

# **Economic Analysis of Water Recovery from Flue Gas: A South African Case Study**

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## **Declaration**

I declare that *The Economic Analysis of Water Recovery from Flue Gas: A South African Case Study* is my own work, that it has not been submitted for any degree or examination in any university, and that all the sources that I have used or quoted have been indicated and acknowledged by complete references.



**Signature:** S Hansen

**Date:** 31 March 2020

## **Acknowledgments**

Firstly, I just want to give thanks to the Lord Jesus Christ for giving me the strength to complete my thesis. In Him I live, in Him I move and in Him I have my being. In the shadow of His wings, I found rest and peace of mind. It was a tough couple of years filled with ebbs and flows. Many times, I felt like giving up or burying my head in the sand. However, God brought me to it and God took me through it. Hallelujah, Amen.

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## **Abstract**

In order to comply with the Air Quality Act 2010, Eskom will have to install flue gas desulphurisation (FGD) plants for both new and old power stations. Wet-flue gas desulphurisation (wet-FGD) is adopted world-wide as an effective flue gas treatment technology and therefore will be adopted by Eskom. During the process of desulphurisation, the flue gas is stripped of SO<sub>2</sub> but gains a substantial amount of water. Sustaining this process requires a continuous supply of fresh water, a scarce resource in many places where power stations are built. This research investigates the economic feasibility of technologies capable of recovering water from flue gas. The following technologies were considered to capture water vapour from flue gas taking Eskom's Medupi Power Station as a case study; condensing heat exchanger technology, desiccant drying systems and membrane technology using membrane modules developed by other students in this project. The water vapour selective membrane technology turned out to be superior.

The study evaluated three options for Medupi Power Station, namely, doing nothing; sourcing and cleaning water suitable to treat the flue gas; and implementing membrane technology to recover the water spent during the WFGD process. A cost-benefit analysis and sensitivity analysis were done on the third option. Option one was not feasible as it would result in Medupi having to shut down and lose millions in revenue. Option two was not profitable in that there is no benefit in cleaning flue gas. Option three was not viable due to the high replacement costs of the membrane modules every five years. However, Eskom would be better off with option two as they would be in compliance with the law and incur less costs in the future. In contrast, the sensitivity studies concluded that, if the membrane modules had a replacement value of 15 years or more, the investment into water vapour selective membrane technology (option three) is feasible.

## **Keywords**

**Economic Analysis, Flue Gas, Water Scarcity, Air Quality Act, Wet-Flue Gas Desulphurisation, Cost-benefit Analysis; Membrane Technology.**

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## List of Acronyms, Abbreviations and Symbols

\$	US Dollar
€	Euro
£	British Pound
ACF	Annual Cash Flows
B/C	Benefit-Cost Ratio
$B_E$	External Benefit
BFW	Boiler-Feed Water
$B_I$	Internal Benefit
BP	British Petroleum
$B_t$	Benefits
$B_T$	Total Benefit
$C_t$	Costs
$CaCl_2$	Calcium Chloride Anhydrous
CBA	Cost-Benefit Analysis
CEA	Cost-Effectiveness Analysis
CER	Cost-Effectiveness Ratio
CMA	Cost-Minimisation Analysis
$C_0$	Initial Investment
$CO_2$	Carbon Dioxide

CPI	Consumer Price Index
CUA	Cost-Utility Analysis
DEAT	Department of Environmental Affairs and Tourism
DPP	Discounted Payback Period
$E_0$	Effectiveness
EA	Economic Analysis
EBITDA	Earnings Before Interest, Taxes, Depreciation and Amortization
ENPV	Expected Net Present Value
EPRI	Electric Power Research Institute
EU	European Union
FGD	Flue Gas Desulphurisation
FPLPS	Flue Gas Pre-Dried Lignite-Fired Power System
$G$	Growth Rate
GDP	Gross Domestic Product
$H_2SO_3$	Sulphurous Acid
$H_2SO_4$	Sulphuric Acid
$i$	Interest Rate
ICE	Internal Combustion Engine

IRR	Internal Rate of Return
KW	Kilowatt
KWh	Kilowatt-per-hour
LiBr	Lithium Bromide Anhydrous
LiCl	Lithium Chloride Anhydrous
LPE	Low Pressure Economizer
m <sup>3</sup>	Cubic Metre
mg/Nm <sup>3</sup>	Milligrams-per-cubic-metre
MIRR	Modified Internal Rate of Return
MW	Megawatt
MWh	Megawatt-per-hour
NPV	Net Present Value
NO <sub>2</sub>	Nitrogen Oxide
O <sub>2</sub>	Oxygen
OC	Opportunity Cost
O & M	Operating and Maintenance Costs
PI	Profitability Index
PM	Particulate Matter
PP	Payback Period
PPI	Producer Price Index

PPC	Production Possibilities Curve
PVC	Present Value of Costs
QALY	Quality Adjusted Life Year
$R$	Rate of Return/Cost of Capital/Discount Rate
R	South African Rand
RMB	Renminbi
SAIAMC	South African Institute of Advanced Materials Chemistry
SO <sub>2</sub>	Sulphur Dioxide
SPB	Simple Payback Period
SPT	Spray Tower
$T$	Time Variable
TAG	Technical Assessment Guide
TIC	Total Investment Cost
TMC	Transport Membrane Condenser
TV	Terminal Value of Cash Inflows
USA	United States of America
UWC	University of the Western Cape
wet-FGD	Wet-Flue Gas Desulphurisation
WRC	Water Research Committee

WTP	Willingness to Pay
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# CHAPTER 1: INTRODUCTION

## 1.1 BACKGROUND AND PROBLEM STATEMENT

This study is about the economic analysis of water recovery from flue gas in the South African context. It uses Eskom as a case study in that it is the biggest flue gas emitter in South Africa.

Eskom is the biggest electricity producer on the African continent and the main electric power producer in South Africa. This organisation is owned by the state and it distributes electricity to 95% of all end users in South Africa and provides 60% of the entire electricity consumption in Africa (Pouris and Thopil, 2015). Eskom has 15 coal power plants of which twelve are base load power stations and three are peak power stations (Wassung, 2010). Base load power stations deliver electricity during periods of base demand; whereas peak power plants operate in tandem with base load power stations to deliver electricity during peak periods (Eskom website, 2017). In addition, the installed capacity of the base load power plants is 35 000 MW (megawatt) and that of the peak power stations are 3 000 MW. According to Eskom (2019), the coal-fired power stations generate 77% of their electricity, thereby implying a major environmental footprint. Power generation also has an impact on water resources because coal-fired power stations are among the most insatiable water users (Pouris and Thopil, 2015). Water is needed to generate electricity and it is argued that the coal power plants each consume, on average, 160 billion litres of scarce freshwater per annum (Eskom, 2017).

Additionally, Eskom has employed wet-cooling systems for those coal power plants where there is sufficient water available; and dry-cooling systems where water is not available in sufficient quantities such as Matimba, Kendal, Majuba, Medupi and Kusile<sup>1</sup> (Pouris and Thopil, 2015). Wet-cooling systems use an ample supply of water in the combustion process for cooling purposes. The water for cooling purposes may come from the ocean,

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<sup>1</sup> The 15 coal power stations; their capacity and cooling method are outlined in Appendix A.

ivers, lakes or canals. Dry-cooling systems, on the other hand, use air instead of water for the same purpose (Pouris and Thopil, 2015). Therefore, dry-cooled power stations use significantly less water<sup>2</sup> than the wet-cooled power stations; however, both emit vast volumes of flue gas into the atmosphere.

Flue gas is defined as gas released into the atmosphere via a pipe or channel (flue), carrying exhaust gases from a furnace, boiler or steam generator during combustion (Zevenhoven and Kilpinen, 2001). The combustion of coal releases poisonous gases via the flue gas stack into the atmosphere. The gases released are primarily carbon dioxide, water vapour, nitrogen oxide (NO<sub>2</sub>) and sulphur dioxide (SO<sub>2</sub>) (Pillay and Moodley, 2000). Nitrogen oxide is a harmful gas produced as a result of high temperatures during combustion and, according to Thermon (2000), it is a respiratory poison that has a harmful effect on humans and animals. Sulphur dioxide is a harmful greenhouse gas and its air particles can encourage chronic lung diseases such as asthma and bronchitis (Boumis, 2019). The amount of sulphur dioxide in untreated flue gas is between 1 000 and 2 000 parts per million (Bladergroen et al, 2019).

According to the Air Quality Act 2010, the emission of sulphur dioxide (SO<sub>2</sub>) and nitrogen oxide (NO<sub>2</sub>) is a health concern; and Eskom being the biggest emitter of flue gas in South Africa must comply with the Act. As per the Air Quality Act, industries have an obligation not to infringe on the right to air that is not detrimental to health and well-being (Molewa, 2012). In addition, industries that are liable for pollution or environmental ruin must take appropriate steps to prevent it from occurring again in future as authorised by law (Molewa, 2012).

In order to be compliant with the act and to curb their emissions, all of Eskom's coal power plants must be equipped with flue gas desulphurisation (FGD) systems by 2020 (Bladergroen et al, 2019). Currently, wet-flue gas desulphurisation is the technology of

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<sup>2</sup> The water consumption footprint of these dry-cooled power stations is approximately 0.1 litres per kilowatt hour (kWh) (Fact sheet, 2011); whereas the footprint of the wet-cooled power stations is approximately 1.9 litres per kWh



choice for Eskom's power stations and its latest power stations, Kusile and Medupi, are equipped with such a treatment system.

According to Dou et al (2009), wet-FGD or wet scrubbing is a system where harmful materials are removed from industrial exhaust gases before they are released into the environment by using a wet substance, e.g., a water and limestone slurry. Sulphur dioxide readily reacts with water or oxygen to form  $\text{H}_2\text{SO}_3$  and  $\text{H}_2\text{SO}_4$ , and the wet scrubbing system uses an alkaline sorbent (limestone) mixed with water to neutralise and remove it from the flue gas (Pillay and Moodley, 2000). Wet-FGD is very effective in that it removes more than 90% of sulphur dioxide and a significant amount of gaseous chlorides and fluorides that are present in flue gases (Pillay and Moodley, 2000); however, in the process, a significant amount of water is added to the flue gas.

According to Bladergroen et al (2019), the water consumption of the dry-cooled plants is expected to increase by 200%, from 0.1 litres/kWh to 0.3 litres/kWh, and that of the wet-cooled power stations will increase by approximately 10%, from 1.9 litres/kWh to 2.1 litres/kWh (Bladergroen et al, 2019). The increased water requirements were not part of the initial design of the power plants as most power stations were designed prior to the implementation of the Air Quality Act 2010. It must also be noted that wet-flue gas desulphurisation consumes roughly two tons of water per MWh power produced in power stations to saturate the flue gas (McNemar, 2006). However, South Africa has been identified as a water scarce country (Inglesi-Lotz & Blignaut, 2012) and the need to comply with the Air Quality Act puts additional strain on the limited water resources.

Water scarcity is a broad area of concern for countries and policy makers all over the world and South Africa is no exception. South Africa is located in a semi-arid<sup>3</sup> region and is considered one of the 30 driest countries on earth (Pouris and Thopil, 2015). In addition, South Africa's annual rainfall of 497 mm is way below the global annual average of 860 mm (Turton, 2008). Compounding the country's woes, the IPCC's 4<sup>th</sup> Assessment Report

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<sup>3</sup> Semi-arid refers to a climate or place that is semi-dry and has less than 20 inches of rain per year (Dictionary Definition)

showed a high likelihood that South Africa's water resources will dwindle due to climate change (IPCC, 2007 cited in Wassung, 2010). De Wit and Stankiewicz (2006) also suggest that total rainfall in the country has declined drastically between 1961 and 2000 and it is expected to decrease further by 50% in the future.

Also, the large population size and low average rainfall places additional pressure on South Africa's limited water resources. The major rivers in South Africa, namely the Orange, Inkomati, Limpopo and Pongola, have a collective annual flow of 49 000 cubic metres per annum, which is less than half of that of the Zambezi River<sup>4</sup>. This emphasises South Africa's limited availability of water in comparison with neighbouring countries (NWRS, 2004 cited in Pouris and Topil, 2015). Global warming further exacerbates the water scarcity situation in South Africa. The limited water quantities in some parts of South Africa destroy vegetation, thus worsening the drought impact of global warming (Wassung, 2010). Public concern over water usage is increasing, especially in the water stressed areas of the country. It has been argued that South Africa may have a permanent water shortage by 2020 (Eskom, 2017) as a result of these dire conditions.

Therefore, it is imperative that technologies are developed to capture water from flue gas to save water and to be reused by the coal power stations. Flue gas treated with wet-FGD (flue gas desulphurisation), which is practically gas saturated with water, shows the best potential for water recovery. There are three basic technologies for water recovery which are condensing heat exchangers, desiccants, and membrane technology (Carney, 2006). Condensing heat exchangers are proposed as a means to capture water and heat from flue gas. In addition, techniques inclusive of flue gas condensation and the use of desiccant drying system are available and have been implemented in Europe and Asia (Daal et al, 2013). However, the recovered water using flue gas condensation is rather acidic and corrosive due to the presence of carbon dioxide, whilst the desiccant drying system produces water of poor quality, and it needs to be regenerated thereafter (Macedonio et al, 2012).

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<sup>4</sup> The Zambezi River is the longest and largest river in Southern Africa.

Membrane technology on the other hand produces a pure water stream ready to be used with no further need of purification (Schildkamp, 2014 cited in Bladergroen et al, 2019). The recovered pure water would be primarily used as boiler feed water which typically should be free from foulants<sup>5</sup>; or it can be used as cooling water. Alternative uses include flue gas desulphurisation make-up water or cleaning water (Macedonio et al, 2012). Membrane technology has been labelled as energy efficient and its compactness and limited use of moving parts are attractive features that promote industrial implementation (Bladergroen et al, 2019).

Furthermore, emitted flue gas contains vast amounts of heat and water that is generally considered a waste stream that is lost to the atmosphere (Feeley et al, 2006). However, if the water and heat could be recovered and reused, they have the potential to lower the water consumption of the plants and increase their productivity. The implementation of the water capturing technologies will enable the power stations to produce freshwater from flue gas that is normally emitted from the stack (Feeley et al, 2006). However, it must be noted that implementing these technologies is costly, in that significant capital expenditures are needed for their implementation. Therefore, it is imperative to consider the economic costs involved in implementing these technologies.

Economic cost refers to the total cost of choosing one action over the other. In other words, it refers to the value one sacrifices when choosing an economic activity over the next best economic activity (Mohr and Fourie, 2008). Economic cost is much broader than accounting cost in that it includes monetary transactions, as well as what economists call opportunity costs. Economists and accountants follow different guidelines when measuring costs. Economists analyse all opportunity costs, whereas accountants analyse only explicit costs (Mankiw, 2009).

Opportunity cost refers to a trade-off between two options. For example, when one decides to invest, there is often the next best alternative that one decides not to take, such as purchasing one stock and forgoing the opportunity to purchase the other (Mohr

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<sup>5</sup> Foulants may refer to poisonous gasses and impurities that are present in the water.

and Fourie, 2008). Another example would be when a firm considers a capital investment, it must account for the return on investment, instead of going ahead with the capital project. Consequently, the firm will proceed with the investment if its opportunity cost is lower than the expected revenues from the new project. Furthermore, economic costs relate to the future in that they guide business decisions as the costs considered here are normally future costs (Mankiw, 2009).

Considering the above discussion, one certain issue comes to the fore. What are the economic costs and benefits of implementing flue gas condensation, desiccants, and membrane separation technology at Eskom's coal-fired power plants?

## **1.2 RESEARCH OBJECTIVES**

The objectives of this study are to:

- Examine the policies and trends concerning flue gas emissions in South Africa.
- Estimate the economic costs and benefits in implementing flue gas condensation, desiccants, and membrane technology at Eskom.
- Make policy recommendations based on the outcomes of the study.

## **1.3 RELEVANCE OF THE STUDY**

The South African Institute of Advanced Material Chemistry (SAIAMC) of the University of the Western Cape (UWC) mandated by the Water Research Commission of South Africa (WRC) is investigating the potential of membrane technology for water recovery from flue gas. The WRC wanted to incorporate an economic analysis aspect into the project, and with economic analysis one looks at different options and compares them. Thus, this study looks at the economic analysis of membrane technology and compares it with that of flue gas condensation and desiccants.

Economic analysis of water recovery from flue gas has never been done in South Africa before (Bladergroen et al, 2019). The study will benefit Eskom and it will assist the managers of the company to make a sound business decision on whether to invest in water capturing technology. In addition, this technology will be applicable only to the dry-

cooled power stations as they do not have sufficient water. As for the wet-cooled power stations, there is no basis for recapturing water, seeing that they have sufficient water.

If these technologies are found to be economically feasible, it will contribute to increasing water-supply resources in South Africa. Upon successful implementation of these technologies, the government can provide more water to water-stressed areas and it may motivate other industries (e.g., paper, cement, and petroleum) to employ water capturing technologies as well. Moreover, this study may shed light on what the cost of water should be in order for the water capturing technologies to be economically feasible. Lastly, this study may pave the way for further economic analysis studies of water capturing technologies in other industries.

#### **1.4 THESIS OUTLINE**

The rest of the thesis is organised as follows: Chapter Two examines the policies and trends concerning flue gas emissions in South Africa. In addition, it outlines the link between flue gas legislation, wet-flue gas desulphurisation and the three water capturing methods, as well as providing additional background on the three methods. This is followed by Chapter Three, which reviews the theoretical literature surrounding economic analysis and the four main types of economic analysis, namely cost-benefit analysis, cost-effective analysis, cost-minimisation analysis and cost-utility analysis. In addition, it outlines the empirical studies on economic analysis and cost-benefit analysis in general and empirical studies on flue gas condensation or condensing heat exchangers, desiccants, and membrane technology. Chapter Four discusses the methodology and data employed in the study. The results of the study are outlined in Chapter Five. The results are supported by Excel models, graphic illustrations, and tables. Chapter Six provides key conclusions and recommendations for future studies.

# **CHAPTER 2: POLICIES AND TRENDS CONCERNING FLUE GAS IN SOUTH AFRICA**

## **2.1 INTRODUCTION**

This chapter briefly examines the policies and trends regarding flue gas emissions in South Africa. Currently, the Air Quality Act 2010 is the only policy that addresses flue gas emissions in South Africa. This chapter will outline the rationale for the Act and its stance on flue gas emissions and compare it with previous years. In addition, it will briefly discuss the link between the Act, wet-flue gas desulphurisation and the water capturing technologies. Furthermore, this chapter provides additional background on the water capturing technologies.

## **2.2 POLICIES AND TRENDS REGARDING FLUE GAS EMISSIONS IN SOUTH AFRICA**

As already stated, the Air Quality Act 2010 is the only policy that addresses the flue gas emissions in South Africa currently. “The Air Quality Act of South Africa is based on the Bill of Rights that is outlined in the Constitution of South Africa. The Bill preserves the rights of all people in the country and upholds the democratic values of human dignity, equality and freedom. The state must respect, protect, promote, and fulfil the rights outlined in the Bill of Rights” (Molewa, 2012: 7).

Section 24 of the Constitution states that everyone has the right:

- “To an environment that is not detrimental to their health or well-being”; and
- “To have the environment protected, for the benefit of present and future generations, through acceptable legislative and other measures that” –
  - “Avoid pollution and environmental ruin”;
  - “Promote protection”; and
  - “Secure environmentally sustainable development and the use of natural resources while fostering economic and social development” (Molewa, 2012: 7).



In order to emphasise this right in terms of air quality, it is necessary to ensure that levels of air pollution are not detrimental to human health or well-being (Molewa, 2012). It follows that the setting of ambient air quality standards is needed, as well as mechanisms to ensure that ambient air quality standards are reached and retained. Therefore, the Air Quality Act provides a goal-driven approach to air quality management at various governance and functional levels and is the legislative means to ensure that the above-mentioned rights are maintained (Molewa, 2012). In an effort to curb flue gas emissions in South Africa, the South African Government in 2012 passed the Air Quality Act 2008, stipulating that sulphur oxide (a poisonous gas present in flue gas) emissions from all solid fuel combustion installations are limited to 500 mg/Nm<sup>3</sup> and 3500 mg/Nm<sup>3</sup> for new and existing installations respectively (Molewa, 2012). Table 2.1 displays the air quality regulations for new and existing plants (Sonjica, 2010) and the timelines for implementation (Anon, 2015).

**Table 2.1: Table of updated air quality regulations**

<b>Application</b>		All installations with design capacity equal to or greater than 50 MW heat input per unit, based on the lower calorific value of the fuel used			
<b>Substance or mixture of substances</b>		<b>Plant status</b>	<b>mg/Nm<sup>3</sup> (0 degree Celsius, 1atm, 10% O<sub>2</sub>)</b>		
<b>Common name</b>	<b>Symbol</b>		<b>2010</b>	<b>2015</b>	<b>2020</b>
Particulate matter	PM	New	50	50	50
		Existing		100	50
Sulphur dioxide	SO <sub>2</sub>	New	500	500	500
		Existing		3500	500

Source: [www.environment.gov.za](http://www.environment.gov.za)

Based on the table above, the sulphur dioxide emission of 3500 mg/Nm<sup>3</sup> for existing installations is too high, and thus by 2020 it must be lowered to 500 mg/Nm<sup>3</sup>. In a nutshell, the Air Quality Act 2010 stipulates that sulphur oxide emissions from all solid fuel combustion installations are limited to 500 mg/Nm<sup>3</sup> for both new and existing installations, respectively. In addition, it was stated that Medupi power station was commissioned after the South African Government passed the Air Quality Act 2008, thereby qualifying as a

new-built power generation facility. Thus, Eskom is required by law to limit the sulphur dioxide level in flue gas to 500mg/m<sup>3</sup>.

### **2.3 LINK BETWEEN THE AIR QUALITY ACT, WET-FLUE GAS DESULPHURISATION AND THE WATER CAPTURING METHODS**

The power utility (Eskom) in its response to comply with the act has adopted wet-flue gas desulphurisation as a technique to curb the emission of SO<sub>2</sub> for their new power plants (Medupi and Kusile) (Molewa, 2012). An intense contact between the aqueous sorbent phase and the flue gas phase is required to bind the sulphur dioxide to the absorbent. In the process, the flue gas gets saturated with water vapour that exists in the gas stack on a continuous basis. Wet-flue gas desulphurisation consumes roughly two tons of water per MWh power produced (McNemar, 2006); as such, a potential for water recovery rests in the water vapour saturated plume.

When the water vapour is not recovered, all the water is lost to the atmosphere. It has been predicted that if 40% to 60% of the water vapour in the flue gas could be recovered, it would lead to a thermal efficiency increase in the plant of up to 5% (Wang, 2012). Moreover, water can be considered as a corrosive agent if the water vapour in the flue gas condenses in the stack. Hence, this could compromise the structural integrity of the stack internals which together with the reduction in thermal efficiency present a need for dehydration of flue gas (Sijbesma et al, 2008). In other words, there is a need to recover the water from flue gas. There are three methods to recover water from flue gas, namely through flue gas condensation/condensing heat exchangers; through desiccant drying systems; and through membrane technology.

- **Condensing heat exchanger technology**

The condensing heat exchanger consists of a long rectangular duct containing water-cooled heat exchangers arranged in series (Macedonio et al, 2012). Hot flue gas enters from the back end of the boiler and is cooled as it passes through the heat exchangers where a portion of the water vapour condenses, thereby producing water in liquid form. In addition, Levy et al (2008) conducted a pilot scale study which revealed that multiple



condensing heat exchangers recovering water from the atmosphere resulted in water recovery efficiencies of 10% to 35%.

However, according to Carney (2006), the condensing heat exchanger has its limitations. The condensed water is often dirty and corrosive, due to the acidic condensate (Macedonio et al, 2012). The water that was recovered needs to be treated further before usage due to the high presence of acid and other contaminants in the water (Carney, 2006). Regardless of its high-water recovery efficiency, it should be noted that heat exchangers used to recover water from flue gas need special anti-corrosion tubing (Wang et al, 2012). There are several challenges concerning water recovery in this manner. Firstly, this water recovery technique requires a substantial amount of cooling hardware to reduce the temperature of the flue gas stream for effective water recovery (Wang et al, 2012). Furthermore, the recovered water needs to be treated before it can be reused due to the acidity of the recovered water. The acidity poses a threat to the integrity of the cooling hardware due to the corrosive nature of acidic solutions. One possible solution to the above problem would be to install acid traps, but this would lead to extra maintenance costs. Hence, there is a need for new and more thorough water capturing technology.

- **Desiccant drying systems**

The use of desiccants is one of the most common methods to capture water from atmospheric air and it is the most accepted method. Giampieri et al (2018) referred to desiccants as substances with a high similarity to water vapour and their ability to dehumidify air. The use of desiccants is the least costly of the three methods to capture water from atmospheric air. In other words, they cost less than the condensing heat exchanger and the membrane condenser. Desiccants can be in both solid and liquid form (Hurdogan et al, 2013). The most frequently used solid desiccants are silica gels, zeolites, synthetic zeolites, activated alumina, carbons, synthetic polymers and molecular sieves (Pankiewicz, 1992 and Giampieri et al, 2018).

Giampieri et al (2018) stated that the solid desiccant system requires a relatively higher temperature to regenerate in contrast to that of liquid desiccants. Also, the solid desiccant does not present any thermal energy recovery prospects due to its continuous moisture absorption and desorption processes. In contrast, the liquid desiccant is beneficial from

different perspectives. Firstly, the liquid desiccant system provides a greater moisture removal capacity and concurrently provides cooling and dehumidification in working conditions (Giampieri et al, 2018). Secondly, the fluid-like nature of liquid desiccant allows removing the latent heat released by the water vapour during the dehumidification process with a third fluid, usually water, thereby keeping its capability to absorb moisture constant during the dehumidification process (Giampieri et al, 2018).

In addition, desiccant systems have been commonly employed in air-conditioning due to their capability to remove moisture from outdoor ventilation air while allowing conventional air-conditioning systems to deal mainly with temperature control (Hurdogan et al, 2013). In these systems, the desiccant eliminates moisture from the air, thereby releasing heat and increasing the temperature in the air.

The limitations of the desiccants include a high energy intensive process to regenerate the desiccants and poor-quality water (Sijbesma et al, 2008). In both the condensing heat exchanger and desiccant technologies, the resultant water is of poor quality which would require treatment before reuse. This creates a need for a technology that recovers the water vapour in flue gas without the impurities that lower the quality of the water.

- **Membrane technology**

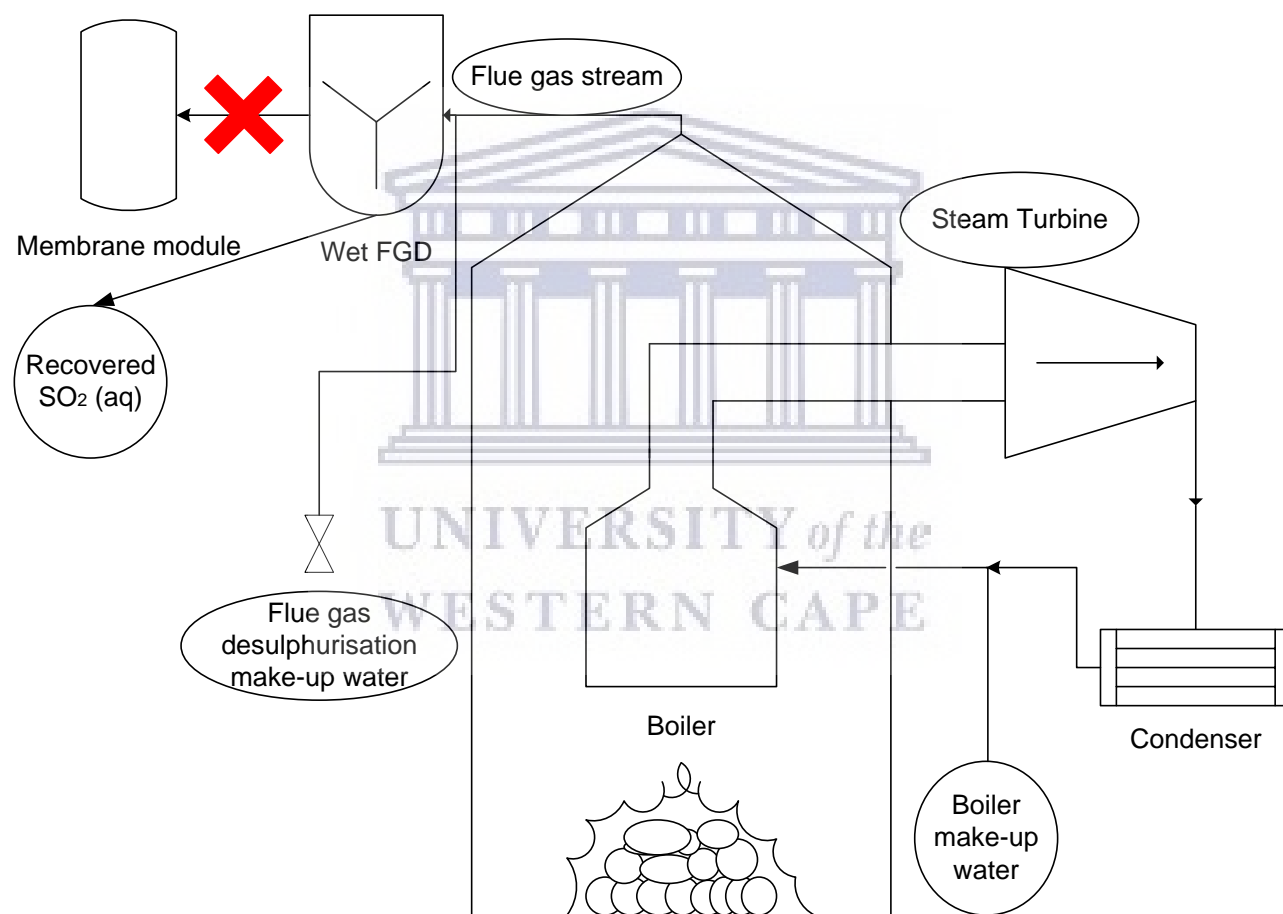
Membrane technology, on the other hand, has been commercially used to separate gases for many years. This technology consists of a separation membrane that extracts a portion of the water vapour and latent heat from the flue gas and returns it to the steam cycle (Wang, 2012). In the membrane condenser, the water vapour condenses in the pores of the membrane tubes and passes into the lumen side of the tubes, which have water flowing through them (Carney, 2006). There are different types of membranes, namely isotropic membranes, anisotropic membranes, metal membranes, ceramic membranes, liquid membranes, and hollow fibre membranes (Baker, 2004).

In addition, it is an energy-efficient alternative in contrast to the other methods due to its productivity, dependability, and small carbon footprint (Macedonio et al, 2012). The water that is recovered is mineral free and of a high quality (Carney, 2006). Unlike condensation or desiccant systems, membrane technology can recover water with the added benefit of

separating it from the impurities that are commonly found in the two former technologies. This results in the recovered water not needing purification, which implies it can be used as make-up water for almost all industrial processes (Wang et al, 2012).

Figure 2.1 presents a conceptual diagram of a membrane module installation retrofitted into a power plant. In figure 2.2, the membrane module concept is presented on both the macro and micro scale with the macro being supplied by Sijbesma et al (2008) on the right and micro on the left.

**Figure 2.1: Potential for water recovery from a wet-FGD system**

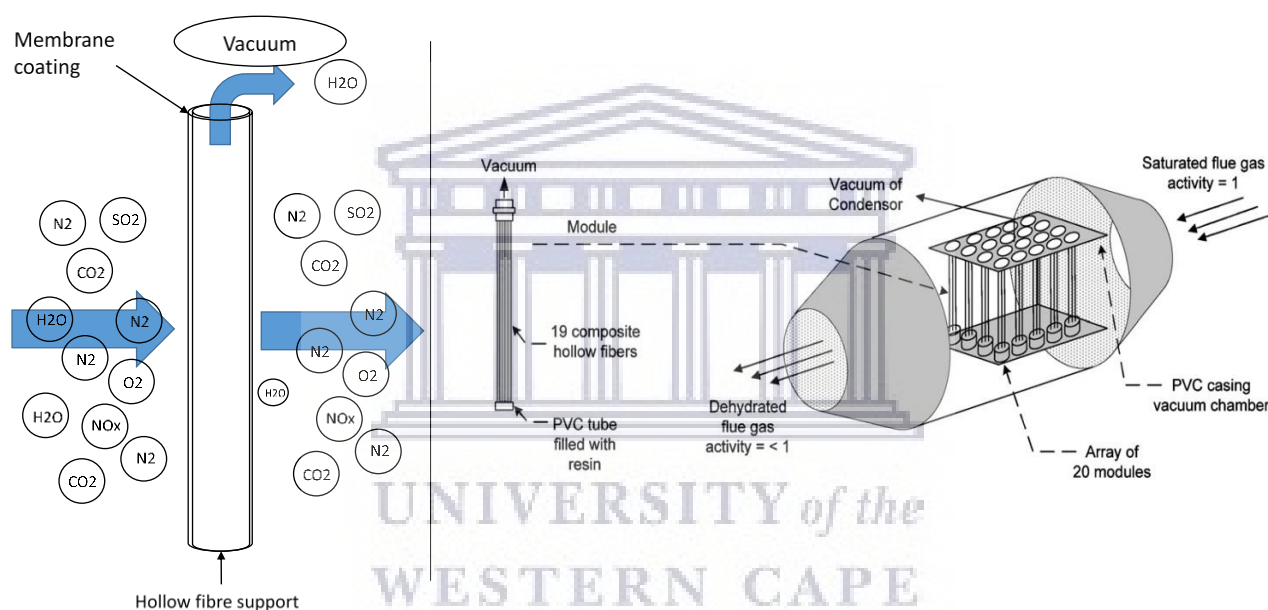


Source: Bladergroen et al (2019:06)

The above figure shows that when coal is combusted for electricity generation, the heat is used to boil water located in the boiler. This produces high pressure steam which in turn is used to drive turbines (Bladergroen et al, 2019). The turbines are connected to a generator which generates electricity. However, the combustion process generates a flue

gas which contains undesired and toxic gases such as  $\text{SO}_2$ ,  $\text{NO}_2$  and  $\text{CO}_2$ . Wet-flue gas desulphurisation is used to wash the flue gas stream in order to lower these toxic gases to an acceptable level according to the air quality act. The use of wet-FGD increases the water content of the already humid gas until saturated (Bladergroen et al, 2019). This implies the amount of water lost with flue gas increases when wet-FGD is used. As seen in the above figure, the ideal point to implement a water vapour recovery technology will be point “X”. As discussed previously, membranes have several advantages over the competing technologies making it the preferred system to implement.

**Figure 2.2: Water recovery from flue gas through membrane technology**



Source: Bladergroen et al (2019:07)

In the above figure, the image on the left shows a single hollow fibre membrane and illustrates the flow of a gas over the membrane with a vacuum being applied inside the fibre (Bladergroen et al, 2019). This causes water vapour molecules to be extracted from the gas leaving a dehydrated gas after the membrane. The extracted water is removed by the applied vacuum at the fibre end. The image on the right is supplied by Sijbesma et al (2008) and shows an array of water vapour selective membrane modules that are placed in the path of a flue gas. A vacuum is applied on the inside of the fibres which makes transport of the water from the gas to inside the fibre possible. This movement of

water molecules is due to a high concentration of water outside the membrane and a low concentration inside the membrane (Bladergroen et al, 2019). If the partial pressure of the water on the outside remains higher than the partial pressure of water on the inside, the flue gas will be dehydrated.

Furthermore, Chen et al (2017) concluded that the fibre membranes possessed excellent heat resistance and they can be used in the event of high-temperature flue gas. Lastly, Macedonio et al (2016) stated that the membrane technology is more superior to the condensing heat exchangers and desiccants in terms of water quality. The heat exchangers and desiccants often produce water that is of a low quality, acidic, corrosive, and dirty (Carney, 2006). Hence, this makes the membrane technology the best choice for water recovery from flue gas.

## **2.4 CONCLUSION**

It is evident that the membrane technology is superior to the desiccants and the condensing heat exchangers when it comes to water recovery and water quality. Figures 2.1 and 2.2 coincide with these conclusions. Condensing heat exchangers have water recovery efficiencies of 10 - 35%, whereas the membrane technology has 40 - 60%. In addition, the membrane technology produces demineralized water that is free from foulants and impurities, whereas the condensing heat exchangers and desiccants produce acidic and corrosive water. It must be noted that boiler feed water must be free of impurities and foulants. Therefore, the membrane technology, and particularly the hollow fibre membrane, is the technology of choice to be evaluated in this study because it produces pure and clean water.

## **CHAPTER 3: LITERATURE REVIEW**

### **3.1 INTRODUCTION**

This chapter outlines the theoretical and empirical literature underpinning this study. Firstly, it will briefly discuss the evolution of economic analysis and examine important definitions and concepts associated with economic analysis. Secondly, this chapter reviews the theoretical literature about the estimation techniques, namely economic analysis, cost-benefit analysis, cost-effective analysis, cost-minimisation analysis and cost-utility analysis. It also provides insight into the benefits and limitations of these estimation techniques. Furthermore, this chapter outlines the empirical studies on economic analysis and cost-benefit analysis in general, as well as empirical studies on flue gas condensation technology, desiccants and membrane technology. Lastly, it looks at the approaches or techniques used in these studies, and comments on the results of these empirical studies.

### **3.2 EVOLUTION OF ECONOMIC ANALYSIS**

Economic analysis refers to the sets of axioms, ideas and propositions that form the foundation of economic theory (Little, 1955). In other words, it was regarded as logic, thereby implying a set of interconnected concepts coupled with certain propositions and axioms, something that should be an informative explanation of reality (House, 1927). Economic analysis goes hand in hand with economic history, statistics and theory. Regarding theory, its purpose was to formulate definitions and logical models which were not only to be considered as descriptive theories, but also as mere instruments aiming to create interesting results (Soudek, 1952). Scientific economic analysis was noted to have an autonomous history of its own, while economic philosophy and politics only served as burdens.

In addition, the development of the definitions and theorems of economic analysis can certainly be presented autonomously from political theory and economic philosophy (Little, 1955). Therefore, economic analysis was not formed by the theoretical opinions that economists had, though it has been often impaired by their political behaviour.



However, empiricists argue that it would not be advisable to disregard economic philosophy and political theory when conducting economic analysis (Little, 1955). Hence, economic analysis should go in tandem with economic philosophy and political theory.

### **3.3 DEFINITIONS AND CONCEPTS**

#### **3.3.1 Economics**

Economics is a broad-ranging discipline in scope. Subsequently, various definitions of economics have been attempted, but with mixed success. Perhaps the most influential definition of economics is due to Lionel Robbins in 1932, who described it as a social science that evaluates human behaviour as a relationship between ends and scarce means which has different uses (Bisin, 2011). Joseph Stiglitz, cited in Mohr and Fourie (2008), defined economics as the study of how the choices of individuals, businesses, governments and other organisations in a society determine the use of scarce resources. Scarcity, choice and opportunity cost are all central elements in economics and thus economic analysis; scarcity implies choice and when choices are made, opportunity costs are incurred (Mohr and Fourie, 2008). These central elements can be illustrated by means of a production possibilities curve (PPC). The PPC depicts the groupings of any two goods or services that are achievable when a society's resources are in full use<sup>6</sup> (Mohr and Fourie, 2008).

#### **3.3.2 Economic Analysis (EA)**

Economic analysis is defined as a methodical approach to determine the effective use of scarce resources (McAfee et al, 2010). It involves the evaluation of two or more options in reaching a definite goal under a specified set of assumptions and restrictions. In addition, it accounts for the opportunity costs of the resources used and tries to quantify the private and public costs of a project to the economy (McAfee et al, 2010).

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<sup>6</sup> See appendix B for a graphic illustration of the production possibilities curve that explains scarcity, choice and opportunity cost.

### **3.3.3 Cost-benefit Analysis (CBA)**

Cost-benefit analysis (CBA) is an economic analysis tool used to determine the viability of a project (Van Sickle et al, 2003). This is done by calculating the implementation cost of a project and weighing it against the projected benefits it will deliver. It estimates both private and social costs and benefits by discounting the future benefits and costs and compares the aggregate costs and aggregate benefits (Watkiss, 2005). Lastly, Sartori et al (2014) defined CBA as a logical method for evaluating the economic costs and benefits of an investment decision in order to assess its impact on welfare.

### **3.3.4 Cost-effective Analysis (CEA)**

Cost-effectiveness analysis is an economic analysis tool used to evaluate the effectiveness of a proposed project against its price (Henderson, 2010). It defines the objectives of a project and it chooses the solution that minimises the discounted capital costs for a given output or maximises the output for a given cost (Edwards, 2011). Unlike CBA, CEA does not assess the benefits in monetary terms, but in physical units (Commonwealth of Australia, 2006). In addition, the CEA tool assists decision-making by comparing the options to achieve a certain goal to their costs and effectiveness (Bambha and Kim, 2004).

### **3.3.5 Cost-minimisation Analysis (CMA)**

Cost-minimisation analysis is an economic analysis tool used to seek out the least costly method to do a project (Henderson, 2010). It calculates and compares input costs and accepts the conclusions to be the same. CMA can be done via linear programming (Dowling, 2006) and the Lagrangian multiplier method (Varian, 2010).

### **3.3.6 Cost-utility Analysis (CUA)**

Cost-utility analysis is an economic analysis tool in which the results of alternative measures are represented in terms of a utility-based unit of measurement, namely the quality adjusted life year (QALY) (Robinson, 1993). The QALY is the most commonly used measure in cost-utility analysis.



### **3.4 THEORETICAL LITERATURE ON ECONOMIC ANALYSIS**

#### **3.4.1 Economic Analysis (EA)**

Economic analysis is employed for two main reasons. The first reason is to understand how the allocation of goods and services and scarce resources are ascertained (McAfee, 2005). Secondly, economic analysis expresses how rule changes and other state interventions affect the market and people and, in some instances, it can be concluded a change in rules is, on balance, socially valuable (McAfee, 2005). Sheps and Birnbaum (1993) referred to economic analysis as a procedure for evaluating the use of resources and compare it to the results in order to find the most suitable course of action from a range of options. In other words, to make choices between the competing alternatives. The main implied assumption of economic analysis is that there is always an alternative method of action available and there is always a choice. However, if there is no alternative, there is no choice (Sheps and Birnbaum, 1993).

Economic analysis is an important component of the water resources development procedures because it assesses the economic reasoning of alternative plans, and it assists decision makers in developing new plans (Cowdin, 2008). Economic analysis is usually done by economists; however, the consequences thereof make it critical that the technical terms, procedures, and tools used in it are clear and logical to the other specialists involved in the analysis (Cowdin, 2008). In other words, it must be clear to the decision makers of the proposed project and to the various stakeholders who will be eventually affected by the project (Cowdin, 2008).

The primary objective of economic analysis is to clearly express the comparative costs of the existing alternatives; weigh these costs against the usefulness of each alternative; and to determine the best and most appropriate alternative (Sheps and Birnbaum, 1993). Another goal of economic analysis is to establish whether a project best reflects its use of resources during the period of analysis, i.e., to determine whether it is economically justified (Cowdin, 2008). If the total benefits of the project are greater than its costs, then the test for economic viability is passed. According to the Commonwealth of Australia (2006), EA aims to answer the following questions, namely:

- Should the project be constructed at all?
- Shall it be constructed now?
- Does it have to be made to a different shape or size?
- Is it going to have a positive net value for a business regardless of who carries the costs and enjoys the benefits?

According to Hamaker and Stouffer (2014) and Commonwealth of Australia (2006), there are seven steps in the economic analysis (EA) process, namely:

- **Prepare statement of objective**

The very first step is defining the nature of the problem to be evaluated, its framework, background and basis. This step indicates the relationship between the objectives of the initiative and the project needs (Commonwealth of Australia, 2006). The objectives should be initially defined with reference to market failure that could lead to government involvement. Thereafter, the expected outcomes from implementing the project should be outlined and be clearly differentiated from the ways to achieve them (Commonwealth of Australia, 2006). Furthermore, the objectives must not be generic in the sense that it will be tough to determine whether they have been achieved or not. According to the Commonwealth of Australia (2006), the questions that are normally considered in this case are:

- What is the aim of the project?
- How do these achievements relate to the firm's goals?
- Do the goals account for the interests of the economy and society as a whole?
- What are the critical factors to achieve these goals?
- Can the goals be measured?
- Do the goals reflect the outcomes?
- Are the goals in line with the government policies?

- **Outlining assumptions and limitations**

The next step is to outline the assumptions and to specify the limitations in achieving the goals to ensure all options evaluated in the analysis are viable (Commonwealth of Australia, 2006). This enables one to easily remove unfeasible options and outline those

assumptions that are important or have no effect at all, e.g., future actions, future economic factors, inflation impacts, benefits and costs, anticipated workload, and the time period of the analysis (Hamaker and Stouffer, 2014). Limitations, on the other hand, can include financial limitations, distributional limitations, institutional limitations, administrative limitations, ecological and political limitations (Commonwealth of Australia, 2006).

- **Identify alternatives**

Economic analysis implies identifying and specifying a set of alternatives. Normally, a “do nothing” option is included as a baseline (Commonwealth of Australia, 2006). This is a required option in that costs and benefits are always measured in contrast to doing nothing. This process is often tedious and expensive; however, it is crucial to provide the decision makers with a range of options (Commonwealth of Australia, 2006). For major investment projects, it is essential to sketch out many potential alternatives and then to select a few for a detailed evaluation. In any case, a suitable level of consultation, either formally or informally, must be undertaken as best practice in determining a set of alternatives (Commonwealth of Australia, 2006). A good example is where a developer decides to acquire a commercial property. The economic analysis, in this regard, should consider the alternatives facing the developer, e.g., doing nothing, acquiring the property, or upgrading the existing property (Commonwealth of Australia, 2006).

- **Identify and estimate costs and benefits**

A fundamental step in economic analysis involves classifying, enumerating and valuing the costs and benefits of each option (Commonwealth of Australia, 2006). The types of benefits and costs depend on the project. An example would be the establishment of a toll motorway to relieve heavy traffic. The relevant costs would be material costs, labour, machinery and equipment to build the road, and the land value reflected in the loss of the land use for alternative purposes (Commonwealth of Australia, 2006). The relevant benefits would be the number of lives saved and reduced travel time, thereby leading to fuel savings and increased productivity, and probably a decrease in traffic on alternative routes (Commonwealth of Australia, 2006).

In addition, the relevant costs of a typical project would be initial capital costs, replacement costs, operating costs and intangible costs (those costs that cannot be translated into monetary terms) (Sartori et al, 2014). The initial capital costs include the cost of the land, construction buildings, machinery and equipment as well as start-up and technical costs such as design and planning, project management and technical assistance, construction supervision and publicity (Sartori et al, 2014). Replacement costs include the costs to repair and replace machinery and equipment. Operating costs include labour costs, cost of raw materials, maintenance costs and rent (Sartori et al, 2014).

Also, the relevant benefits of a typical project would include primary and secondary benefits, tangible and intangible benefits and private and public benefits. According to Anderson and Settle (1977) cited in Cowdin (2008), primary benefits may refer to the increases in goods and services and/or reduced costs, and reduced damages or losses to those that are directly impacted by the project. For example, for a typical water project, the increase in goods and services includes improved water quality and increased water supply and reduced damage or loss is in the case of flood damage. Secondary or indirect benefits refer the values enjoyed by the individuals not directly involved as a result of the economic activity induced by the project (Cowdin, 2008). A good example of an induced benefit is the increased revenue from farm produce and supplies to farmers who received water from the project.

Moreover, tangible benefits can be easily be translated into monetary terms, whereas intangible benefits cannot be easily translated into monetary terms (Cowdin, 2008). Private benefits stem from the purchase of private goods and services by businesses and individuals. The purchase and consumption of private goods and services depends on the price, and those who do not pay, cannot enjoy the benefits from using that good or service (Mohr and Fourie, 2008), for example, food, clothing, motor vehicles, houses, etc. Public benefits stem from the use of goods and services that are consumed by the public, for example national defence, public emergency services, streetlights, roads, parks, etc. The consumption of public goods and services by one person does not prevent another

person from consuming the same good or service in that public goods and services are usually not exchanged in a marketplace (Mohr and Fourie, 2008).

Estimating the scale of costs normally requires assistance from economists, accountants and specialists because it is a complex task. It must be noted that all estimates of costs and benefits are subject to uncertainty and risk (Commonwealth of Australia, 2006). Sometimes the levels of risk and uncertainty are very high because future costs and benefits cannot be predicted accurately. Hence, it is recommended that the best average estimate on each cost and benefit is used to predict the average net social benefit that is expected to ensue given the levels of risk and uncertainty (Commonwealth of Australia, 2006). Thereafter, the analyst must approximate and specify the number of outcomes that is likely to take place. This is normally done through sensitivity analysis that shows how the anticipated results will change due to variations in key variables (Commonwealth of Australia, 2006).

- **Rank alternatives using economic measures of merit**

The fifth stage in the economic analysis involves ranking the alternatives using economic measures of merit. Economic measures<sup>7</sup> of merit include net present value (NPV), payback period, discounted payback period, internal rate of return (IRR), modified internal rate of return (MIRR), and profitability index (PI) (Hamaker and Stouffer, 2014). These measures of merit enable one to rank the alternatives in the EA process.

- **Perform sensitivity analysis**

The penultimate step in the economic analysis process is to conduct sensitivity studies. As stated, a sensitivity analysis is a "what-if" exercise that tests how the conclusions of an EA will change due to variations in the other assumed variables (Hamaker and Stouffer, 2014). Sensitivity studies should especially be conducted when the outcomes of the economic analysis are close and when there is ambiguity about an assumption that

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<sup>7</sup> The economic merit measures of NPV, payback and discounted payback, IRR, MIRR and PI are explained in detail under the section on Cost-benefit analysis (CBA).

can influence the calculation of costs and benefits in the EA (Hamaker and Stouffer, 2014), for example, fluctuating fuel costs, variations in inflation rate and building costs.

In addition, sensitivity analysis goes together with economic analysis (EA) in that it explores the elements of the EA which may be uncertain or controversial (Hadley, 2011). The objective is to reduce the likelihood of undertaking bad projects while not failing to accept good projects. Also, sensitivity analysis is the first step to risk analysis, because it is a “what if” analysis testing which variables are important, e.g., NPV and IRR (Hadley, 2011). It applies to all projects where costs and benefits are easily quantified; however, when costs and benefits are difficult to quantify, one may also employ sensitivity analysis. Consequently, what one wants to know from sensitivity analysis is which data has a significant impact on the results (Chinneck, 2000). Then one can concentrate on getting accurate data for those items or run through several scenarios (scenario analysis) with various values of the crucial data in place in order to get an idea of the range of possible outcomes (Chinneck, 2000).

Moreover, in order to compensate for the risk and uncertainties in the data, probabilities may be assigned to variables in order to quantify the likely impact. These probabilities serve as weights in order to calculate an expected value (Commonwealth of Australia, 2006). For example, assuming a project that has two probable results. The likelihood of achieving a net present value of \$5 million is 60%, whereas the likelihood of achieving a net present value of \$3 million is 40%. Thus, the expected net present value (ENPV) can be estimated as:  $ENPV = (0.6 \times \$5m) + (0.4 \times \$3m) = \$4.2\text{million}$  (Commonwealth of Australia, 2006). Nevertheless, such a single value may not completely compensate for the uncertainty associated with predicting the result. Therefore, it is usually fitting to convey the possible results in a way that includes the expected results, as well as results under different scenarios (best case or worst-case scenarios) (Commonwealth of Australia, 2006).

- **Prepare results and recommendations**

Writing up the results and providing recommendations is the last step in the economic analysis process. In this step, the reasons for the recommendations should be clearly outlined, as well as the assumptions used to estimate the project's costs and benefits



(Commonwealth of Australia, 2006). Normally, the important assumptions are outlined at the start of the report and the detailed list of assumptions can be included as an annexure or supplementary report depending on their enormity (Commonwealth of Australia, 2006). The report should document and enhance the transparency of the EA process. Therefore, sufficient details must be provided that allow the outcomes of the analysis to be replicated by others (Commonwealth of Australia, 2006). According to the Commonwealth of Australia (2006), the report should normally include the below information:

- An abstract specifying the important assumptions, conclusion(s) and recommendation(s)
- Contextual overview of the study – why it was done
- Objectives of the study or project
- Important risks associated with the study or project
- List of alternative measures considered
- Timelines of costs, benefits and net-benefits
- Important assumptions that the study is based on
- The cost of capital used in the study
- NPV estimates
- Sensitivity studies
- Additional relevant information containing distributional impacts, other tangible and intangible costs and benefits
- Assessment of the chosen option in contrast to alternative measures
- How the results of the project could be assessed at a later stage
- Concluding remarks

Also, McAfee (2005) stated that economic analysis was employed in many instances as, for example, when British Petroleum (BP) used a complex economic model to estimate the oil and gasoline demand by refineries that serve as their clients. BP also employed the same model to set the price for its Alaskan crude oil (McAfee, 2005). Economic analysis was also employed by specialists in the anti-trust suit brought by the U.S. Department of Justice both to understand Microsoft's incentive to eliminate its competitor, Netscape, from the market and to understand consumer behaviour in response to such a

step from Microsoft (McAfee et al, 2010). Analysts in financial markets employ economic models to predict the profits of firms in order to forecast their share prices. Also, governments employ a range of economic models in order to predict budget surpluses or deficits and to revise or change environmental legislation (McAfee et al, 2010).

Moreover, economic analysis has provided a conceptual framework for identifying and understanding contemporary environmental problems (Little, 1955) and for directing effective and efficient policies towards them. No environmental problem is fully understood without conducting economic analysis (Dunoff, 2000). In addition, economic analysis may enrich our understanding regarding environmental pollution, seeing that it has been fruitful regarding environmental pollution on the international side. It was argued that sound economic analysis is useful to address critical issues such as the need to control federal spending, the trade deficit, tax reform, the agriculture crisis, and deregulation (Sprinkel, 1986). Sound economic analysis can properly bring attention to these costs and critically evaluate whether the likely benefits to the targeted industry justify those costs over the long run (Sprinkel, 1986). Tweeten and Zulauf (1998) argued that economic analysis played a pivotal role in public policy for agriculture. Also, if implemented well, economic analysis reaches goals and delivers significant information regarding alternative courses of action in a world that is often constrained by limited resources (Sheps & Birnbaum, 1993). Lastly, economic analysis has in most cases proven to be indispensable in that it serves as a valuable input in business and government decision-making (Sprinkel, 1986).

In contrast, claiming that economic analysis is beneficial does not imply that it is the most suitable method to answer every problem (Markham, 1954). Like all other methods of analysis, economic analysis has its drawbacks because they are a big part of the process of economic evaluation (Sheps and Birnbaum, 1993). In addition, it was argued that economic analysis presupposes the capability to estimate the cost and benefits of various policies (Dunoff, 2000), but in a case such as environmental pollution it becomes difficult to quantify the costs and benefits of economic policies aimed at combating environmental pollution. Further limitations of economic analysis include the fact that the assumptions on the use and availability of resources will not always be accurate and binding and that



decision makers are not always economically rational (Dunoff, 2000). Also, economic analysis does not always fully consider the alternative uses of resources as well as the distribution issues linked to it, for example, who benefits and who loses and whether these benefits or losses are reasonable (Sheps and Birnbaum, 1993). Moreover, there is the problem of using suitable rates of returns and the costly nature of economic assessments and that their usefulness for decision-making must be assessed. Therefore, if a costly economic analysis does not create benefits, it should not be undertaken in that the resources used for it cannot be used somewhere else (Sheps and Birnbaum, 1993). Lastly, Sheps and Birnbaum (1993) stated that economic evaluation was too reductionist, in other words, everything is estimated in monetary terms, and that it was immoral to evaluate human health and well-being in this way.

Finally, economic analysis refers to a family of analytical methods that are designed to evaluate two or more options in terms of costs and results (Round et al, 2014). The four main forms of economic analysis are cost-benefit analysis (CBA), cost-effective analysis (CEA), cost-minimisation analysis (CMA) and cost-utility analysis (CUA), and each approach has its own assumptions and limitations.

### **3.4.2 Cost-benefit Analysis (CBA)**

Cost-benefit analysis is a commonly used technique; thus, it is important that its methods be properly understood (Prest & Turvey, 1965). The purpose of this technique is to enable efficient resource allocation, thereby illustrating a project's convenience to society (Sartori et al, 2014). Also, CBA assesses the desirability of a project in that it enumerates and evaluates all its important costs and benefits (Prest & Turvey, 1965). This analysis identifies the costs of a proposed project by looking at what counts, who counts and the time period. In other words, the initial investment costs, the replacement costs, operating costs and revenues. In addition, it considers the benefits of the proposed project as well. Benefits are the values of goods and services produced by the project and/or by activities stemming from the project. Benefits play a critical role in determining the economic justification of a project and in allocating costs among different project purposes and sponsors (Cowdin, 2008).

Performing a CBA involves some common technical issues, namely opportunity cost, project lifetime, setting a discount rate, dealing with depreciation and interest, and decision rules (Commonwealth of Australia, 2006). The concept of opportunity cost is of great importance in CBA. Opportunity cost was already described as the value of the best opportunity forgone (Mohr and Fourie, 2008); in other words, the cost of using a resource is the cost of forgoing the best alternative use. Normally, this implies valuing a resource in terms of its actual market price or, if there is none, on estimates of the amount producers are willing to pay for it (Commonwealth of Australia, 2006). Willingness to pay refers to the maximum monetary value that an individual or business places on a resource, good or service, and it considers the actual price and any consumer or producer surplus (Commonwealth of Australia, 2006). Also, a cost-benefit analysis involves a thorough consideration of a project's lifetime, its time horizon and its residual value, and the project must be reviewed over its estimated lifetime (Commonwealth of Australia, 2006). In a cost-benefit analysis, all the costs and benefits of a project should generally be discounted over its lifetime. However, when evaluating projects with extended lifetimes, it becomes irrelevant to discount distant costs or benefits relative to the present (Commonwealth of Australia, 2006). Hence, it may be suitable for the CBA to be done on a shorter timeframe in that it compensates for the increasing uncertainties related to future estimations and extrapolated data.

Moreover, setting a discount rate is integral in conducting a CBA, in that costs and benefits need to be discounted into present value terms; and handling of depreciation and interest payments is done on a cash accounting basis (Commonwealth of Australia, 2006). The entire cash value of a capital item is documented in the evaluation at the time of purchase and it is, thereafter, fully depreciated over the lifespan of the project. Depreciation is an accrual accounting term allowing for a yearly expense for the capital item, but it is a non-cash outflow and therefore it must be disregarded from a cost-benefit analysis (Commonwealth of Australia, 2006). If it were to be included in the CBA, it would lead to double counting in that the full value of the item was already accounted for when it was purchased. If a project were to extend way beyond the economic life of an asset or item, its replacement costs are simply reflected in the cash flow during the year of replacement, and provision is made for the terminal value of the asset once the project

ends. Also, in a cost-benefit analysis, interest payments are also omitted from the cashflow in that they are implicitly accounted for in the discounting process (Commonwealth of Australia, 2006).

Lastly, numerous decision rules or techniques are normally employed in the cost-benefit analysis of typical projects. These include net present value (NPV), payback period (PP), discounted payback period (DPP), internal rate of return (IRR), modified internal rate of return (MIRR), and profitability index (PI) / benefit-to-cost ratio (B/C).

#### **3.4.2.1 Net present value (NPV)**

Most cost-benefit analyses employ the net present value (NPV) method as measure of merit. The NPV method accounts for the initial capital costs of the project and its expected costs and benefits over its lifetime (Maliva, 2014). Net present value is also a sophisticated capital budgeting technique that accounts for the time value of money (Melzer, 2012). Ardalan (2012) defined capital budgeting as a planning process for projects on assets with cash flows that exceed a one-year period. The NPV method discounts all the projected future cash flows back to present value terms. The rate which is used to discount the cash flows is called the rate of return or the cost of capital (Melzer, 2012) and the NPV method considers the after-tax cost of capital.

Two fundamental things are needed when conducting an NPV analysis. Firstly, NPV requires an estimation of the initial capital costs and revenues; secondly, an appropriate rate of return must be estimated (McAfee et al, 2010). Estimating the rate of return can be problematic, mostly due to the risk associated with the investment payoffs, but also due to the motivation of project managers to increase the payoffs and minimise the costs, thereby making the project look more attractive to the executives (McAfee et al, 2010). In addition, most firms choose to finance their investment projects through retained earnings (the profits from previous activities) rather than through debt (borrowing). Thus, a firm that goes ahead with one investment project cannot undertake another investment project, and the discount rate must reflect the internal corporate value of funds (McAfee et al, 2010). Consequently, discount rates that range from 15% to 20% are normally used to estimate the net present value of projects from big companies (McAfee et al, 2010).

In addition, for the NPV rule, an investment's cash flows would typically include the annual cash flows that the project generates over its lifetime minus the costs involved, e.g., maintenance costs, replacement costs, etc (Ardalan, 2012). In deciding whether an investment decision is worthwhile, one would like the NPV to be positive. The higher the NPV the better the investment would be (Melzer, 2012). With a positive NPV, the company will earn more than its cost of capital. If the NPV is negative, then the investment would often be rejected as soon as it would be earning less than what the company requires.

Also, it was argued that NPV is the most reliable technique for capital budgeting and it is superior to the other techniques (Ardalan, 2012). The advantage of using NPV is that it can handle multiple discount rates without any issues. Each cash flow can be separately discounted from the others (Melzer, 2012). However, it was argued that the NPV is a fundamentally intricate method that requires assumptions at each stage, for example the discount rate, and the probability of getting cash payments. Also, Ermenyi (2015) argued that it is difficult to interpret the results of NPV. With NPV, the decision makers will not be able to predict profitability. Will it be low, average or high profitability? Even though a project has a high NPV, there is no clear answer that it leads to high profitability (Flanagan et al, 1989 cited in Ermenyi, 2015). Lastly, McAfee et al (2010) stated that NPV performs poorly because, when the question is whether to proceed with the project or postpone the project, NPV responds "yes or no" to investment, but when the choice is "yes or wait," NPV requires amendment.

#### **3.4.2.2 Payback period (PP)**

Another capital budgeting technique is the payback period or payback method. PP refers to the time it will take the company to recover its initial investment costs as calculated from cash inflows (Melzer, 2012). In a mixed stream of cash flows, the annual cash inflows must be consolidated until the company recovers its initial capital costs (Aldaran, 2012). Investment projects with the shortest payback period are usually chosen.

The payback method has many advantages in addition to its unique measurement unit (time duration). Bhandari (1985) stated that the payback method is easy to calculate and

understand. The payback method is also regarded as a safety measure for any uncertainty related to a project. Also, this method emphasises the liquidity part of an investment decision, whereby it can be understood as a breakeven concept frequently employed by businessmen (Bhandari, 1985).

Other things being equal, the inverse of the payback period can serve as a reasonable approximation of the internal rate of return of a project (Bhandari, 1985). The payback period is very popular in that it is very easy to calculate; however, it does not account for the time value of money, thereby making it an unsophisticated technique for capital budgeting (Melzer, 2012). Another weakness of this method is that it disregards the cash flows which occur after the payback period. The implication of these weaknesses is that PP does not assess the profitability of a project and is therefore not consistent with the stockholder's goal of maximising wealth (Melzer, 2012). The fact that the payback method assumes that the cost of money is non-existent cannot be justified in view of the high cost of capital. Hence, an over reliance on PP without considering the time value of money amounts to a colossal neglect of profitability for the sake of liquidity (Bhandari, 1985). Moreover, the use of the payback method due to it being easy to calculate cannot be defended either. Lastly, another drawback with PP is that it subjectively determines the minimum required payback period, thereby implying that the same data could lead to different decisions (Bhandari, 1985).

#### **3.4.2.3 Discounted payback period (DPP)**

The discounted payback period or method is another capital budgeting technique. This is not a new concept and it is there to remedy some of the weaknesses of the payback period, in that it accounts for the time value of money (Bhandari, 1985). It shares the same definition as the payback method; however, it accounts for time value of money as well. DPP can also be interpreted as the length of time for the project to reach  $NPV = 0$ . With this method, the projected cash flows are discounted by the cost of capital (Rangel et al, 2016).

The advantages of this technique are the fact that it accounts for the time value of money, thus compensating for the risk and uncertainty of a project's cash flows through the

discount rate (Bhandari, 1985). Projects which are determined feasible according to this method are certain to be profitable. The discounted payback technique guarantees the profitability of a project in the same way as the NPV method by accounting for the time value of money and by discounting cash flows at the required cost of capital (Bhandari, 1985). In addition, DPP has other benefits in that it is easy to calculate and understand; and provides an objective principle to guide decision-making. The discounted payback decision rule provides an objective criterion for decision-making. The estimation of the cumulative net present value for calculating DPP is by far less complex than the estimation of IRR (Bhandari, 1985).

Also, DPP is more conservative than PP in measuring the relative liquidity of an investment project. This means that if any investment is classified as liquid as per the payback method it may not even be acceptable as per the discounted payback method (Bhandari, 1985). Moreover, DPP is a better measure of break-evenness than is the payback period. The traditional payback period provides a period beyond which the investment project generates an accounting profit; however, the discounted payback period goes further by providing a period beyond which an investment project generates an economic profit (Bhandari, 1985). Furthermore, Bhandari (1985) argued that the NPV, IRR, and PI techniques deliver little evidence of the break-evenness of an investment project, compared to the DPP.

Lastly, another major feature of the discounted payback method lies in its linkages with the other criteria that account for the time value of money, namely net present value (NPV), internal rate of return (IRR) and profitability index (PI). For example, the DPP refers to the time period in which the total NPV of a project will equal to zero; the IRR is the same as the discount rate and the PI equals one (Bhandari, 1985). One final advantage of DPP is the fact that the decision to accept or reject "independent" projects will be the same as the NPV criteria and therefore consistent with the investor's objective of maximising wealth. However, the drawbacks are that it does not provide the grounds that justify whether the investment will increase the value of the firm (Bhandari, 1985). The DPP calculation requires an estimate of the discount rate and it also disregards the



cash flows occurring beyond the discounted payback period (Melzer, 2012), thereby it leads to the rejection of projects which might be profitable in the long run.

#### **3.4.2.4 Internal rate of return (IRR)**

The internal rate of return (IRR) method is another technique for capital budgeting and it is possibly the most sophisticated technique used for evaluating investment alternatives (Melzer, 2012). The IRR is the discount rate that equates the present value of all the expected cash flows with the initial investment. In other words, it is the discount rate at which the NPV is equal to zero (break-even point) (Leonard, 2017). In addition, the IRR calculates the rate that makes the discounted benefits equal the discounted costs (Cowdin, 2008). The IRR can be estimated analytically, and it can be estimated by means of a financial calculator and all spreadsheet programmes, e.g., Microsoft Excel (Melzer, 2012).

Normally, an investment project is desirable if its IRR is greater than its discount rate. If evaluating two mutually exclusive projects, the one with the greater internal rate of return will be selected (DEAT, 2004). The IRR is the lowest suitable discount rate sometimes referred to as the 'hurdle rate' (DEAT, 2004). It is a useful tool that makes logical sense to decision makers and includes all cash flow connected to a project and it accounts for the time value of money. The IRR is a common method because of its reporting simplicity; its greatest strength and major limitation is that it uses one single rate of return to assess every investment (Study Guide, 2008).

In addition, the IRR does not compensate for changing rates of return; hence it is not suitable to evaluate for long-term projects with varying rates of return. The notion that IRR assumes cash flows are reinvested at the IRR can be misleading in that a single project can have many internal rates of return (DEAT, 2004). This occurs when there are changing annual net benefit flows and, in this event, the IRR calculation may look like a quadratic equation, hence the multiple internal rates of return. Another limitation of IRR is its ineffectiveness with projects that have a multiple of both positive and negative cash flows. Lastly, the IRR cannot distinguish between projects that vary in magnitude and size (DEAT, 2004).

#### **3.4.2.5 Modified internal rate of return (MIRR)**

The modified internal rate of return (MIRR) method was created to remedy the limitations of the IRR method (Rangel et al, 2016). The MIRR is also a sophisticated capital budgeting technique and it assumes that cash flows are reinvested at the firm's opportunity cost of capital. By assuming that the cash flows are reinvested at the cost of capital, MIRR reflects the true profitability of a project better than the IRR. The benefit of this technique is that it eliminates the issue of multiple IRR solutions (Rangel et al, 2016). Also, this technique shows whether the investment project increases the value of the firm. MIRR accounts for the time value of money, all the cash flows of the project, and the risk of forthcoming cash flows through the cost of capital in its decision criteria (CFA Institute, n.d).

However, there are some limitations associated with MIRR, in that it requires a rate of return in order to accept or reject a project. Lastly, when evaluating projects that are mutually exclusive, MIRR might not provide the value-maximising decision due to capital rationing (CFA Institute, n.d).

#### **3.4.2.6 Profitability index (PI) / Benefit-cost ratio (B/C)**

Furthermore, there is a technique called the profitability index (PI). PI is the ratio of the initial capital cost to the present value of future cash flows (Ermenyi, 2015). The PI can also be referred to as the benefit-cost ratio. The benefit-cost ratio can be expressed by dividing the discounted benefits by the discounted costs (Cowdin, 2008). The great advantage of PI is that it provides an objective framework around which discussions, corrections and amendments take place (Ermenyi, 2015). The PI makes the NPV more meaningful and it is more popular than the NPV because it is easier to understand. These two methods go together because, if the PI is more than one, the NPV is positive and vice versa (Rangel et al, 2016). The NPV and PI normally lead to the same decision whether to accept or reject an investment project, but the PI goes a bit further by showing how much a project stands to earn or lose (Ermenyi, 2015).

Also, the benefits of the PI index are that it tells the firm whether an investment increases or decreases its value. It accounts for the time value of money and helps ranking and



picking investments projects while rationing capital (Gurau, 2012). The PI index considers all the cash flows and the risk involved with them via the cost of capital. Moreover, a great benefit of the PI is in the budget allocation of a variety of projects or where productivity is critical (DEAT, 2004). For example, a city can get its water from any source or combination thereof. In this regard, the NPV criterion would find the single best alternative to satisfy the city's needs, whereas the PI or B/C ratio would allow water engineers to establish the most efficient combination of alternatives (DEAT, 2004). However, the drawbacks are that it requires a discount rate in order for it to be estimated; and it might not provide the correct decision while comparing mutually exclusive projects under consideration, thus making it ineffective for mutually exclusive projects (Rosen, 1995 cited in DEAT, 2004).

On a different note, CBA is a versatile tool for decision-making, and it guides a wide range of decisions (Commonwealth of Australia, 2006). It is used to analyse capital expenditure because any investment or project that requires significant expenditure is subjected to an estimation of its costs and benefits. CBA is used to analyse a policy option, in that most policies infer benefits on some people while imposing costs on others. These costs and benefits can then be estimated in the same way as that of capital expenditures (Commonwealth of Australia, 2006). CBAs are also employed when a firm chooses to use or dispose of an existing asset by addressing issues such as whether or not to sell, whether to relocate, and whether to repair or replace an asset (Commonwealth of Australia, 2006). Cost-benefit analysis is used in the post-evaluation of a project or programme, to determine whether the project or programme was of benefit to society. Moreover, the DEAT (2004) stated that CBAs are applied in the private sector as well as in a social setting. They are used to evaluate the viability of projects and to rank them, to analyse the impact of legislation and to validate investment in capital items and technology. Also, CBAs are used to determine effective ways to cut costs, to determine the relative benefits of leasing and subcontracting, to quantify intangible costs and benefits, and to ensure that decision makers in the public sector are held accountable (DEAT, 2004).

Furthermore, there are benefits in undertaking a cost-benefit analysis. The benefit of a CBA is that it facilitates meaningful comparisons by providing a common basis for comparison with any other proposal that has been similarly assessed (Commonwealth of Australia, 2006). CBA is conducive to good performance management in that it shows the project benefitted the community. Also, an important benefit of CBA is that it provides a good measure of an investment's net benefit, thereby allowing unrelated projects to be compared directly (Commonwealth of Australia, 2006). The decision rules that CBA employs are standard and widely used, it informs decision makers and shareholders by simplifying non-prescriptive information, and it is adaptable and flexible enough to account for income distributional effects, monetary efficiency, environmental sustainability, and the impacts of externalities (DEAT, 2004). Also, cost-benefit analysis inspires clear and logical thinking about the true value added and it gives an estimation on the value of a project relative to an estimate of the value of what would have happened if there was no project at all. In a CBA, the conclusions of an evaluation are more robust and credible (Commonwealth of Australia, 2006).

In light of the above, it must be noted that cost-benefit analysis has general limitations which must be taken into account at the outset (Prest & Turvey, 1965) because it is only a technique for taking decisions within a framework which has to be decided upon in advance and which involves a wide range of considerations, many of them of a political or social nature. CBA can only be used for projects where the costs and benefits can precisely be put into monetary terms (Maliva, 2014); however, if the project cannot be accurately quantified, the analysis becomes hampered. CBA does suffer from difficulty in translating all costs and consequences into monetary terms (Coons and Kaplan, 1996). Cernea (1999) argued that, although CBA justifies a project economically, when the total benefits are greater than the total costs, it disregards how these costs and benefits are distributed. In other words, CBA does not ask who pays the costs, nor who benefits or loses; it only assesses the total impact of the project to determine how it performs compared to other projects. Dreze and Steyn (1987) argued that this technique is not relevant and serviceable for what one might call large scale investment decisions.

Lastly, CBA disregards the risks incurred by individuals from various subsets. The project's real risks of impoverishment are dispersed differently than its benefits (Cernea, 1999). It was argued that, although the total benefits are real, they inevitably do not offset the costs from each individual. Cernea (1999) stated that the cost-benefit analysis can be effortlessly influenced or manipulated in any way by omitting costs incurred by the project. For example, it can be manipulated in a manner by which costs, and benefits are valued, especially if accurate market prices cannot be obtained or are inconclusive; or in the way the discount rate is estimated to calculate the current value of a condemned asset (Cernea, 1999). Finally, regardless if the CBA method is at its peak and has no issues, it is unable to answer the economic and ethical questions involving forced displacement, thus depending on its conclusions is practically doubtful from both a social and market perspective (Cernea, 1999).

### **3.4.3 Cost-effective Analysis (CEA)**

According to Tietenberg and Lewis (2012), this tool can be used to evaluate the projected costs of reaching a specific result. Also, it can be used to compare the costs and impacts of different ways to achieve the same objective. Hence, cost effectiveness is expressed as a ratio between cost and outcome (Johanneson, 1995 cited in Zou et al, 2013). The cost effectiveness ratio is expressed in the below equation:

$$CER = C_0/E_0 \quad (3.4.3)$$

Where  $C_0$  refers to the initial capital costs in the first year and  $E_0$  denotes the outcome in the first year (Zou et al, 2013). If the ratio is smaller, the cost-effectiveness will be higher and vice versa. Each alternative or option has its own estimated cost-effectiveness ratio, thereby each of them can be classified as the most cost-effective (lowest ratio) to the least cost effective (highest ratio) (Commonwealth of Australia, 2006).

Moreover, the cost-effectiveness technique is used where the costs and benefits cannot be easily measured in monetary terms or where valuation data would be expensive to collect or likely to be controversial in nature (Edwards, 2011). Also, it is a suitable method where valid and reliable estimation of benefits are not feasible (Maliva, 2014). The cost-effectiveness method argues that, unlike cost-benefit, a low cost does not equal greater

effectiveness and vice versa (Henderson, 2010). Furthermore, according to Maliva (2014) and Edwards (2011), this method has its limitations in that it considers only the costs to reach a predetermined goal or principle. Another limitation of CEA is that it can rank an entire list of projects without any guarantee that any of them are going to be implemented.

#### **3.4.4 Cost-minimisation Analysis (CMA)**

The strength of cost-minimisation analysis (CMA) lies in the reader's acceptability that the results are indeed equivalent (Newby and Hill, 2003). CMA is primarily used when cost savings are the main objective, and it should outweigh all other considerations. CMA has significant and reasonable appeal to specialists and decision makers who strive for simplicity in their studies and evidence (Briggs and O'Brien, 2001). For example, if two treatments in question yield the same results, then the one with the lowest cost will be chosen.

CMA is an appropriate method of analysis when the data on costs and outcomes is available. However, it was argued that even if this data is readily available, the CMA method is rarely used because it is "too simple" (Briggs and O'Brien, 2001). Cowdin (2008) argued that CMA is the least comprehensive analysis that achieves precise physical aims at the lowest cost. Also, CMA is very limited in the sense that it can only compare options that yield the same results (Newby and Hill, 2003). CMA is frequently perceived as being the poorest among the methodologies in health-economics, whereby many analysts equating it as being a simple cost analysis. Such a perception is largely due to the poorly controlled and disorganised use made of this methodology to date (Haycox, 2009).

#### **3.4.5 Cost-utility Analysis (CUA)**

Cost-utility analysis measures the value or usefulness obtained from each of several candidate designs that are under consideration for implementation (Robinson, 1993). The value developed by this analysis is a subjective measuring of intangible variables that are affected by design. The results of a CUA are similar to the use of CBA; however, CBA is a quantifiable analysis which measures the tangible elements of a proposed project (MacKillop and Sheard, 2018). Cost-utility analysis, in contrast, derives utility units which

are a measure of intangible elements of a proposed project, e.g., desires. Hence, it relies more on intuition and judgment (MacKillop and Sheard, 2018). CUA is employed when policy makers are concerned about two or more measures of success, for example, reducing unemployment and poverty, and maintaining the quality of the environment. Diverse projects have different anticipated effects on the above measures, and they require an assessment of the 'utility' of the different combinations of these measures (Gorr, 1998 cited in DEAT, 2004).

Cost-utility analysis is one of the best economic valuation methods when it comes to allocating health resources (Robinson, 1993) in that it assesses the efficiency of healthcare interventions. In addition, CUA is preferred over CBA because the latter requires monetization of all costs and outcomes, an impossible task where pain and suffering are involved (Hildred and Beauvais, 1995). With CUA, measuring the results may be subjective in nature; however, the advantage thereof is that it shows the benefit of an intervention as perceived by the people who receive it; therefore, it is an analysis with a different dimension or perspective. In practice, this form of analysis seeks to address the needs of the patients or parents who have normally been neglected (Sheps & Birnbaum, 1993).

However, CUA is also the most controversial economic analysis technique. The controversy stems mainly from the measurement of utility (Coons and Kaplan, 1996). Utility is the value or worth placed on a level of health status, or improvement in health status, as measured by the preferences of individuals or society. Health state utilities or preference values are needed to calculate QALY (Coons and Kaplan, 1996). However, there is no agreement as to the most suitable measurement approach. Also, Round et al (2014) argued that CUA does not provide enough grounds to support decisions on resource allocation, but it is a useful method and it performs an essential role better than other techniques.

### **3.5 REVIEW OF PREVIOUS STUDIES**

#### **3.5.1 Empirical Studies on Economic Analysis and Cost-benefit Analysis**

It was said that the key strength in economic analysis and more particularly cost-benefit analysis lies in their versatility. In other words, they are very versatile methods to guide decision-making. Economic analysis was employed by Schwarz et al (1990) in their study on indirect sludge drying. This study reports on an engineering and economic evaluation of the use of indirectly heated sludge dryers prior to incineration. Cost estimates of sludge incineration for four different designs incorporating sludge dryers are compared with the corresponding costs of conventional sludge incineration. The five different designs included hollow-disk, hollow-paddle, hollow-screw, screw-conveyor dryers and thin-film dryers (Schwarz et al, 1990). For the economic analysis, the principle of amortized capital costs was used to calculate the overall project costs and costs per dry tonne of sludge. The analysis included inflation and escalation of operating and maintenance costs (O & M costs). Benefits in the form of the electricity savings were subtracted from the O & M costs to get the net O & M costs. The net O & M costs were then added to the amortized annual capital costs in order to derive the total annual costs. In addition, simulations were done on the hollow-disk and thin-film dryers. Sensitivity analysis was also done in this study in order to determine the sensitivity of the costs to the input parameters (Schwarz et al, 1990). Based on the economic analysis, it was found that there is an economic advantage of drying the sludge prior to incineration, in comparison to conventional incineration. Drying sludge partially not only reduces the total costs, but it saves energy as well.

On a different note, a study conducted by Roy et al (2004) utilised economic analysis as a decision-making tool in their study. This study took place in Kolkata, India, and assessed the demand for quality drinking water. The study assumed that individual households were able to value changes in water quality services, thus willingness to pay (WTP) was used as the theoretical framework for this study. This study also made use of fieldwork in the form of surveys as a means for collecting data. Thereafter, statistical analysis was employed to analyse the survey data and it was found that the WTP reflected the economic evaluation of improved water quality; spending power and education levels of households were important determining factors of willingness to pay. This study further recommended that any sustainable water management policy decision through the



imposition of a water tariff needs to consider households' income distribution patterns and expenditure classes (Roy et al, 2004).

In addition, Shah (2005) integrated economic analysis into a drinking water project in the Anantpur District in the Indian state of Andhra Pradesh. The project was undertaken due to the drought that plagued the district. The study looked at the cost of delivery and benefits of a drinking water supply project. The project entailed laying of pipelines; construction of water storages; construction of balancing, overhead service and ground level service reservoirs; construction of booster stations, storage tanks and cisterns; and the installation of generators and pump houses. The study found that the project was carried out in quick time and has largely met its aim of supplying sufficient and safe water to the district (Shah, 2005).

Punyawadee et al (2008) conducted a cost-benefit analysis of the Flue Gas Desulphurisation Technology (FGD) used at the Mae Moh Power Plant in Thailand. The main aim of this study was to evaluate the impacts of this technology on the welfare of the people, the surrounding environment and agricultural and forest productivity. In addition, the start-up costs, operational costs and other costs were compared with the residual value and all the projected benefits of the FGD technology over a period of 25 years (Punyawadee et al, 2008). The projected benefits of the FGD to agriculture in Thailand were approximately 80 million baht in net present value. It was said that, because of the FGD, there will be increases in teak productivity (teak wood plantations). Investment in teak productivity, as a result of the FGD system, was said to be 706 million baht. Also, the FGD system was said to bring about improvements in human health. In contrast, it has been found that this technology has not been cost effective, i.e., it is an economic burden rather than benefit to society (Punyawadee et al, 2008). There was too much risk attached to the system. For example, it was projected that the incremental benefits of the FGD system, over its lifetime, totals to 4.7 billion baht. However, the projected costs involved totalled to 13.8 billion baht (Punyawadee et al, 2008). Hence, the projected costs outweighed the benefits by a huge margin.

Moreover, a study conducted by House et al (2011) was about economic and energetic analysis of capturing carbon-dioxide from ambient air. The main aim of this study was to

determine whether the methods to capture and mitigate carbon-dioxide emissions were economically feasible. This study was conducted in the USA and it incorporated the economic analysis of methods to capture carbon-dioxide and methods to mitigate carbon-dioxide emissions. This study only estimated the private costs and benefits of carbon-dioxide capturing. Based on the economic analysis, it was found that air capture processes are significantly more expensive than mitigation technologies. For example, air capture costs \$1,000 per ton of CO<sub>2</sub>, whereas mitigation technologies cost \$300 per ton of CO<sub>2</sub> (House et al, 2011).

In addition, Herzog (2011) made use of economic analysis in his study on technologies for CO<sub>2</sub> separation and capture. This study was conducted in an energy laboratory in Cambridge, USA. The focus of this study was CO<sub>2</sub> capturing from power plants. The study presented an overview on the technology, a detailed cost analysis of the technology and opportunities to lower costs in the future. For the cost analysis, a composite cost model for several types of power plants, e.g., coal-fired and gas, was developed, followed by a sensitivity analysis. Herzog (2011) concluded that new technologies like gasification showed the most promise for coal-fired power plants. By 2012, the incremental costs for CO<sub>2</sub> sequestration could be far less than 1 cent per kWh for coal plants and 1.5 cents per kWh for gas plants.

Furthermore, Molinos-Senante et al (2011) used cost-benefit analysis as a decision-making tool in their study on reusing wastewater for environmental purposes. The project took place in Spain and 13 wastewater treatment plants in the Valencia region that use effluent<sup>8</sup> for environmental purposes were used as a case study. Molinos-Senante et al (2011) argued that economic feasibility studies of wastewater-reuse projects should be completed using the cost-benefit analysis technique. The total benefit of the project was estimated by accounting for the internal benefit, the external benefit and the opportunity cost as outlined in the below equation.

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<sup>8</sup> Effluent refers to treated sewage water (non-potable water), mostly used in construction sites.



$$B_T = B_I + B_E - OC \quad (3.5.1)$$

where  $B_T$  is the total benefit (total income minus total costs);  $B_I$  represents the internal benefit (internal income minus internal costs);  $B_E$  represents the external benefit (positive externalities minus negative externalities); and  $OC$  refers to the opportunity cost. The results of this study indicated that only some of the projects were economically feasible based on internal benefit; however, when external benefits were included, all projects were economically feasible. The study concluded that future economic feasibility studies on water-reuse should numerically evaluate economic, environmental and resource availability (Molinos-Senante et al, 2011).

### **3.5.2 Empirical Studies on Flue Gas Condensation Technology / Condensing Heat Exchangers**

A study conducted in India regarding a Teflon coated condensing heat exchanger stated that the technology enabled boiler efficiency to exceed 90% (Azmatullah, 2005). It was said that the Teflon coated heat exchanger reduced fuel consumption and it enabled a mid-size industrial plant to save an average of \$1,000 per day on energy costs; thereby the technology paid for itself after 25 months (Azmatullah, 2005). Another study conducted by Feeley et al (2006) at Lehigh University in 2006 incorporated the development of a condensing heat exchanger for a coal-fired power plant. The study took a cost-benefit approach and it concluded that this technology would benefit these power stations in that it would enable them to produce freshwater from flue gas, which is normally lost through evaporation. The total cost to employ this technology per power plant was \$691,888 (Feeley et al, 2006).

In addition, Terhan and Comakli (2016) conducted a study on a condensing heat exchanger in Turkey. This exchanger was to be added onto a 60MW gas-fired heating system in order to recover latent heat from exhaust flue gas. They incorporated theoretical analysis and economic analysis (annual equivalent benefit and payback method) in their study. The analyses concluded that the initial investment was \$83,711.16; operating costs and recurring costs were \$7,375.80 and \$5,279.48 respectively; and the annual savings in terms of energy was \$407,369.16. Hence, the payback period was less than one year,

thereby making this heat exchanger economically viable. Moreover, a study conducted by Wei et al (2017) in China stated that the condensing heat exchanger concurrently saves water and energy and decreases pollutant emissions. This flue gas heat recovery system comprised of a direct-contact heat exchanger, heat pump, and precipitation tank. Technical economic analysis of this system was performed, and it found that the initial investment was 28.8 million Renminbi<sup>9</sup> (RMB), the annual revenue in terms of water and energy savings was 7.4 million RMB and the payback period was approximately 3.8 years. Hence, Wei et al (2017) concluded that there was an economic advantage with this system.

Furthermore, Han et al (2017) incorporated economic analysis into their study on low pressure economizer (LPE) and spray tower (SPT) heat exchangers in China. The economic analysis model calculated the total investment cost (TIC) and the annual cash flows in terms of electricity sale income, heat supply income and water saving income. It then estimated the NPV and payback period on the below equation:

$$NPV = \sum \frac{ACF}{(1+r)^t} - TIC \quad (3.5.2)$$

Where t refers to the time/year in question. It was found that the TIC for the LPE and SPT heat exchangers were \$2.53 million and \$2.06 million respectively and the ACF for the LPE and SPT heat exchangers were estimated to be \$990,000 and \$500,000, respectively. The net present value (NPV) was calculated based on a ten-year life cycle of both the LPE and SPT and the interest rate was assumed at 8% per year. The NPV of the LPE and SPT heat exchangers, after ten years, was estimated to be \$4,090,000 and \$1.3 million, respectively. The payback periods for the LPE and SPT were estimated to be 2.98 years and 5.18 years, respectively. Hence, the analysis concluded that both the LPE and SPT heat exchangers were economically viable.

In addition, Han et al (2017) conducted another study in China on the LPE and SPT heat exchangers. However, this study was about a flue gas pre-dried lignite-fired power system

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<sup>9</sup> RMB stands for Renminbi, which is China's official currency.

(FPLPS) to recover waste heat and water from high-moisture lignite. The FPLPS system integrated the fan mill flue gas dryer with an open pulverizing system and it yielded an increase in boiler efficiency (Han et al, 2017). In addition, the system integrated the LPE and SPT heat exchangers to realise the extraction from water from lignite. Economic analysis on the LPE and SPT were done and it was found that the FPLPS system along with the LPE and SPT heat exchangers improved plant efficiency by a range of 1.14% to 1.47% depending on the moisture content of the lignite (Han et al, 2017). Furthermore, the water recovery ratio from the LPE and SPT were 39.4% and 83.3% respectively. The discounted payback period of both the LPE and SPT heat exchangers were both around three years. Lastly, parametric analysis on both the SPT and LPE were conducted and it was concluded that the economic viability of both SPT and LPE was dependent on the moisture content of the lignite and the market price (Han et al, 2017).

### **3.5.3 Empirical Studies on Desiccants**

A study conducted by Gandhidasan and Abualhamayel (1996) in Saudi Arabia proposed the use of a liquid desiccant to capture fresh water from the atmosphere. The proposed system used a single flat, tilted surface exposed to atmosphere as an absorber. Calcium chloride was chosen as the liquid desiccant due to it being inexpensive and readily available. The strong desiccant flowed as a thin film over the surface and in contact with the ambient atmospheric air. In addition, this study asserted that, if the vapour pressure of water in ambient air surpasses the vapour pressure of the desiccant, transfer of mass takes place from ambient air to the desiccant (Gandhidasan and Abualhamayel, 1996). The desiccant that absorbs moisture from ambient air will be diluted. The water-rich desiccant will then be heated to condense the vapour stream, thereby producing water. The results of this study concluded that, if the flow rate of the desiccant increased coupled with an increase in ambient humidity and wind velocity, the amount of water absorbed by the desiccant increased. Also, Gandhidasan and Abualhamayel (1996) concluded that further studies were still in progress.

Badami and Portoraro (2009) made use of economic analysis in their study about using a liquid desiccant cooling system for an innovative small-scale trigeneration plant. The trigeneration plant consisted of a co-generator that uses an automotive derived gas fired

internal combustion engine (ICE) coupled with a liquid LiCl-water desiccant cooling system that recovers heat from the flue gases and from the ICE cooling water (Badami and Portoraro, 2009). The authors argued that economic analysis of the plant played an integral role in the viability of this study. They made use of earnings before interest, taxes, depreciation and amortization (EBITDA); net present value (NPV); simple payback period (SPB); and internal rate of return (IRR) as economic measures of merit. It was found that the EBITDA, also calculated as the difference between total annual profits and costs, of the plant was €28,500 per year; the NPV after 15 years varied from €200,000 to €220,000; the SPB varied from 6.80 years to 7.60 years; and the IRR varied from 9.7% to 11.5% (Badami and Portoraro, 2009). Based on these economic measures of merit, the authors concluded that this desiccant cooling system might be viable from an economic point of view.

Also, Angrisani et al (2016) utilised economic and energy analysis in their study on a novel geothermal heating and cooling system in Ischia, Sicily. This heating and cooling system was based on the coupling between a low or medium-enthalpy geothermal source and an Air Handling Unit that includes a desiccant wheel. The study also used simple payback period (SPB) and net present value (NPV), but it went a bit further by incorporating the profitability index (PI) as an economic measure of merit. Based on the economic assessment, the proposed system showed a SPB of 1.2 years; an NPV of €327,500 after 20 years; and a PI of 9.60, which coincided with a significant economic saving of €28,900 per year. Angrisani et al (2016) concluded that, under these evaluations, the proposed system can be extremely profitable.

In addition, Srivastava and Yadav (2018) conducted an experimental investigation to produce water from atmospheric air by using composite desiccant material in Haryana, India. The composite desiccant materials have better absorption capacity compared to the conventional solid and liquid desiccants. And they do regenerate at low temperatures. In this study, the composite desiccant material was made up of sand (host material) and hygroscopic salts, namely Lithium Chloride Anhydrous (LiCl), Lithium Bromide Anhydrous (LiBr) and Calcium Chloride Anhydrous (CaCl<sub>2</sub>). The LiCl, LiBr and CaCl<sub>2</sub> mixed with the sand was denoted as CM-1, CM-3 and CM-2 individually. A scheffler reflector, a material

handler and a water measuring vicker were used in conjunction with the composite material to generate water from atmospheric air (Srivastava and Yadav, 2018). It was found that the maximum water generated per day for CM-1, CM-2 and CM-3 were 90ml, 115ml and 73ml respectively (Srivastava and Yadav, 2018) and their annual cost of generating water was \$0.71, \$0.53, and \$0.86 individually.

### **3.5.4 Empirical Studies on Membrane Technology**

Jevons and Awe (2010) outlined the economic benefits of reverse osmosis membrane technology and compared it with evaporators. This study investigated as to how food ingredient manufacturers in the European Union (EU) can limit their carbon footprint, recover water, and save on water and energy costs. Jevons and Awe (2010) argued that membrane technology, individually or in conjunction with evaporation, shows economic benefits such as water recovery and reuse and potential value-added products recovered from the food ingredient production waste streams. It was found that reverse osmosis membrane technology can achieve a greater than 75% reduction in operating costs compared to mechanical vapour recompression evaporators. Although the evaporators (€950,000) have similar low operating costs as the membrane technology (€973,000), their capital cost of €2,057,000 is significantly higher than that of the membrane technology (€900,000). Lastly, Jevons and Awe (2010) concluded that companies that employ evaporators as a de-watering step in the manufacturing of products, e.g., dairy, sugar, sweeteners, beverages, organic acids, and renewable biofuels, can potentially lower their carbon footprint with membrane technology.

In addition, a cost-benefit analysis regarding transport membrane condenser (TMC) technology was conducted by the Gas Technology Institute in Illinois USA in 2012. The Institute analysed the TMC technology in terms of boiler feed water (BFW) and Flue Gas Desulphurisation makeup water saving and there were four power plants. Firstly, it was assumed that the price of de-mineralized water is \$5.25/1000 gallons and BFW makeup water required 10 gallons of water per MWh (Wang, 2012). The first power plant had total makeup water savings of \$ 1,443,200 per year; the second power plant had water savings of \$445,200 per year; the third had total makeup water savings of \$151,800; and the fourth power plant had water saving of \$37,900 per year (Wang, 2012). Also, the initial



investment of the TMC technology for first, second, third and fourth power stations was \$1,570,000; \$1,570,000, \$770,000, and \$260,000, respectively. Hence, the technology had payback periods of 1.09 years, 3.53 years, 3.12 years, and 3.30 years respectively, thereby making it economically viable (Wang, 2012).

Also, Zhai and Rubin (2012) did a study on membrane-based carbon-dioxide ( $\text{CO}_2$ ) capture systems for coal-fired power plants. This took place in Pittsburgh in the USA. The study aimed to evaluate the performance and cost of two-stage polymeric membrane systems for carbon-dioxide capture at coal-fired power plants. Also, it investigated the impacts on membrane capture systems of key parameters and designs using a widely used costing method that permits comparative evaluation for different  $\text{CO}_2$  capture technologies in a common framework (Zhai and Rubin, 2012). The costing method utilised in this study was based on the Electric Power Research Institute's (EPRI) Technical Assessment Guide (TAG), which was widely adopted as an industry benchmark (EPRI, 1993 cited in Zhai and Rubin, 2012). The initial results demonstrated the viability of the membrane systems in capturing carbon-dioxide at coal-fired power plants. However, to simultaneously achieve a 90% carbon-dioxide capture and a 95% product purity, adding the two-stage membrane system will double a power plant's cost of energy and that plant may incur a high energy penalty of up to 30% of its gross electric output. Sensitivity studies were conducted on the results and it concluded that using both compressors and vacuum pumps to lower feed gas compression pressure is effective in reducing the membrane system's energy penalty. Also, improving the membrane properties and lowering the production costs of permeable membranes would lower the capture costs and further enhance the viability of the membrane technology (Zhai and Rubin, 2012).

Moreover, a study conducted by Macedonio et al (2017) incorporated the implementation of membrane condenser technology at a power plant in Italy. This study investigated three different membrane condenser configurations in terms of recovered liquid water and energy consumption. The first configuration was the cooling of waste gas via an external coolant medium before entering the membrane; the second one was the cooling of the waste gas by a cold sweeping gas when entering the membrane; and the third was a combination of configuration one and two. A simulation study and an experiment were

done, and it found that configuration two had the least energy consumption and configuration three achieved the highest water recovery (Macedonio et al, 2017).

Furthermore, Mittal (2018) did a study on zeolite membrane separation processes, and he incorporated techno-economic analysis in his study. This study was conducted at the University of Minnesota in the USA. The objectives of this study were to design and build a comprehensive mathematical model of a zeolite membrane separation process for accurate performance prediction under a wide variety of operating conditions, and to develop and optimise a conceptual process design approach and perform a techno-economic evaluation for several significant application specific flowsheets (Mittal, 2018). Mittal argued that zeolite membrane separation is a promising alternative to the traditional energy intensive industrial separation techniques, e.g., distillation. The economic analysis was done to determine the NPV (net present value) profits of the membranes over base case distillation. A discount rate of 10% per annum was assumed, an economic life of five years and a replacement cost of 50% of the initial investment was assumed (Mittal, 2018). The initial investment and operating costs of the membranes were calculated to be approximately \$10 million and \$5.38 million, respectively. The NPV profits were calculated over a 20-year period, and it was found the membrane separation process resulted in zero profit in contrast to distillation. Lastly, Mittal (2018) concluded that additional enhancements are needed to reduce the area requirement or equivalently bring down the membrane costs in order to achieve a payback period of one year.

### **3.6 CONCLUSION**

This chapter outlined the literature regarding economic analysis. It gave a brief history of economic analysis as well as the definition of economic analysis. This chapter discussed the four main techniques of economic analysis. With reference to this study, the cost-benefit method is by far the most appropriate method of economic analysis to be used in this study because it is a versatile tool for decision-making. Under this approach, one will be able to accurately estimate the economic costs and benefits of the water vapour selective membrane technology for Eskom.



In addition, the empirical studies on economic analysis and cost-benefit analysis emphasise their versatility as decision-making tools. Also, the empirical studies on flue gas condensation technology and desiccants showed that there was economic viability in implementing these technologies. However, it has already been stated that the membrane technology is more superior than flue gas condensation and desiccant drying systems. In contrast, the studies on the technologies were limited in the sense that they incorporated only a few of the economic measures of merit e.g., net present value (NPV), the payback period (PP), the internal rate of return (IRR), and the profitability index (PI); and only some of them made use of sensitivity analysis.

More importantly, the studies on membrane technology were very limited and one dimensional in that two of them only made use of net present value (NPV) and the payback period. In addition, none of these studies made use of sensitivity analysis. However, it must be noted that there was not much literature available that deals specifically with the economic analysis of membrane technology. Therefore, this study followed the cost-benefit approach and went a step further by including the net present value (NPV), payback period (PP), discounted payback period (DPP), internal rate of return (IRR), modified internal rate of return (MIRR), and the profitability index (PI) as measures of economic merit. The inclusion of all these measures was done to add more substance and depth to this study. Lastly, this study also employed a sensitivity analysis by changing some of the variables and adding a few more scenarios, to see how these changes impact the results.

## CHAPTER 4: RESEARCH METHODOLOGY

### 4.1 INTRODUCTION

This chapter explains the methodology used in conducting the research. It is structured as follows. It begins with the analytical framework used in this study. In addition, it indicates the sources of data and provides a brief description of the data. Also, it provides a description of the variables, and outlines the scope and limitations of the study.

### 4.2 ANALYTICAL FRAMEWORK

This study made use of the cost-benefit method to estimate the costs and benefits of the membrane technology. Under the cost-benefit approach, this study made use of the net present value (NPV) method, the payback method, the discounted payback method, the internal rate of return (IRR) method, the MIRR method and the profitability index as economic measures of merit. In addition, it also employed sensitivity analysis to test the results by changing the variables. In other words, to see how the results changed when the variables were changed.

#### 4.2.1 Net Present Value (NPV) Method

The net present value (NPV) method was employed in this analysis. The NPV (in its simplest form) is given by the below equation (Melzer, 2012):

$$\text{NPV} = \text{present value of cash inflows} - \text{initial investment} \quad (4.2.1)$$

According to Maliva (2014), the above equation can be rewritten in this form:

$$\text{NPV} = -C_0 + \left( \sum \frac{B_t}{(1+r)^t} - \sum \frac{C_t}{(1+r)^t} \right) \quad (4.2.2)$$

Where  $C_0$  is the initial investment in year 0;  $B_t$  denotes the projected benefits and  $C_t$  denotes the costs in year  $t$ . The cost of capital is denoted by " $r$ ", and the time variable is denoted by " $t$ ".

In addition, if the cash flows are assumed to be same year-on-year, the NPV can be estimated by the below equation (Excel Forum, 2020):

$$NPV = \frac{CF_0}{r-g} - \text{Initial Investment} \quad (4.2.3)$$

The initial investment refers to the start-up cost of the whole system, e.g., the entire cost of the membrane condenser system. The growth rate of the cash flows is denoted by “*g*”. The projected costs for each year include the operating costs, replacement costs, opportunity costs and maintenance costs. The projected benefits include the energy and water savings. Also, the cost and benefits were discounted into present value terms by the discount rate.

### **Decision rule**

The membrane condenser system is economically feasible if it has a positive NPV and vice versa.

#### **4.2.2 Payback Method / Period (PP)**

The payback method was also employed to determine the amount of time the membrane condenser technology took to pay itself off. The payback period is found by dividing the initial investment by the annual cash inflows. Melzer (2012) provided the below equation to calculate the payback period:

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Cash Flows}} \quad (4.2.4)$$

In other words, to calculate the payback period one divides the total cost of the membrane condensers by the anticipated net-benefits. The annual cash flows refer to the anticipated net-benefits, that is the savings minus the costs.

### **Decision rule**

The shortest payback period was chosen and vice versa.

#### **4.2.3 Discounted payback method / period (DPP)**

The discounted payback method was also employed for the same reason as the payback method. However, with this technique the projected cash flows were discounted in present value terms in order to yield a more accurate answer. The discounted payback

period was estimated by dividing the initial investment of the project by the present value of the annual cash flows. To calculate the DPP, the present value of annual cash flows was calculated first. The present value of the annual cash flows was calculated using the compound interest formula (Melzer, 2012):

$$\text{Present value of Annual Cash Flows} = \frac{\text{Future Value of Annual Cash Flows}}{(1+i)^n} \quad (4.2.5)$$

where “*i*” refers to the discount rate expressed as a decimal; and “*n*” refers to the number of interest periods, e.g., years. Thereafter, the DPP was estimated by the below equation:

$$\text{Discounted payback period} = \frac{\text{Initial Investment}}{\text{Present Value of Annual Cash Flows}} \quad (4.2.6)$$

### Decision rule

The shortest discounted payback period was chosen and vice versa.

#### 4.2.4 Internal Rate of Return (IRR) Method

The internal rate of return method was also employed in this analysis. This was done in order to determine whether the cost of capital of the membrane condenser technology outweighs its IRR. The IRR can be estimated by the below equation (Excel Forum, 2020):

$$\text{IRR} = \frac{\text{Cash Flows}}{\text{Initial Investment}} + g \quad (4.2.7)$$

Where “*g*” represents the growth rate of the cash flows. If cash flows are assumed to grow indefinitely by the same amount, the IRR can be estimated in this way. However, if cash flows differ year-to-year, the IRR is estimated by means of Microsoft Excel.

### Decision rule

Normally, one would accept the project if the IRR is greater than the discount rate and reject it if it is lower.

#### 4.2.5 Modified Internal Rate of Return (MIRR) Method

The MIRR method was used in comparison with the IRR method. In that remedied the IRR’s drawbacks. The MIRR yielded a more accurate answer, in that it assumed that the

cash flows were reinvested at the cost of capital. According to Balyeat and Cagle (2015), the procedure to estimate the MIRR is as follows:

Firstly, calculate the present value of the costs (PVC) associated with the project, using cost of capital ( $r$ ) as the discount rate:

$$PVC = \sum_{t=0}^n \frac{Cash\ Flow_t}{(1+r)^t} \quad (4.2.8)$$

Secondly, calculate the terminal value (TV) of the cash inflows expected from the project:

$$TV = \sum_{t=0}^n Cash\ flow_t (1+r)^{n-t} \quad (4.2.9)$$

Lastly, obtain the MIRR by solving the following equation:

$$PVC = \frac{TV}{(1+MIRR)^n} \quad (4.2.10)$$

This study used these equations to estimate the MIRR for the Medupi power station.

### Decision rule

Normally, one would choose the project which MIRR is greater than its cost of capital and reject it when the MIRR is lower than the cost of capital.

#### 4.2.6 Profitability Index (PI)

The profitability index was employed to determine the profitability of the hollow-fibre membrane condenser system for each coal-fired power stations. According to Ermenyi (2015), the PI is estimated using the below equation:

$$PI = \frac{\text{Present value of future cash flows}}{\text{Initial investment}} = 1 + \frac{NPV}{\text{Initial investment}} \quad (4.2.11)$$

This analysis employed this equation to estimate the profitability index of the Medupi power station.

### Decision rule

If the PI is greater than 1.0, the investment adds value, hence invest. However, if the PI is less than 1.0, the investment destroys value, thus do not invest. In contrast, if the PI is equal to 1.0, one would be indifferent as to accept or reject the investment.

#### **4.2.7 Sensitivity Analysis**

Afterwards, this study employed sensitivity analysis by varying the variables and creating different assumptions to determine the sensitivity of the results under changing variables and different assumptions. Sensitivity analysis is about varying the key assumptions underlying the project. Sensitivity analysis made the results of this CBA more credible and it compensated for uncertainty. The variables that were altered were the discount rate and the inflation rate. The discount rates used were altered, i.e., they were changed by 50, 100 and 150 basis points. The projected inflation rates were used to calculate the cash flows and replacement costs that would take place after the year 2019.

In addition, the below five scenarios were used to test the results under the varying assumptions:

- What if the interest rates decline by 50, 100 and 150 basis points?
- What if the cost of the membrane modules double?
- What if the cost of the membrane modules decreases by half (50%)?
- What if the annual cash flows are the same indefinitely?
- What if the membrane modules have an economic life of 20 years?

### **4.3 SOURCE OF DATA AND DESCRIPTION OF VARIABLES**

#### **4.3.1 Data**

The study relied on experimental data obtained by the South African Institute of Advanced Material Chemistry (SAIAMC) at the University of the Western Cape (UWC) where membrane modules capable of recovering water from humidified flue gas are being developed. The performance of prototype membrane modules is currently being measured at UWC using a model gas with a composition similar to the gas exiting a commercial wet-flue gas desulphurisation system. SAIAMC provided estimates on

material cost to produce membrane modules and the experimental data revealing how much water was recovered at specific operational conditions using these modules.

In addition, this study conducted telephonic interviews with representatives of Eskom to determine the cost of electricity and the cost of demineralized water. It also conducted telephonic interviews with the Department of Environmental Affairs in order to derive the cost of non-compliance, in other words, the consequences should Eskom not adhere to the Air Quality Act 2010.

Data on the hollow-fibre membrane module was obtained from SAIAMC. Cost estimates on the membrane module were obtained from the Ludwin Daal Costing Report, compiled by a company called DNV KEMA Energy & Sustainability, which is based in the Netherlands. These estimates were expressed in Euros, which was converted into Rands.

#### **4.3.2 Description of Variables**

The variables used in this study were:

- **Initial investment/initial outlay (-C<sub>0</sub>)**

The initial investment included the number of membranes modules, condenser, vacuum pump, and piping and reticulation. These cost estimates were obtained from the Ludwin Daal Costing Report compiled by DNV KEMA.

- **Costs (C<sub>t</sub>)**

The cost variable included the operating costs, replacement costs, and opportunity costs.

- **Operating costs**

Operating costs included the costs to maintain the membrane technology. Operating costs in this regard included energy and maintenance costs for the pump house associated with pumping the water for Medupi Power Station.

- **Replacement costs**

Replacement costs included the cost to repair and replace the membrane condensers, machinery, and equipment. The membrane modules have a five-year replacement value;



hence replacement costs will only come into effect after five years. However, the condenser, vacuum pump and piping and reticulation have a 20-year replacement value.

- **Opportunity cost**

Opportunity costs included the costs of the next alternative forgone. The opportunity cost in this regard would be the money that Eskom would save if they chose not to implement the membrane technology.

- **Benefits (Bt)**

The primary benefit included the projected cost savings in terms of demineralized water. The water benefit / loss was reflected in the difference between the cost of water, purified and pumped from the water source and the cost of water recovered from the saturated flue gas downstream the wet-FDG system. In addition, an added benefit was the energy savings. The membrane technology saved energy in that that no reheating of flue gas was necessary.

- **Cost of capital (r/i)**

The cost of capital, the discount rate or the interest rate is the cost of using the funds of creditors and owners. In other words, it is the rate of return that the creditors and owners require as compensation for their contributions of capital. The government bond rate (10 years and longer) was used as the discount rate in this study. This was because Eskom is a large state-owned company, and they borrow from the bond market. Currently, the bond yield fluctuates between 8.00% and 9.00%. Therefore, an average rate of 8.50% was assumed.

- **Time period (n/t)**

The time period refers to the period of the analysis. This assessment was done over a five-year, ten-year, 15-year and 20-year period.

- **Inflation rate**

Inflation is the general rise in the prices of goods and services in a country. The Consumer Price Index (CPI) is regularly used to calculate inflation. However, inflation is also measured by the Producer Price Index (PPI). The operating costs and replacement costs, except the rent, increases year-on-year due to inflation. The inflation rate was also used

as the growth rate of cash flows in the analytical framework of this study. The average annual inflation rates of 2014 to 2018 were used. Also, these average inflation rates were used to predict future inflation rates (e.g., from 2019 onwards). The below table illustrates the average annual inflation rates of South Africa from 2014-2018.

**Table 4.1: Average annual inflation rates for the years 2016 to 2022**

Year	Inflation rate
2014	6.10%
2015	4.60%
2016	6.40%
2017	5.30%
2018	4.70%
Average inflation rate	5.40% <sup>10</sup>

Source: StatsSA, 2019

It was said that South Africa's inflation has been quite stable for the past years, levelling off between 4.50% and 6.30%, and is in fact expected to stabilise at around 5.00% in the future (Statista, 2019). The projected average annual inflation rates were used as the growth rate of the cash flows in the analysis as well as the sensitivity studies.

- **Exchange rate**

The exchange rate is simply the price of one currency in terms of another (Mohr and Fourie, 2008). The rand to euro exchange rate was used in this analysis, due to the fact that the data on the hollow fibre membrane condenser is denoted in euros. Hence, it had to be converted into rands. The average annual exchange rates were used in this study. The below table shows the average annual rand/euro exchange rate from 2018.

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<sup>10</sup> 5.40% is the average of the inflation rates of 2014 to 2018

**Table 4.2: Average annual rand/euro exchange rates for 2014 to 2018**

Year	Rand/Euro Exchange rate
2014	R14.40
2015	R14.16
2016	R16.29
2017	R15.06
2018	R15.61

Source: *www.resbank.co.za and author's own calculations, 2019*

#### **4.4 PROJECT SCOPE AND LIMITATIONS**

The South African Institute of Advanced Material Chemistry (SAIAMC) of the University of the Western Cape (UWC) mandated by the Water Research Commission (WRC) is investigating the potential of membrane technology for water recovery from flue gas. Membrane technology has been proposed as an efficient and effective means to recover water from flue gas. However, it comes at a cost and one must consider the economic cost implications of this technology. The scope of this study included the economic analysis of water vapour selective membrane technology at Eskom's Medupi Power Station. Medupi is situated in the most water-stressed region in South Africa, with the nearest water source being the Crocodile river that is over 100 kilometres away. For Medupi to be equipped with wet-FGD, the water must be pumped from the Crocodile river.

The cost benefit analysis is expected to guide Eskom management and policy makers at the Department of Environmental Affairs on how to implement and comply with the Air Quality Act when operating coal fired power stations in areas with severely limited water resources. While wet-flue gas desulphurisation is the preferred choice of technology worldwide to bring SO<sub>2</sub> emissions within acceptable limits, it certainly proves to be challenging when water is not readily available. Since Medupi was commissioned after the South African Government passed the Air Quality Act 2008, it qualifies as a newly built power generation facility and is required by law to limit the SO<sub>2</sub> level in flue gas to 500 mg/Nm<sup>3</sup>. Moreover, the implementation of the FGD facility is the World Bank precondition for the financing of the coal-fired power station. However, the water required to treat the vast amounts of flue gas was simply not available in the area. As a result, a large investment had to be made to supply the required quantity of water to the FGD

system. The cost benefit analysis focused on the feasibility around water recovery from flue gas using the water vapour selective membrane technology as described in earlier chapters of this study.

The limitations of this study include the fact that the results were based on estimations only. It also only used Medupi power station as an example. In addition, this study was done from a financial point of view, because only the private costs and benefits were estimated. As per SAIAMC, the social costs and benefits of the water vapour selective membrane technology were not part of the scope of this study. Thus, they were not estimated in this study.



## **CHAPTER 5: RESULTS AND DISCUSSION**

### **5.1 INTRODUCTION**

This section estimates the costs and benefits of implementing the water vapour selective membrane technology at Eskom's Medupi Power Plant, as per the second research objective. In addition, it discusses the consequences should Eskom do nothing and continue to emit. Thereafter, it estimates the cost and benefits should Eskom choose to implement the membrane condenser technology by means of net present value analysis (NPV analysis); payback and discounted payback periods; internal rate of return (IRR); modified internal rate of return (MIRR); and profitability index (PI). Lastly, this section performs a sensitivity analysis on the CBA.

### **5.2 ESTIMATING THE COSTS AND BENEFITS OF WATER VAPOUR SELECTIVE MEMBRANE TECHNOLOGY**

This section explores three options that Eskom has. Option one is Eskom doing nothing and continues emitting. Option two is Eskom spends R467.4 million on building a pipeline to pump water from the Mokolo-Crocodile catchment area and clean the water to treat the flue gas at Medupi Power Station. Option three is Eskom spends R364.1 million which consists of installing membrane systems (R266.3 million with pay-off over five years) and infrastructure (R97.8 million with pay-off over 20 years) that recovers 858m<sup>3</sup> of water per hour and reuses that water for the FGD process, thereby preventing option two.

#### **5.2.1 Option One – Doing Nothing**

If Eskom chooses to do nothing and continue emitting flue gas into the atmosphere, there will be implications involved. The upside of doing nothing is that Eskom gets to keep the money that they would have spent had they implemented the membrane technology. However, the downside of doing nothing comes with grave consequences. They would thus not comply with the law and face the prospect of heavy fines. In addition, if a power station emits SO<sub>2</sub> levels that are higher than the maximum threshold outlined in the Air Quality Act, that power station can no longer operate, and thus must shut down (Herbst, Deidre. Telephone interview. 14 June 2019). For example, if this power station were to

shut down, it would result in loss of revenue for Eskom, loss of power and jobs for the people. In addition, if Medupi Power Station were to shut down, it loses the opportunity to earn R96 million<sup>11</sup> per day; that is revenue in excess of R35 billion per annum. Also, Eskom borrowed money from the World Bank to finance the Medupi Power Station, and as a pre-condition of the World Bank, Eskom must implement an FGD system. Thus, doing nothing is not an option for Eskom.

### **5.2.2 Option Two – Clean the Water and Treat the Flue Gas**

This option entails Eskom spending R 467.4 million on building a pipeline to pump water from the Mokolo-Crocodile catchment area and clean the water to treat the flue gas at Medupi Power Station. Thereby, Eskom would be complying with the Air Quality Act.

The infrastructure cost to secure water for Medupi is part of a R12.3 billion investment known as the Mokolo-Crocodile Water Augmentation Project Phase 2A (Eskom 2019). This project will augment water supplies to the Lephalale municipality, Eskom's Matimba and Medupi power stations, Exxaro's Grootegeeluk coal mine, and will also enable the further development of the mineral and energy prospects in the larger Waterberg region with a delivery capacity of 197 million m<sup>3</sup> per annum. Since the FGD system at Medupi power station will consume 3.80% of this capacity (7.5 million m<sup>3</sup>/a, 858 m<sup>3</sup>/hr (Eskom 2019), the effective investment cost to secure water for FDG at Medupi was set at R467.4 million.

The interest rate for borrowing such capital is estimated at 8.50%. With a payback period assumed to be 20 years, the monthly payments mount up to approximately R4,056,206. The energy and maintenance cost for the pump house associated with pumping the water for Medupi is estimated at R500,000/month. As mentioned, the infrastructure provides water for Medupi's FGD at a rate of 858m<sup>3</sup>/hr, which is 617760 m<sup>3</sup>/month. This brings the raw water cost to R4.00/m<sup>3</sup>. Purification of the raw water to the required quality will cost in the order of R5.00/m<sup>3</sup>. Total cost estimate for FDG water is R9.00/m<sup>3</sup> (See table 5.4).

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<sup>11</sup> See appendix C for a full breakdown of daily revenue

It should be noted that the wet-flue gas desulphurisation plant at Medupi uses 858m<sup>3</sup>/h to reduce the SO<sub>2</sub> emissions to limits that comply with the Air Quality Act. Downstream the FDG process, this water, which has been pumped in from the Crocodile River, purified to acceptable limits, is now ready to exit the power plant together with the flue gas. However, cleaning flue gas is not profitable and undertaking this option will result in cash outflows of approximately R4,556,206 per month for the next 20 years.

### 5.2.3 Option Three – Implementing Water Vapour Selective Membrane Technology

This option entails Eskom spending R364,082,591 which consists of installing membrane systems (R266,254,431 with pay-off over five years) and infrastructure (R97,828,160 with pay-off over 20 years) that recovers 858m<sup>3</sup> of water per hour and reuses that water for the FGD process, thereby complying with the law and preventing option two.

The cost estimates are based on the lab scale membrane module calculations and it shows that each pilot scale membrane module can collect 1.32kg water per hour. In order to capture all the water that is added to the flue gas during the FGD process, 647 821 membrane modules are needed (858 000 l/h / 1.32 = 647 821 modules). A breakdown of the cost of a membrane module is presented in Table 5.1. Each membrane module (produced at large volume) costs R411.

**Table 5.1: Membrane module cost breakdown at volume<sup>12</sup>**

Item	Detail of item	Quantity/ module	Cost /module
Membrane	R900/km	250 m	R225.00
Frames	Currently SS316, 2mm	1	R10.00
Resin	R222/L for 25l drum, estimated at R130/l at much large orders. The quantity of resin required per module is	0.6 L	R78.00

<sup>12</sup> This membrane module cost breakdown was made on the assumption of 100 000 modules per year and 400 modules per day



Item	Detail of item	Quantity/ module	Cost /module
	currently 0.86L. However, can still be optimised to an estimated 0.6L/module		
Spacer set	5 spacers per set, 2 sets per module, injection moulded cost R5.5 per set	2	R11.00
Labour	Winding, cutting, QC, based on 20 modules/p/p/d	R50	R50.00
Consumables	Mould costs, cutting blades (1000 modules per mould and blade)	0.001 * R7000	R7.00
Equipment	Winding machines R500 000, 1-year warranty	0.000001	R5.00
Overheads	Factory rental, utilities, admin (R200 000/month, 8000modules per month)	R200 000 / 8000	R25.00
<b>Total</b>			<b>R411.00</b>

Source: Bladergroen et al, 2019

A full-size water recovery plant will require R266,254,431 (647 821 \* R411) in terms of membrane modules for five years before replacement is required (Ludwin Daal Costing Report, 2013). In addition to the membrane module a further investment of R97,828,160 is required for additional capital expenses. A breakdown of these capital expenses is provided in the table below.

**Table 5.2: Breakdown of capital cost related to membrane technology infrastructure**

Item	Details (Year)	Cost (R)
Membrane modules	647,821 modules (0.8m <sup>2</sup> /module, 1.32kg/h/module based on 50% recovery from 95%RH 55-degree Celsius flue gas), 5-year warranty	R266,254,431
Condenser	€1,853,000 (2014 cost)	R34,737,748

Item	Details (Year)	Cost (R)
Piping and gas reticulation	€2,960,000 (2014 cost)	R55,490,412 <sup>13</sup>
Vacuum pump	Rotary vane vacuum pump (100000 m <sup>3</sup> /h at 10 mbar, with gas ballast) built by Busch (x10)	R7,600,000
<b>Total</b>		<b>R364,082,591</b>

Source: Ludwin Daal Costing Report (2013) and author's own calculations

The table above shows the complete breakdown of the capital costs of the water vapour selective membrane technology as it consists of membrane modules, a condenser, piping and gas reticulation. The membrane modules have a lifetime of five years, whereas the condenser, vacuum pump, piping and gas reticulation have a lifetime of 20 years. In addition, there are operating costs involved as well. The below table provides a breakdown of the operating expenses after one year.

**Table 5.3: Breakdown of operating cost related to membrane technology infrastructure**

Cost Variable	Cost
Variable costs	R3,600,000 <sup>14</sup>
<b>Total Operating costs after 1 year</b>	<b>R3,600,000</b>

Source: Author's own calculations

Based on the above table, the operating expenditure includes variable costs, which are made up of energy and maintenance costs. In addition, to the costs, the membrane technology has benefits in terms of water savings.

<sup>13</sup>Converted to Rand (R14.40/Euro, 2014) and compensated for annual inflation.

<sup>14</sup> Monthly running cost for vacuum pump and air-cooled condenser of R300,000

As mentioned, the infrastructure provides water for Medupi's FGD at a rate of 858m<sup>3</sup>/hr, which is 617760 m<sup>3</sup>/month. This brings the raw water cost to R4.00/m<sup>3</sup>. Purification of the raw water to the required quality will cost in the order of R5.00/m<sup>3</sup>. Total cost estimate for FDG water is R9.00/m<sup>3</sup>. The table below estimates the cost for importing and extracting water.

**Table 5.4: Cost comparison between importing or extracting water<sup>15</sup>**

Item	Investment Total (R)	Cost per month (R)	Water cost when imported from Mokolo-Crocodile scheme (R/m <sup>3</sup> )	Water cost when extracted from Flue gas (R/m <sup>3</sup> )
Membrane modules payback over 5 years	R266,254,431	R4,437,574		R7.20/m <sup>3</sup>
Infrastructure item with 20 years warranty	R467,400,000	R1,947,500	R3.20/m <sup>3</sup>	
	R97,828,160	R407,617		R0.70/m <sup>3</sup>
Monthly pumping and maintenance cost		R500,000	R0.80/m <sup>3</sup>	
Monthly running cost for vacuum pump and air- cooled condenser		R300,000		R0.50/m <sup>3</sup>
Water purification (investment + running cost)			R5.00/m <sup>3</sup>	-
<b>Total cost</b>			<b>R9.00/ m<sup>3</sup></b>	<b>R8.40/m<sup>3</sup></b>

Source: Author's own calculations

The cost of de-mineralized water to compensate for this capital expenditure and operating expenditures over the expected operational lifetime of the membranes (five years) was estimated to be R8.40/m<sup>3</sup>. It must be noted that the water from the membrane technology

<sup>15</sup> This is based on the assumption of 617 760m<sup>3</sup>/month.

is pure, thus pumping costs and purification costs do not apply, thereby this translates to a saving of R5.20 per m<sup>3</sup> and the recovered water can be reused for FGD purposes.

Also, the membrane modules recover 858 m<sup>3</sup> of water per hour, thus it translates to 7,516,080 m<sup>3</sup> per year. With a saving of R5.20 per m<sup>3</sup>, the annual water savings amount is approximately R39,083,616<sup>16</sup> per year. Moreover, as a secondary benefit, the membrane technology saves energy in that no reheating of flue gas is necessary. Energy savings amount to approximately R10,685,654<sup>17</sup>. In summary, the annual cash flows will thus be the annual operating costs minus the annual water and energy savings.

Based on time periods of 5, 10, 15 and 20 years and cost of capitals of 8.5%, 9%, 9.5%, and 10%, the economic measures of merit are indicated in the table below.

**Table 5.5: Initial economic measures of merit**

Initial Investment	R364,082,591			
Time Period	5 Years			
Discount Rate	8.50%	9.00%	9.50%	10.00%
NPV	(R163,136,354) <sup>18</sup>	(R165,832,001)	(R168,471,196)	(R171,055,456)
PP <sup>19</sup>	-	-	-	-
DPP	-	-	-	-
IRR	-10.26%	-10.26%	-10.26%	-10.26%
MIRR	-3.66%	-3.48%	-3.29%	-3.11%

<sup>16</sup> The water savings are subjected to increase annually due to inflation.

<sup>17</sup> According to the Ludwin Daal Costing Report (2013), energy savings amounted to 570,000 Euros in 2014. Thus, this figure was converted to Rands using the R14.40/Euro exchange rate of 2014 and compensated for annual inflation to 2019. In addition, the energy benefits increase annually due to inflation.

<sup>18</sup> The brackets indicate negative figures.

<sup>19</sup> Payback periods and discounted payback periods could not be estimated due to high replacement costs of membrane modules every five years.

<b>PI</b>	0.55	0.54	0.54	0.53
<b>Viable?</b>	No	No	No	No
<b>Time Period</b>	<b>10 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>9.00%</b>	<b>9.50%</b>	<b>10.00%</b>
<b>NPV</b>	(R201,588,604)	(R204,737,658)	(R207,755,776)	(R210,649,853)
<b>PP</b>	-	-	-	-
<b>DPP</b>	-	-	-	-
<b>IRR</b>	-5.96%	-5.96%	-5.96%	-5.96%
<b>MIRR</b>	3.54%	3.86%	4.19%	4.51%
<b>PI</b>	0.45	0.44	0.43	0.42
<b>Viable?</b>	No	No	No	No
<b>Time Period</b>	<b>15 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>9.00%</b>	<b>9.50%</b>	<b>10.00%</b>
<b>NPV</b>	(R234,852,729)	(R237,629,130)	(R240,216,228)	(R242,629,478)
<b>PP</b>	-	-	-	-
<b>DPP</b>	-	-	-	-
<b>IRR</b>	-4.21%	-4.21%	-4.21%	-4.21%
<b>MIRR</b>	5.54%	5.92%	6.29%	6.67%
<b>PI</b>	0.35	0.35	0.34	0.33
<b>Viable?</b>	No	No	No	No
<b>Time Period</b>	<b>20 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>9.00%</b>	<b>9.50%</b>	<b>10.00%</b>
<b>NPV</b>	(R263,628,733)	(R265,436,113)	(R267,037,973)	(R268,458,799)
<b>PP</b>	-	-	-	-

<b>DPP</b>	-	-	-	-
<b>IRR</b>	-3.30%	-3.30%	-3.30%	-3.30%
<b>MIRR</b>	6.42%	6.83%	7.23%	7.64%
<b>PI</b>	0.28	0.27	0.27	0.26
<b>Viable?</b>	No	No	No	No

Source: Author's own calculations

Based on the above table, after all the time periods, the net present values under the different discount rates are negative and the payback periods and discounted payback periods cannot be estimated. The internal rates of return and modified internal rates of return are less than the discount rates. Also, the profitability indexes are less than 1. Hence, after 5, 10, 15 and 20 years, the investment into membrane technology is not economically viable. In summary, over a time period of 5, 10, 15 and 20 years, coupled with an increasing interest rate, option three is not viable.

### 5.3 SENSITIVITY ANALYSIS

The sensitivity analysis was done on option three. In the sensitivity studies, the following scenarios were evaluated:

#### 5.3.1 What if the interest rates decline by 50, 100 and 150 basis points?

The below table shows the economic measures of merit if the interest rates were to decline by 50, 100 and 150 basis points.

**Table 5.6: Declining interest rates**

<b>Initial Investment</b>	<b>R364,082,591</b>			
<b>Time Period</b>	<b>5 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>8.00%</b>	<b>7.50%</b>	<b>7.00%</b>
<b>NPV</b>	(R163,136,354)	(R160,382,686)	(R157,569,374)	(R154,694,743)
<b>PP</b>	-	-	-	-

<b>DPP</b>	-	-	-	-
<b>IRR</b>	-10.26%	-10.26%	-10.26%	-10.26%
<b>MIRR</b>	-3.66%	-3.84%	-4.03%	-4.21%
<b>PI</b>	0.55	0.56	0.57	0.58
<b>Viable?</b>	No	No	No	No
<b>Time Period</b>	<b>10 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>8.00%</b>	<b>7.50%</b>	<b>7.00%</b>
<b>NPV</b>	(R201,588,604)	(R198,301,293)	(R194,867,951)	(R191,280,320)
<b>PP</b>	-	-	-	-
<b>DPP</b>	-	-	-	-
<b>IRR</b>	-5.96%	-5.96%	-5.96%	-5.96%
<b>MIRR</b>	3.54%	3.22%	2.89%	2.57%
<b>PI</b>	0.45	0.46	0.46	0.47
<b>Viable?</b>	No	No	No	No
<b>Time Period</b>	<b>15 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>8.00%</b>	<b>7.50%</b>	<b>7.00%</b>
<b>NPV</b>	(R234,852,729)	(R231,870,157)	(R228,662,993)	(R225,211,118)
<b>PP</b>	-	-	-	-
<b>DPP</b>	-	-	-	-
<b>IRR</b>	-4.21%	-4.21%	-4.21%	-4.21%
<b>MIRR</b>	5.54%	5.16%	4.79%	4.41%
<b>PI</b>	0.35	0.36	0.37	0.38
<b>Viable?</b>	No	No	No	No
<b>Time Period</b>	<b>20 Years</b>			



Discount Rate	8.50%	8.00%	7.50%	7.00%
NPV	(R263,628,733)	(R261,588,250)	(R259,283,595)	(R256,679,778)
PP	-	-	-	-
DPP	-	-	-	-
IRR	-3.30%	-3.30%	-3.30%	-3.30%
MIRR	6.42%	6.02%	5.61%	5.21%
PI	0.28	0.28	0.29	0.29
Viable?	No	No	No	No

Source: Author's own calculations

Based on the above table, after all the time periods, the net present values under the different discount rates are negative and the payback periods and discounted payback periods cannot be estimated. The internal rates of return and modified internal rates of return are less than the discount rates. Also, the profitability indexes are less than 1. Therefore, after 5, 10, 15 and 20 years, the investment into membrane technology is not economically viable. In summary, over a time period of 5, 10, 15 and 20 years, coupled with a declining interest rate, option 3 is still not viable.

### 5.3.2 What if the cost of the membrane modules doubles?

If the cost of the membrane modules were to double from R266,254,431 to R532,508,862 then the initial investment of the membrane technology will increase to R630,337,022. However, the results are the same as the initial results. The net present values under the different discount rates are negative and the payback periods and discounted payback periods cannot be estimated. The internal rates of return and modified internal rates of return are less than the discount rates. Also, the profitability indexes are less than 1. Therefore, if the cost of the membrane modules were to double, the investment will not be viable (These estimates are shown in Appendix D).

### 5.3.3 What if the cost of the membrane modules decreased by half?

If the cost of the membrane modules were to decrease by half from R266,254,431 to R133,127,216 then the initial investment of the membrane technology will decrease to R230,955,376. However, the results are the same as the initial results. The net present values under the different discount rates are negative and the payback periods and discounted payback periods cannot be estimated. The internal rates of return and modified internal rates of return are less than the discount rates. Also, the profitability indexes are less than one. Therefore, if the cost of the membrane modules were to decrease by half, the investment will not be viable (these estimates are shown in Appendix E).

#### 5.3.4 What if the annual cash flows are the same indefinitely<sup>20</sup>?

The below table illustrates the economic measures of merit if the cash flows are assumed to be the same indefinitely.

**Table 5.7: Annual cash flows are the same for an indefinite period**

<b>Initial Investment</b>	<b>R364,082,591</b>			
<b>Annual Cash Flows</b>	<b>R46,169,270</b>			
<b>Growth Rate</b>	<b>5.40%</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>9.00%</b>	<b>9.50%</b>	<b>10.00%</b>
<b>NPV</b>	R1,125,248,691	R918,397,124	R761,997,159	R639,597,186
<b>PP</b>	7.89 Years	7.89 Years	7.89 Years	7.89 Years
<b>DPP</b>	8.56 Years	8.60 Years	8.63 Years	8.67 Years
<b>IRR</b>	18.08%	18.08%	18.08%	18.08%
<b>MIRR</b>	-	-	-	-
<b>PI</b>	4.09	3.52	3.09	2.76

<sup>20</sup> It must be noted that replacement costs do not apply in this scenario

<b>Viable?</b>	Yes	Yes	Yes	Yes
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Source: Author's own calculations

Based on the above table, the net present values under the different discount rates are positive and the payback periods and discounted payback periods are positive and less than the assumed periods of 10, 15 and 20 years. The internal rates of return are greater than the discount rates. The modified internal rates of return could not be estimated. Also, the profitability indexes are greater than one, indicating that the membrane technology is profitable. Hence, in the absence of replacement costs for the membrane modules, and if the cash flows were the same each year for an indefinite period, the investment into membrane technology will be viable.

### 5.3.5 What if the membrane modules have an economic life of 20 years?

The below table shows the economic measures of merit if the membrane modules have an economic life of 20 years.

**Table 5.8: Membrane modules with economic life of 20 years**

<b>Initial Investment</b>	R364,082,591			
<b>Time Period</b>	5 Years			
<b>Discount Rate</b>	8.50%	9.00%	9.50%	10.00%
<b>NPV</b>	(R163,136,354)	(R165,832,001)	(R168,471,196)	(R171,055,456)
<b>PP</b>	6.74 Years	6.74 Years	6.74 Years	6.74 Years
<b>DPP</b>	9.67 Years	9.94 Years	10.24 Years	10.55 Years
<b>IRR</b>	-10.26%	-10.26%	-10.26%	-10.26%
<b>MIRR</b>	-3.66%	-3.48%	-3.29%	-3.11%
<b>PI</b>	0.55	0.54	0.54	0.53

<b>Viable?</b>	No	No	No	No
<b>Time Period</b>	<b>10 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>9.00%</b>	<b>9.50%</b>	<b>10.00%</b>
<b>NPV</b>	R10,697,453	R1,772,259	(R6,839,470)	(R15,151,192)
<b>PP</b>	6.74 Years	6.74 Years	6.74 Years	6.74 Years
<b>DPP</b>	9.67 Years	9.94 Years	10.24 Years	10.55 Years
<b>IRR</b>	9.10%	9.10%	9.10%	9.10%
<b>MIRR</b>	8.81%	9.05%	9.29%	9.53%
<b>PI</b>	1.03	1.00	0.98	0.96
<b>Viable?</b>	Yes	Yes	No	No
<b>Time Period</b>	<b>15 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>9.00%</b>	<b>9.50%</b>	<b>10.00%</b>
<b>NPV</b>	R161,076,942	R143,467,615	R126,715,197	R110,769,651
<b>PP</b>	6.74 Years	6.74 Years	6.74 Years	6.74 Years
<b>DPP</b>	9.67 Years	9.94 Years	10.24 Years	10.55 Years
<b>IRR</b>	14.34%	14.34%	14.34%	14.34%
<b>MIRR</b>	11.18%	11.44%	11.70%	11.97%
<b>PI</b>	1.44	1.39	1.35	1.30
<b>Viable?</b>	Yes	Yes	Yes	Yes
<b>Time Period</b>	<b>20 Years</b>			

Discount Rate	8.50%	9.00%	9.50%	10.00%
NPV	R291,166,659	R263,259,165	R237,070,072	R212,473,468
PP	6.74 Years	6.74 Years	6.74 Years	6.74 Years
DPP	9.67 Years	9.94 Years	10.24 Years	10.55 Years
IRR	16.31%	16.31%	16.31%	16.31%
MIRR	11.74%	12.01%	12.28%	12.56%
PI	1.80	1.72	1.65	1.58
Viable?	Yes	Yes	Yes	Yes

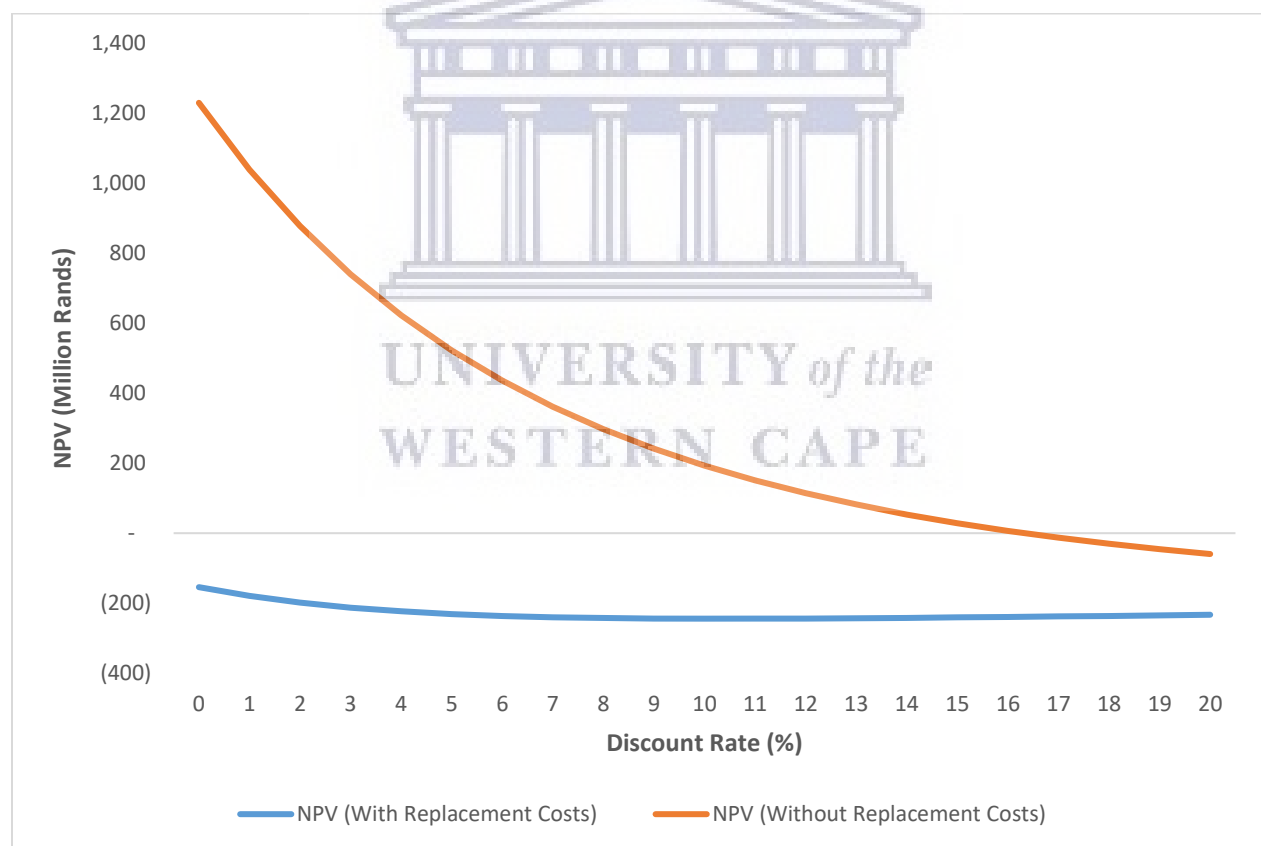
Source: Author's own calculations

Based on the above table, after five years the net present values under the different discount rates are negative and the payback periods and discounted payback periods are greater than five years. The internal rates of return and modified internal rates of return are less than the discount rates and the profitability indexes are less than one. Hence, after five years the investment into membrane technology is not viable. In contrast, after ten years there is some economic viability in the membrane technology if the discount rate is 9.00% and below. At a discount rate of 9.00% and lower, the net present values are positive, and the payback and discounted payback periods are less than ten years. In addition, the internal rates of return and modified internal rates of return are slightly greater than the cost of capital and the profitability indexes are equal to and greater than one. However, at a discount rate of 9.50% and greater, the net present values are negative, the payback periods are less ten years and discounted payback periods are slightly greater than ten years. Also, the internal rates of return and modified internal rates of return are slightly less than the discount rates and the profitability indexes are less than one. Hence, the investment into membrane technology will not be viable after ten years coupled with an interest rate of 9.50% and above.

Nevertheless, after 15 years and 20 years, the net present values under the different discount rates are positive and in excess of R100 million and the payback periods and discounted payback periods are less than 15 and 20 years. The internal rates of return and modified internal rates of return are higher than the discount rates and the profitability indexes are greater than one. Therefore, after 15 and 20 years, the investment into membrane technology will be viable if the membrane modules have no replacement costs for 20 years.

The below figure illustrates the net present value profile of the membrane technology. It compares the net present values of the initial option three with that of the last scenario of the sensitivity analysis.

**Figure 5.1: Net present value profile**



Source: Author's own calculations

Based on the above figure, the net present values of option three are negative due to the replacement costs of membrane modules every five years. However, if the membrane

modules were to have an economic life of 20 years, then the membrane technology will have positive net present values as indicated in the above figure.

In summary, if the interest rates were to decline by 50, 100 and 150 basis points, the investment into membrane technology will not be viable. Also, if the cost of the membrane modules were to increase by 100% or to decline by 50%, the investment will not be viable. However, if the annual cash flows are the same each year for an indefinite time period, the investment into membrane technology will be viable. Moreover, if the membrane modules had the same economic life of 20 years as the other infrastructure, e.g., condenser, vacuum pump, piping and reticulation, the investment into membrane technology will be viable.

#### **5.4 CONCLUSION**

This chapter estimated the costs and benefits of implementing water vapour selective membrane technology at Medupi Power Station. Eskom faced three options, namely, doing nothing, cleaning flue gas at a cost of R467.4 million, or implementing water vapour selective membrane technology at a cost of R364.1 million, thereby preventing the second option. It was found that by doing nothing Eskom might have to shut down its power plant, thereby leading to an annual revenue loss of more than R35 billion. Also, Eskom obtained a loan from the World Bank to finance the power station and, as a pre-condition, Eskom must have an FGD system in place. Hence, doing nothing was not an option. In addition, option 2 was also not economically feasible since cleaning flue gas was not profitable and this would have resulted in monthly outflows of R4.6 million for the next 20 years.

Moreover, a cost-benefit analysis (CBA) was conducted on option three and it was found that this option would also not be economically feasible after 5, 10, 15 and 20 years. According to the results of the CBA, the net present values under the different interest rates were negative; both the payback and the discounted payback periods could not be estimated; the internal rates of return and modified internal rates of return were less than the discount rates; and the profitability indexes were less than one. In contrast to the empirical studies in the literature review which showed economic viability of the



technologies in other countries, the initial results of this study concluded that investing in membrane technology would not be feasible in South Africa. Therefore, Eskom would currently be better off going for option two. Although cleaning flue gas will not be profitable for them, they will incur less costs in the future as opposed to option three, and they will also be in compliance with the Air Quality Act.

Furthermore, a sensitivity analysis was conducted on the results of the CBA using five scenarios. It was found that the first three scenarios yielded the same conclusions as the initial CBA. If the interest rates were to decline, option three is not viable. Also, if the cost of the membrane modules were to double or decrease by half, option three is still not viable. However, scenarios four and five yielded positive results. If the annual cash flows are the same each year indefinitely, option three would be feasible. Lastly, if the membrane modules have an economic lifetime of 20 years, option three would be feasible.



# **CHAPTER 6: CONCLUSIONS AND POLICY RECOMMENDATIONS**

## **6.1 INTRODUCTION**

This chapter provides a summary of the study. In addition, it provides the key conclusions of the study and the implications thereof. Also, it provides some policy recommendations that may guide future research for studies on water recovery from flue gas.

## **6.2 SUMMARY OF THE STUDY**

This study examined the policies and trends regarding flue gas emissions in South Africa. The Air Quality is the only policy that addresses flue gas emissions in South Africa. Eskom's coal power plants were said to be the emitters of flue gas in South Africa and, in order to be compliant with the Act, Eskom had to implement wet-flue gas desulphurisation systems at Medupi and Kusile power stations. Wet-flue gas desulphurisation entailed an increase in water requirements of these power stations, and thus a need to recover water from flue gas to supplement the water requirements. The three methods to recover water from flue gas were flue gas condensation technology, desiccant drying systems, and water vapour selective membrane technology.

In addition, this study aimed to estimate the economic costs and benefits of implementing these three methods at Eskom. It was found that the water vapour selective membrane technology is superior to flue gas condensation technology and desiccant drying systems. Thus, it was used as the technology of choice in this study. The study also outlined some of the empirical studies on membrane technology, flue gas condensation, and desiccants, and the results showed that the implementation of these technologies were feasible in other countries. However, these studies were very limited in their use of economic measures of merit. Also, the literature available that deals specifically with the economic analysis of membrane technology, was very limited.

Moreover, the study followed the cost benefit approach (CBA) and utilised NPV, PP, DPP, IRR, MIRR, and PI as measures of economic merit to estimate the economic costs and benefits of implementing water vapour selective membrane technology. However, the

economic costs, and benefits of implementing the technology could not be estimated since shadow prices and externalities were not part of the scope of this study. As a result, this study estimated the private costs and benefits of implementing water vapour selective membrane technology at Eskom's Medupi Power Station. Eskom was faced with three options, namely, doing nothing; pumping water from the Crocodile River to clean and treat flue gas at Medupi Power Station; and implementing a membrane system to recover flue gas at Medupi Power Station. Doing nothing was not an option because Medupi would then have to shut down and lose revenue in excess of R35 billion per annum. The second option was not profitable because it would result in yearly outflows of R4.6 million for 20 years. A cost-benefit analysis was done on the third option and it concluded that this option was not feasible due to the cost of the membrane modules that must be replaced every five years; currently Eskom would be better off going for the second option in that they would comply with the law and incur less costs in the future. However, a sensitivity analysis was done on the third option and it concluded that if the membrane modules had an economic life of 15 years or more, this option would be feasible.

### **6.3 KEY CONCLUSIONS AND IMPLICATIONS**

In conclusion, based on the results of the study, the investment into water vapour selective membrane technology would currently not be feasible in the South African context. As a result, Eskom should clean the flue gas because that would be a better alternative moving forward in that they would comply with the law.

### **6.4 RECOMMENDATIONS FOR FUTURE STUDIES**

Considering the findings of the study, it is recommended that:

- There be a buy-in from both the public and the private sector to invest in research regarding the development of membrane modules with economic lifetimes of 15 years and more, in South Africa.
- As far the pure financial analysis is concerned, the investment into water vapour selective membrane technology is not feasible, but if one considers the shadow prices and externalities, the result could be different.
- More similar studies must be done in other industries that emit flue gas in South Africa.

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## APPENDICES

### Appendix A: Coal-Fired Power Stations and their Capacities

Coal-Fired Power Plant	Capacity (MW)	Cooling
Arnot	2 352	Wet, re-circulating
Camden	1 510	Wet, re-circulating
Duvha	3 600	Wet, re-circulating
Grootvlei	1 200	Wet, re-circulating and dry
Hendrina	2 000	Wet, re-circulating
Kendal	4 116	Indirect dry
Komati	940	Wet, re-circulating
Kriel	3 000	Wet, re-circulating
Kusile	4 800	Direct dry
Lethabo	3 708	Wet, re-circulating
Majuba	4 110	Wet, re-circulating and dry
Matimba	3 990	Direct dry
Matla	3 600	Wet, re-circulating
Medupi	4 788	Direct dry
Tutuka	3 654	Wet, re-circulating

Source: [www.eskom.co.za](http://www.eskom.co.za) and Wassung, 2010.

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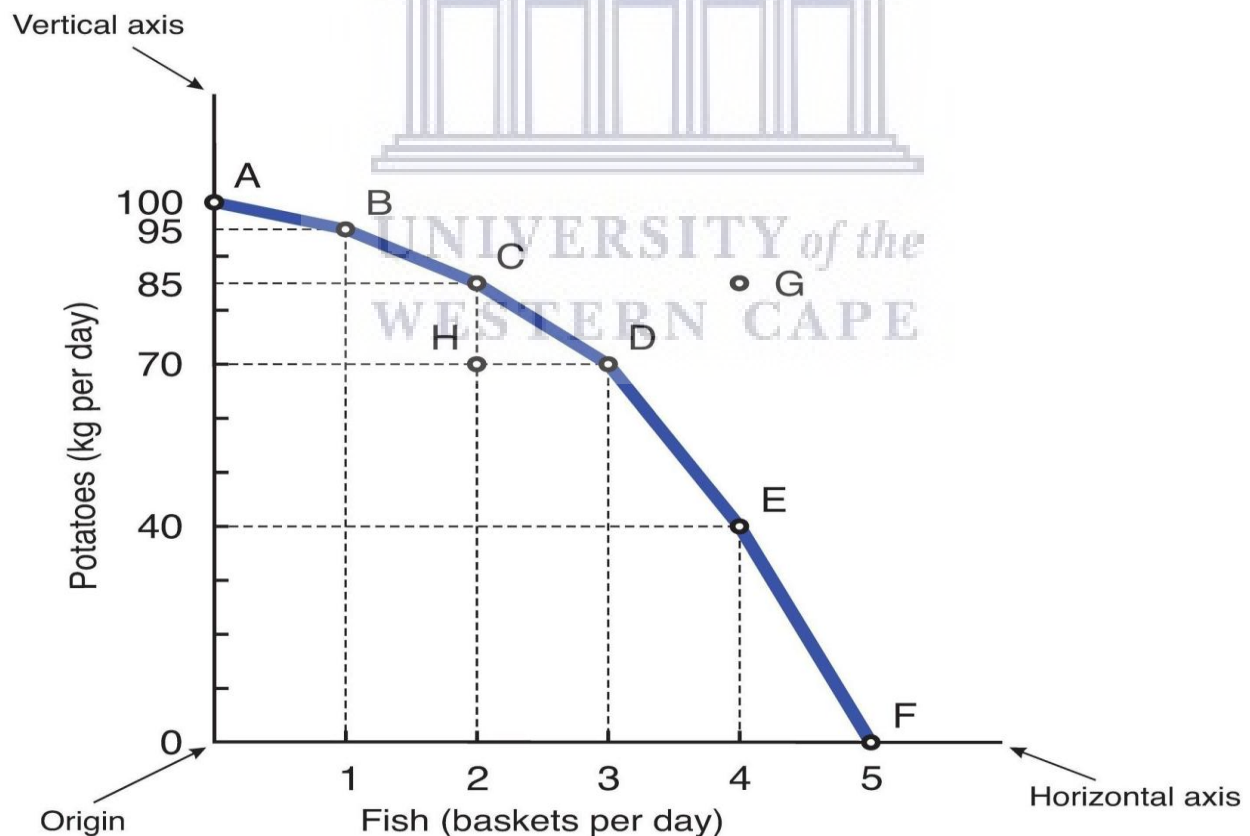
## Appendix B: Illustration of PPC Curve Explaining Scarcity, Choice and Opportunity Cost

Possibility	Fish (Baskets per day)	Potatoes (Kg per day)
A	0	100
B	1	95
C	2	85
D	3	70
E	4	40
F	5	0

Source: Mohr and Fourie (2008:8)

The above table shows the possible combinations of two goods, namely fish and potatoes for the Wild Coast community. Potatoes is on the y-axis and is indicated in kilograms (kg) per day. Fish, on the other hand, is on the x-axis and is indicated in baskets per day.

### A production possibilities curve for the Wild Coast community



Source: Mohr and Fourie (2008:8)

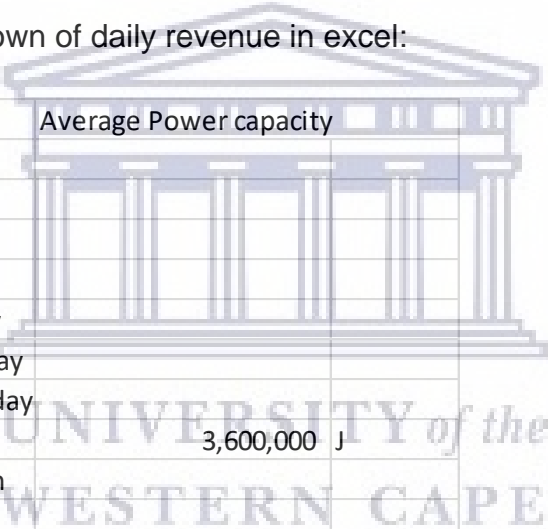
In the above figure, scarcity is illustrated by the fact that all points to the right of the curve e.g., point G, are unattainable. The curve thus forms a frontier or boundary between what is possible and what is not possible. Choice is illustrated by the need to choose among the available combinations along the curve. Opportunity cost is illustrated by the negative slope of the curve, which implies that more of one good can only be obtained by sacrificing the other good. Hence, opportunity cost refers to the trade-off between the two goods.



## Appendix C: Breakdown of Daily Revenue

According to Bladergroen (2019, personal communication), the average capacity of Medupi Power Station is **4,000 MW (Megawatt)**, that means they produce **4,000 MJ/s**. There are **3,600 seconds** in **1 hour** and **24 hours in 1 day**, thereby Medupi produces, on average, **345,600,000 MJ/day (4,000\*3,600\*24)**. In addition, **1 kWh equals 3,600,000 J**. Thus, **345,600,000 MJ/day multiplied by 1,000,000 and then divided by 3,600,000 equals 96,000,000 kWh/day**. The average cost of electricity is about **R1.00 per kWh** (Bladergroen, 2019). Thus, the revenue of electricity generation for Medupi Power Station will be approximately **R96,000,000**. The annual revenue will be approximately **R35,040,000,000**.

Please see below breakdown of daily revenue in excel:



4,000	MW	Average Power capacity	
4,000	MJ/s		
3,600	s/h		
24	h/day		
345,600,000	MJ/day		
96,000,000	kWh/day		
96,000	MWh/day		
1	kWh	3,600,000	J
1,000	R/MWh		
96,000,000	R/day		
35,040,000,000	R/year		

- $4,000 \text{ MJ/s} * 3,600 * 24 = 345,600,000 \text{ MJ/day}$
- $1 \text{ kWh} = 3,600,000 \text{ J}$
- $(345,600,000 \text{ MJ/day} * 1,000,000) / 3,600,000 = 96,000,000 \text{ kWh/day}$
- $1 \text{ kWh} = \text{R}1.00$  (Average cost of electricity)
- $96,000,000 * \text{R}1.00 = \text{R}96,000,000$  revenues per day
- $\text{R}96,000,000 * 365 = \text{R}35,040,000,000$  revenues per annum

# Appendix D: Membrane Modules Costs Double

<b>Initial Investment</b>	<b>R630,337,022</b>			
<b>Time Period</b>	<b>5 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>9.00%</b>	<b>9.50%</b>	<b>10.00%</b>
<b>NPV</b>	(R193,858,328)	(R199,713,588)	(R205,446,227)	(R211,059,542)
<b>PP</b>	-	-	-	-
<b>DPP</b>	-	-	-	-
<b>IRR</b>	-3.77%	-3.77%	-3.77%	-3.77%
<b>MIRR</b>	0.81%	1.00%	1.19%	1.39%
<b>PI</b>	0.69	0.68	0.67	0.67
<b>Viable?</b>	No	No	No	No
<b>Time Period</b>	<b>10 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>9.00%</b>	<b>9.50%</b>	<b>10.00%</b>
<b>NPV</b>	(R240,843,110)	(R248,677,394)	(R256,195,854)	(R263,414,595)
<b>PP</b>	-	-	-	-
<b>DPP</b>	-	-	-	-
<b>IRR</b>	-1.04%	-1.04%	-1.04%	-1.04%
<b>MIRR</b>	5.46%	5.80%	6.14%	6.48%
<b>PI</b>	0.62	0.61	0.59	0.58
<b>Viable?</b>	No	No	No	No
<b>Time Period</b>	<b>15 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>9.00%</b>	<b>9.50%</b>	<b>10.00%</b>
<b>NPV</b>	(R281,488,528)	(R290,072,189)	(R298,129,759)	(R305,700,754)
<b>PP</b>	-	-	-	-

<b>DPP</b>	-	-	-	-
<b>IRR</b>	0.11%	0.11%	0.11%	0.11%
<b>MIRR</b>	6.71%	7.10%	7.48%	7.87%
<b>PI</b>	0.55	0.54	0.53	0.52
<b>Viable?</b>	No	No	No	No
<b>Time Period</b>	<b>20 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>9.00%</b>	<b>9.50%</b>	<b>10.00%</b>
<b>NPV</b>	(R316,649,910)	(R325,068,019)	(R332,779,322)	(R339,854,462)
<b>PP</b>	-	-	-	-
<b>DPP</b>	-	-	-	-
<b>IRR</b>	0.73%	0.73%	0.73%	0.73%
<b>MIRR</b>	7.25%	7.67%	8.08%	8.49%
<b>PI</b>	0.50	0.48	0.47	0.46
<b>Viable?</b>	No	No	No	No

Source: Author's own calculations

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# Appendix E: Membrane Modules Costs Decrease by 50%

Initial Investment	R230,955,376			
Time Period	5 Years			
Discount Rate	8.50%	9.00%	9.50%	10.00%
NPV	(R147,775,367)	(R148,891,208)	(R149,983,680)	(R151,053,413)
PP	-	-	-	-
DPP	-	-	-	-
IRR	-20.74%	-20.74%	-20.74%	-20.74%
MIRR	-12.41%	-12.24%	-12.08%	-11.91%
PI	0.36	0.36	0.35	0.35
Viable ?	No	No	No	No
Time Period	10 Years			
Discount Rate	8.50%	9.00%	9.50%	10.00%
NPV	(R181,961,350)	(R182,767,789)	(R183,535,737)	(R184,267,482)
PP	-	-	-	-
DPP	-	-	-	-
IRR	-14.18%	-14.18%	-14.18%	-14.18%
MIRR	-0.69%	-0.39%	-0.09%	0.21%
PI	0.21	0.21	0.21	0.20
Viable ?	No	No	No	No
Time Period	15 Years			
Discount Rate	8.50%	9.00%	9.50%	10.00%
NPV	(R211,534,830)	(R211,407,600)	(R211,259,463)	(R211,093,840)
PP	-	-	-	-

<b>DPP</b>	-	-	-	-
<b>IRR</b>	-11.76%	-11.76%	-11.76%	-11.76%
<b>MIRR</b>	2.84%	3.19%	3.55%	3.90%
<b>PI</b>	0.08	0.08	0.09	0.09
<b>Viable ?</b>	No	No	No	No
<b>Time Period</b>	<b>20 Years</b>			
<b>Discount Rate</b>	<b>8.50%</b>	<b>9.00%</b>	<b>9.50%</b>	<b>10.00%</b>
<b>NPV</b>	(R237,118,144)	(R235,620,160)	(R234,167,299)	(R232,760,967)
<b>PP</b>	-	-	-	-
<b>DPP</b>	-	-	-	-
<b>IRR</b>	-10.67%	-10.67%	-10.67%	-10.67%
<b>MIRR</b>	4.46%	4.85%	5.23%	5.61%
<b>PI</b>	-0.03	-0.02	-0.01	-0.01
<b>Viable?</b>	No	No	No	No

Source: Author's own calculations

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