase significantly with extended direct sorbent injection system operation while achieving only very low 25% SO$_2$ reduction. Figure 8-1 presents a general comparison of low efficiency DSI vs higher efficiency removal technologies for operation throughout station life. Although this comparison is not specific to Medupi, the impact of the high sorbent cost on life cycle costing is clear.
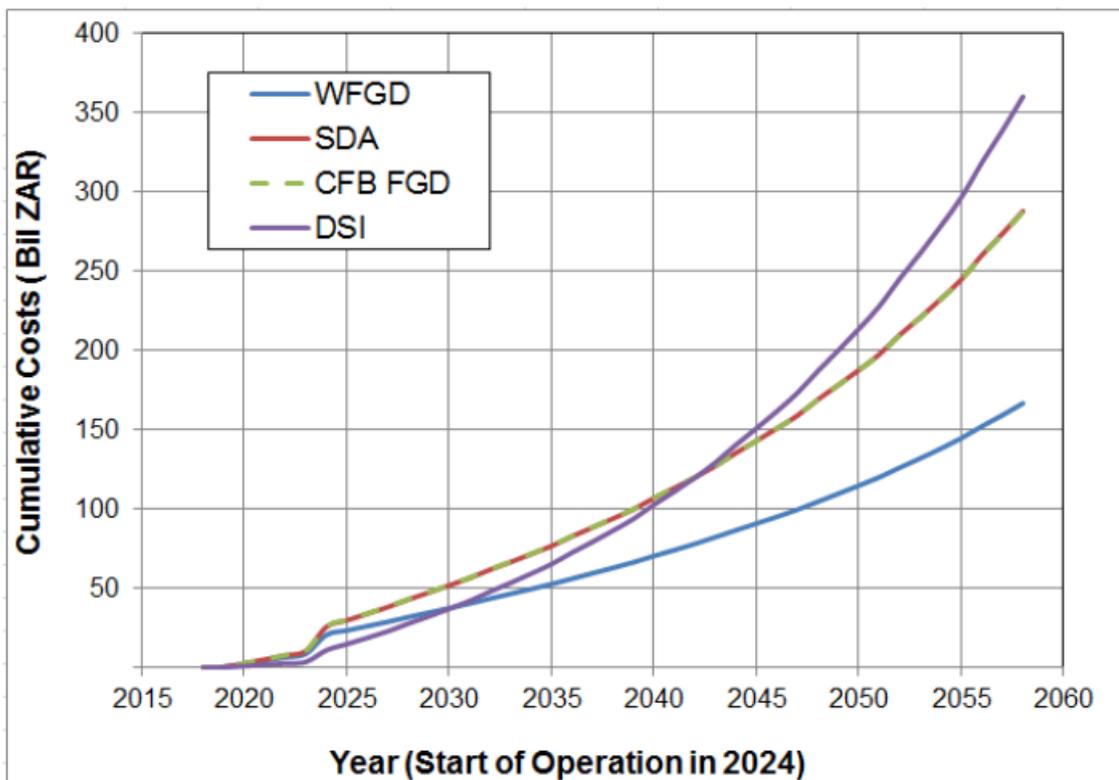

Figure 8-1: Indicative comparison of DSI with high efficiency FGD technologies

9. CONCLUSION

Based on the discussion above, it is concluded that of the direct sorbent injection options, DSI upstream of the GAH using hydrated lime is the most feasible option considered in order to achieve the requisite SO_2 removal efficiency of up to 25% while avoiding increased boiler erosion and slagging. Achieving the required efficiency is, however, highly dependent on temperature profiles and distribution, moisture content in the flue gas, residence time through the duct and FFP and the reactivity of the sorbent. Since sorbent and waste characteristics are unknown, extensive testing will be required to inform conceptual development of this solution.

Nevertheless, direct sorbent injection is technically unfeasible due to risks relating to GAH fouling and blockage and the requirement for extensive modification of FFP, DHP and waste management and disposal facilities.

Furthermore, due to the extended implementation timeframe and consequent short period for which the plant would be operational as well as the substantial new plant and plant modification requirements, the cost is prohibitively high.

It is thus concluded that direct sorbent injection is not feasible for interim SO_2 reduction to below the current license limit of 3500 mg/Nm^3 until such time as the WFGD is installed.

10. RECOMMENDATION

It is recommended that direct sorbent injection is not pursued for interim SO_2 reduction at Medupi Power Station.

There are currently many unknowns regarding sorbent quality and availability. It is thus recommended that pilot studies be conducted to understand the local sorbent behaviour and enable future decision making on direct sorbent injection at other coal fired power stations within the Eskom fleet.

11. AUTHORISATION

This document has been seen and accepted by:

Name	Designation
Ebrahim Patel	Senior Consultant: Air Pollution Control
Sandile Peta	Manager: Boiler Auxiliary CoE (acting)
Rajesh Ramluckun	Project Engineering Manager: Medupi FGD Retrofit Project
Nalini Ghela	Senior Manager: Project Engineering

12. REVISIONS

Date	Rev.	Compiler	Remarks
December 2019	0.1	J Fourie	First draft
January 2019	1	J Fourie	Finalised document for authorisation

13. DEVELOPMENT TEAM

The following people were involved in the development of this document:

Jeanne Fourie

Ruveshnee Govender

Koogendran Govender

14. ACKNOWLEDGEMENTS

Candice Stephen

Nireshni Naidoo

15. REFERENCES

Directorate: Mineral Economics. (2003). *A review of the dolomite and limestone industries in South Africa.* Pretoria: The Department of Minerals and Energy.

Haji-Sulaiman, M., Scaroni, A. W., & Yavuzkurt, S. (1990). Optimum sulfation temperature for sorbents used in fluidised bed coal combustion. *Fuel Processing Technology*, 227-240.

Mongeon, R. K., Mustonen, J., & Lachapelle, D. (1984). Wall-fired design criteria for dry sorbent SO2 control with low-NOx burners. *The First Joint Symposium on Dry SO2 and Simultaneous SO2/NOx Control Technologies.* San Diego: Riley Stoker.

Ramane, L., & Modiselle, M. (2010). *Lime Industry in South Africa.* Pretoria: Department of Mineral Resources.

Sargent & Lundy . (2017). *Dry Sorbent Injection for SO2/HCl Control Cost Development Methodology.* Chicago: Eastern Research Group, Inc.

Schantz, M., Allen, J., Biehn, C., Glesmann, S., Hunt, G., Lehmkuhler, J., . . . Silva, T. (2016). *Dry Sorbent Injection for Acid Gas Control: Process Chemistry, Waste Disposal and Plant Operational Impacts.* Arlington: Institute of Clean Air Companies.

Srivastava, R., & Jozewicz, W. (2001). Flue Gas Desulfurization: The State of the Art. *Journal of the Air & Waste Management Association, 51:12, 1676-1688*, 13.

U.S Department of Energy. (2000). *LIMB Demonstration Project Extension and Coolside Demonstration: A DOE Assessment.* National Energy Technology Laboratory. Pittsburgh: U.S Department of Energy.

APPENDIX A: DIRECT SORBENT INJECTION FOR SO_2 REDUCTION AT MEDUPI POWER STATION

Table A-1: Results of high level calculations for SO_2 reduction with direct sorbent injection based on Medupi Acceptance Test process data

Parameter	Unit	FSI		ESI		DSI (upstream of GAH)		DSI (downstream of GAH)	
Sulphur content in coal	%	1.8	2.2	1.8	2.2	1.8	2.2	1.8	2.2
Temperature at injection location	°C	1374.04	1373.07	410.57	411.21	410.57	411.21	145.65	145.71
Flue gas volume flow	Nm^3/s (dry, 10% O_2)	1080.57	1086.80	1080.57	1086.80	1080.57	1086.80	1080.83	1087.07
SO_2 produced	Nm^3/s (dry, 10% O_2)	3600.94	4381.17	3600.94	4381.17	3600.94	4381.17	3600.05	4380.09
SO_2 reduction efficiency required	%	2.80	20.11	2.80	20.11	2.80	20.11	2.78	20.09
$CaCO_3$ required for reduction efficiency	ton/day	1235.78	1512.22	-	-	-	-	-	-
Ca/S NSR		2							
CaO required for reduction efficiency	ton/day	-	-	588.53	720.18	588.53	720.18	588.53	720.18
$Ca(OH)_2$ required for reduction efficiency	ton/day	-	-	893.80	1093.74	893.80	1093.74	893.80	1093.7
Ca/S NSR		3							
CaO required for reduction efficiency	ton/day	-	-	882.80	1080.28	882.80	1080.28	882.80	1080.2
$Ca(OH)_2$ required for reduction efficiency	ton/day	-	-	1340.70	1640.61	1340.70	1640.61	1340.70	1640.6
Ca/S NSR		4							
CaO required for reduction efficiency	ton/day	-	-	1177.07	1440.37	1177.07	1440.37	1177.07	1440.3
$Ca(OH)_2$ required for reduction efficiency	ton/day	-	-	1787.60	2187.48	1787.60	2187.48	1787.60	2187.4

Assumption made that $CaCO_3$ of 85% purity and $Ca(OH)_2$ of 87% are available.

High level calculations conducted using Steinmüller Engineering design tools.