# Treatment of Flue Gas Desulphurisation Effluent with Freeze Crystallization

# AL Tau<sup>1</sup>, JP Maree<sup>2,3</sup>, A Adeniyi<sup>1</sup> and MS Onyango<sup>1</sup>

**Abstract**— Kusile was the first power station of Eskom to implement a wet flue gas desulfurization system for the control of  $SO_2$  and other greenhouse gasses. The waste water from the flue gas desulfurization (FGD) plant contained a high total dissolved solids (TDS) concentration of 50 000 mg/L due to: (i) absorption of SO<sub>2</sub>, chloride and boron from the coal to the FGD waste water, (ii) dissolution of sodium, potassium, magnesium, manganese and calcium form the limestone when reacted with the acid gasses from the combustion chamber. A large portion of the calcium sulphate in solution precipitated as gypsum due to its limited solubility.

The study focused on disposal, electrical and chemical cost of three FGD waste water management methods. It was found that the cost for a 4 800MW plant will amount to R9.7 million per month for disposal at a toxic waste disposal site, R11.41 million per month when pre-treated with lime/sodium carbonate followed by evaporation and R0.96 million per month when treated with Freeze crystallization. Freeze crystallization was found to be the most cost effective as it did not need chemical pre-treatment and it consumes less energy than evaporation (330kJ/kg in the case of freeze versus 2 260kJ/kg in the case of evaporation). Energy usage was found to be 100 kWh/kg ice. The TDS of the Feed amounted to 50 000 mg/L compared to less than 3 000 mg/L in the melted ice.

*Keywords*— brine, refrigerant, FGD wastewater, evaporative crystallization, freeze/cooling crystallization, ROC process.

#### I. INTRODUCTION

#### A. Background

Eskom is the second largest consumer of fresh water in South Africa, accounting for approximately 2% of the country's total water consumption on an annual basis [1]. Eskom needs additional water optimization technologies to meet emissions regulations, while still minimizing resource and financial impacts. Coal continues to be the dominant source of energy for South Africa, due to its availability. Coal is a significant source of pollution. The major wasteproducts of coal combustion in a power station are coal ashes, wastewater, and gaseous emissions (NOx, SOx etc) to the atmosphere. Sulphur emissions, in particular, pose an environmental concern since they contribute to acid rain formation and ozone depletion. Control of gaseous emissions is one of the areas that is receiving considerable attention in support of sustainable development and has led to environmental regulations and legislation becoming increasingly stringent. Eskom being the main power utility in South Africa is committed to improving its environmental performance. Eskom operates on a zero liquid effluent discharge (ZLED) policy, which limits the release of water to the environment [2, 3]. Kusile coal-fired power station has installed Wet Flue Gas Desulphurization (FGD) plant to reduce gaseous emission, particularly sulphur.

#### B. Description of wet flue gas desulfurization system

A wet limestone FGD system typically includes the following unit operations: limestone preparation, storage and handling system, FGD spray tower absorber, dewatering system of the resulting by-product and wastewater treatment system [4, 5, 6, 7].

During the operation of FGD scrubber, the flue gas enters the FGD absorber module and flows upwards, and makes contact with the calcium carbonate slurry that originates from a spray zone at the top of the absorber [5, 8]. The  $SO_2$ is absorbed from the flue gas into the slurry, where it is neutralized with the calcium carbonate to form calcium sulphite hemihydrate (CaSO<sub>3</sub>.1/2H<sub>2</sub>O). The slurry is collected in a reaction tank, at the bottom of the scrubber, where the reactions have sufficient time to complete, and where air is added to oxidise the calcium sulphite hemihydrate to calcium sulphate dihydrate (CaSO<sub>4</sub>.2H<sub>2</sub>O), also known as gypsum [9]. The slurry is then continuously recycled. Thus wet FGD technologies require large volumes of water, about 160 m<sup>3</sup>/hour/unit on load in order to form the limestone slurry (4 m<sup>3</sup>/hour/unit on load), which requires treatment [10]. As  $SO_2$  is removed from the flue gas, the gypsum solid and other element concentrations, in the reaction tank are formed and increase with time in the form of gypsum-slurry. At a certain solids concentration set point (approximately 15%), a portion of the gypsum-slurry is bled off and sent to a dewatering system, to separate the water from the gypsum.

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The dewatering system is achieved by feeding the  $CaSO_4$ ·2H<sub>2</sub>O slurry into a horizontal vacuum belt filter, which produces wastewater that needs to be managed to achieve the Zero Liquid Discharge (ZLD) and solid cake material, gypsum [11, 12]. Schutte et al., (2018) indicated that Kusile Power Station is expected to produce about 900 000 tons of gypsum per annum.

The FGD wastewater has significantly high concentrations of chlorides, magnesium, calcium and heavy metals and thus cannot be re-used elsewhere in the station. The total dissolved solids (TDS) in the FGD wastewater can be as high as 50,000 mg/L which includes silica. The soluble salts in the FGD gypsum can be regulated by washing the gypsum prior to drying [9]. The pollutant content in this wastewater depends on the type of coal burned and the amounts of impurities and heavy metals in the coal and limestone used [5, 10].

# C. Current waste water disposal

FGD waste water is currently discharged at a cost of R2 000/t. A volume of 9 670 m<sup>3</sup> was disposed at a toxic waste disposal site during the period 1 Jan 2019 to 30 Apr 2019 (Pers. Comm, Eskom Rep, 2019). At a flowrate of 6.63 m<sup>3</sup>/h (for 6 units), the cost amounts to R9.7million per month (Error! Reference source not found.).

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Parameter	Value
Volume disposed in 4 months with 3 units	
(m <sup>3</sup> )	9 670.00
Flow rate disposed for 3 units (m <sup>3</sup> /h)	3.31
Flow rate disposed for 6 units (m <sup>3</sup> /h) (Eskom	
figure)	6.63
Transport cost (R/m <sup>3</sup> )	1 000.00

TABLE I: Waste transport and disposal cost

### D.FGD wastewater treatment options

# 1) Evaporation

Cost  $(R/m^3)$ 

Cost (R/month)

Disposal cost (R/m<sup>3</sup>)

Currently, the FGD wastewater is concentrated and the blow-down removed to a hazardous waste site. A treatment plant, containing 3 stages (Pre-treatment, evapoconcentration and crystallization) was constructed to produce clean water. Pre-treatment involves lime softening and ferric chloride flocculation of the water, with subsequent clarification, to precipitate metals and minimize scale formation on the heat exchangers. It produces a product water with approximately 1 500 mg/L calcium and 320 mg/L magnesium. Not all the calcium is removed as it required as a seeding slurry in the evaporator/concentrator. The pH of the clarified water is then corrected to between 7 and 8, minimizing any further precipitation downstream and flows to the brine concentrator tanks [5]. In the brine evaporation-concentration, the treated water is acidified to pH 4-5 to convert the alkalinity to carbon dioxide, which will, later be removed via the deaerator. This limit carbonate scaling of the heat exchanger. Sodium carbonate is added to prepare for the seeded slurry process. Once the calcium sulphate becomes saturated, it precipitates out of solution [5].

Heat Exchange and deaeration will then be used where the FGD wastewater flows into a heat exchanger at approximately 37°C and is heated to 96°C by counter-flow of the hot distillate and condensate from the brine concentrator and crystallizer respectively. The water vapor is removed from the top of the vessel after passing through a series of baffles to limit solids carry over. The carbon dioxide, dissolved oxygen and non-condensable gases are then removed via the aerator [5].

#### 2) Freeze crystallization as an alternative to evaporation

Freeze desalination is an available technology for desalinating saline brine at better energy consumption compared to distillation and evaporation (333kJ/kg for freezing versus 2500 kJ/kg for evaporation [13]. Other benefits of freeze crystallization include: (i) no pre-treatment and (ii) less prone to corrosion and metallurgical challenges [14].

The key process stages in the freeze desalination of saline water are (i) pre-cooling of the process feed wastewater, (ii) cooling and formation of ice through freezing in a heat exchanger, (iii) separation of the ice crystals from the concentrated stream (brine) [14]. Freeze crystallization further involves the recovery of ice of high purity and good salt recovery. Rapid nucleation and formation of crystals results with impure ice crystals due to the faster rate of growth [13]. The overall principle of rejection of salt as water changes phase to solid gave existence of freeze desalination which is the alternative technique for recovery of salt and water in the form of ice. The formation of small dimensions of ice crystal lattice structures which releases salts ions during the phase change as opposed to being part of the lattice is the phenomenon that governs the salt rejection in freeze crystallization [15].

The basic models of freeze desalination include direct, indirect, vacuum and eutectic freeze crystallization. Progressive and suspension freeze crystallization techniques are the categories of indirect freeze method on cold surfaces. Direct contact freezing crystallization make use of refrigerant in direct contact with the saline solution for heat exchange, meanwhile indirect contact freezing crystallization make use of refrigerant without direct contact with the saline solution for heat exchange [16]. Progressive freezing operates on the principle that the saline solution is filled in a tube to be concentrated and is immersed progressively in a path of a cold refrigerant. By making use of high vacuum for the vaporization of the portion of water that provides the effect of refrigeration results with

1 000.00

2 000.00

9 670 000

reduction in temperature of the saline solution which ultimately yields crystallization of ice [16].

# Eutectic freeze crystallization operates on principles such that simultaneous recovery of salts and pure water from the wastewater/brine by operating at eutectic point of the saltwater system. Eutectic point is the operational point where the composition of a solution that consist of lowest temperature of crystallization than any other composition of the same wastewater with the composition and temperature being below that of the solvent and solute which crystallize out from the wastewater. Depending on the concentration of salt, different wastewater/brine have different eutectic compositions and temperatures [17].

During freeze crystallization, the ice quantity being crystallized from the brine is affected by the concentration of the solute in the mother liquor, coefficient of heat transfer and difference in temperature between refrigerant and the saline water. This is defined by the following thermodynamic equation:

 $Q = m_b.Cp.dT + m_iL$ 

Where:

Q - refrigeration unit's cooling capacity,

m<sub>i</sub> - mass fraction of ice in the slurry, m<sub>b</sub> - mass of brine

L - fusion ice's latent heat of fusion which is 333kj/kg,

m - brine mass flow rate and dT is the brine differential temperature,  $C_{p}$ -specific heat capacity [18].

The electrical conductivity of the brine being treated in freeze crystallization can be a good indicative of the removal of salt from the mother liquor by calculating how much percentage salt is being removed from the brine by making use of the following basic calculation [19]:

Salt removal (%) =  $(C_{f} - C_{i})/C_{f} \ge 100$ 

Where:  $C_f$  initial electrical conductivity of the brine being fed and  $C_i$  melted ice electrical conductivity measured using calibrated conductivity meter.

This study investigated the key operations of a FGD plant, such as at Kusile Power Station, with the purpose to simulate and model possible technical solutions to treat the effluent and to directly treat Kusile FGD wastewater with Freeze crystallization.

#### **II.OBJECTIVES**

The following objectives were set for this investigation:

To develop an understanding of the operation of a coalfired power station.

To develop an understanding of the sources of impurities that contributes to the poor water quality of the FGD waste water.

To compare the cost of effluent management for the following scenarios: (i) disposal at toxic waste disposal sites (ii) treatment with softening + evaporation (iii) freeze crystallization.

#### III. METHODOLOGY

#### A. Feedstock

Wastewater from a flue gas desulphurization plant was collected from a power station in Mpumalanga. The feed wastewater had a pH of 7.17, conductivity of 7.59 mS/cm and TDS of 4 820 mg/L.

#### B. Equipment and procedure

A freeze crystallization pilot plant used consists of the following unit operations: 15 kW Chiller with primary refrigerant; cooling reactor where the primary refrigerant is used to cool secondary refrigerant (30% MeOH, in water) and a Clarifier for salt/liquid/ice separation and a Filter for liquid/ice separation.

The flue gas desulphurization wastewater was treated with freeze crystallization. It was fed from the feed storage tank into heat exchanger using a Watson-Marlow feed pump. In the heat exchanger, secondary refrigerant at -6°C was used to cool the waste water. Ice slurry was pumped to brine/ice separator for separation of the ice crystals from the concentrated brine. The concentrated brine was recycled to the cooling reactor. The secondary refrigerant was recycled between the cooler reactor and the chiller with set point temperature between -7°C and -8°C. The clarifier was used for liquid/salt separation by gravity. Feed, brine and ice samples were collected during each run for pH, conductivity and TDS analyses. The following temperatures were measured: Feed, Brine, Ciller refrigerant in and out, Cooler reactor in and out. Energy consumption in kWh of the chiller and pumps was monitored. Pressure in the pipe where the brine flows in within the heat exchanger was collected. The pilot scale unit was running on semi-batch mode when feeding the brine.

#### C. Experimental

The following relationships were studies: (i) feed, brine and ice quality over time of operation (ii) energy utilization for (a) cooling and (b) ice formation.

#### D.Analytical

Samples of feed wastewater, ice and concentrated brine at various stages of the freeze crystallization were collected and analysed for Temp, TDS, pH and conductivity [20]. The measurement for electrical conductivity was conducted by making use of a calibrated Knick Stratos Eco 2505 meter.

#### E. OLI software

OLI ESP software was used to predict the water quality of the FGD waste water: (i) after chemical pre-treatment with alkalis such as  $Ca(OH)_2$  and  $Na_2CO_3$  and (ii) when treated with freeze crystallization [21]. The Stream Analyzer of OLI was used to perform single point equilibrium calculations, multiple point survey calculations for a complete trend analysis for characteristics such as temperature, pressure, pH and composition effects, and simple mix and separation capability. The calculations provide liquid phase and solid phase separations for a specialized model.

# IV. RESULTS AND DISCUSSIONS

The treatment options were based on a spreadsheet-based calculations to determine the following parameters: coal usage, water usage, gas flow, chemical usage, waste water chemical composition from FGD plant (Appendix A).

# A. Water losses

Intake water from the Vaal River (or Osuthu Dam) amounts 887 m<sup>3</sup>/h to make-up for the following water losses: (i) 491.6 m<sup>3</sup>/h evaporation in the scrubber (**Intake** water from the Vaal River (or Osuthu Dam) amounts 887 m<sup>3</sup>/h to make-up for the following water losses: (i) 491.6 m<sup>3</sup>/h evaporation in the scrubber (**Error! Not a valid** bookmark self-reference.) (ii) 22.4 m<sup>3</sup>/h losses as gypsum crystal water (**Error!** Not a valid bookmark self-reference.) (iii) 212.1 m<sup>3</sup>/h disposal by Enviroserv (iv) 5 m<sup>3</sup>/h for ash conditioning/dust suppression (estimate), (v)156 m<sup>3</sup>/h boiler water make-up (estimate)

- Boiler feed water is produced in the IX plant where 156 m3/h Vaal River water is treated. The regenerant (Na2SO4) is passed on to the Holding Recycle Dam.
- The Holding Recycle Dam receive waste streams from the various sections of the Power Station (IX regenerant, gypsum dewatering plant, SO2 scrubber).
- Waste water from the FGD plant is currently disposed at waste disposal site at cost of R2 000/t. The volume produced during the period 1 Jan 2019 to 30 Apr 2019 amounts to 9.67 ML/4 months or 3.36 m3/h. At a disposal cost of R2 000/t the disposal cost amounts to R58.8m/month.

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Process stages	Flowrate (m <sup>3</sup> /h)	Comment
Evaporation on FGD plant	491.6	Table 4
Gypsum crystal water	22.4	Table 4
Disposal by Enviroserv	212.1	Table 8
Ash conditioning	5.0	Estimate
Boiler water make-up	156.0	Estimate
Total intake from Vaal River/Osothu		
Dam	887.1	

# TABLE II: Water losses at Kusile

#### **B.** Evaporation

The FGD Effluent Treatment Plant includes the following stages: pre-treatment, evaporation (brine concentration) and crystallization [5]. Water needs to be pre-treated for removal of metals ( $Mg^{2+}$ ,  $Ca^{2+}$  and  $Mn^{2+}$ ) to prevent scaling of the elements during evaporation. OLI software simulations showed the following:

• With a Na<sub>2</sub>CO<sub>3</sub> dosage of 25 195 mg/L the TDS was increased from the 41 818 to 42 773 mg/L due to Na+ addition, precipitation of Mn<sup>2+</sup> as MnO<sub>2</sub>, and

partial removal of  $Mg^{2+}$  as  $Mg(OH)_2$  (Error! Not a valid bookmark self-reference.). At a price of R2 500/t lime cost amounts to R125.98/m<sup>3</sup>

With a NaOH dosage of 16 651 mg/L, the TDS was increased from the 41 862 to 46 237 mg/L due to Na+ addition, precipitation of Mn<sup>2+</sup> as MnO<sub>2</sub>, and partial removal of Mg<sup>2+</sup> as Mg(OH)<sub>2</sub> (Error! Not a valid bookmark self-reference.). At a price of R9 000/t lime cost amounts to R149.86/m<sup>3</sup>.

Calcium and magnesium will be removed in the pretreatment stage to protect the evaporation system from chemical scaling. Lime (Ca(OH)<sub>2</sub>) and soda ash (Na<sub>2</sub>CO<sub>3</sub>) with pH adjustment, to between 9 and 10, would be used for water softening. The softened water flows into the evaporation process or brine concentrator where the temperature is increased to about 96°C and further processed in the falling-film type evaporator. Commissioning is planned for December 2021. Error! Reference source not found. shows the following:

- Electricity cost for evaporation amounts to R8.75m/month. The electricity price was taken at R1/kWh.
- The cost for Na<sub>2</sub>CO<sub>3</sub> and evaporation is estimated at R7 313 146 million/month (R125.98/m<sup>3</sup>).

The total treatment cost of pre-treatment plus evaporation amounts to  $R2\ 077/m^3$ . This is similar to the cost of waste disposal.

17	TABLE III. Treatment of FOD endent with Na2CO3							
Na2CO3 [mg/L]	μd	Mn(+2) Aq [mg/L] (Y2)	Mg(+2) Aq [mg/L] (Y2)	Ca(+2) Aq [mg/L] (Y2)	Na(+1) Aq [mg/L] (Y2)	TDS (mg/L)	R/m³	
0	6.4	5 823	3 340	578	3 257	41 862	0.00	
3 176	7.4	4 174	3 339	563	4 634	41 527	15.88	
6 342	7.6	2 525	3 337	548	6 011	41 190	31.71	
9 500	8.0	878	3 336	533	7 386	40 855	47.50	
12 650	9.2	3	3 331	99	8 759	41 186	63.25	
15 796	9.2	0	2 951	3	10 136	43 136	78.98	
18 935	9.3	0	2 258	3	11 524	43 966	94.67	
22 067	9.3	0	1 590	2	12 915	44 910	110.34	
25 195	9.5	0	989	1	14 306	46 137	125.98	
28 323	9.6	0	560	1	15 693	48 039	141.62	
31 455	9.7	0	357	1	17 073	50 779	157.27	

TABLE III: Treatment of FGD effluent with Na<sub>2</sub>CO<sub>3</sub>

Temp. = 25°C; Na<sub>2</sub>CO<sub>3</sub> = R5 000/t

NaOH [mg/L]	Hq	Mn(+2) Aq [mg/L] (Y2)	Mg(+2) Aq [mg/L] (Y2)	Ca(+2) Aq [mg/L] (Y2)	Na(+1) Aq [mg/L] (Y2)	(T/ <sup>gm</sup> ) SQT	K/m <sup>3</sup>
0	6.4	5 823	3 340	578	3 257	21 126	0.00
2 397	8.7	4 181	3 339	562	4 634	20 862	21.57
4 788	8.8	2 531	3 337	547	6 011	20 590	43.09
7 172	9.0	882	3 336	533	7 386	20 319	64.55
9 551	9.2	404	2 818	524	8 759	20 703	85.96
11 923	9.3	306	2 131	515	10 131	21 300	107.31
14 290	9.3	209	1 446	507	11 501	21 896	128.61
16 651	9.5	111	762	497	12 870	22 491	149.86
19 006	10.0	12	79	488	14 238	23 085	171.05
21 376	12.6	0	0	599	15 607	24 493	192.38
23 741	12.8	0	0	299	16 977	25 582	213.67

Temp. =  $25^{\circ}$ C; NaOH = R9 000/t

TABLE V: Treatment of FGD process water through pre-treatment and evaporation

Parameter	Value				
	Feed	Na <sub>2</sub> CO <sub>3</sub>	Evaporation		
			Distillate	Brine	
Salt rejection (%)			98		
Water recovery (%)			90.00		
Flowrate (m <sup>3</sup> /h) (Eskom value)	6.63		5.96	0.66	
Chemical dosage and					
Na <sub>2</sub> CO <sub>3</sub> dosage (mg/L) (OLI)		25 195		24 691	
Na <sub>2</sub> CO <sub>3</sub> usgae (t/month)		1 463			
Na <sub>2</sub> CO <sub>3</sub> price (R/t)		5 000			
Na <sub>2</sub> CO <sub>3</sub> cost (R/m <sup>3</sup> )		126			
Na2CO3 cost (R/month)		7 313 146			
Chemical composition					
рН					
Acidity (mg/kg as CaCO <sub>3</sub> )					
Cl- (mg/kg H2O)	8 000	8 007	160	78 560	
SO4 <sup>2-</sup> (mg/kg H <sub>2</sub> O)	20 939	20 987	419	205 625	
HCO3 <sup>-</sup> (mg/kg H2O)		1 802	0	0	
H <sup>+</sup> (mg/kg H <sub>2</sub> O)			0	0	
Na <sup>+</sup> (mg/kg H <sub>2</sub> O)	3 257	14 306	65	31 980	

TABLE IV: Treatment of FGD effluent with NaOH

K <sup>+</sup> (mg/kg H <sub>2</sub> O)	44	44	1	432
Mg <sup>2+</sup> (mg/kg H <sub>2</sub> O)	3 340	989	67	32 799
Ca2+ (mg/kg H2O)	640	2	13	6 282
Mn <sup>2+</sup> (mg/kg H <sub>2)</sub> O	5 823	0	116	57 185
TDS (mg/kg)	42 043	46 137	841	412 863
Cation (meq/L)	662	705	13	6 497
Anion (meq/L)	662	692	13	6 497
Sludge composition				
Mg(OH)2 (mg/kg H2O)		476		
MgCO <sub>3</sub> (mg/kg H <sub>2</sub> O)		12 272		
CaCO <sub>3</sub> (mg/kg H <sub>2</sub> O)		1 596		
MnCO3 (mg/kg H2O)		12 194		
Suspendid solids (mg/kg H <sub>2</sub> O)		26 538		
Electricity cost				
Energy needed for evaporation (m.Hv) (kW)			3 744	
Electricity cost (R/kWh)			1.50	
Electricity cost			4 097	
Eskom's estimated cost			8 750	
(K/month) Chemical and electricity cost (R/m <sup>3</sup> )			2 360	
Chemical and electricity cost (R/month)			11 410 808	

# C. Freeze crystallization

As an alternative to evaporation, saline solutions can be treated with freeze crystallization. During the freeze crystallization process, the following process steps occur, nucleation, crystal growth, separation and melting. The techniques of crystallization include eutectic point, direct contact, indirect contact and vacuum operation [16]. These methods allow ice formation on cold surfaces that then require the removal of the ice layers. ROC Water Technologies has developed a system where ice does not stick to the cold surface. The efficiency of the desalination and the characteristics of the products obtained, from the process, are controlled by operating parameters such as initial concentration, rate of growth, temperature of the refrigerant used and flow rate. When heat is removed from brine, reaching its freezing point, ice crystals start to form, their crystallization excludes the unwanted impurities and the physical chemistry of the ice is similar to pure water [16]. It should be noted that the theoretical energy required to drive an evaporation process is seven times more than that of freezing [13]. The heat of fusion of ice is 333 kJ/kg compared to the heat of evaporation of water which is 2 260 kJ/kg.

# 1) Ice crystals and concentrate recovery

These results showed that clean ice was produced that can be melted under ambient conditions. The feed wastewater was processed in the freeze crystallization unit and the first ice point was found to be at - 1°C. The first 1 hour was spent on cooling the feed wastewater. Ice crystals started to form within a period of 2 hours after starting the experiment. The ice crystals were retained on a filter for 30 min to dewater before ice samples were taken. Fig. 1 shows ice crystals as formed. Error! Reference source not found. shows that the feed wastewater had a TDS of 4 820 mg/L, the product ice a TDS of 1 003 mg/L (after 7 h) and the brine a TDS of 6 392 mg/L (after 7h). The ice purity improved from 4 263 mg/L TDS at the beginning to 1 003 mg/L after 7 h of operation. The total ice production was 49.46 kg within total hours ran of 9 hours (Error! Reference source not found.). The brine can be concentrated further to the level where salts will crystallize out. Na<sub>2</sub>SO<sub>4</sub> will crystallize at around 45 g/L and NaCl at 350 g/L, when exceeding its solubilities.

# 2) Energy utilization

**Error! Reference source not found.** shows the energy utilization with respect to brine temperature, actual and theoretical energy utilization. On average, the COP (coefficient of performance) for cooling from  $21^{\circ}$ C to  $-1^{\circ}$ C was 0.86 and for ice formation was 0.31. For a larger system these COP values will be higher than 2 and 1 respectively due to less heat losses.

**Error! Reference source not found.** shows the cost when FGD effluent is treated with Freeze crystallization. In this case no  $Na_2CO_3$  pre-treatment is required, only electricity for the chiller. The electricity cost of only freeze crystallization amounts to R821 772/m. This figure was calculated for a water recovery of 86.4% and salt rejection of 90.0% salt. The TDS of the melted ice was 4 840 mg/L and that of the brine 225 073 mg/L. A mass of 2.68 g  $Na_2SO_4$  .10H<sub>2</sub>O/kg water will also be produced as a solid. The cost of Freeze Crystallization is estimated at R958 388/m (R198.22/m<sup>3</sup>) (**Error! Reference source not found.**).



Source: Own compilation Fig. 1: Ice crystals formation during freeze crystallization

TABLE VI: Water quality of feed, brine and melted ice samples

Sample	Sample		Parameter			
Name	Number	рН	TDS (mg/L)	Electrical conductivity (mS/cm)	Amount of ice (kg)	
Feed	1.00	7.17	4 820	7.59		
	1.00	8.13	5 585	11.24		
	2.00	8.07	5 591	11.57		
Concentrate	3.00	7.85	5 958	11.94		
Concentrate	4.00	7.73	6 115	12.27		
	5.00	7.67	6 296	12.62		
	6.00	7.26	6 392	12.72		
	1.00	7.96	4 263	8.53		
	2.00	7.98	2 984	6.01	14.27	
Maltad Iaa	3.00	8.02	1 573	3.15		
Melted Ice	4.00	8.07	1 472	2.96	14.46	
	5.00	8.12	1 318	2.66		
	6.00	8.30	1 003	2.02	20.73	
Total					49.46	

Feed volume = 117 L

Time	Temp	Energy	Accumul ated energy	lce recove ry	Coo	ling
					E used (kWh/t) (actual)	E utilized (theor)
h	°C	kWh	kWh	kg	kWh/t	kWh/t
0.00	21		0			
0.50	7	2.53	2.53		21.6	16.3
1.00	2	3.00	5.53		25.6	5.8
1.50	-1	1.30	6.83		11.1	3.5
					Ice form	nation
2.00	-1		6.83			
3.50	-1	4.28	11.11	14.27	299.93	91.67
6.00	-1	4.33	15.44	14.46	299.45	91.67
9.00	-1	6.19	21.63	20.73	298.60	91.67
			Total	49.46		

TABLE VII Process control	data for freeze crystallization
171DLL 111.1100035 CONU01	und for meete erystamization

Total

Chiller temp = -7°C; Volume = 117 L

TABLE VII: Treatme	nt of FGD effluent withou	it chemical pre-treatment
TIDLE VII. HOULING	in of I OD enfluent without	it enemiear pre treatment

% water removal	H20 [mg]	Hq	S(+6) Aq [mg] (Y2)	(mg)	TDS (mg/L)
0.00	1 000 000	6.15	20 432	41 312	41 318
9.60	904 000	6.12	20 337	41 178	45 560
19.20	808 000	6.08	20 243	41 044	50 810
28.80	712 000	6.04	20 148	40 910	57 478
38.40	616 000	6.00	20 054	40 776	66 225
48.00	520 000	5.94	19 958	40 640	78 203
57.60	424 000	5.87	19 860	40 501	95 603
67.20	328 000	5.77	19 757	40 356	123 185
76.80	232 000	5.62	19 644	40 195	173 583
86.40	136 000	5.34	18 714	38 828	289 738

#### Temp. = $0^{\circ}C$

TABLE VIII: Treatment cost of freeze crystallization

Parameter	Feed	Freeze crystallization					
		Melted ice	Brine	Solids			
Salt rejection		90.0					
Water recovery		96.4					
(%) Flowrate		80.4					
(m <sup>3</sup> /h) (Eskom value)	6.63	5.73	0.90				
Chemical composition							
		Mass (mg) (from o	originally in 1 L)	-			
H <sub>2</sub> O (mg)	1 000 000	864 000	136 000	136 000			
Cl- (mg)	8 000	800	7 200	-			
SO42- (mg)	20 939	2 094	16 620	2 225			
Na <sup>+</sup> (mg)	3 257	326	2 548	383			
K <sup>+</sup> (mg)	44	4	40	-			
Mg <sup>2+</sup>	3 340	334	006	-			
Ca <sup>2+</sup> (mg)	417	42	35	340			
Mn <sup>2+</sup> (mg)	5 823	582	5 241	-			
TDS (mg/kg)	41 821	4 182	34 690	2 949			
Cation (meq)	650	65	552	34			
Anion (meq)	662	66	549	46			
	Concentration (mg/L)						
			136				
H <sub>2</sub> O (mg)	1 000 000	864 000	000 52	136 000			
Cl <sup>-</sup> (mg)	8 000	926	941	-			
SO4 <sup>2-</sup> (mg)	20 939	2 424	122 206	16 363			
Na <sup>+</sup> (mg)	3 257	377	18 735	2 817			

K+ (mg)	44	5	291	-
(			22	
Mg <sup>2+</sup> (mg)	3 340	387	103	-
Ca <sup>2+</sup> (mg)	417	48	260	2 503
			38	
Mn <sup>2+</sup> (mg)	5 823	674	537	-
TDS (mg/kg)	41 821	4 840	255 073	21 683
Cation (meq)	650	75	4 057	248
Anion (meq)	662	77	4 037	341
Sludge				
composition				
CaSO <sub>4</sub> .2H <sub>2</sub> O mg/kg H <sub>2</sub> O			2 597.42	
Na <sub>2</sub> SO <sub>4</sub> .10H <sub>2</sub> O				
mg/kg H <sub>2</sub> O			2 684.01	
solids				
mg/kg H <sub>2</sub> O				
Electricity				
cost				
Energy needed				
for Freeze				
(m.Hv) (kW)		751		
Electricity cost				
(R/kWh)		1.50		
Electricity cost				
for cooling and				
freezing		001 770		
(R/III0IIII)		621 //2		
electricty cost				
(R/m <sup>3</sup> )		169.96		
(iem)		10).)0		
Capital cost				
Capital cost				
(R/(ML/d)		45 000 000		
Capital cost for				
this flowrate		10.000 0.00		
(R/(ML/d)		10 337 864	Eq I	
Capital				
$cost (P/m^3)$		28.26		
Capital and		20.20		
electricty cost				
(R/m <sup>3</sup> )		198.22		
Capital and				1
electricty cost				
(R/month)		958 388		

Note: Cap cost 1 = Cap cost 2 x (Flow 1/Flow 2)<sup>0.8</sup> Interest = 10%/a Period = 120 months

# V. CONCLUSIONS

The waste water from the flue gas desulfurization (FGD) plant contained a high total dissolved solids (TDS) concentration of 50 000 mg/L due to: (i) absorption of SO<sub>2</sub>, chloride and boron from the coal in the FGD waste water, (ii) dissolution of sodium, potassium, magnese and calcium form the limestone when reacted with the acid gasses from the combustion chamber. A large portion of the calcium sulphate in solution precipitated as gypsum due to its limited solubility.

It was found that the cost for a 4 800MW plant will amount to **R9.7 million per month for disposal at a toxic** waste disposal site, **R11.41 million per month when pre**treated with lime/sodium carbonate followed by evaporation and **R0.96 million per month when treated** for Freeze crystallization. Freeze crystallization was found to be the most cost effective as it did not need chemical pretreatment and it consumes less energy than evaporation (330kJ/kg in the case of freeze versus 2 260kJ/kg in the case of evaporation). Energy usage was found to be 100 kWh/kg ice.

The TDS of the Feed amounted to 50 000 mg/L compared to less than 3 000 mg/L in the melted ice.

#### VI. RECOMMENDATIONS

It is recommended that Freeze Crystallization be considered for treatment of FGD waste water.

#### VII. ACKNOWLEDGEMENT

TIA Seed Fund, F'SAGRI, University of Limpopo and ROC Water Technologies (PTY) Ltd for financial support. NIPMO, who sponsored the grant for the innovation award of 2021 NSTF-South32 that was received by ROC Water. Dr Kelley Reynolds-Clausen, Ms Akashnie Raghu, Mr Tshitso Tamane and Mr Evans Ramabina provided valuable information on Power Stations operations. Tshwane University of Technology made analysis service facilities.

# VIII. APPENDIX A - INTEGRATION OF WATER TREATMENT WITH THE INTEGRATED POWER PLANT

Appendix A showed the procedure was followed to compare the treatment cost between evaporation and freeze crystallization of the FGD waste water. It was caried out stepwise as shown below:

- i. Determination of coal and limestone usage for a 4 800 MW coal fired power station. (
- ii. Coal usage, Limestone usage, sulphur production, ash production).
- iii. Calculation of water losses in the FGD plant (

iv.).

v. Calculation of water quality of FGD waste water from:

**a.** The SO<sub>2</sub>, chloride and boron loads absorbed in the FDG scrubber generated by the coal (

Parameter	Design
A. Gas from combustion chamber	
SO2 (t/h)	39.87
CO2 (t/h)	4 700.04
H2O (g) (t/h)	769.10
O2 (t/h) (due 5% excess coal)	170.91
N2 (t/h)	11 963.73
Total gas (t/h)	17 643.64
Gas heat capacity (kJ/kg.K)	1.05
Temp of scrubbing water after contact with gas (°C)	85

Temp of SO2/CO2 gas from combustion chamber (°C)	160
Gas sensible heat (MW)	385.95
B. SO2 scrubbing on FGD plant	
FGD water from Holding Recycle Dam (m3/h) (from background)	548.4
Recycle water (m3/h) (from background)	960.0
Water evaporated in scrubber (m3/h)	491.6
Scrubber Fly ash (%)	5.0
Scrubber Fly ash production (t/h)	13.6
Temp of cold ash (°C)	80
Temp of hot ash (°C)	160
Ash heat capacity (kJ/kg.K)	0.95
Ash sensible heat (MW) (m.Cp.dT)	0.29
Temp of feed water (°C)	25.00
Temp of scrubber water due to 5% ash water (°C)	25.29
Water heat capacity (kJ/kg.K)	4.18
Water energy for cooling (MW) (m.Cp.dT + m.H)	0.32
Water sensible heat (25.29 to 85°C) (MW)	66.56
Gas sensible heat (85 to 160°C) (MW)	10.75
Evaporation sensible heat (MW)	308.64
Sensible heat from heating water and evaporation	385.95
C. Water losses together with gypsum	
Gypsum production (t/h)	107.1
Crystal water (t/h)	22.4
Moisture content (%)	20.0
Free water in gypsum (t/h)	32.1
Total water (t/h)	54.6

B. SO2 scrubbing on FGD plant	
FGD water from Holding Recycle Dam (m3/h) (from background)	548.4
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Moisture content (%)	20.0
Free water in gypsum (t/h)	32.1
Total water (t/h)	54.6

# **d.** ).

**e.** Calculation of the mass of gypsum that crystallized form solution due to the limited solubility of gypsum (

Parameter	Design
A. Gas from combustion chamber	
SO2 (t/h)	39.87
CO2 (t/h)	4 700.04
H2O (g) (t/h)	769.10
O2 (t/h) (due 5% excess coal)	170.91
N2 (t/h)	11 963.73
Total gas (t/h)	17 643.64
Gas heat capacity (kJ/kg.K)	1.05
Temp of scrubbing water after contact with gas (°C)	85
Temp of SO2/CO2 gas from combustion chamber (°C)	160
Gas sensible heat (MW)	385.95
B. SO2 scrubbing on FGD plant	
FGD water from Holding Recycle Dam (m3/h) (from	1
background)	548.4

# b. ).

c. Calculation of the load of calcium, magnesium, sodium and potassium dissolved from limestone as it reacts with  $SO_2$  in the FGD plant (

Parameter	Design
A. Gas from combustion chamber	
SO2 (t/h)	39.87
CO2 (t/h)	4 700.04
H2O (g) (t/h)	769.10
O2 (t/h) (due 5% excess coal)	170.91
N2 (t/h)	11 963.73
Total gas (t/h)	17 643.64
Gas heat capacity (kJ/kg.K)	1.05
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Temp of SO2/CO2 gas from combustion chamber (°C)	160
Gas sensible heat (MW)	385.95

Recycle water (m3/h) (from background)	960.0
Water evaporated in scrubber (m3/h)	491.6
Scrubber Fly ash (%)	5.0
Scrubber Fly ash production (t/h)	13.6
Temp of cold ash (°C)	80
Temp of hot ash (°C)	160
Ash heat capacity (kJ/kg.K)	0.95
Ash sensible heat (MW) (m.Cp.dT)	0.29
Temp of feed water (°C)	25.00
Temp of scrubber water due to 5% ash water (°C)	25.29
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Water energy for cooling (MW) (m.Cp.dT + m.H)	0.32
Water sensible heat (25.29 to 85°C) (MW)	66.56
Gas sensible heat (85 to 160°C) (MW)	10.75
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Sensible heat from heating water and evaporation	385.95
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Crystal water (t/h)	22.4
Moisture content (%)	20.0
Free water in gypsum (t/h)	32.1
Total water (t/h)	54.6

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Temp of cold ash (°C)	80
Temp of hot ash (°C)	160
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Temp of feed water (°C)	25.00
Temp of scrubber water due to 5% ash water (°C)	25.29
Water heat capacity (kJ/kg.K)	4.18
Water energy for cooling (MW) (m.Cp.dT + m.H)	0.32
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Gas sensible heat (85 to 160°C) (MW)	10.75
Evaporation sensible heat (MW)	308.64
Sensible heat from heating water and evaporation	385.95
C. Water losses together with gypsum	
Gypsum production (t/h)	107.1
Crystal water (t/h)	22.4
Moisture content (%)	20.0
Free water in gypsum (t/h)	32.1
Total water (t/h)	54.6

# h. ).

Parameter

vi. Determination of the volume of air needed for cooling of the condensate in the case of Kusile (dry power station) (

Value

A. Gas from combustion chamber H2O (g) (t/h) O2 (t/h) (due 5% excess coal) Total gas (t/h) Gas heat capacity (kJ/kg.K) Temp of scrubbing water after contact with gas (°C) Temp of SO2/CO2 gas from combustion chamber (°C) Gas sensible heat (MW) **B. SO2 scrubbing on FGD plant** FGD water from Holding Recycle Dam (m3/h) (from Recycle water (m3/h) (from background) Water evaporated in scrubber (m3/h) Scrubber Fly ash (%)

n of the	Coal usage (t/h)	1 913.2	
Design	Limestone usage (t/h)	62.3	
Design	Water intake (m3/h)	520.6	
39.87	Coal composition		
37.07	Chloride (g/t coal)	2 008.7	
4 700.04	Boron (g/t coal)	5.0	
769.10	Sulphur (g S (as SO4)/t coal)	28 131.5	
170.91	Limestone composition and Holding Recycle Dam		
11 963.73	Sodium (g/t limestone)	2 000.0	
17 643.64	Potassium (g/t limestone)	50.0	
1.05	Magnesium (g/t limestone)	8 071.2	
85	Calcium (g/t limestone)	380 000.0	
160	Chemical load in FGD plant		
385.95	Chloride (kg/h)	3 843.0	
	Boron (kg/h)	9.6	
5494	Sulphate (kg/h)	53 820.6	
348.4	Sodium (kg/h)	124.6	
960.0	Potassium (kg/h)	3.1	
491.6	Magnesium (kg/h)	502.8	
5.0			

f. ).

Parameter

SO2 (t/h) CO2 (t/h)

N2 (t/h)

background)

g. Determination of the chemical composition of the FGD waste water that needs to be treated (

Calcium (kg/h)	23 671.1	
TDS (kg/h)	81 974.7	
Anions (meq/L)	1 229.5	
Cations (meq/L)	1 230.4	
Chemcial composition		
	Before crystalli- zation	After crystalli- zation
Chloride (mg/L)	7 381.4	7 381.4
Boron (mg/L)	18.4	18.4
Sulphate (mg/L)	103 376.5	5 821.9
Sodium (mg/L)	239.3	239.3
Potassium (mg/L)	6.0	6.0
Magnesium (mg/L)	965.7	965.7
Calcium (mg/L)	45 466.5	4 818.8
TDS (mg/L)	157 453.8	19 251.5
Anions (meq/L)	2 361.6	329.2
Cations (meq/L)	2 363.4	331.0
Sludge		
CaSO4.2H2O (mg/L)		174 785.4
CaSO4.2H2O (t/h)		91.0
CaSO4.2H2O (t/a)		797 142.1
Water in gypsum (20%) (m3/h)		18.2
Water losses due to evaporation (Table 5.5) (m3/h)		491.6

vii.).

viii. Determination of the water consumption needed of cooling of the condensate in the case of a wet power station (Error! Reference source not found.).

A. Understanding of the operation of a coal-fired power station



shows a schematic diagram of the Kusile Power Station, where: (i) coal and air is fed to the burning chamber to generate steam, (ii) dry ash (14.2% of the coal) is transported via conveyer belts to the Ash Dump where it is conditioned with little amount of water for dust suppression, (ii) bottom ash (15%) is removed from the bottom of the boiler (iii) flue gas flows from the burning chamber via the electrostatic precipitator (ESP) to the flue gas scrubber, (ii) fly ash is removed before/in/after the ESP via cyclones (iv) ESP gas is passed though the wet scrubber for removal of  $SO_2$  as gypsum, after contacted with water,  $CaCO_3$  and air, (v) a small portion (5%) fly ash is trapped in the scrubber, (vi) the gypsum slurry (15% CaSO<sub>4</sub>.2H<sub>2</sub>O) is dewatered, (vii) the resulting wastewater will be passed through the water treatment plant (Na<sub>2</sub>CO<sub>3</sub> treatment to allow CaCO<sub>3</sub> followed by crystallization, evaporation). Freeze crystallization can be an alternative treatment option. (viii) water/steam is recycled through the boiler-turbinecondenser-boiler to generate 4 800 MW electricity, (ix) saturated steam is condensed through dry cooling in the Condenser.

#### B. Coal usage and ash production

Kusile power station was designed to produce 4 800 MW electricity. **Error! Reference source not found.** shows the chemical composition of a typical coal.

shows the coal usage (1 913 t/h), ash production (271.7 t/h), SO<sub>2</sub> production (19.93 t/h as S) and limestone usage needed in the FGD plant (62.29 t/h as 100% CaCO<sub>3</sub>). Combustion chamber where 1 913 t/h coal is burned to produce steam for electricity generation and 17 643 t/h of flue gas. This high volume of flue gas is due to the 80% N<sub>2</sub> in air. The ash is split between bottom ash (15%) and fly ash (85%). A small portion of the fly ash ends up in the scrubber due process inefficiencies. Ash is transported on a dry basis. Minimum water is used for dust suppression.

C. Flue gas desulfurization

shows that 39.9 t/h SO<sub>2</sub> is produced which is associated with a total flue gas production of 17 643 t/h. If the temperature of the flue gas from the combustion chamber is 160°C, and dropped to 85°C after contact with the FGD scrubber, the flue gas sensible heat has dropped by 385 .95 MW (Calculation: 17 643 x 1000 / 3 600 x 1.05 x (160 - 85)/1000).

After removal of fly ash in the ESP it is passed through the FGD plant for SO<sub>2</sub> removal. It was calculated that 491.6  $m^3/h$  water evaporated during the scrubbing process. This volume corresponds with the flow of 548.4  $m^3/h$  (13 162  $m^3/d$ ) that is fed from the Holding Recycle Dam as make up for the water losses due to evaporation and water in the gypsum sludge (54.6  $\text{m}^3/\text{h}$ ).

# D. Water quality of FGD waste water

calculates the chemical composition of FGD waste water from the coal (mass and chemical composition) and flow rate and chemical composition of intake water. It compares well with the chemical composition of the actual waste water.

# E. Steam for power generation

Parameter	Design
A. Gas from combustion chamber	
SO2 (t/h)	39.87
CO2 (t/h)	4 700.04
H2O (g) (t/h)	769.10
O2 (t/h) (due 5% excess coal)	170.91
N2 (t/h)	11 963.73
Total gas (t/h)	17 643.64
Gas heat capacity (kJ/kg.K)	1.05
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Recycle water (m3/h) (from background)	960.0
Water evaporated in scrubber (m3/h)	491.6
Scrubber Fly ash (%)	5.0
Scrubber Fly ash production (t/h)	13.6
Temp of cold ash (°C)	80
Temp of hot ash (°C)	160
Ash heat capacity (kJ/kg.K)	0.95
Ash sensible heat (MW) (m.Cp.dT)	0.29
Temp of feed water (°C)	25.00
Temp of scrubber water due to 5% ash water (°C)	25.29
Water heat capacity (kJ/kg.K)	4.18
Water energy for cooling (MW) (m.Cp.dT + m.H)	0.32
Water sensible heat (25.29 to 85°C) (MW)	66.56
Gas sensible heat (85 to 160°C) (MW)	10.75
Evaporation sensible heat (MW)	308.64
Sensible heat from heating water and evaporation	385.95
C. Water losses together with gypsum	
Gypsum production (t/h)	107.1
Crystal water (t/h)	22.4
Moisture content (%)	20.0
Free water in gypsum (t/h)	32.1
Total water (t/h)	54.6

Parameter	Value	
Coal usage (t/h)	1 913.2	
Limestone usage (t/h)	62.3	
Water intake (m3/h)	520.6	
Coal composition	02010	
Chloride (g/t coal)	2 008 7	
Boron (g/t coal)	5.0	
Sulphur (g S (as $SO4$ )/t coal)	28 131 5	
Limestone composition and Holding Recycle Dam	20151.0	
Sodium (g/t limestone)	2 000.0	
Potassium (g/t limestone)	50.0	
Magnesium (g/t limestone)	8 071.2	
Calcium (g/t limestone)	380 000.0	
Chemical load in FGD plant		
Chloride (kg/h)	3 843.0	
Boron (kg/h)	9.6	
Sulphate (kg/h)	53 820.6	
Sodium (kg/h)	124.6	
Potassium (kg/h)	3.1	
Magnesium (kg/h)	502.8	
Calcium (kg/h)	23 671.1	
TDS (kg/h)	81 974.7	
Anions (meq/L)	1 229.5	
Cations (meq/L)	1 230.4	
Chemcial composition		
	Before crystalli- zation	After crystalli- zation
Chloride (mg/L)	7 381.4	7 381.4
Boron (mg/L)	18.4	18.4
Sulphate (mg/L)	103 376.5	5 821.9
Sodium (mg/L)	239.3	239.3
Potassium (mg/L)	6.0	6.0
Magnesium (mg/L)	965.7	965.7
Calcium (mg/L)	45 466.5	4 818.8
TDS (mg/L)	157 453.8	19 251.5
Anions (meq/L)	2 361.6	329.2
Cations (meq/L)	2 363.4	331.0
Sludge		10/ 201
CaSO4.2H2O (mg/L)	1	1/4/85.4

CaSO4.2H2O (t/h)	91.0
CaSO4.2H2O (t/a)	797 142.1
Water in gypsum (20%) (m3/h)	18.2
Water losses due to evaporation (Table	
5.5) (m3/h)	491.6

shows that 253 000 t/h air is needed for condensing the steam. The calculations were based on air heating from  $25^{\circ}$ C to  $90^{\circ}$ C while the steam temperature was decreased from  $350^{\circ}$ C to  $85^{\circ}$ C.

Error! Reference source not found. shows that water needed for cooling amounts to 5.2 L/kg (q) coal in the case of a dry-cooled power station (where air is used for cooling of the condensate). In the case of a wet-cooled power station the water needed for condensation of the steam amounts 3.5 L/kg coal (s), 1.4 L/kWh (t). No water is used for steam condensation in the case of a dry-cooled power station. Energy production from coal amounts to 2.5 kWh/kg coal (r).

TABLE X: Typical South African coal analysis Source: Hosseinzadeh et al., (2015)

Parameter	Value	
Proximate analyses		
Fixed carbon (%)	56.6	
Volatile material (%)	27.1	
Moisture content (%)	2.1	
Ash (%)	14.2	
Ultimate analyses		
Carbon (%)	67.5	
Hydrogen (%)	4.26	
Nitrogen (%)	1.76	
Sulphur (%)	1.00	
Oxygen (by difference) (%)	9.18	
Gross calorific value (MJ/kg)	27.37	

TABLE XI: Coal usage and ash production at Kusile power
station

Parameter	Design
A. Coal section	
Energy production (MW)	4 800
Energy efficiency (%)	33
Coal energy value (MJ/kg)	27.4
Coal usage (t/h)	1 913
Gypsum production with 20% water (t/a)	900 000
CaSO <sub>4</sub> .2H <sub>2</sub> O production (t/a)	720000
Operation time (d/a)	280
CaSO <sub>4</sub> .2H <sub>2</sub> O production (t/h)	107

Sulphur oxidised from coal (t/h as S)	19.93
CaCO <sub>3</sub> needed for neutralization (t/h)	62.29
Sulphur content in coal (%)	1.04
Carbon content in Coal (%)	67
Ash (t/h)	271.7
B. Bottom ash	
Bottom ash (%)	15.0
Bottom ash production (t/h)	40.8
C. ESP Fly ash	
ESP Fly ash (%)	80.0
ESP Fly ash production (t/h)	217.3

TABLE XII: Flue gas flow rate, composition and temperature

Parameter	Design
A. Gas from combustion chamber	
SO <sub>2</sub> (t/h)	39.87
CO <sub>2</sub> (t/h)	4 700.04
$H_2O(g)(t/h)$	769.10
O <sub>2</sub> (t/h) (due 5% excess coal)	170.91
N <sub>2</sub> (t/h)	11 963.73
Total gas (t/h)	17 643.64
Gas heat capacity (kJ/kg.K)	1.05
Temp of scrubbing water after contact with gas (°C)	85
Temp of $SO_2/CO_2$ gas from combustion chamber (°C)	160
Gas sensible heat (MW)	385.95
B. SO <sub>2</sub> scrubbing on FGD plant	
FGD water from Holding Recycle Dam (m <sup>3</sup> /h) (from background)	548.4
Recycle water (m <sup>3</sup> /h) (from background)	960.0
Water evaporated in scrubber (m3/h)	491.6
Scrubber Fly ash (%)	5.0
Scrubber Fly ash production (t/h)	13.6
Temp of cold ash (°C)	80
Temp of hot ash (°C)	160
Ash heat capacity (kJ/kg.K)	0.95
Ash sensible heat (MW) (m.Cp.dT)	0.29
Temp of feed water (°C)	25.00
Temp of scrubber water due to 5% ash water (°C)	25.29
Water heat capacity (kJ/kg.K)	4.18
Water energy for cooling (MW) (m.Cp.dT + m.H)	0.32
Water sensible heat (25.29 to 85°C) (MW)	66.56
Gas sensible heat (85 to 160°C) (MW)	10.75
Evaporation sensible heat (MW)	308.64

Sensible heat from heating water and evaporation	385.95
C. Water losses together with gypsum	
Gypsum production (t/h)	107.1
Crystal water (t/h)	22.4
Moisture content (%)	20.0
Free water in gypsum (t/h)	32.1
Total water (t/h)	54.6

# TABLE XIII: Chemical composition of FGD waste water.

Parameter	Value	
Coal usage (t/h)	1 913.2	
Limestone usage (t/h)	62.3	
Water intake (m <sup>3</sup> /h)	520.6	
Coal composition		
Chloride (g/t coal)	2 008.7	
Boron (g/t coal)	5.0	
Sulphur (g S (as SO4)/t coal)	28 131.5	
Limestone composition and Holding Recycle Dam		
Sodium (g/t limestone)	2 000.0	
Potassium (g/t limestone)	50.0	
Magnesium (g/t limestone)	8 071.2	
Calcium (g/t limestone)	380 000.0	
Chemical load in FGD plant		
Chloride (kg/h)	3 843.0	
Boron (kg/h)	9.6	
Sulphate (kg/h)	53 820.6	
Sodium (kg/h)	124.6	
Potassium (kg/h)	3.1	
Magnesium (kg/h)	502.8	
Calcium (kg/h)	23 671.1	
TDS (kg/h)	81 974.7	
Anions (meq/L)	1 229.5	
Cations (meq/L)	1 230.4	
Chemcial composition		
	Before crystalli- zation	After crystalli- zation
Chloride (mg/L)	7 381.4	7 381.4
Boron (mg/L)	18.4	18.4
Sulphate (mg/L)	103 376.5	5 821.9
Sodium (mg/L)	239.3	239.3
Potassium (mg/L)	6.0	6.0
Magnesium (mg/L)	965.7	965.7
Calcium (mg/L)	45 466.5	4 818.8
TDS (mg/L)	157 453.8	19 251.5

2 361.6	329.2
2 363.4	331.0
	174 785.4
	91.0
	797 142.1
	18.2
	491.6
	2 361.6 2 363.4

TABLE XIV: Air flow needed for saturated steam condensation

Parameter	Design
Air flow (t/h)	253 187
Cold air in (°C)	25
Hot air out (°C)	90
Gas heat capacity (kJ/kg.K)	1.05
Energy from air cooling (MW) (m.Cp.dT)	4 800
Water pressure (Bar)	3.5
Water heat capacity (kJ/kg.K)	4.18
Water in (°C)	350
Water out (°C)	85
Water flow (m <sup>3</sup> /h)	15 600
Estimated water losses	156

TABLE XV: Water consumption of a wet Power Station for cooling with similar capacity to Kusile

Parameter	Unit	Value	
Energy generated from burning coal			
Coal mass flow	kg/s	1.0	
Coal mass flow	kg/h	3 600	
Coal energy value	kJ/kg	27 370	
Power	kW	27 370	
Energy utilization	%	33.0	
Energy production	kWh/kg coal	2.5	
Energy needed for evaporation			
Water mass flow, m	kg/s	1.0	
Water mass flow	kg/h	3 600	
Heat capacity, Cp	kJ/kg.K	4.18	
Heat of vaporization, $\lambda$	kJ/kg	2 260	
Temperature difference, dT	К	75	
Energy needed for boiling	kW	314	
Energy needed for evaporation (H = $m.\lambda$ )	kW	2 260	
Total energy	kW	2 574	
Energy required for evaporation	kWh/kg H <sub>2</sub> O	0.71	

Water usage	L/kg coal	3.5
Water usage	L/kWh	1.4
Design capacity	MW	54.0
Coal consumption	t/h	1 913
Water evaporated	m³/h	6 715

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Fig. 2: Flow diagram of Kusile Power Station