



Next-generation, affordable SO₂ abatement for coal-fired power generation – A comparison of limestone-based wet flue gas desulphurization and Sulfacid® technologies for Medupi power station

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Synopsis

Coal is used to generate more than three-quarters of South Africa's electricity, while numerous coal-fired boilers are employed for steam generation in industrial processes. However, coal-fired power generation is responsible for the release of the largest quantities of SO₂ emissions to the atmosphere and leads to detrimental health and welfare effects in communities in the proximity of coal-fired plants. The classical industrial SO₂ abatement solution for the coal-fired power generation industry is wet flue gas desulphurization, which uses a limestone adsorbent and produces a gypsum by-product (WFGD L/G). In South Africa, due to the poor quality of the limestone the gypsum product is unsaleable and is co-disposed with coal ash. In comparison, the Sulfacid® process technology converts SO₂ contained in industrial flue gas into saleable sulphuric acid using a catalytic process requiring only water and air. This process does not require limestone. The scale of the latest commercial applications of the Sulfacid® SO₂ abatement technology in the chemical, fertilizer, and copper mining industries demonstrates the potential and readiness of this technology to be employed in the coal-fired electricity and steam production sectors. This paper provides a first-order direct comparison between the techno-economic aspects of the WFGD (L/G) and Sulfacid® technologies using the requirements specified for the 6 × 800 MWe Eskom coal-fired Medupi power station. The results indicate that affordable flue gas desulphurization technology exists that could be adopted by the South African industry to reduce SO₂ emissions to legislative limits and beyond.

Keywords

SO₂ abatement, coal-fired power, and heat generation, sulphuric acid, wet fluidized gas desulphurization, Sulfacid®, waste-to-chemicals.

Introduction

Coal-fired power generation in South Africa remains indispensable for maintaining economic activity now and into the foreseeable future, even with the introduction of renewable energy. During the period April 2018 to March 2019, approximately 77% of all electricity in South Africa was generated by 15 coal-fired power plants which, in addition to gas, hydro-, and nuclear power, formed part of a total of 92% Eskom-generated electricity supplied to the national grid (Stats SA, 2018a, 2018b, 2019; Eskom, 2019). Flue gas from coal-fired power plants contains sulphur dioxide (SO₂) that originates from the sulphur in the coal, and which has detrimental health and welfare effects on communities living in the proximity to the plants.

Sulphur is contained in coal predominantly as organic sulphur (S) and pyritic sulphur (Calkins, 1994), with typical total sulphur contents of 0.54% (by mass) for thermal export coal, > 1% for Sasol syngas production coal, < 2% for Eskom thermal power generation coal, and 2% (range 0.4–3.0%) for discard coal (Hall, Eslait, and den Hoed, 2011; Steyn and Minnitt, 2010; Makgato and Chirwa, 2017). During pulverized coal combustion, the organic and pyritic sulphur is converted mostly into SO₂, and in small quantities into sulphur trioxide (SO₃) (Müller, Schnell, and Scheffknecht, 2013), with only approximately 10% of the sulphur captured in the coal ash (Harrison, 2006). The SO₂ flue gas concentration for Eskom power plants typically ranges from 1 623 mg/Nm³ (dry, 10% O₂) for 0.7% S (air-dried basis) at Kriel power station to a maximum of 3 934 mg/Nm³ for 1.8% S at Medupi power station (Harris, 2014; Girmay and Chikobvu, 2017; Kolker, Senior, and Alphen, 2016). Likewise, the SO₂ emissions for the Eskom coal-fired power plant fleet (single point sources) range from 26 Mt/a for Komati power station to 429 Mt/a for Matimba power station (van Geuns, 2018; Mathebula, 2017). Most of the Eskom coal-fired power stations are located in, and impact the air quality in, the Highveld and Waterberg Priority Areas (South Africa, 2007, 2012a, 2012b, 2015).

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The atmospheric dispersion, transportation, and conversion of concentrated SO₂ (Harrison, 2006) from these power plant stacks result in diluted SO₂ concentrations ranging from 20 µg/m³ to more than 500 µg/m³ at ground level (WHO, 2005; South Africa, 2009) in the form of dry (gas and particulates) and wet depositions (droplets) to which humans, nature, and infrastructure are exposed (Hazi, Heikkinen, and Cohen, 2003; Pretorius, Piketh, and Burger, 2017). Human inhalation of SO₂ is associated with both short- and long-term adverse health problems, affecting the nose, upper respiratory tract, and lung function (WHO, 2005). In fact, integrated research reviews by the US Environmental Protection Agency (EPA) found a causal relationship between respiratory morbidity (illnesses), particularly in individuals with asthma, and short-term exposure to SO₂ (EPA, 2017). The EPA also found that cardiovascular effects and mortality are caused by short- and long-term human exposure to particulate matter (PM) with a nominal aerodynamic diameter < 2.5 µm (PM_{2.5}) that is composed primarily of sulphate (SO₄²⁻) and nitrogen oxides (NO_x) (EPA, 2009). Based on these types of studies, human mortality and morbidity rates for communities living in the proximity of Eskom coal-fired power stations could be estimated (Langerman and Pauw, 2018).

Despite South African legislation to limit the coal-fired power plant stack and ground-level ambient SO₂ concentrations, multiple exceedances of atmospheric emission licence (AEL) limits are reported by environmental groups (Sahu, 2019) and by the Department of Environment, Forestry and Fisheries (DEFF) (Gwase, 2019). Government's failure to implement the Highveld Priority Area air quality management plan, in view of the constitutional right of citizens to an environment that is supportive of their health and wellbeing (South Africa, 2016), has led to pending litigation by the Centre for Environmental Rights (CER) against the President of South Africa, the Minister of Environmental Affairs, and Chief Air Quality Officer (CER, 2019). Furthermore, in an apparent attempt by government to help the industry with legislative compliance, the SO₂ limit of 500 mg/Nm³ for existing coal-fired plants that was set in 2010 was relaxed to 1 000 mg/Nm³ in 2020 (South Africa, 2010, 2020).

Eskom is in the process of implementing wet flue gas desulphurization (WFGD) technology on its 6 × 800 MWe Kusile coal-fired power station that is under construction in the Mpumalanga region and is planning to retrofit the same SO₂ abatement technology to its operational 6 × 800 MWe Medupi power station in the Waterberg region (Bagus, van Wyk, and Chang, 2018; Harris, 2014). Besides water, power and steam, the WFGD (L/G) abatement process requires limestone as an adsorbent, generates additional taxable CO₂ during the SO₂ abatement process, and produces unsaleable gypsum as a by-product (Bagus, van Wyk, and Chang, 2018). Owing to the lack of a market for the gypsum by-product, additional volumes of waste (in addition to coal ash) need to be handled, increasing the life-cycle cost for waste disposal (Gruenewaldt, 2013; Campbell, 2015; Vosloo, 2018; Koralegedara *et al.*, 2019). From an economic viewpoint, this means that WFGD (L/G) incurs a capex (capital expenditure at the start of its life-cycle and sustains a net negative opex (operational expenditure during its life, resulting in a net negative cost of ownership at the end of its life-cycle. Furthermore, the scarcity, quality, and transportation cost of limestone in South Africa poses a threat to the further implementation of WFGD (L/G) for SO₂ abatement by Eskom

(Stephen *et al.*, 2014). In fact, Steyn and Kornelius (2018) argued in a recent paper that the implementation of the WFGD technology in the Highveld Priority Area will not provide a net benefit over a 30-year period from 2020 to 2050, mainly because of the continued net negative opex.

The challenge is, therefore, that while South Africa is dependent on coal-fired power and heat generation that generates harmful SO₂ emissions, the WFGD (L/G) technology currently being implemented at Kusile power station is not economically viable for further roll-out to the Eskom coal-fired power plant fleet.

Fortunately, next-generation SO₂ emission abatement technology is becoming available that seems to provide a net positive opex, resulting in a break-even and net profit during lifetime deployment. The back-end (before the stack) Sulfacid® process technology, developed by Lurgi AG and improved and patented by Luxembourg company Carbon Process & Plant Engineering S.A. (CPPE) directly converts SO₂ and SO₃ contained in any industrial flue gas, using only water and air, into saleable sulphuric acid (H₂SO₄) of various grades using a fixed bed of activated carbon, without requiring any limestone or producing CO₂ or gypsum (Strickroth, 2017a, 2017b).

The purpose of this paper is to conduct a first-order techno-economic comparison between the WFGD (L/G) and Sulfacid® SO₂ abatement technologies as applied to Eskom's 6 × 800 MWe Medupi coal-fired power plant, using publicly available data, to determine whether affordable SO₂ abatement could be implemented on coal-fired power plants in South Africa. The Medupi power plant has been chosen for this comparative study because Eskom's financial loan conditions require the implementation of an SO₂ abatement technology (World Bank, 2015), the sulphur content of the coal and resulting SO₂ concentrations are the highest in the Eskom fleet, and because this new station has a remaining life of 60 years (Cheng, van Wyk, and Bagus, 2018).

The following sections of this paper provide a historical literature review of the WFGD (L/G) and Sulfacid® technologies, followed by a description of the method of high-level first-order comparison that was used. The results from the techno-economic comparison are presented and discussed. The results indicate the possibility of affordable next-generation SO₂ abatement for coal-fired power generation. The limitations of this study are highlighted, and conclusions drawn suggesting that further comparative analysis be conducted by academia, industry, and government.

Literature survey

Flue gas desulphurization technologies

Flue gas desulphurization (FGD) technologies remove oxides of sulphur (SO_x) from flue gases, generally by reaction or absorption with alkaline absorbents, and can be categorized by the nature of the process flow (thermal or chemical regeneration of absorbent or non-regenerative one pass through), water usage (wet, semi-dry, and dry) and by-product production (commercially marketable commodity or landfill waste) (Lisnic and Jinga, 2018). Different absorbents are used for the wet (limestone, lime, caustic soda, ammonia, and seawater), semi-dry (limestone and lime), and dry process variants (limestone and dolomite) of the FGD technologies (Lisnic and Jinga, 2018). Therefore, WFGD (L/G) could be categorized as a wet, limestone-

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based absorbent, non-regenerative one pass through technology producing a gypsum by-product. Sulfacid® could be described according to this classification as a wet, water-based absorbent, regenerative one pass through technology producing a sulphuric acid by-product.

Evolution of the WFGD (L/G) technology

The first WFGD installation was in 1931 at the Battersea coal-fired power station in London (UK) with the spraying of water on counterflow flue gases to convert some of the SO₂ into an acidic sulphite solution (Biondo and Marten, 1977). In 1935 a modified WFGD system was installed at the Swansea coal-fired power station, where a lime slurry was mixed with water and sprayed onto counterflow flue gases. Further upgrades of the FGD process and the installation at the Fullham coal-fired power station in 1938 led to the extraction and disposal of gypsum as a by-product (Biondo and Marten, 1977). Many WFGD installations were completed worldwide for SO₂ abatement of coal-fired flue gases, with the limestone forced oxidation (LSFO) or limestone – gypsum (L/G) process variant being chosen by most of the utilities, primarily due to the abundance and low price of limestone (Lisnic and Jinga, 2018). In 2012 a WFGD (L/G) installation at the Rovinari coal-fired power plant in Romania was able to reduce the SO₂ flue gas concentration to 250 mg/Nm³ (Lisnic and Jinga, 2018), and this technology is continually undergoing further developed (Dragomir *et al.*, 2017).

The WFGD (L/G) installation at Eskom's Kusile power plant achieved an SO₂ removal efficiency of only 93% during performance testing (Ezeh, 2018). Nevertheless, the required WFGD efficiency of > 98%, water consumption of < 0.21 l/kWh, and worldwide installed capacity of > 80% as in 2012 (Carpenter, 2010) played a major role in Eskom's decision to implement WFGD (L/G) at Medupi (Cheng, van Wyk, and Bagus, 2018). The major drawback of applying this technology in South Africa is the requirement for large volumes of scarce and costly high-quality limestone (Stephen *et al.*, 2014; Haripersad and Swart, 2015), production and co-disposal of unsaleable gypsum with coal ash (Gruenewaldt, 2013; Vosloo, 2018; Koralegedara *et al.*, 2019), as well as the production of additional (taxable) CO₂ that results in a net negative opex and a net negative cost of ownership during the installation's life-cycle.

Description of the WFGD (L/G) technology employed for Medupi power station

WFGD (L/G) process description

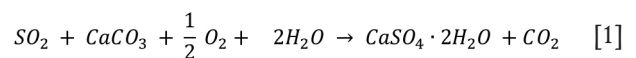
The WFGD (L/G) SO₂ emission abatement system consists predominantly of an absorber, as shown in Figure 1.

It is anticipated that the limestone-forced-oxidation (LSFO) version of the WFGD technology will be implemented on Medupi power station (Stephen, 2017). In this technology, limestone is pulverized and slurried with process water. The slurry is sprayed onto the untreated flue gas, reacting with SO₂ to form a gypsum slurry (Figure 1). Excess oxygen is provided during this process to ensure 'the oxidation of sulphite species to form sulphates' (Stephen, 2017, p. 35) and gypsum is formed as a by-product. In this manner, the sulphur dioxide from the untreated flue gas is absorbed by the limestone slurry and the desulphurized gas exits the absorber to the stack. The gypsum slurry by-product is then removed from the absorber and dewatered before it is added to the boiler ash stream for disposal on the ash dump. The liquid stream from the gypsum dewatering plant is fed to the liquid

waste treatment plant where usable water is separated for recycle and the final liquid waste sent for disposal. The WFGD (L/G) technology and solution is therefore a three-step process: (a) limestone slurry preparation, (b) SO₂ absorption, and (c) gypsum dewatering (Stephen, 2017).

WFGD (L/G) process chemistry and quantities

The overall balanced chemical reaction for the WFGD (L/G) technology solution is given by Pimenta (2010, p. 6) for absorber operational conditions at 60°C and pH 5, as shown in Equation [1]. SO₂ reacts with calcium carbonate/limestone (CaCO₃), oxygen (O₂), and water (H₂O) to form a gypsum slurry/calcium sulphate dihydrate (CaSO₄ · 2H₂O) and carbon dioxide (CO₂).



According to Equation [1], one ton of SO₂ reacts with 1.56 t of limestone (reagent), 0.25 t of oxygen, and 0.56 t of water to form 2.13 t of gypsum, 0.56 t of slurry water, and 0.69 t of CO₂. The SO₂ in the untreated flue gas is removed to allow the treated flue gas to exit the chemical process.

The commercial WFGD (L/G) process parameters and quantities calculated for the abatement of sulphur dioxide using 85% pure limestone for Medupi power station are given by Cheng, van Wyk, and Bagus (2018).

Evolution of the Sulfacid® FGD technology

The CPPE Sulfacid® FGD technology differs from classical FGD technologies as categorized by Lisnic and Jinga (2018) as it does not require an alkaline absorbent such as limestone but converts sulphur oxides into sulphuric acid by adsorption in a cold wet catalytic process on a fixed bed of activated carbon, requiring only water and air. Particulate matter and heavy metals are removed in a water-based quench step to condition the SO_x-containing flue gas before it is release across the activated carbon bed. Intermittent spraying of water on the bed washes out the formed sulphuric acid and thereby regenerates the bed. The stationary activated carbon bed is guaranteed for 10 years

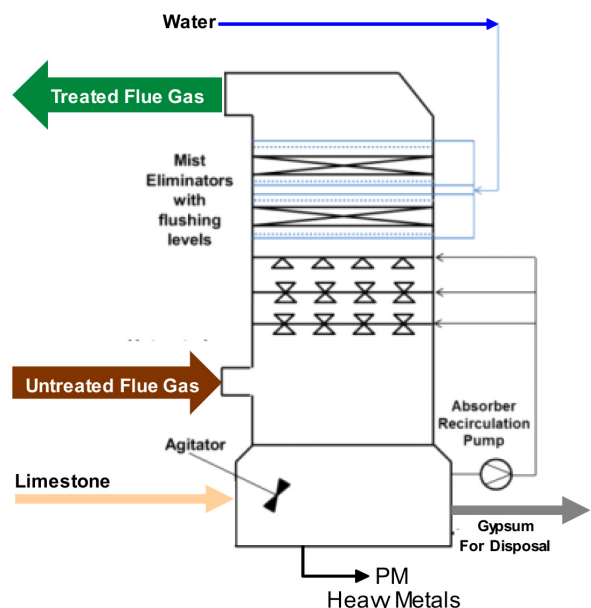


Figure 1 – Schematic layout of the absorber of the WFGD (L/G) SO₂ abatement system (adapted from Stephen, 2017)

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of optimal operation during steady-state and fluctuating volume flows (start-up and shutdown transients) as well as fluctuating SO_x flue gas concentrations.

The first commercial Sulfacid[®] plant was built in 1966 in Germany and operated for flue gas desulphurization at a detergent manufacturing facility (Scheidel, 1968; Grüpner, 1970). This was followed by Sulfacid[®] plants capable of treating increased flue gas volume flows for an oil-fired generator in 1967 and sulphur-burning and titanium dioxide plants in 1968 (ibid.). Since then, Sulfacid[®] plants have been installed in more than 20 countries for SO_x abatement in the chemical, pigment, smelting, medical catalyst recovery, and fertilizer manufacturing industries. Interestingly, in 1972 a pilot Sulfacid[®] plant was installed and operated successfully at the 4 × 110 MWe Prunerov coal-fired power plant in the Czech Republic (Svejcar, 1976).

Scheidel (1968) cites the much higher volume flow, unfamiliarity of chemical processes, and a lack of on-site use of sulphuric acid as reasons why coal-fired utilities have chosen WFGD with limestone as the preferred SO₂ abatement technology until now. This situation is about to change, due to:

- The size and scale of the latest commercial applications of the Sulfacid[®] SO₂ abatement technology in the chemical, fertilizer, and copper mining industries (up to 1 000 000 Nm³/h), which demonstrate its potential and readiness to be employed for coal-fired plants
- The economic pressure to install SO₂ abatement systems that are financially viable, environmental pressures that require lower scrubbing limits of flue gases, and the requirement for systems that form part of integrated multi-pollutant abatement (NO_x and Hg) and CO₂ carbon capture and utilization solutions.

For example, in Morocco, one of the recently completed Sulfacid[®] plants achieved approximately 98% SO₂ flue gas reduction from > 600 ppmv (1254 mg/Nm³, 10% O₂) to < 15 ppmv (31 mg/Nm³, 10% O₂), against a legislative emission limit of 157 ppm (328 mg/Nm³, 10% O₂), while also producing marketable sulphuric acid, using only water and air (Africa Outlook Magazine, 2019). In fact, it has been demonstrated that the Sulfacid[®] technology is able to remove and convert SO₂ into sulphuric acid for SO₂ levels in flue gases from 3 000 ppmv (6 272 mg/Nm³, 10% O₂) down to < 9 ppmv (19 mg/Nm³, 10% O₂) (Strickroth, 2017a, 2017b). This indicates that the Sulfacid[®] technology has the potential to remove SO₂ contained in the flue gases of coal-fired power plants to meet current and future legislative requirements.

Description of the Sulfacid[®] technology as could be applied to Medupi power station

The Sulfacid[®] SO₂ emission abatement system consists of a packed bed type venturi quench and a fixed bed activated carbon Sulfacid[®] reactor, as shown in Figure 2.

Untreated flue gas from the baghouse enters the venturi quench where the temperature of the flue gas is reduced, the gas stream is saturated through evaporation, water-soluble heavy metals are removed, and the flue gas de-dusted (PM removal) to provide optimal process conditions for the downstream Sulfacid[®] reactor. Adequate removal of PM from the flue gas prior to entry into the Sulfacid[®] reactor protects the activated carbon bed from blockage and increased pressure drop. The venturi quench solution that contains PM and heavy metals is drawn off regularly for liquid/solid separation. The dewatered solids

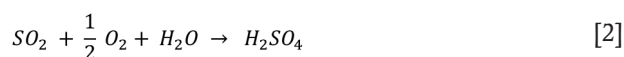
could be disposed or potentially utilized in construction materials (Rastogi and Kumar Paul, 2020). The separated liquid is further treated in a liquid waste treatment process, after which most of the liquid is returned to the venturi quench while a small stream is disposed.

The cooled, dedusted flue gas then enters the Sulfacid[®] reactor, where a special activated carbon-based catalyst bed converts SO₂ and SO₃ into H₂SO₄. The activated carbon bed is continuously sprayed at the top with process water for countercurrent regeneration of the catalyst. Dilute sulphuric acid (15 wt.%) is continuously produced by the process, and the gas phase SO₂ is reduced to the specified concentration (the design can be adapted to meet current or future concentrations for SO₂ < 50 mg/Nm³).

Activated carbon in the Sulfacid[®] reactor provides a buffering capacity to maintain reactor performance for normal variations in SO₂ concentration and flow rate that may be expected during the operation of a power generation unit. The treated flue gas then exits the reactor to the stack. The concentration of the sulphuric acid from the Sulfacid[®] reactor could be increased from 15 wt.% to 50 wt.% and more using a mechanical vapour compression process that requires steam and electrical power. The recovered water is re-used as process water in the Sulfacid[®] system.

Sulfacid[®] process chemistry and quantities

The conversion of SO₂ into sulphuric acid on the activated carbon catalyst takes place according to the balanced chemical reaction as shown in Equation [2].



According to Equation [2], one ton of SO₂ reacts with 0.25 t of O₂ and 0.28 t of water to form 1.53 t of H₂SO₄ with a 100 wt.% concentration.

The process parameters and quantities for the commercial Sulfacid[®] process designed for the Medupi power plant are given by CPPE (2019).

Methodology

Approach for first-order techno-economic comparison of WFGD (L/G) and Sulfacid[®] technologies for Medupi power station

The Eskom data, as employed for the WFGD (L/G) system for Medupi power station, was used in an unchanged format. A new conceptual design of the Sulfacid[®] system for Medupi power

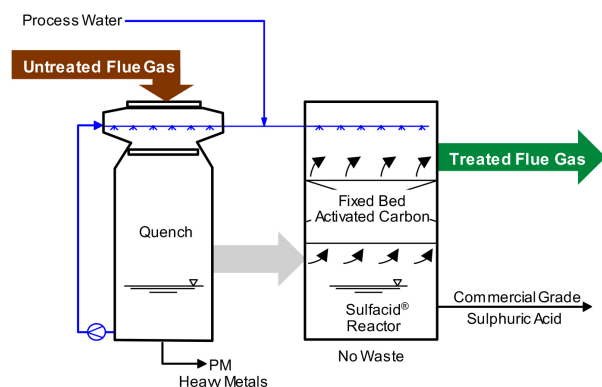


Figure 2—Schematic layout of the venturi quench and Sulfacid[®] reactor of the Sulfacid[®] SO₂ abatement system (CPPE, 2019)

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station was done using the same design parameters. Process flow data and quantities for the WFGD (L/G) SO₂ abatement system to retrofit the 6 × 800 MWe Eskom Medupi coal-fired power plant units were obtained from the publicly available FGD retrofit basic design report (Harris, 2014), supplemented by information contained in a published master's thesis for the same design configuration (Stephen, 2017). Similarly, data on capex, quantities, and unit costs that comprise opex was obtained from the publicly available Medupi FGD technology selection study report (Cheng, van Wyk, and Bagus, 2018).

The CPPE Sulfacid® SO₂ abatement system conceptual design (process flow, quantities, and 3D configuration) as well as costing (CPPE, 2019) were based on the same input and boundary condition information as for the WFGD (L/G) SO₂ abatement system as specified in Harris (2014), Stephen (2017), and Cheng, van Wyk, and Bagus (2018) to ensure common and comparable flue gas input and output conditions.

Assumptions for technical data

Specified input data for untreated flue gas

Input data for the untreated flue gas exiting the Medupi baghouse for a single 800 MWe unit, as given in Table I, was assumed as the input boundary condition for the WFGD (L/G) and Sulfacid® abatement system designs.

Required output data for treated flue gas

The required SO₂ concentration in the Medupi flue gas after abatement is specified as 400 mg/Nm³, dry at 6% O₂ (Harris, 2014).

Assumption related to installation position

The installation position for both SO₂ abatement systems is after the baghouse ID fans with a tie-in to the existing emission stack ducting.

Assumptions for economic data

Cost estimation accuracy, inclusions, and exclusions

- All cost estimates are based on a 'conceptual-level accuracy of ±30% in 2017 South African Rand' (Cheng, van Wyk, and Bagus, 2018, p. 27).
- 'The cost estimates include allowances for auxiliary electricals, control system upgrades, and other required

Table I

Input data at the baghouse outlet of the 800 MWe Medupi power plant unit

Description	Value	Unit
Volume flow*	2 590 000	Nm ³ /h
SO ₂ (max.)*	5 855	mg/Nm ³
NO _x as NO ₂ **	650	mg/Nm ³
PM**	50	mg/Nm ³
SO ₃ *	53	mg/Nm ³
HCl*	160	mg/Nm ³
O ₂ **	6.0	vol.%
CO ₂ **	13.3	vol.%
H ₂ O _{vapour} **	8.8	vol.%
N ₂ **	79.4	vol.%
Ar**	0.9	vol.%
Gasified ash**	5.4	t/h
Annual operational hours*	7 884	h

Note: All values for dry flue gas at 6% O₂; * Harris (2014); ** Stephen (2017)

BOP [balance of plant] system upgrades.' (Cheng, van Wyk, and Bagus, 2018, p. 28).

- Further details on cost assumptions (inclusions and exclusions) are given in Cheng, van Wyk, and Bagus (2018).

Specific assumptions related to capex

- 'The capital cost estimates include direct and indirect costs as an overnight price, but exclude Owner's costs.' (Cheng, van Wyk, and Bagus, 2018, p. 28).
- The same capex of R 17.677 billion for both systems is assumed for the design, construction, and commissioning of six unitized SO₂ abatement systems and includes indirect costs, contingency, and escalation (Cheng, van Wyk, and Bagus, 2018).

Specific assumptions related to opex

- 'The operating cost estimates were based on operation at full-load conditions. The annual operating costs also account for increases in auxiliary power requirements, additional labour requirements, water costs, and additional costs for consumables (Cheng, van Wyk, and Bagus, 2018, p. 28).
- The process quantities for the WFGD (L/G) system were used for a 96% pure limestone absorbent as given in Harris (2014, pp. 61–63, Table V).
- The unit costs for process inputs and outputs were used as specified in Cheng, van Wyk, and Bagus (2018, p. 32, Table VII) for both systems.
- The required labour for operating the Sulfacid® system is deemed to be 50% that of a WFGD (L/G) system. This is due to the absence of limestone-related equipment such as offloading, conveying, storage, milling, and water mixing.
- No sale of the gypsum by-product is assumed for the WFGD (L/G) system.
- It is assumed that all the produced sulphuric acid is sold for each financial year. The sales price of sulphuric acid (50 wt.%) was taken as R800 per ton as obtained from a prominent chemicals distributor in South Africa.
- An effective CO₂ emission tax rate of R48 per ton was assumed (National Treasury, 2018), although CO₂ emissions are taxable at R120 per ton (South Africa, 2019). Emissions tax was calculated only for CO₂ generated from the abatement chemistry and not for the required auxiliary electricity consumption or process steam.

Specific assumption for life cycle cost estimation

Cost of ownership (COO) is estimated using the simplified relationship between capex, annual opex, and life cycle as shown in Equation [3].

$$COO = Capex + (Annual Opex * Life Cycle) \quad [3]$$

- A life cycle period of 30 years (2020–2050) was assumed, similar to Steyn and Kornelius (2018) in their economic assessment of the reduction of SO₂ on the South African highveld.

Results

The results for the techno-economic comparison are given in Tables II, III, and IV.

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Table II

Comparison of selected process quantities for the WFGD (L/G) and Sulfacid® SO₂ abatement systems to retrofit 6 × 800 MWe Medupi coal-fired power plant units

Description	WFGD (L/G) (quantity per annum)	Sulfacid® (quantity per annum)	Difference (relative to WFGD (L/G))
Limestone reagent/sorbent (kt/a)	991	0	-100%
Gypsum disposal (kt/a)	1 839	0	-100%
Abatement process-generated CO ₂ (kt/a)	459	0	-100%
Crystallizer salts disposal (kt/a)	31	0	-100%
Wastewater disposal (kt/a)	445	221	-50%
Operating labour (h/a)	185 120	92 560	-50%
Process water consumption (thousand m ³ /a)	9 299	8 704	-6%
Process water consumption rate (l/kWh)	0.25	0.23	-6%
Pre-treatment solids disposal (kt/a)	60	60	0%
Auxiliary power rate (MWh/h)	54.45	60.00	10%
Auxiliary power consumption (MWh/a)	429 284	473 040	10%
Sulphuric acid (50 wt.%) (t/a)	0	2 081 376	100%
Steam (kt/a)	124	705	468%

Table III

Comparison of operational costs using relevant process quantities for the WFGD (L/G) and Sulfacid® SO₂ abatement systems to retrofit the 6 × 800 MWe Medupi power plant units

Description	Cost per unit	WFGD (L/G) (quantity per annum)	WFGD (L/G) (expense / income per annum)	Sulfacid® (quantity per annum)	Sulfacid® (expense / income per annum)
Limestone reagent/sorbent (R/t)	-R 475	991 295	-R471 million	0	0
Gypsum disposal (R/t)	-R 30	1 838 940	-R55 million	0	0
CO ₂ carbon tax (R/t)	-R 48	459 120	-R22million	0	0
Crystallizer salts disposal (R/t)	-R 1000	31 351	-R31million	0	0
Auxiliary power (R/MWh)	-R 421	429 284	-R181 million	473 040	-R199 million
Process water (R/m ³)	-R 21	9 299 178	-R196 million	8 703 936	-R184 million
Wastewater disposal (R/t)	-R 477	444 658	-R212 million	221 409	-R106 million
Steam (R/t)	-R 91	124 173	-R11 million	704 830	-R64 million
Pre-treatment solids disposal (R/t)	-R 680	59 911	-R41 million	59 911	-R41 million
Operating labour (R/hr)	-R 240	185 120	-R44 million	92 560	-R22 million
Annual opex			-R1 265 million		-R616 million
Sulphuric acid sales (50 wt.%)	R 800	0	0	2 081 376	R1 665 million
Net annual opex			-R1 266 million		R1 049 million

Table IV

Comparison of life cycle cost for WFGD (L/G) and Sulfacid® SO₂ abatement systems to retrofit 6 × 800 MWe Medupi coal-fired power plant units

Description	WFGD (L/G)	Sulfacid®
Capex	-R17.677 billion	-R17.677 billion
Opex (annual)	-R1.266 billion	-R0.616 billion
Net opex (annual)	-R1.266 billion	R1.049 billion
Cost of ownership (30 years)	-R55.657 billion	R 3.793 billion
Break-even (payback in years)	No break-even	16.9

Discussion

The techno-economic comparison between the WFGD (L/G) and Sulfacid® technologies and systems applied for the retrofitting of the 6 × 800 MWe Medupi power plant indicate the possibility of affordable SO₂ abatement for a modern coal-fired power plant using the Sulfacid® technology. The affordability originates from the process quantities that result from the two different technologies as well as the opex and life cycle costs.

Comparison of process quantities

The major difference between the two technologies and systems

becomes apparent when comparing the process quantities in Table II. The Sulfacid® process does not use limestone, does not generate CO₂ from the process chemistry, nor a gypsum by-product, and there is no need to dispose of crystallizer salts. From a by-product point of view, both processes produce similar bulk quantities, *i.e.* WFGD (L/G) produces 1.8 Mt gypsum while Sulfacid® produces 2.1 Mt sulphuric acid. The Sulfacid® process produces 50% less disposable wastewater because it does not require water to generate a lime slurry stream, and also uses 50% less labour due to the simplicity of the process equipment compared to WFGD (L/G), since no limestone-related equipment is required. Both processes require similar process water quantities but the Sulfacid® process converts the process water into a saleable product. Furthermore, the Sulfacid® process uses 10% more auxiliary power, predominantly to overcome the pressure drop across the fixed bed of activated carbon. For the Sulfacid® process to re-use some of the process water, the sulphuric acid is concentrated from 15 wt.% to 50 wt.% using mechanical vapour compression. This compression process requires auxiliary power and also steam, and therefore the Sulfacid® process requires 468% more steam than the WFGD (L/G) process. Most process quantities for the Sulfacid® process in Table II are less than or similar to the WFGD (L/G) process, except for the steam requirements.

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Comparison of operational costs

The differences in the process quantities between the two technologies, systems, and processes multiplied by the process quantity unit cost results in a net negative annual opex for WFGD (L/G) compared to a net positive opex for Sulfacid®, as shown in Table III. The absence of costs for limestone, gypsum disposal, taxable CO₂, and disposal of crystallizer salts for the Sulfacid® process results in an annual opex saving of approximately –R579 million compared to the WFGD (L/G) process. These savings, in addition to the production of approximately 50% less wastewater, leads to the total annual opex of the Sulfacid® process being approximately 50% lower than for WFGD (L/G) technology, *i.e.* –R616 million *vs.* –R1 266 million. The sale of the sulphuric acid by-product results in a net positive annual opex for the Sulfacid® process (R1 049 million) compared to a net negative annual opex for the WFGD (L/G) process (–R1 266 million).

Comparison of life cycle cost

The positive net annual opex of R1 049 million for the Sulfacid® process makes it possible to realize a payback of the assumed capex of R17.677 billion over 16.9 years for a 30-year plant life cycle as shown in Table IV.

Sulphuric acid markets and sales prices

Globally, sulphuric acid is used in the manufacturing for fertilizers (68%), petroleum refining (24%), metal mining (5%), and other industrial applications (3%) (Modiselle, 2013). The global sulphuric acid market is expected to grow by 2.3% (CAGR for 2019–2027) (Business Wire, 2019b) and by 3.8% (CAGR for 2019–2024) in the fertilizer industry (Business Wire, 2019a). The growth in the fertilizer market is fuelled by the increase in the global population and the reduction in the availability of arable land, which requires an increase in crop production per hectare (IFA, 2018).

However, when large quantities of sulphuric acid become available in the South African market for local use and export due to the deployment of the Sulfacid® technology, it could be expected that the sales price of R800 per ton/t, which leads to a break-even of 16.9 years, may drop. To maintain the affordability of the Sulfacid® process with a break-even of 30 years, given the assumptions of this study, the price of sulphuric acid needs to be above R579 per ton.

A future perspective

Expanding the function of a coal-fired power plant beyond electricity generation and stream production towards the on-site manufacturing of chemical commodities from flue gas (waste-to-chemicals) (Deloitte and VCI, 2017) demands a deliberate paradigm shift (Kuhn, 1970) towards a sustainable circular economy (Potting *et al.*, 2017) from utility owners, policymakers, financiers, and governments. Sulphuric acid from converted coal-fired flue gases creates an opportunity not only for security of supply, regional sales, and export, but also for on-site beneficiation to fertilizer and other products and the formation of new, viable, special economic industrial zones and clusters.

Sulphuric acid derived from the Sulfacid® SO₂ abatement system circumvents the need to construct new sulphuric acid production plants that burn pyrite (Runkel and Sturm, 2009) thereby avoiding emissions and greenhouse gases associated with additional industrial plants. Furthermore, the ability of the Sulfacid® SO₂ abatement system to reduce SO₂ flue gas

concentrations beyond compliance limits (< 19 mg/Nm³, 10% O₂) to produce sulphuric acid demonstrates that coal-fired plants could be operated with negligible environmental impact.

Finally, the Sulfacid® SO₂ abatement system forms part of the CPPE suite of modular activated carbon reactors that are able to capture hazardous pollutants such as Hg, Cd, dioxins, and furans and convert NO_x and CO₂ into ammonium nitrate and ammonium bicarbonate fertilizer products to enable complete coal-fired flue gas abatement and conversion.

Limitations of the comparative study

The first-order techno-economic comparison between the WFGD (L/G) and Sulfacid® SO₂ abatement technologies as applied to the 6 × 800 MWe Medupi power station needs to be followed up by a deeper level, comprehensive comparison executed by independent experts in this field to verify the results reported in this paper.

Conclusion

This paper provided a first-order techno-economic comparison between the WFGD (L/G) (wet flue gas desulphurization using limestone and producing a gypsum by-product) and Sulfacid® technologies using the same input parameters and assumptions and applied for SO₂ abatement of the 6 × 800 MWe Medupi power station. The Sulfacid® technology converts SO₂ into saleable sulphuric acid and uses approximately the same water and power inputs as the WFGD (L/G) technology, but without the need for limestone or the adverse effects of producing unsaleable gypsum or additional CO₂. Furthermore, for the same capex, the Sulfacid® technology shows a break-even of 16.9 years and a net positive cost of ownership over its life cycle.

The benefit of the utilization and roll-out of the CPPE Sulfacid® technology for coal-fired power generation in South Africa could have benefits for the environment, the economy, and society. SO₂ emissions from coal-fired power stations could be reduced to < 50 mg/Nm³ (current legislation requires 1000 mg/Nm³) while producing saleable sulphuric acid. The drastic reduction in SO₂ emissions in the Waterberg, Highveld, and Vaal Priority Areas would improve the working and living environment. The addition of further modular CPPE reactors will convert SO₂, NO_x, and CO₂ into saleable fertilizer salts for the agricultural sector, and create the Chemistry 4.0 circular economy. Saleable products from coal-fired flue gas will avoid stranded assets, promote the formation of economic growth points at power stations, create new asset classes, provide security of commodity supply and promote export opportunities. This in turn, will lead to job retention in the current coal value chain, new job creation, and the sustainable and environmental friendly utilization of South Africa's vast coal reserves.

Given a 'conceptual-level accuracy of ±30% in 2017 South African rand' (Cheng, van Wyk, and Bagus, 2018, p. 27) and using the assumptions as specified by Eskom for the WFGD (L/G) system and assumptions for the Sulfacid® system for Medupi power station, this comparative study shows that affordable SO₂ abatement is possible by employing the CPPE Sulfacid® technology on a modern coal-fired power plant. It is recommended that independent assessments be done by academia, industry and government to verify the findings of this study.

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