A Model for Optimization of Green House Gases (GHG) Capture Technologies in Power Plants

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Abstract

Greenhouse gases from power plants are a threat to society, biodiversity and food security. South Africa is relying on traditional methods such as coal to generate energy. The International Energy Agency (IEA) forecasts a global increase of greenhouse gases to about 62 billion tons in 2050. In order to reduce greenhouse gases release, it is necessary to develop GHG (Green House Gas) capture technologies and renewable energies. This research paper is based on the analysis of greenhouse gas technologies which are widely utilised to capture greenhouse emissions from fossil based power generation process. These capture technologies are: amine scrubbing and flue gas desulphurization (semi wet and wet). The research paper covers the following aspects, background of the GHG capture technologies, applications, efficiencies, economies of scale and summary of the operating philosophy. The paper also provides strategies that can be implemented to combat climate change. Analytical Hierarchical Process (AHP) methodology is used to analyse the input data and simulation of the results. AHP analysis is done on constituencies such as water consumption, reliability, capital expenditure and energy consumption of the greenhouse gas capture technologies. The results indicate the semi wet scrubber has an optimal cost benefit compared to other capture technologies.

Keywords
Greenhouse gases, Energy generation methods, Intergraded resource plan.

1. Introduction
The world has since the year 2000 experienced the effects of global warming. The primary cause of the global warming is attributed to greenhouse gases from coal fired plants and chemical/petrochemical plants. Currently, coal is the primary source of energy globally; about 85% of power generation is from fossil fuels (Kapdi, et al., 2004). In order to reduce the concentration of GHG in the atmosphere, industrialized countries must reduce greenhouse gas emission levels to about 5.2% (Peter, et al., 2012). The International Energy Agency (IEA) pointed out that to achieve this goal, CO2 capture and storage technology is required. It is imperative to start developing and rollout more greenhouse gas capture technologies, such as amine scrubbing and flue gas desulphurisation in order to meet GHG reduction demand (Peter, et al., 2012). Research conducted at the Council for Scientific and Industrial Research (CSIR) provides analysis of the South African energy integrated resource planning. The study highlights that, investing more on renewable energies will translate to reduction of CO2 as well as water reduction since coal fired power generation uses substantial amounts of water for cooling processes. The CSIR study suggests that, South Africa should avoid building new coal fired powerand nuclear plants and focus on least cost mix for new regeneration capacity with emphasis on photo-voltaic, gas and wind energy. South Africa could save up to 87 Billion rands by 2040 and could translate to 18% reduction in price of electricity per KWh if South Africa follows

least-mix proposed by CSIR (Wright, et al., 2016). This paper provides analysis of the current outlook of the South African energy mix. The current energy mix indicates that, South Africa is more reliant on fossil fuel.

Power plants with greenhouse gas capture technologies utilise substantial amount of water for cooling processes and energy for pumping, compression, etc. For feasibility/viability purposes, it is imperative for GHG capture technologies to be energy efficient, cost effective, and consume less amounts of water. The research analyse energy efficiencies, capital investment requirements, water consumption, and reliability of the greenhouse gas capture plant. The research also provides an in-depth review of strategies that can be implemented to combat climate change.

2. Conceptual approach of GHG operational process

The expansion and growth of interconnected devices over the internet continue to create an array of opportunities (Masood, et al., 2016). Internet of Things (IOT) and Big Data Analytics provide new opportunities and technologies that drive effective Demand Resource Management. The integration of independent heterogeneous operating systems in an interoperable ecosystem, System of Systems (SoS), generate huge and complex big data, which is useful for disaster prevention and preparedness (Emmanouil & Nikolaos, 2015). The importance of Big Data in DRM (prevention and preparedness) is described by (Emmanouil & Nikolaos, 2015). Data generation (IoT), acquisition, storage, and analytics, are phases of operation of a big data management system. Big Data analytics is a solution to the challenges of modelling and processing large amount of unstructured complicated data using traditional management tools and processing techniques (Emmanouil & Nikolaos, 2015). Descriptive analytics, predictive analytics, and prescriptive analytics, are important methodologies and applications composed in the fourth phase of a big data management system. Therefore, modelling and processing disaster risk information from IoT heterogeneous devices using Big Data Analytics enable timely risk information by (Cheng, et al., 2012).

- Extrapolating and interpreting risk data.
- Predicting the future.
- Providing advice for decision making by vulnerable population.

According to (Graeme, et al., 2008) reversible chemical reaction is regarded as one of the matured CO2 capture technology. The capture, reversible release and storage of carbon dioxide from combustion flue gases is regarded by governments and industries as a viable near-term option for capturing GHG. Future coal based power plants may be designed to capture GHG before combustion using coal gasification systems or use of pure oxygen combustion instead of air to obtain a concentrated CO2 stream for treatment. Capturing GHG also requires substantial amount of energy and water consumption is relatively high. Feasibility study and sensitivity analysis are essential to provide better indication of the removal efficiency and energy required (Graeme, et al., 2008). Energy demand is increasing at exponential rate due to population growth, economic growth and industrialization; this triggers the need for new build energy generation plants. Circa 2005, South Africa started experiencing black outs and load shedding. This was caused by the shortage of energy supply to the grid. Government was then obliged to respond to the shortage of energy supply. Construction of Medupi and Kusile power plants had to be expedited.

Energy efficiency analysis and capturing process

Capturing greenhouse gases can consume up to 30% of the energy that could be used for the grid Graeme, et al., 2008). Correct sizing of equipment is crucial, not only in improving energy efficiency, but also in reducing associated costs; capital investment, maintenance and operational costs. Davison's theory (2006) states that, energy losses due to CO2 separation units in integrated gasification combined cycle plants are lower than those in the pulverized coal post combustion capture plants, since a less energy intensive physical scrubbing process can be used in Integrated Gas Combined Cycle (IGCC) (Tim, et al., 2010). Improving energy efficiency and using alternative sources of energy reduces emissions. Implementing GHG emission controls could be a more viable option. Main equipment of the power generation system include: - boiler, turbine, cooling water system and a generator. GHG capture technologies traps gases such as CO2, SO2 before flue gases are released through the stack/chimney. Figure 1 below is the schematic for GHG capture process in a power plant (Murlidhar, 2003).

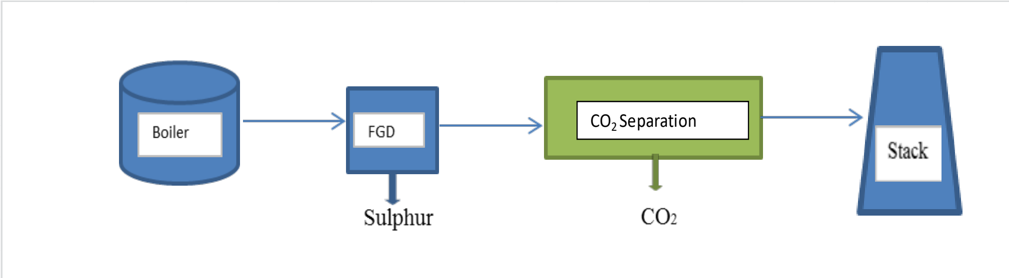

Figure 1. Simplified schematic of a flue gas clean-up train for a coal-fired power plant

Economic models for GHG capture

Cost of greenhouse house gas capture consists of the following; separation, compression, transportation and injection. These are dependent on many external factors which include: - the distance, and characteristics of the storage reservoir (Herzog & Golomb. 2004). Significant and rapid reduction of greenhouse gas emissions is recognized as necessity to mitigate the potential climate change effects from global warming. Post combustion, together with storage of carbon dioxide produced from the use of fossil fuels for electricity generation is a vital technology needed to achieve these reductions Graeme, et al., 2008). Other costs associated with GHG capture is transportation, this varies due to a number of reasons which include; distance, population density, permeability, underground conditions. Economies of scale are realized when dealing with over 10 million metric tons per year. Comparing pipeline transportation with truck transport, the former becomes cheaper with later costing 6 USD/tonne/100km, vs. 0.5 USD /tonne/100km (Herzog & Golomb. 2004). The study conducted by (Jeremy & Herzog, 2000) estimates that, the cost of CO2 transportation and injection would add about 150/ton of carbon dioxide. Literature elaborates on the importance of transportation cost, the effects of reducing capital expenditure vs. increment in operational costs (energy consumption cost). This analysis emphasizes the importance of considering complete life cycle and systems operations for the greenhouse gas emission plants. Greenhouse gas emissions are not only from power plants, smelter plants also emit substantial amounts of GHG's. Implementing new facilities and processes in the aluminium casting industry to reduce GHG is imperative in controlling air pollution.

Economic models i.e. general equilibrium models can be used as a basis for estimating the CO2 market price; this method can be used for feasibility studies during developmental phase of capture technologies (Peter, et al., 2012). Peter, et al., (2012), emphasises the significance of looking at the GHG capture technology as a system i.e. from capture to injection/usage of CO2. Commercialization is regarded as an added benefit in capturing CO2. It is also used for enhancing oil recovery in wells. The application of the Carbon Capture and Storage (CCS) technologies in power plants needs modification of existing technologies. In order to reduce energy consumption, the constituents such as enhancing high gas to liquid mass and heat transfer rates in absorber and stripper, reduce equipment volume and capital cost, develop a more suitable model for scaling up purposes are imperative. Concerning absorption operation, implementation of a rotating packed bed is recommended; this has been proved to process higher mass and heat transfer. The holistic systems engineering approach plays a critical role in ensuring the life cycle of the capture technology in conjunction with the plant are analysed. Rochelle, (2009) states that, further research is necessary on amine systems in order to provide an opportunity to improve the efficiency of the system. This requires the following; reducing energy cost, smaller absorbers, heat exchangers, and compressors. Redesigning piping systems, having pre-heaters and/or economizers might contribute in improving energy use (Dennis, et al., 2014).

Research findings (South African energy mixture)

Renewable energies are imperative in developing sustainable energy supply and pollution control i.e. developing renewable energies or carbon free technologies. However, renewable energies will not resolve the energy demand on its own, considering the current growth and some areas in South Africa still need electrification. The current energy mix in South Africa is illustrated in Figure 2.

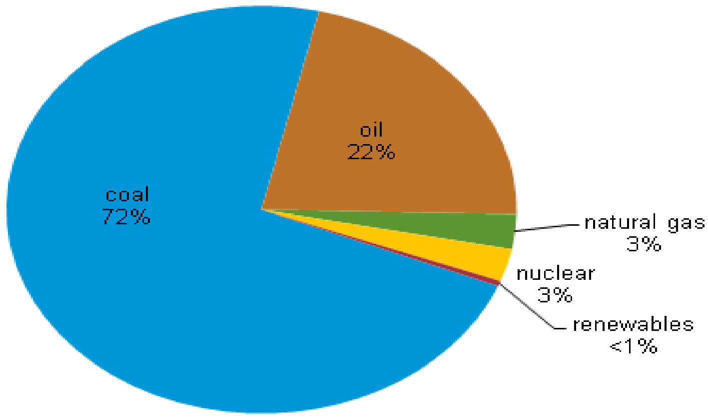

Figure 2. Total Primary Energy supply in SA (2013), BP statistical review

The breakdown above does not reflect good indication towards developing clean energy. Some of the power stations do not have emission control systems. South Africa should consider developing such technologies. The challenge is that, some of the plants are close to their lifespan, therefore investing on GHG capture technologies for plants close to being decommissioned might not be beneficial.

Research findings (strategies for combatting climate change)

There are strategies that have been developed to combat climate change; these strategies have certain applications and limitations. Preventing energy loss in industrial processes such as installing insulation, using material with acceptable thermal conductivity, utilisation of pre heaters can assist in reducing greenhouse gases (Horward, 1998).The summary in Table 1 depicts their applications and short comings.

Table 1. Strategies for combating climate change (Dennis, et al., 2014)

Strategy	Application	Advantages	Limitations
Enhance energy efficiency& energy conservation	Applied mainly in commercial & industrial buildings	Energy saving from 10% to 20% achievable	May involve extensive capital investment
Adopt clean technology	Integrated gasification combined cycle, hydro, solar	Use local natural resources	Higher fuel cost for conventional natural gas

Research findings (power generation technology, Integrated gas combined cycle and Pulverised coal)

Figure 3 depicts analysis of the efficiency Pulverized Coal/Fuel (PF) and Integrated Gas combined Cycle after application of GHG reduction technologies. Based on the analysis done on power cycle technologies with capture technologies, with post combustion for PC/ PF and pre combustion for IGCC, it is evident that Green House Gas (GHG) captures affects the performance of the plants (refer to Figure 3). The first sets of bar depict pulverized fuel and integrated gas combined cycle without GHG captures technologies fitted. The second pair of bars depicts power plants with post combustion capture technologies (Fluor design). Post combustion refers to the process whereby gases are captured after the combustion process. From the figure above, it's evident that Power plants fitted with capture technologies are less efficient that the power plants without capture technologies. The 3rd bar in the figure above depicts PF (pulverized fuel) and IGCC (integrated gas combined cycle) fitted with post combustion from MHI (Mitsubishi Heavy Industries).

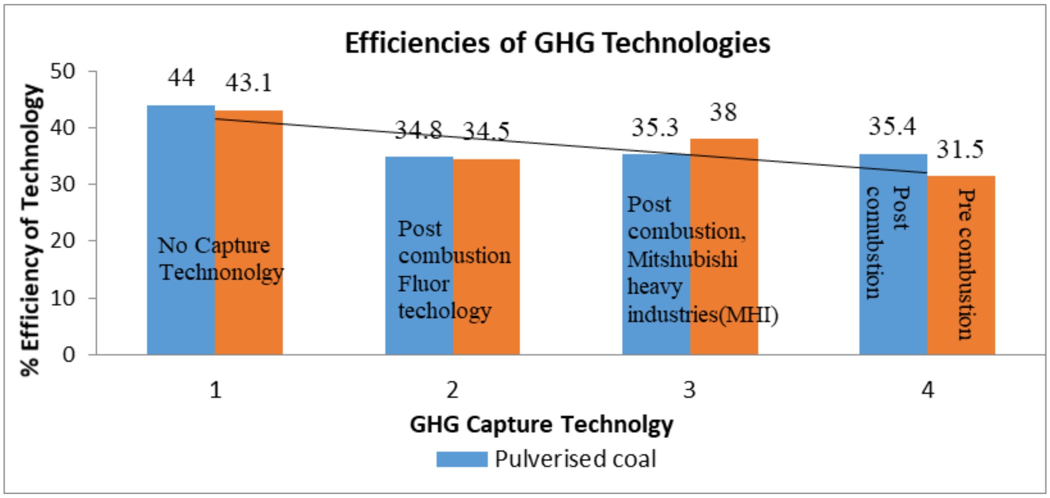

Figure 3. Net efficiencies for PC vs IGCC in percentages (%)

Figure 3 depicts variance in terms of efficiencies between Flour design and MHI design. The variance indicates that, MHI design is more efficient than Fluor design although these capture flue gases at post combustion. The variance in net efficiencies between PF fitted with MHI design and PF fitted Fluor design is about 0.5%, whereas the variance between IGCC fitted with MHI design and IGCC fitted with flour design is about 3.5%. The last sets of bars illustrate IGCC fitted with pre-combustion capture and PF with post combustion capture; results indicate that PF is more efficient than IGCC, when both plants are fitted with capture technologies. The comparison is done at various phases of combustion, for PF is done post combustion and IGCC pre combustion, this might have an influence on the results. This could be caused by the fact that different capture technologies can affect the overall efficiency of the plant at different stages of the process. For example, pre capture happens before combustion takes place whereas post capture takes place after the combustion process.

3. Analytical Hierarchical Process Method

The primary objective of the paper is to determine the most cost beneficial technology using a mathematical model. The paper focuses on four variables which are energy consumption, water consumption, reliability and Capex. Analytical Hierarchal Process (AHP) method was chosen on the basis that it is a common mathematical tool used to analyse different variables. The method takes into consideration all the variables needed to make multi criterion decisions. AHP analyses the constituents/variables hierarchically. The method develops a matrix that compares attributes in pairs. AHP was originally devised by Saaty circa 1980's to provide a framework for solving different types of multi- criterion decision problems based on the relative priorities assigned to each criterion's role in achieving the objective (Robert, et al., 2001). AHP is summarized in the steps below:

- Step one consists of defining the problem as well as determining the knowledge required.
  Step two is the structure decision for the detailed GHG constituent ranking To perform comparisons, a scale of numbers indicating the importance of constituents over the other is needed as illustrated by Table 2. This method has been used throughout the industry as a tool for decision making. The process is tailored to suit different objectives.
- Step three, construct a set of pair wise comparison, each element in the upper level is utilized to compare to the element immediately below it. A pair wise comparison is constructed to establish individual criteria priority value (CPV). Saaty method is used to calculate CPV using standard AHP preference criteria.
- Step 4 is the analysis of factor results obtained from step 3. These variables are analysed together with the objective to determine cost benefit analysis.

Overall plant capacity depends on the efficiency and reliability of the plant; hence the main focus of the study is aligned to these elements. For any capital investment to be regarded as viable, it needs to bring cost benefits or compliance, such as safety, pollution, and environment. Therefore the main focus of the research is to provide analytical models for all these constituents which are imperative in selecting the most beneficial greenhouse capture technology. Table 3 depicts the AHP inputs. The three capture technologies models analysed are detailed in Table 3. Figure 4 depicts the decision tree and the levels adopted for AHP analysis.

Table 2. Ranking(s) allocated to each constituents

Intensive or relative importance	Constituents	Definition	Explanation
1	Capital investment	Equal Importance	Constituents contribute equally important
5	Water consumption	Moderate importance	Judgment slightly favours one constituent over the other
7	Energy Consumption	Strong importance	Constituent strongly favoured and its dominance is demonstrated in practice
9	Reliability	Very important	Favoring one constituents over the other is of highest order

Table 3. AHP inputs for the capture technologies

Technologies	Water consumption	Capex	Energy consumption	Reliability
Amine scrubbing	282 m^3/hr	+/- 295 Million USD	Energy intensive, reduces plant efficiency by 30%. Cost of electricity can escalate between 80-85%	Reliable, 0.8 using factor 0-1 for AHP analyses
FGD- Spray semi dry scrubber	Approximately 470 m^3/hr	+/_4 Billion (ZAR)	Low energy consumption (+/- 2%)	Maintenance cost are quite high, reliability factor 0.4
FGD- Wet	Relatively high, required is approximately 1175m^3/hr	+/-16 Billion million (ZAR)	Fuel (only coal) properties specified	Reliability factor of 0.9

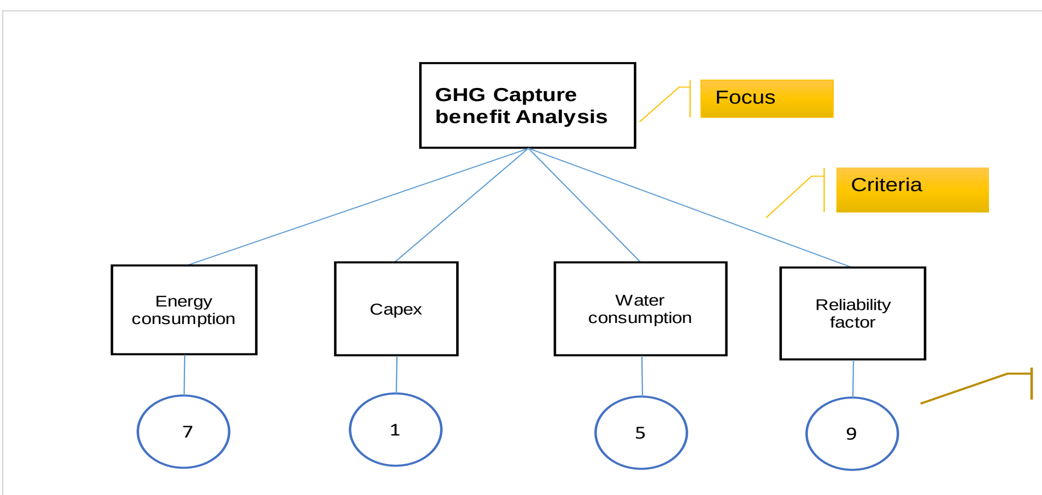

Figure 4: AHP levels

Results are determined following the AHP process; the process explains all the steps that are mandatory to achieve cost benefit. Tables 4 to 8 depict the methodology followed to obtain results. The first table (pairwise) is the input data for all three technologies to be analysed, with the four constituents as input data. These inputs consist of Capex (capital expenditure), water consumption, energy consumption and reliability, revealed by Table 4.

Table 4. Pairwise comparison

	Capex (USD)	**water consumption m3/hr**	**Energy consumption**	**Reliability**
Capex	1	4	8	11
Water consumption (m^3/hr)	0.25	1	5	7
Energy consumption	0.13	0.2	1	4
Reliability	0.09	0.14	0.25	1

The next step is to normalise, which requires each number in the column to be divided by total value of each column. The total number of fraction in each column must add up to one in order to verify the correctness of the analysis, displayed in Table 5. Results depicted in Table 6 and Table 7, are determined by taking the average of variables from normalised stage. The next phase is to calculate the AHP results, as depicted in Table 8.

Table 5. Normalised results

	Capex(USD)	**Water consumption (m^3/hr)**	**Energy consumption**	**Reliability**
Capex	0.68	0.75	0.56	0.48
Water consumption	0.17	0.19	0.35	0.30
Energy consumption	0.09	0.04	0.07	0.17
Reliability	0.06	0.03	0.02	0.04
Sum (∑)	1.00	1.00	1.00	1.00

Table 6. Integrated variables for GHG capture technologies

Variables	**Criteria**
Water consumption	0.17
Energy consumption	0.09
Reliability	0.06
Capex	0.68

Table 7. Factors for variables

Equipment	**water consumption (m^3/hr)**	**Energy consumption**	**Capex**	**Reliability**
FGD- wet	0.71	0.71	0.80	0.44
FGD- semi dry	0.18	0.12	0.13	0.07
Amine	0.12	0.18	0.07	0.49

Table 8. Cost benefit results

Equipment	**AHP results**	**Capex x(10^9)**	**Normalized cost**	**Benefit cost**
FGD- wet	0.53	R 1.10	1.67	3.15
FGD- semi dry	0.10	R 0.66	0.32	3.27
Amine	0.37	R 0.29	0.14	0.38
		R 2.05		

From the analysis done, semi dry FGD has higher cost benefit compared to wet FGD and Amine. The results depict that these two technologies (FGD wet and semi wet) have similarities, while amine scrubbing technology differs substantially from wet and semi wet FGD. From the results, it's evident that amine scrubber has high reliability factor compared to other technologies. Energy efficiency is quite critical since less efficient technologies results in higher fuel inputs subsequently, demanding more coal to be burnt. The first two technologies focus on capturing SO_2, however in this research study, the focus is on CO_2. An analysis on energy consumption between the solvents required to remove CO_2 vs. solvents required to remove SO_2 will need to be done. This will give a better indication of the energy inputs required.

Conclusion

Considering all the climate change effects that have been experienced in recent years, it is essential that state organs prioritise implementation of greenhouse gases capture technologies and expedite development of renewable energies. Due diligence in selecting optimal GHG is imperative, constituents such as water consumption, reliability, energy efficiency are some of the critical fundamentals which can be used as a basis to select the most optimal GHG capture technology. The research has provided some strategies which can be implemented in reducing toxic gases, which are harmful to human lives and biodiversity. It is recommended that a pilot plant be built in South Africa in order to have practical analysis of the performance of GHG technologies. Comparative studies can then be performed in a more controlled environment. The research has provided a balanced argument between renewable energies and fossil fuels. The research recommends implementation of renewable energies and fossil fuel plants should be fitted with GHG capture technologies.

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