Impacts and control of coal-fired power station emissions in South Africa

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Dedication

I dedicate this work to my parents, Willem and Christa Jansen van Rensburg. This is to thank you for always putting my education first. Without your love, patience and support I would not have been where I am today.

You taught me by example to be curious about the world around me and to never stop learning.

Contents

Abstract

South Africa is a major role player in coal generated energy both regionally and globally. It is the main electrical power generator in Africa, and falls under the top ten coal producers and consumers in the world. The South African energy sector of which 85% to 94% is constituted by coal-fired power plants is one of the major emitters of criteria pollutants (Particulate Matter (PM), Nitrogen Oxides (NO_x) and Sulphur Dioxide (SO_2)) as well as Carbon Dioxide (CO_2) emissions in the country.

The South African electricity industry and air quality regulation thereof has undergone many changes over the past decade. The most prominent of these changes is the promulgation of the Listed Activities and Associated Minimum Emission Standards (MES) identified in terms of section 21 of the National Environmental Management Air Quality Act (NEM:AQA) that came into effect in 2010. The South African energy crisis, on the other hand, is placing enormous amounts of strain on the South African energy generating system and economy since the middle 2000's.

The MES stipulates that emissions are to be measured by means of Continuous Emissions Monitoring Systems (CEMS) instead of being calculated by means of a mass balance methodology as has been done traditionally. The paper "***A critical comparison of gaseous coal-fired large boiler emission estimation in South Africa***" (Chapter3) compares the emissions estimation techniques in terms of cost, ease of operation/calculation, data quality and practicality in the South African context. It was found that calculation techniques are by far cheaper and simpler to implement than CEMS, which need expertly trained operators and are replaced every 10-15 years. The data quality of both methods is currently similar in South Africa. If operated properly, and if proper quality assurance/quality control measures are in place, CEMS can obtain emissions measurements with lower uncertainties than that of calculation methods. However, there is still a knowledge-gap in operating these systems in our country and the data availability requirements of the legislation cannot currently be achieved. Calculations are simple and cost effective techniques that can be used as a backup to CEMS measurements and it is believed that this technique should be used in conjunction with CEMS until such time as the quality of South African CEMS measurements is proven.

The paper entitled "***The impact of the South African energy crisis on emissions***" (Chapter 4) investigates the effect the South African energy crisis had (and still has) on emissions from various sources, including power stations. Since 2007, the start of the South African energy crisis, the existing coal-fired power station fleet has been under enormous strain. During this period, maintenance was brought to a halt and this caused the deterioration of the overall condition of the fleet. Emissions abatement technology used at existing power stations also suffered from lowered maintenance and as a result the removal efficiencies of these systems decreased. This led to an overall increase in coal-fired power station emissions from the majority of criteria emissions (especially emissions of pollutants that are abated) and emissions of CO_2. This means that, if the energy crisis persists, emissions from power stations may be much higher than expected and this should be taken in account in future planning.

The paper "***A perspective of South African coal-fired power station emissions***" (Chapter 5) predicts future coal-fired power station emissions for a range of different scenarios based on pressures facing the energy generating industry at present, and possibly in the future. The scenarios differ in terms of different retrofit rates of power stations with emissions abatement technologies and different energy demand outlooks. The worst case scenario assumes a relatively high energy demand outlook and further assumes that the energy crisis persists over the next 15 years whereas the best case scenario assumes lower energy demand and abatement retrofits at some stations. Worst case emissions are roughly double that of best case emissions during 2030 for PM, SO_2 and NO_x. Another important finding is that it is unlikely that the South African climate commitment target of 280 Mt CO_2 in 2030 will be made, unless energy demand dramatically decreases in the future.

The listed activities and associated MES identified in terms of section 21 of the NEM:AQA set blanket Minimum Emission Standards for all large boilers (>100 MW) including coal-fired power stations. Tension sometimes arise between the ambient air quality standards and MES, as power stations are expected to comply with MES irrespective of whether ambient air quality standards in their vicinity are met and their potential impact on human health. This may lead to the unnecessary instalment of costly abatement technology, the funding which may have been applied with greater effect to health exposure reduction elsewhere. The paper "***Emissions management and health exposure: Should all power stations be treated equal?***" compares the potential health exposure to 15 power stations within the Highveld of South Africa in order to propose an emissions management strategy that is optimized for reduced health exposure and cost. It was found that the health exposure to power station emissions varies greatly from station to station and from pollutant to pollutant Potential human health exposure in the form of intake fractions estimated in this investigation differed up to two orders of magnitude for SO_2, NO_x and primary PM_{10}. Secondary PM emissions differed less, due to the fact that these pollutants form away from the source and are therefore able to disperse more evenly in the atmosphere. Based on the findings of this study the author believe that a more logical solution to the effective management of power station emissions, with optimal human health and reduced cost as end goal, may be to address power station emissions on an individual power station basis.

Keywords: *Coal-fired power station, energy crisis, emissions management, health exposure*

Preface

This study investigates coal-fired power station emissions in South Africa following a holistic approach. This study has four main objectives and each objective is addressed by a separate article. The objectives of this study are outlined below:

Objective 1: To compare CEMS and mass balance coal-fired power station emission estimation methods.

The article "***A critical comparison of gaseous coal-fired large boiler emission estimation in South Africa***" compares the two different methods (CEMS and mass balance methods) in terms of cost, ease of operation, data quality and practicality for use at South African coal-fired power stations.

Objective 2: To investigate the effect of the South African energy crisis on emissions.

The article entitled "***The impact of the South African energy crisis on emissions***" investigates the increasing effect of an energy restricted environment on emissions.

Objective 3: To make projections of future South African coal-fired power station emissions.

The article entitled "***A perspective of South African coal-fired power station emissions***" makes projections for future emissions scenarios from South African coal-fired power stations. These scenarios are based on past experiences and different future retrofits of power stations with emissions abatement technology as well as different projected energy demand scenarios.

Objective 4: To develop a coal-fired power station emissions management strategy for the Highveld of South Africa.

The article entitled "***Emissions management and health exposure: Should all power stations be treated equal?***" compares human health exposure to individual power station emissions within the Highveld of South Africa in order to understand how the human health exposure to emissions from individual power stations differ.

The article model adopted by the Faculty of Natural Sciences in terms of the General Rules of the North-West University has been followed as the research component of this post-graduate study. The work presented in this thesis was conducted by the author from beginning 2014 to end 2015 and contains original data that has never been published or previously submitted for degree purposes to any university.

The author was personally involved in the conceptualization, research and the writing of the thesis and journal articles. Where use has been made of work by other researchers, such work is duly acknowledged in the text.

The overarching format and reference style in this thesis is in accordance with the specifications provided in the Manual for Post-graduate Students of the North-West University. This thesis is presented in article format, utilizing articles that have already been peer-reviewed and published and others that have been submitted to a journal for review. These articles are included with permission from the journals and conference proceedings in which they appear. Thus, the articles in Chapters 3 through 6, although reformatted to the same style as the rest of the thesis, retained their original content as published (or submitted). In the case of Chapter 4 (manuscript 2), an extended version of the paper is provided with the kind permission of the Wessex Institute of Technology (WIT). A summary of the manuscripts and relevant journals/conference proceedings to which they have been submitted or where they have been published is given below:

Manuscript 1:

I. Pretorius, J.B. Keir, S.J. Piketh and **R. P. Burger**, 2015. A critical comparison of gaseous coal-fired large boiler emission estimation in South Africa. Submitted to the *CLEAN – Soil, Air, Water* Journal.

Manuscript 2:

I. Pretorius, S.J. Piketh and **R. P. Burger**, 2015. The impact of the South African energy crisis on emissions. *WIT Transactions on Ecology and The Environment*, 198, ISSN 1743-3541 (on-line). ***Published with open access. Used with kind permission from WIT Press. Extended version.***

Manuscript 3:

I. Pretorius, S.J. Piketh, R.P. Burger and **H. Neomagus**, 2015. A perspective of South African coal-fired power station emissions. *Journal of Energy in Southern Africa*, 26(3), 27-40. ***Published. Used with permission.***

Manuscript 4:

I. Pretorius, S.J. Piketh and **R. P. Burger**, 2015. Emissions management and health exposure: Should all power stations be treated equal? Submitted to the Atmospheric Environment Journal.

A number of peer reviewed and non-peer reviewed conference contributions have also followed from this research. A summary thereof is given below:

I. Pretorius, **S.J. Piketh** and **R.P. Burger**, 2015. Emissions management and health impacts: are all power stations equal? National Association for Clean Air, oral presentation, peer reviewed.

I. Pretorius, **S.J. Piketh** and **R.P. Burger**, 2015. The impact of the South African energy crisis on emissions. 23rd International Conference on Modelling, Monitoring and Management of Air Pollution, oral presentation, peer reviewed.

I. Pretorius, **S.J. Piketh** and **R.P. Burger, 2014**. South African coal fired power station emissions: the present, the past and the future. International Global Atmospheric Chemistry Symposium, poster presentation, non-peer reviewed.

I. Pretorius, **S.J. Piketh**, **R.P. Burger** and **H. Neomagus**, 2014. South African coal-fired power stations emissions: the past, the present and the future. National Association for Clean Air, oral presentation, peer reviewed.

I. Pretorius, **S.J. Piketh** and **R.P. Burger**, 2013. Particulate matter emissions from coal fired power stations in South Africa. International Union for Air Pollution Prevention and Environmental Protection Associations International Conference, poster presentation, peer reviewed.

I would like to thank the following people for their assistance with the work presented in this thesis:

To my supervisor and co-supervisor, **Prof. Stuart Piketh** and **Mr. Roelof Burger**, many thanks for their advice, leadership and support. Thank you further for all the opportunities you granted me to gain experience by supporting me to present at conferences both nationally and internationally.

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To all the anonymous reviewers of journals and conference proceedings, thank you so much for putting aside the time to review my/our work and thank you for your constructive comments which led to the improvement of my study.

Lastly, I want to thank my husband, **Johan Pretorius**, for his patience, support, advice and for teaching me not to take life too seriously.

Glossary

BS	British Standards
CEMS	Continuous Emissions Monitoring System
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DEA	Department of Environmental Affairs
DME	Department of Minerals and Energy
DOE	Department of Energy
ESP	Electrostatic Precipitator
FB	Fractional Bias
FFP	Fabric Filter Plant
FGD	Flue Gas Desulphurization
FRIDGE	Fund for Research into Industrial Development Growth and Equity
GDP	Gross Domestic Product
GE	Gross Error
Mt	Megaton
Gt	Gigaton
Hg	Mercury
HNO_3	Nitric Acid

HPA	Highveld Priority Area
IOA	Index of Agreement
IRP	Integrated Resource Plan for Electricity
K	Kelvin
km	Kilometre
LCC	Lambert Conic Conformal
LHV	Lower Heating Value
LNB	Low NO_x Burner
m	Metre
m/s	Metres per Second
MB	Mean Bias
MES	Minimum Emission Standards
MM5	Fifth-Generation Penn State/NCAR Mesoscale Model
MW	Megawatt
N_2O	Nitrous Oxide
NCEP	National Centre for Environmental Prediction
NEM:AQA	National Environmental Management: Air Quality Act
NER	National Energy Regulator
NH_3	Ammonia
NMSE	Normalised Mean Square Error
NO_2	Nitrogen Dioxide

NO_3	Nitrate
NO_x	Oxides of Nitrogen
o	Degrees
O_3	Ozone
OCGT	Open Cycle Gas Turbine
OFA	Over-Fire Air
PDF	Probability Density Function
PM	Particulate Matter
PM_{10}	Particulate Matter with a diameter of 10 micron or less
$PM_{2.5}$	Particulate Matter with a diameter of 2.5 micron or less
RMSE	Root Mean Square Error
SACRM	South African Coal Roadmap
SANAS	South African National Accreditation System
SANEA	South African National Energy Association
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SO_3	Sulphur Trioxide
SO_2	Sulphur Dioxide
SO_4	Sulphate
SOFA	Separated Over-Fire Air
TWhSO	Terawatt hour Sent Out

MWhSO	Megawatt hour Sent Out
µm	Micron
UCLF	Unplanned Capability Loss Factor
US EPA	U.S. Environmental Protection Agency
WIT	Wessex Institute of Technology

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1 Introduction and literature review

South Africa is a major role player in coal-generated energy both regionally and globally (Spalding-Fletcher and Matibe, 2003; Von Blottnitz, 2006). Because of the availability of large resources of relatively affordable coal, the country is heavily dependent on coal for its energy production. The South African energy sector of which around 85% to 94% is constituted by coal-fired power plants is one of the major polluters in the country (Fund for Research into Industrial Development Growth and Equity (FRIDGE), 2004). South Africa is therefore a prominent emitter of criteria pollutants (Particulate Matter (PM), Sulphur Dioxide (SO_2) and Nitrogen Oxides (NO_x)) as well as Carbon Dioxide (CO_2) from coal-fired power stations on the African continent and in the world (Von Blottnitz, 2006; Zhou *et al.,* 2009).

This literature study begins with a brief overview of the South African energy sector in Section 1.2. The drivers of energy demand in South Africa are discussed in Section 1.3. The South African air quality regulation philosophy is explained in Section 1.4 where after the global and regional impacts of coal-fired power station emissions and the control of these emissions are investigated in Sections 1.5 and 1.6.

1.1 The South African energy sector

The South African economy is known to be energy-intensive, with the implication that the country uses a large amount of energy for every rand of economic output (Hughes *et al.,* 2002; Nkomo, 2005; Winkler, 2007). This can be explained by the fact that historically, industrial and residential electricity tariffs in South Africa were amongst the world's lowest, and this attracted many energy intensive industries (South African National Energy Association (SANEA), 1998; Winkler, 2005). There are several reasons for the low electricity tariffs in South Africa. South Africa took advantage of large economies of scale in coal mining and power stations are often situated near mines and thus benefit from long-term coal contracts at low cost (Chamber of Mines, 2001; Winkler; 2005). Municipal distributors and large industrial and mining customers are responsible for the bulk of electricity sales. This reduced overhead costs per unit of sales (National Energy Regulator (NER), 2000; Winkler, 2005). Large investments made in previous decades led to significant overcapacity which enabled the electricity price to be set at a very low marginal cost (Davis and Steyn, 1998; Van Horen and Simmonds, 1998; Eberhard, 2000; Winkler, 2005). Traditionally, Eskom did not pay tax or dividends to government and the price of electricity has never included any part of the environmental or social impacts associated with electricity generation (Spalding-fletcher and Matibe, 2003). The low electricity tariffs led to the establishment of many energy- and electricity-intensive industries in South Africa. These industries are among the main contributors to economic growth and exports, and are responsible for more than 60% of national electricity sales (Trollip, 1996; Berger, 2000; Department of Minerals and Energy (DME), 2000; Spalding-Fletcher and Matibe, 2003).

Around 70% of South Africa's total primary energy supply is derived from coal, and coal-fired power stations provide between 85% and 94% of total electricity (Ziramba 2009; Menyah and Wolde-Rufael, 2010). The reason for the heavy dependence on coal is the fact that South Africa has large coal reserves. However, since 2008, official estimates for South African coal reserves have dramatically reduced from ~48 Gigatons (Gt) to ~30 Gt, as published in the BP Statistical Review of World Energy 2008 (Hartnady, 2010). Recently, a re-assessment based on the complete statistical history of production from southern Africa has indicated that the present remaining reserve for the entire subcontinent comprises only about 15 Gt (Hartnady, 2010). Current forecasts predict that the peak South African coal production rate of 284 Megatons (Mt) per year will be reached in 2020 (Hartnady, 2010). It is expected that roughly half (12 Gt) of the economically recoverable resource (around 23 Gt) will be exhausted at this stage where after the annual production rate will decline (Hartnady, 2010).

Of total coal consumption in South Africa, 70% is used for electricity generating purposes, 20% is used by Sasol for the production of liquid fuels and chemical products, 5% is consumed by local industry, 3% is utilized in the metallurgical industry and 2% is used domestically, mainly for cooking and heating purposes (South African Coal Roadmap, 2011; Shahbaz *et al.,* 2013). South African coal has relatively high ash contents, low calorific values and characteristically low sulphur, sodium, potassium and chlorine contents (Falcon and Ham, 1988). High grade coals are exported whereas lower grade coals are used domestically (Eberhard, 2011).

Emissions from South African coal-fired power plants are significant on a global scale. In a study done by von Blottnitz (2006), comparing emissions from South African thermal power plants to those of 15 European countries, it was found that total emissions of PM, Nitrogen Dioxide (NO_2) and SO_2 from thermal power generation in South Africa are higher than those in any of the European countries investigated. Reasons for this are the high reliance on coal as a fuel in South Africa (coal is a fuel that is more difficult to burn cleanly than other fossil fuels) and the high specific emissions associated with South African coal combustion. The energy sector in

South Africa is the biggest contributor to SO_2 and NO_x emissions and second highest contributor to PM emissions of all sources of air emissions in the country (70%, 55% and 36%, respectively) compared to industrial, commercial and institutional fuel burning (27%, 23% and 44%), vehicle emissions (2%, 21%, 5%), biomass burning (0%, 0.3%, 6%) and domestic burning (0.8%, 0.2%, 9%) (Department of Environmental Affairs (DEA), 2012 after FRIDGE, 2004). The CO_2 emissions intensity (CO_2 emissions per economic output) of South Africa was found to be one of the highest in the world with CO_2 emissions exceeding that of many developing and developed countries (Spalding-Fletcher and Matibe, 2003; Winkler, 2007). Therefore, the country is an outlier in terms of its carbon footprint, in that it is the world's 24th largest economy but 12th largest contributor of greenhouse gas (GHG) emissions (Ruffini, 2013) and 7th largest emitter of GHG emissions per capita in the world (Sebitosi and Pillay, 2008; Menyah and Wolde-Rufael, 2010).

In 2012, South Africa had a total nominal generating capacity of 44115 Megawatt (MW) of which 37715 MW (85%) of the total capacity originated from coal-fired power plants. On an international scale, South Africa's coal-fired electrical power generation is comparable to that of Canada (45103 MW), Mexico (47736 MW) Saudi Arabia (46374 MW) Thailand (43939 MW) and Australia (47231) (United Nations, 2013). Eskom, one of the largest utilities in the world, is responsible for the generation of approximately 95% of South African electricity and 45% of Africa's electricity (Eskom, 2010). Eskom power is exported to Botswana, Lesotho, Mozambique, Namibia, Swaziland and Zimbabwe. Eskom owned coal-fired power plants, all of which are base load plants, include Arnot, Duvha, Camden, Grootvei, Hendrina, Kendal, Komati, Kriel, Lethabo, Majuba, Matla, Matimba and Tutuka (Eskom, 2012a). The remaining 5 % of electricity is generated by coal-fired power plants owned by the private sector (Kelvin Power Plant), municipalities (Rooiwal and Pretoria West power stations) and Sasol. Currently two additional Eskom power stations are under construction, namely Kusile and Medupi. The first unit of Medupi came online mid-2015 and the first unit of Kusile is expected to come online in 2016, although the precise date remain uncertain (Eskom, 2013; Eskom personal communication).

Since the middle 2000s South Africa has been experiencing an on-going energy crisis. The reasons for the energy crisis are three-fold. A dramatic increase in demand was experienced after 1994 when the economic sanctions of the apartheid era were lifted and economic growth was high (Inglesi and Pouris, 2010). The free basic energy policy was implemented in 2001 where an amount of electricity was supplied to poor households free of charge. This was done as part of a drive to provide basic services to previously disadvantaged households (Inglesi and Pouris, 2010). In 2004 the government delayed making a decision to fund the building a new power station when it became apparent that new energy capacity was needed (Inglesi and Pouris, 2010). It is believed that the energy demand/supply balance will remain vulnerable for at least until Medupi comes fully online (Eberhard, 2013).

1.2 Drivers of energy demand

Energy is a basic human necessity and is also a key promoter of economic growth and human livelihoods. It is believed that economic growth, population growth and energy prices are the three main macro-economic driving forces behind energy demand (Department of Energy, 2013).

Economic growth is often expressed in terms of Gross Domestic Product (GDP). However, using GDP as an indication of economic growth and associated energy demand often does not paint the entire picture. It is important to look at the structure of the economy and how GDP is divided between the primary, secondary and tertiary sectors as energy consumption per economic output generally decreases from the primary and secondary sectors to the tertiary sector (Davidson *et al.,* 2006).

Changes in demographic trends have a relatively small direct impact on energy demand as the residential sector only accounts for roughly 20% of final energy consumption in South Africa. However, population changes can have major indirect consequences, such as changes in labour, consumption of goods and other factors that are reflected in the GDP (Davidson and Winkler, 2003; Davidson *et al*., 2006). Urbanization of the rural population, a trend that is prominent in South Africa, has been shown to increase the demand for energy (Huang, 2014).

Energy demand is further dependant on the price of energy. The relationship between energy price and energy demand in South Africa has been variable in the past (Inglesi, 2010) but it is believed that as real electricity prices rise in South Africa (as they have done since 2008), consumers will again become more sensitive to price and prices will again play an important role in determining electricity consumption in South Africa (Deloitte, 2012).

Many international studies have also identified technical innovations and ambient temperature as important role players in energy demand. Technology innovations such as reduced costs of abatement and the replacing of inefficient technologies with energy-saving techniques have a decreasing effect energy demand (Wing, 2006; Momani, 2013; Wang, 2013; Huang, 2014). It has been evident in numerous international studies that energy use decreases with rising ambient temperature due to a reduction of energy demand for heating purposes (Peirson and Henley, 1994; Pardo *et al.*, 2002; Petrick *et al*., 2012; Huang, 2014).

1.3 The South African air quality regulation philosophy

Internationally and locally, air quality regulation has been driven by two main philosophies, namely a more traditional “command and control” philosophy and a modern “market mechanisms” philosophy (Driesden, 2009). The “command and control” philosophy is based on a central government setting limits of allowable pollution output per industry. The pollutant limits typically reflect the existing pollution reduction technology capabilities (Driesden, 2009). Market mechanisms, on the other hand, refer primarily to pollution taxes and environmental benefit trading but can also include the offering of subsidies for low polluting technologies, the use of information to create incentives for environmental improvement and simple abandonment of regulation in favour of voluntary regulation (Driesden, 2009).

The market based approach has gained widespread support in recent years due to the fact that, in contrast to the traditional “command and control” regulatory approach, market based approaches allow more flexibility in how the environmental goal is reached. The reason for this is that market based regulation enables the individual agent to use his or her typically superior information to select the best means of meeting an assigned emission reduction responsibility instead of relying on the regulatory authority to identify the best course of action. This leads to higher flexibility which can ultimately achieve environmental goals at lower cost, which in turn, makes the goals easier to achieve and easier to establish (Tietenberg, 1990).

In South Africa, at present, the “”command and control” philosophy is largely utilized in the air quality regulation arena. However, there are some indications that a shift towards market based mechanisms may take place in the near future. The recent publication of the Draft Carbon Tax Bill for public comment is once such an example (National Treasury, 2015).

South African air quality is currently regulated by means of command and control strategies as stipulated in the National Environmental Management: Air Quality Act (NEM:AQA) (Act no. 39 of 2004). Ambient air quality standards establish the highest allowable concentration in the ambient air for each conventional pollutant. In order to reach these prescribed ambient standards, emission limits (according to the Listed Activities and Associated Minimum Emission

Standards (MES) identified in terms of section 21 of the NEM:AQA) are imposed on a number of activities which were identified as having the potential for having a detrimental effect on the environment and the health of people (NEM:AQA, 2004).

Even though the current air quality regulation in South Africa mainly follows a “command and control” approach, there is some transitioning taking place towards a market based approach. There are two examples of this. Firstly, the South African government is considering implementing a carbon tax as an instrument to reduce carbon emissions and to assist in the transitioning from a carbon intensive to low carbon economy (National Treasury, 2013; Alton *et al.,* 2014). Secondly, government has recently published a Carbon Offsets Paper and a Draft Air Quality Offsets Guideline for public comment, thereby showing their intent to consider emissions offsetting as an additional tool to control emissions in the future (National Treasury, 2014; DEA, 2015).

1.4 Impacts of coal-fired power station emissions

Various studies across the globe have shown that emissions from coal-fired power stations can be harmful to the environment and human health (Radim *et al*., 1996; Gaffney and Marley, 2009; Mauzerall *et al*., 2005; Mukhopadhyay and Forssell, 2005; Curtis *et al*., 2006; Sarnat *et al.*, 2008). The most important primary emissions associated with coal-fired power stations which are known for their adverse environmental and/or human health impacts include PM, SO_2, NO_x, mercury (Hg) and GHG. Ozone (O_3) is an important secondary pollutant that forms photo-chemically in a reaction with NO_x (a primary coal-fired power station emission) (Mauzerall *et al*., 2005; Curtis *et al.,* 2006; Gaffney and Marley, 2009).

Coal-fired power stations are the main contributors to SO_2, NO_x, Hg and GHG emissions of all sources in South Africa. The percentage contribution of coal-fired power stations to total PM, SO_2, NO_x, Hg and GHG emissions in the country are summarised in Table 1-1 (Scorgie *et al*., 2004, Masekoameng et al., 2009; DEA, 2014) (even though some of this work was done more than a decade ago, the coal-fired power generation sector changes little during that time and these estimates are believed to still be representative);.

Table 1-1: The percentage (%) contribution of coal-fired power stations to total PM, SO_2, NO_x, Hg and GHG emissions in South Africa.

Pollutant	Percentage contribution of coal-fired power stations to total South African emissions (%)
PM	36 [a]
SO_2	70 [a]
NO_x	55[a]
Hg	65 [b]
GHG	78 [c]

[a] Based on estimations by Scorgie *et al.,* (2004).

[b] Based on 2006 estimations by Masekoameng *et al*., (2010).

[c] Based on the 2010 value of the GHG National Inventory Report South Africa 2000-2010 (DEA, 2014).

1.4.1 Primary and secondary PM

PM emissions from coal-fired power stations can either be a primary pollutant in the form of fly-ash emissions directly to the atmosphere or a secondary pollutant when emitted SO_2 and NO_x gasses oxidize to form sulphate (SO_4) and nitrate (NO_3), respectively (Levy *et al*., 2003; Gaffney and Marley, 2009). The primary PM particles that are able to escape PM abatement technology generally have sizes in the order of 0.8 to 2 micron (µm) whereas secondary PM is generally smaller with sizes <1 µm (Pitts, 1986; Linak *et al.,* 2000; Gaffney and Marley, 2009). Because these particles are extremely small, they have atmospheric residence times in the order of weeks and can travel vast distances (Finlayson-Pitts and Pitts, 1986; Gaffney and Marley, 2009; Jia and Jia, 2014). This size range is effective in scattering solar radiation and is therefore able to impact both visibility and climate (Gaffney and Marley, 2009). These particles further act as hygroscopic nuclei for the forming of cloud droplets and they extend the lifetime of clouds by competing for the available water vapour thereby forming more numerous but smaller cloud droplets (Twomey 1977; Twomey 1991; Gaffney and Marley, 2009). The smaller droplets scatter more in the backward direction than larger aerosols causing a cloud albedo effect which subsequently results in regional cooling (Jimoda, 2012; Gaffney and Marley, 2009). This phenomenon is known as the first indirect radiative forcing effect of aerosols (Jimoda, 2012). PM from power stations can also be responsible for a second indirect radiative forcing effect. The second indirect radiative forcing effect takes place as a result of increased rainfall suppression and an increased cloud lifetime due to increased hygroscopic nuclei concentration which prevent droplets from reaching a threshold radius in order to produce rain (Jimoda, 2012).

This second indirect effect was recognized by Haywood and Boucher (2000) and IPCC (2001) to be a major agent of climate change (Jimoda, 2012).

Fly ash is known to contain various potentially toxic trace materials such as heavy metals and radionuclides. The transition metals are of particular concern due to indications of cardiopulmonary damage associated with the inhalation of these constituents (Dreher *et al*., 1996; Gaffney and Marley, 2009). Secondary PM from coal-fired power stations is the main constituents responsible for the formation of acid rain. Acid rain changes the acidity of inland water bodies and speeds up the deterioration of construction materials (Charlson and Wigley, 1994; Gaffney and Marley, 2009).

By the 1970's, very high PM concentrations from extreme pollution events have been correlated to acute increases in human mortality. More recently, however, it was shown that long term exposure to much lower concentrations of combustion-related PM is an important environmental risk factor for cardiopulmonary and lung cancer mortality (Pope *et al.,* 2002). Fine PM emissions have further also been correlated with respiratory and cardiovascular diseases in humans (Sarnat *et al.,* 2008). A study of 110 children over 10 years have shown that exposure to fine PM in adolescent years had a measurable and potentially important effect on lung function growth and performance (Avol *et al.,* 2001).

1.4.2 SO_2

Significant associations have been found between ambient SO2 concentrations and hospitalizations for asthma or other respiratory illnesses, particularly for children and the elderly. For susceptible individuals, the inhalation of SO2 can cause inflammation of airways, bronchitis, and decreases lung function. Epidemiological studies in European cities have found that long-term exposure to low concentrations of SO2 are linked to increased risk of developing lung and heart conditions (United States Environmental Protection Agency (US EPA), 2008).

1.4.3 NO_x

NO_x can react with constituents in the atmosphere to form secondary pollutants such as O_3, Nitrous Oxide (N_2O) and NO_2. NO_2 is of particular concern with respect to health impacts. NO_2 can aggravate asthmatic conditions in children and exposure to NO_2 can also increase susceptibility to viral and bacterial infections. In high concentrations it can cause airway inflammation whereas in low concentrations, NO_2 cause decreased lung function in asthmatics (US EPA, 2008).

1.4.4 Ozone

O_3 is indirect pollutant from coal-fired power stations which forms when NO_x emitted by power stations react with hydrocarbons and carbon monoxide (CO) through a series of photochemical reactions. O_3 is known to be damaging to human health and crops and it is now recognized as the most important rural air pollutant (Ashmore, 2005; Mauzerall *et al.*, 2005). O_3 is also a GHG and therefore contributes to global climate change (Ashmore, 2005).

1.4.5 Mercury

Hg is a toxic emission from coal-fired power stations and can be released by coal-fired power stations in one of three forms, namely vapour phase elemental Hg, vapour phase oxidized Hg, or adsorbed onto particulate surfaces (UNEP/Chemicals, 2002; Gaffney and Marley, 2009). Hg is widespread in different ecological zones such as the atmosphere, soil and water. In aquatic systems there is evidence of Hg accumulation with higher concentrations detected in carnivorous fish. The main human exposure pathway to Hg is through fish consumption and inhalation (Zhang and Wong, 2007). Coal-fired power stations are responsible for the highest Hg emissions of all sources in South Africa (Figure 1-1) (Masekoameng *et al.,* 2010). It was estimated that approximately 39 tons of Hg were emitted into the atmosphere by South African coal-fired power stations in 2006 (Masekoameng *et al.,* 2010).

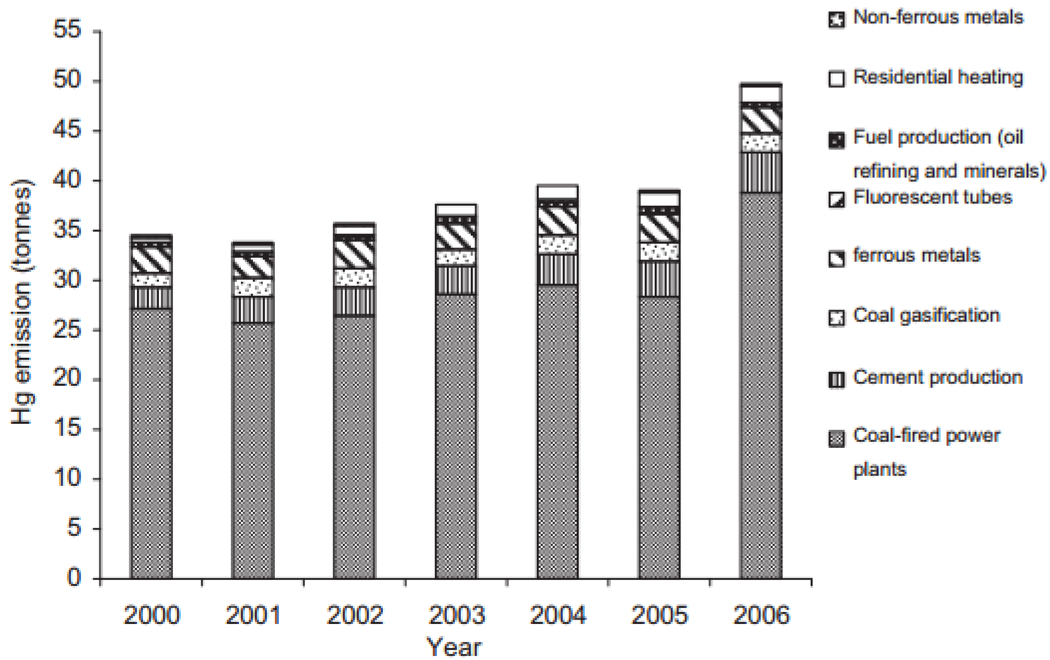


Figure 1-1: The total contribution to Hg emissions from different South African sources during 2000 to 2006 (Masekoameng *et al.,* 2010).

1.4.6 Greenhouse gasses

Coal-fired power stations account for around 90% of total South African CO_2 emissions, the GHG that is the major contributor to global warming (Department of Environmental Affairs, 2009). Coal is known to be the fossil fuel with the highest carbon content and therefore has the highest output rate of CO_2 per energy unit. Coal-fired power stations are major emitters of methane (CH_4), N_2O, both which are also GHGs (Gaffney and Marley, 2009).

It has been shown that South African GHG emissions increase with economic growth because of the fact that the South African economy is energy intensive. For this reason GHG emissions will continue to escalate if the South African economy continues to grow (Winkler *et al.,* 2011; Wu *et. al.*, 2015). South Africa is responsible for emitting an estimated 1.4% of combined total global anthropogenic GHG emissions at present (Seymore *et al.*, 2014).

1.4.7 Multiple pollutants

Research has found that coal-fired power station emissions decreases life expectancy of the surrounding population by 2.5 to 3.5 years (Gohlke et al., 2011) and that exposure to coal-fired power station emissions (SO_2, PM, NO_2, CO and O_3) during pregnancy can cause low birthweight (SrámRJ *et al.,* 2005). The research also showed that coal-fired power station emissions are associated with an increase in infant mortality (Gohlke et al., 2011).

1.5 Coal-fired power station emission control

Emissions control at coal-fired power stations can take place either before, during or after the combustion of coal takes place. Sulphur and ash can be removed from coal before it is burned whereas the formation of, for instance, NO_x emissions can be minimised during the combustion process by modifying furnace processes. Finally, pollutants can be removed from the flue gas stream after combustion but prior to escaping to the atmosphere (Franco and Diaz, 2009).

1.5.1 Pre-combustion cleaning

Pre-combustion cleaning (also called beneficiation) is used to decrease the mineral and ash content in the coal. It can either take the form of physical or biological cleaning. For both processes coal must firstly be crushed and ground into small particles. Physical cleaning separates unwanted matter from coal by relying on differences in physical characteristics such as density, for example. Physical cleaning can therefore only remove matter that is physically different from the coal. Approximately 30-50% of pyritic sulphur and 60% of ash-forming minerals can be removed by this method. Physical cleaning, however, cannot remove organic sulphur or nitrogen (Cholakov and Shopov, 2001).

Biological cleaning is a process whereby suitable bacteria remove impurities from a coal-water slurry. This method is able to remove around 90% of total sulphur (both pyritic and organic) and 99% of ash from the coal; however, this process is still under development and still needs to be tested at commercial scale (Cholakov and Shopov, 2001; Chiang and Cobb, 2000).

1.5.2 PM control

Primary PM emissions originating from coal-fired power stations are either controlled by means of Electrostatic Precipitators (ESP) or Fabric Filter Plants (FFP) after combustion took place. An ESP works by imparting a charge to particles in the flue gas stream. The particles are then attracted to an oppositely charged collection surface in the form of a plate or tube and removed from this surface to a hopper by means of vibrating or rapping. The effectiveness of an ESP depends on both the electrical resistivity of the particles in the flue gas and on the size distribution of the particles. The more sulphur present in the coal, the lower the resistivity of the fly ash and the more effective the ESP will be in removing PM from the flue gas stream (Staudt, 2011). Flue gas conditioning (by means of injecting Sulphur Trioxide (SO_3)) can be done in order to decrease the resistivity of ash resulting from the combustion of low sulphur coal (Trivedi and Phadke, 2008). ESPs are more effective at removing larger particles (they capture around 99% of total PM) than they are in removing particles that are 2.5 µm or smaller ($PM_{2.5}$) (they are only able to capture 80% to 95% of these particles) (Staudt, 2011).

A FFP removes PM by means of trapping particles in the flue gas before they exit the stack. FFPs are made of woven or felted filter material in the shape of a cylindrical bag or a flat, supported envelope. Included in the FFP system are dust collection hoppers and a cleaning mechanism for periodic removal of the collected particles (Staudt, 2011).

1.5.3 NO_x control

NO_x emissions can either be controlled by means of combustion or post-combustion methods. Combustion controls work by minimizing the formation of NO_x within the furnace and are usually lower in both capital and operational cost than post-combustion controls. Combustion controls reside within the furnace itself and include such methods as low NO_x burners (LNB), over-fire air (OFA), and separated over-fire air (SOFA) (Staudt, 2011; Moretti and Jones, 2012).

When NO_x emissions have to be reduced to a level lower than what is achieved with combustion controls alone, post-combustion controls may be necessary to achieve even lower emissions of NO_x. Combustion and post-combustion NO_x controls can be (and often are) used in combination. Post-combustion NO_x controls include Selective Catalytic Reduction (SCR) (with removal efficiencies of 90% or greater), Selective Non-Catalytic Reduction (SNCR) (with a removal efficiency in the range of 25-30%) and hybrid SCR/SCNR systems (with removal efficiencies greater than SNCR systems are able to achieve). These systems work by means of using ammonia or urea as a reagent that reacts with NO_x either on the surface of a catalyst (SCR), in the absence of such a catalyst (SCNR), or a combination of these (SCR/SCNR Hybrid) (Staudt, 2011; Moretti and Jones, 2012).

1.5.4 SO_2 control

At present, post-combustion SO_2 control is done by means of either wet or dry Flue Gas Desulfurization Plants (FGD). Wet FGD systems are capable of high rates of SO_2 removal. Modern wet systems are capable of SO_2 removal in excess of 90%. In a wet FGD, a lime or limestone slurry reacts with SO_2 in the flue gas stream within a large absorber vessel. Wet FGD systems are both capital and water intensive (Srivastava, 2010; Staudt, 2011).

A dry FGD works by means of injecting hydrated lime and water (either separately or combined as a slurry) into a large vessel to react with the SO_2 in the flue gas. The term “dry” refers to the fact that, although water is utilized, the amount of water added is only just enough to maintain the gas above the dew-point temperature. Modern dry FGD systems are able to capture SO_2 at rates of 90% or more (Srivastava, 2010; Staudt, 2011).

1.5.5 Mercury control

Hg contents in coal vary greatly with coal type and even within coal types. When Hg is released during combustion it becomes entrained in the flue gas stream in one of three forms, namely particle-bound Hg, gaseous elemental Hg, and gaseous ionic Hg. Particle-bound Hg is the species that can be captured the easiest in existing emission control devices, such as FFPs or ESPs as a co-benefit. Ionic Hg is extremely water soluble and is therefore relatively easily captured in a wet FGD. Ionic Hg can also be adsorbed onto fly ash or other material, and may thereby become particle-bound Hg that is captured by an ESP or FFP. Elemental Hg is less water soluble and less prone to adsorption and therefore the hardest form of Hg to capture. It will remain in the vapor phase where it is not typically captured by control devices unless first converted to another form more readily captured. Activated carbon or halogens can be injected into the gas stream in order to aid the conversion (Staudt, 2011; Moretti and Jones, 2012).

1.5.6 Proposed CO_2 control

CO_2 emissions from coal-fired power stations can be controlled by two possible approaches. The first is to reduce the CO_2 emissions per energy unit generated by increasing the thermal efficiency of the power station. The second is through the capture and sequestration of carbon (Marion *et al.,* 2003).

South Africa’s coal-fired power stations generally exhibit high thermal efficiencies for conventional pulverized bed combustion technology. The average thermal efficiency was above 34% in 2003 before declining to 31% in 2012 as a result of the deterioration of the power station fleet condition during the energy crisis period (Eskom, 2012; Spalding-Fletcher and Matibe, 2003). The thermal efficiencies of new steam power stations can exceed 40% (on lower heating value (LHV)) and state of the art supercritical steam boilers allow higher steam temperatures and pressures, enabling thermal efficiencies close to 50% (LHV) (Marion *et al*., 2003).

Carbon capture can be done either before, during or after combustion of coal takes place (Kanniche *et al.,* 2009). Pre-combustion capture of CO_2 works by means of capturing CO_2 in a synthesis gas after the conversion of CO to CO_2 takes place. During the combustion process CO_2 can be captured when coal is combusted with near pure oxygen and recycled flue gas or CO_2 or water/steam to produce a flue gas consisting essentially of CO_2 and water (Dillon *et al.*, 2004; Kanniche *et al.,* 2009).

Recently, a study has been done to assess the technological and economic viability of oxy-fuel technology for six South African coal-fired power stations. The study found that the CO_2 emission rates of power stations can be reduced by a factor of 10 for all the plants when retrofitted to oxy-fuel combustion. This technology type has high energy requirements and it was estimated that between 27% and 29% of generated energy will be needed for the CO_2 capture process. The total estimated capital and operational costs for the six plants differed and caused the resulting projected electricity price to be between double and triple that of the original electricity tariff (when stations are not making use of this technology) (Oboirien *et al.,* 2014).

There are several possible methods for removing CO_2 from the flue gas stream after combustion has taken place. These include absorption by amines, different adsorption techniques and the use of membranes, etc. These CO_2 capture methods have significant energy requirements and may reduce a power plant's relative efficiency and net power output by approximately 40%. Approximately 85% to 95% of CO_2 in the gas stream can be removed in this way (Marion *et al.*, 2003). This control technology is not yet widely used commercially. The very first commercial-scale power plant making use of this technology is the 110 MW Boundary Dam power station in Canada which became operational in October 2014 (Goldenberg, 2014). Considerable uncertainty still exists around whether this type of emissions control is a viable option for large coal-fired power stations (Hansson and Bryngelsson, 2009).

1.5.7 Current control measures at South African coal-fired power stations

At present, the only pollutants that are controlled at operational South African coal-fired power stations are primary PM and NO_x. For PM control, approximately two thirds of operational stations make use of ESPs whereas the other third makes use of FFPs. In general, the FFP removal efficiencies are higher than those of ESP's, by design. In South Africa, plants making use of ESP's experience additional difficulties associated with the low sulphur content of coal fuels (and therefore low resistivities of fly ash), and various operational and maintenance challenges. In order to mitigate the problem of high resistivity fly ash, flue gas conditioning (by means of SO_3 injection) is done at the majority of plants that make use of ESPs. A summary of the capacities and PM abatement technology utilized at each power station in South Africa during 2013 is given in Table 1-3 (Eskom, personal communication). Eskom plans to retrofit some of the ESPs currently found at existing power stations with FFPs in the future at Duvha (the remaining three units), Grootvlei (the remaining three units), Kriel (six units), Matla and Tutuka (six units). At present only the new power station Medupi's unit six has low NO_x burners installed.

Table 1-2: The PM emissions control devices installed at South African coal-fired power stations as well as the generating capacity of each station.

Power station	Installed Capacity (MW)	PM Emission Control Device
Arnot	2100	FFP
Camden	1600	FFP
Duvha	3600	Units 1-3: FF Units 4-6: ESP
Grootvlei	1200	Units 2-4: ESP Units 1,5,6: FFP
Hendrina	2000	FFP
Kelvin	600	FFP
Kendal	4116	ESP
Komati	1000	ESP
Kriel	3000	ESP
Lethabo	3708	ESP
Majuba	4110	FFP
Matimba	3990	ESP
Matla	3600	ESP
Pretoria West	300	ESP*
Rooiwal	180	FFP
Tutuka	3654	ESP
Sasol 1	130	ESP
Sasol 2&3	520	ESP

* Where information on PM control device could not be obtained, the type of device was inferred from emission factors.

Even though South African coal-fired power stations only make use of PM control technologies at present; Eskom has undertaken to retrofit stations with NO_x (in the form of LNB) and possibly SO_2 emissions control (FGD) in the future. Stations that are earmarked for LNB retrofits are

Tutuka (2020-2025), Matla (2012-2015) and Majuba (2020-2025). The retrofit of a dry FGD at Kendal is under consideration (Eskom, personal communication).

Medupi and Kusile, two new power stations that are currently under construction will make use of the newest, state-of-the-art, emissions control. Both will have supercritical boilers (and therefore high heat conversion efficiencies and relatively low CO_2 emissions), FFPs for PM removal, LNBs for NO_x control, and FGDs for SO_2 removal. Kusile will make use of a wet FGD whereas Medupi will be retrofitted with a dry FGD during the period 2019-2022 (Eskom, personal communication).

1.6 Motivation for the research

The major share of South African electricity is generated by coal-fired power stations. The industry and air quality regulation thereof has undergone many changes over the past decade. The most notable of these changes was the promulgation of the Listed Activities and Associated MES identified in terms of section 21 of the NEM:AQA by the DEA in 2005 that came into effect in 2015. Apart from specifying a blanket set of MES with which all power stations have to comply, this legislation also stipulates that emissions are to be measured by means of Continuous Emissions Monitoring Systems (CEMS) instead of being calculated by means of a mass balance methodology as has been done traditionally.

Since 2007, the commencement of the South African energy crisis, the existing coal-fired power station fleet has been under enormous strain. Due to decreased maintenance, the condition of the entire fleet deteriorated and the thermal efficiency of the fleet decreased. Emissions abatement technology used at existing power stations also suffered from lowered maintenance and the removal efficiencies of these systems decreased. This led to an overall increase in coal-fired power station emissions from the majority of criteria emissions (especially emissions of pollutants that are abated) and emissions of CO_2.

To date no detailed studies have been done to quantify and determine the potential human health exposure to individual South African coal-fired power stations. Also lacking in the literature are details regarding how the coal-fired power station emission footprint itself have been impacted by the energy crisis, and whether the mandatory use of CEMS instead of mass balance calculations are justified. This study serves the purpose of filling this knowledge gap.

1.7 Study aims and objectives

This study has four objectives and each objective is addressed by a separate article. The objectives of this study are outlined as follows:

Objective 1: To compare CEMS and calculation-based coal-fired power station emission estimation methods.

The Listed Activities and Associated MES identified in terms of section 21 of the NEM:AQA stipulates that emissions from coal-fired power stations are to be measured by means of CEMS from April 2015 onwards. Traditionally emissions from coal-fired power stations were calculated by means of a combination of plant-specific emission factors and mass-balance methods.

The article "***A critical comparison of gaseous coal-fired large boiler emission estimation in South Africa***" compares the two different methods (CEMS and calculation methods) in terms of cost, ease of operation, data quality and practicality for use at South African coal-fired power stations.

Objective 2: To investigate the effect of the South African energy crisis on emissions.

The energy crisis placed enormous pressure on the existing power station fleet and emissions abatement technology. Electricity tariffs increased as a direct result of the energy crisis and this forced poor households to make use of alternative, more affordable fuels for their energy needs. The use of Open Cycle Gas Turbines increased to alleviate pressure on the existing fleet and many private businesses and higher income households started to make use of backup generators for energy generation during periods of load shedding. The article entitled "***The impact of the South African energy crisis on emissions***" investigates the increasing effect of an energy restricted environment on emissions.

Objective 3: To make projections of future South African coal-fired power station emissions.

In the light of the current challenges facing the energy generation sector in South Africa it is more important than ever to understand past contributing factors to power station emissions in order to implement proper planning for the future. The article entitled "***A perspective of South African coal-fired power station emissions***" makes projections for future emissions scenarios from South African coal-fired power stations. These scenarios are based on past experiences and different future retrofits of power stations with emissions abatement technology as well as different projected energy demand scenarios.

Objective 4: To develop a coal-fired power station emissions management strategy for the Highveld of South Africa.

The Listed Activities and Associated MES identified in terms of section 21 of the NEM:AQA sets a blanket set of standards applicable to all coal-fired power plants in South Africa, irrespective of the ambient air quality in the vicinity of the power station. The article entitled "***Emissions management and health exposure: Should all power stations be treated equal?***" compares human health exposure to individual power station emissions within the Highveld of South Africa in order to understand how the human health exposure to emissions from individual power stations differ. The question this paper aims at answering is whether all coal-fired power stations are equal in terms of their impact on human health and ambient air quality or if each station has a unique footprint and therefore should be managed as such.

1.8 Organization of this document

The methodology and data used for the purpose of this study are described in Chapter 2. The article entitled "***A critical comparison of gaseous coal-fired large boiler emission estimation in South Africa***" is given in Chapter 3 whereas the article "***The impact of the South African energy crisis on emissions***" is outlined in Chapter 4. Chapter 5 contains the third article, namely "***A perspective of South African coal-fired power station emissions***". The final article entitled "***Emissions management and health exposure: Should all power stations be treated equal?***" is contained within Chapter 6. Final remarks and conclusions are stated in Chapter 7.

2 Data and methods

2.1 Introduction

The data and methods employed are explained in detail within each article (chapter). The purpose of this chapter is to give a brief description of the methodology used and, in some cases, to provide additional information not included in the articles themselves.

2.1.1 Journal article: *A critical comparison of gaseous coal-fired large boiler emission estimation in South Africa*

This paper takes the form of a review and a thorough literature study was conducted. This literature included South African legislation and a substantial number of internal Eskom research reports and internal documentation. An interview was carried out with the auditing firm responsible for auditing Eskom's reported emissions. This was done in order to understand the process followed in the auditing process and the data quality and confidence levels associated with the emissions calculation process.

2.1.2 Journal article: *The impact of the South African energy crisis on emissions*

South Africa currently serves as a laboratory for investigating the effects of an energy restricted environment on emissions. Knowledge gained from experiences in South Africa is important to document as numerous countries in the world are currently experiencing energy shortages and will most probably face similar problems to South Africa in the future. In the process of compiling this article, a literature study also played a prominent role in the investigation method. Historical power station emission trends were compiled from data obtained from Eskom annual reports over the past 15 years. Emissions from OCGT and backup generators were calculated from United States Environmental Protection Agency (US EPA) AP42 emissions factors and activity rates.

2.1.3 Journal article: *A perspective of South African coal-fired power station emissions*

The article makes projections for future emissions scenarios from South African coal-fired power stations based on past experiences and different future scenarios. A detailed outline of methods used during this investigation is explained within section 5.2 entitled “Methods” within the article itself.

2.1.4 Journal article: *Emissions management and health exposure: Should all power stations be treated equal?*

This article compares human health exposure to individual power station emissions within the Highveld of South Africa. Potential human health exposure is presented by means of intake and intake fraction. Dispersion modelling outputs were combined with census population data in order to establish the pollutant concentrations to which population groups in the Highveld Priority of South Africa are exposed. More detail on the potential human health exposure determination, the dispersion modelling endeavour including the model used, model setup, meteorological input data and post processing is given in the sections to follow.

2.1.4.1 Potential human health exposure estimation

Potential human health exposure to individual power stations is estimated by means of making use of two entities, namely intake and intake fraction. The methodology followed in calculating intake and intake fraction is summarised in Section 7.2 within the article itself and is also discussed below.

Intake can be defined as the total mass of a pollutant from a specific source that enters human lungs (in units of mass) whereas intake fraction is the mass fraction of a pollutant from a specific source that enters the lungs of humans (a dimensionless value).

Intake and intake fraction for a population exposed to the emissions of a single coal-fired power station over a specific time period are closely related and mathematically defined as follows (Lu and Fang, 2015; Bennet *et al.*, 2002; Zhou *et al.*, 2006):

$$I = \sum_{i}^{N} P_i \times C_i \times BR$$

$$iF = \frac{\sum_i^N P_i \times C_i \times BR}{Q}$$

Where i is a location for which the size of the population is known and P_i is the population at this location. C_i is the long term average concentration at location i (in grams per cubic metre (kg/m^3)), whereas *BR* is the population average breathing rate for which a nominal value of 20 m^3/day was assumed (Hao *et al.,* 2007 and Zhao *et al.* 2006). *Q* is the total power station emission rate during the study period of the pollutant in question, or in the case of secondary pollutants, its precursor (kg/s).

Population data for the purpose of calculating intake and intake fraction values were obtained from 2011 Census data (Statistics South Africa, 2012). A map indicating the population density as determined by the 2011 census within the study domain as well as the locations of the power stations investigated is given in Figure 2.1. The long-term concentration to which populations are exposed (C_i) was determined at the centre location of each 2011 small area census block by means of dispersion modelling. The dispersion modelling process is discussed in more detail within the sections to follow.

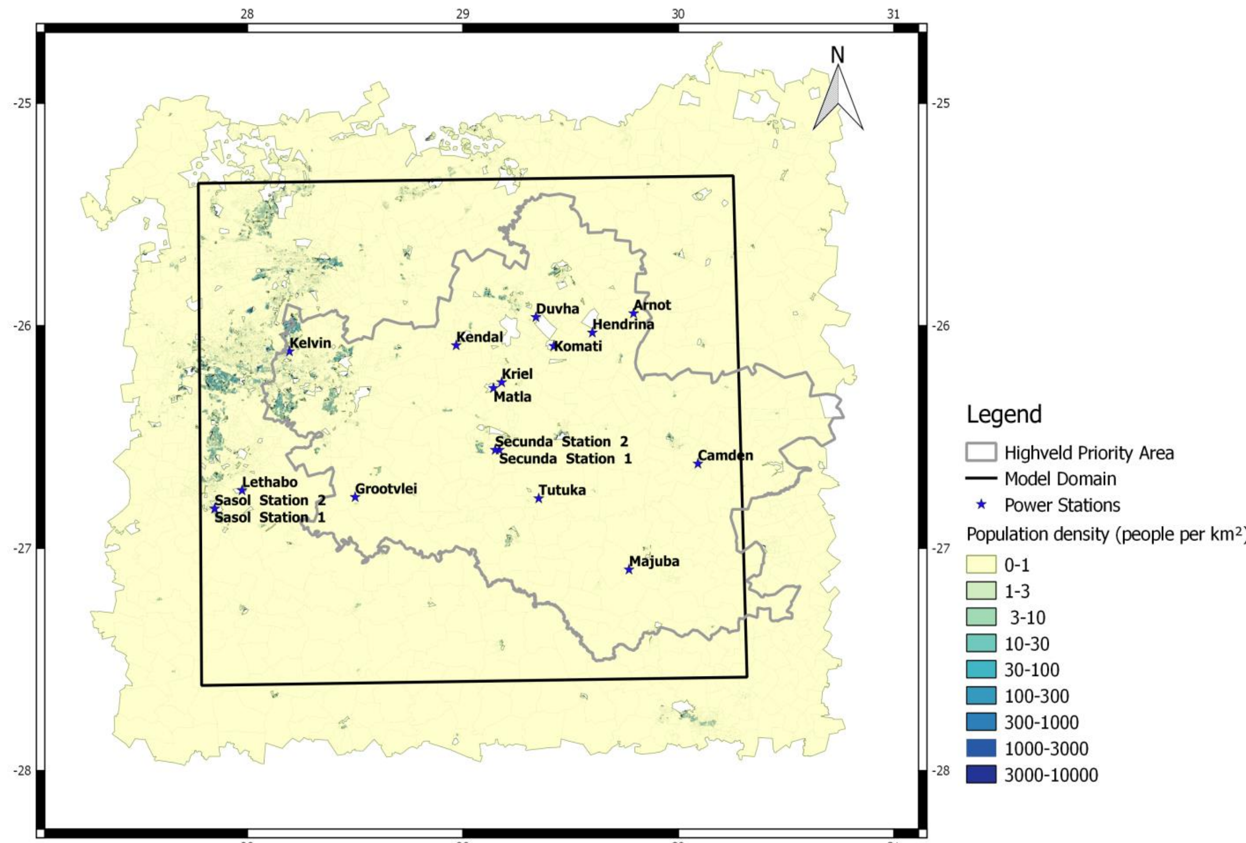


Figure 2-1: The population density within the study area as derived from 2011 Census data as well as the locations of the different power stations investigated.

2.1.4.2 Emission factors and source characteristics

The emission factors and source characteristics used as input into the dispersion model is discussed in this section and in Section 7.2.4 within the manuscript itself. Source characteristics and emission factors were obtained directly from the utility (in the case of Eskom-owned power stations) and from past atmospheric impacts reports (in the case of Sasol-owned power stations). Information for the only privately owned power station, namely Kelvin, was unavailable and therefore estimated from other power stations of similar age and generating capacity. The annual average PM_{10}, SO_2 and NO_x emission factors (calculated as an average for 2001, 2012 and 2013) and type of PM control used (the only type of emissions control currently utilised at South African power stations) of the power stations investigated are summarized in Table 2-1.

Where data was available, the seasonal diurnal trends in emissions output per power station were also taken in account in the dispersion modelling endeavour. The normalized diurnal trends in energy output of all power stations for which such data could be obtained are shown in Figure 2-2. The positions, generating capacities, stack heights; stack diameters, flow rates and exit temperatures of each power station investigated and used as input into the dispersion model are summarized in Table 2-2.

Table 2-1: The total annual PM_{10}, SO_2 and NO_x emission rate (an average of 2011 to 2013) in tons per annum (tpa) as well as PM emissions control installed per power station.

Power station	Emissions abatement installed	Total annual emission rate (tpa)		
		PM_{10}	SO_2	NO_x
Arnot	FFP	750	9380	52540
Camden	FFP	1300	8010	31190
Duvha	FFP (Units 13); ESP(Units 4-6)	3110	14690	75280
Grootvlei	ESP (Units 2-4); FFP (Units 1,5-6)	4860	6090	27070
Hendrina	FFP	910	13620	49390
Kendal	ESP	4950	25750	98890
Komati	ESP	2070	1910	13330
Kriel	ESP	11180	11720	94600
Lethabo	ESP	8450	22170	108260
Majuba	FFP	2790	20060	138620
Matla	ESP	12950	20150	108390
Tutuka	ESP	15770	22250	109260
Kelvin	FFP	*1240**	*1150**	*8000**
Secunda Station 1	ESP	5260	184120	57870
Secunda Station 2	ESP	4680	163770	51470
Sasol Station 1	ESP	740	5300	7320
Sasol Station 2	ESP	850	7030	8830

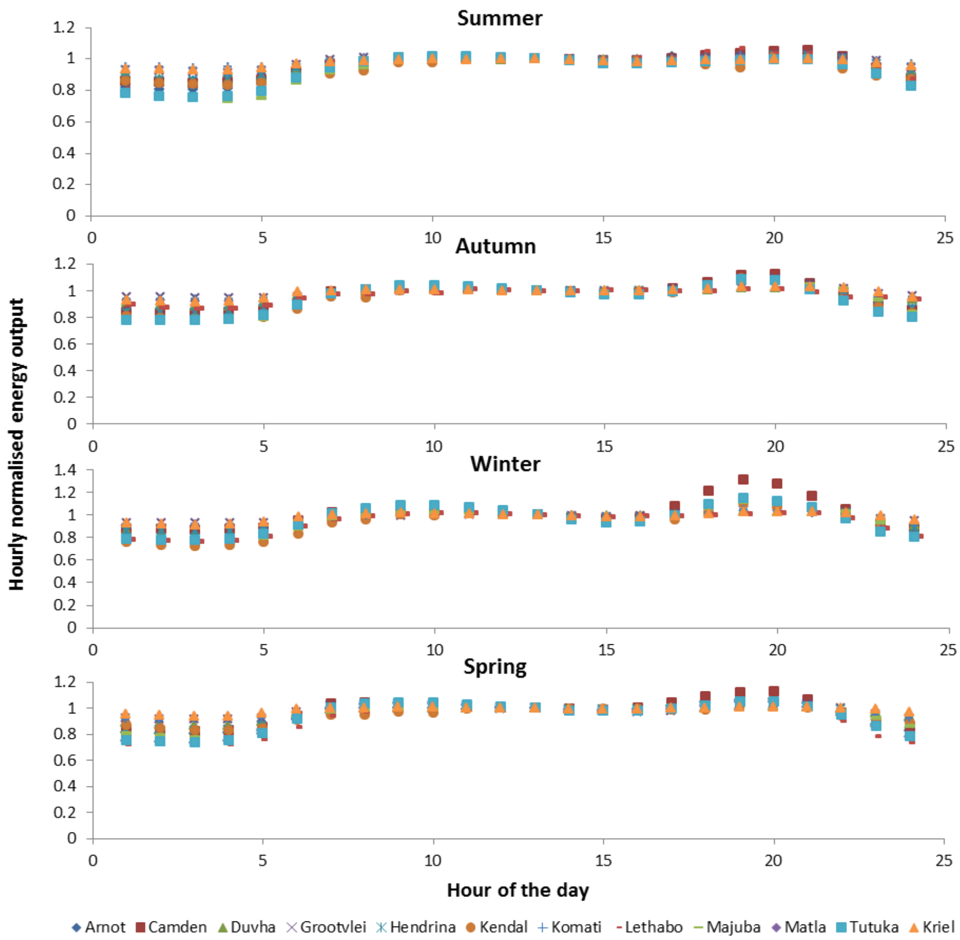


Figure 2-2: Normalized seasonal diurnal energy output profiles per power station.

Table 2-2: Source characteristics of each power station investigated in this study.

Power station	Position		Generating Capacity (MW)	Stack height (m)	Effective stack diameter (m)	Flow rate (m/s)	Exit temperature (K)
	Latitude	Longitude					
Arnot	-25.944	29.792	2100	195	16	25	418
Camden	-26.62	30.091	1600	155	17	14	423
Duvha	-25.961	29.339	3600	300	18	27	413
Grootvlei	-26.77	28.5	1200	152	13	22	418
Hendrina	-26.031	29.601	2000	155	16	22	411
Kendal	-26.088	28.969	4100	275	19	24	413
Komati	-26.091	29.422	1000	220	17	10	418
Kriel	-26.254	29.18	3000	213	20	19	413
Lethabo	-26.740	27.975	3700	275	17	28	433
Majuba	-27.096	29.771	4100	250	17	35	398
Matla	-26.28	29.142	3500	275	19	26	408
Tutuka	-26.776	29.352	3600	275	17	29	413
Kelvin	-26.115	28.195	600	220	17	10	418
Secunda Station 1	-26.558	29.169	600	301	14	25	458
Secunda Station 2	-26.558	29.15		250	14	25	458
Sasol Station 1	-26.822	27.848	140	75	9	6	433
Sasol Station 2	-26.822	27.848		145	8	10	433

2.1.4.3 Dispersion modelling

The CALMET/CALPUFF modelling suite (Earth Tech, Concord, MA) was used for the dispersion modelling purposes of this study. Traditionally, this model is recommended by the U.S. Environmental Protection Agency (US EPA) for simulating long-range transport (US EPA, 2000) as a result of its ability to handle complex three-dimensional wind fields. This model was decided to be best suited for this study due to a number of reasons, including its ability to model dispersion impacts over a large domain and the fact that both primary and secondary pollutant concentrations can be estimated - an important component given the context of our analysis. Although other prominent regional-scale models exist (such as UAM, Models-3, or REMSAD), CALPUFF was selected due to its South African regulatory approval. The model has been used in numerous health exposure studies elsewhere in the world (see for example Levy *et al*., 2002; Zhou *et al.,* 2003; Hao *et al.*, 2007).

The CALPUFF modelling system consists of three main components, namely a meteorological pre-processor, CALMET, the dispersion model CALPUFF and the postprocessor CALPOST (Scire *et al.,* 1999). In short, CALMET can be described as a meteorological model which includes a diagnostic wind field generator containing objective analysis and parameterized treatments of slope flows, kinematic terrain effects, terrain blocking effects, a divergence minimization procedure, and a micro-meteorological model for overland and overwater boundary layers. CALPUFF is a multi-layer, multi species, non-steady-state Lagrangian Gaussian puff model that is able to handle complex terrain effects, overwater transport, coastal interaction effects, building downwash, wet and dry removal, as well as simple chemical transformation. It is able to simulate emissions at downwind distances ranging from tens of metres (m) up to 300 kilometres (km) for multiple point, volume area and/or line sources with either constant or variable emissions. CALPUFF is the recommended model for assessments in need of detailed descriptions of physical and chemical atmospheric processes associated with Level 3 assessments as described in the South African Draft Regulations Regarding Air Dispersion Modelling (Notice 1035 of 2012 in terms of NEM:AQA (Act No. 39 of 2004) (DEA, 2012). CALPOST is a post processing module that is used for the computation of time-averaged concentrations and deposition fluxes predicted by the CALPUFF model (Scire *et al.*, 1999).

2.1.4.3.1 Model options

The CALMET, CALPUFF and CALPOST model settings were largely based on the peer reviewed report of the Atmospheric Impact Reports in support of Sasol's and Natref's application for postponement and exemption from certain requirements for the NEM:AQA, no 39 of 2004 Minimum Emission Standards (Exponent, 2014). The peer review was done by Exponent Inc., model developers of the CALPUFF modelling suite.

Default options were mainly used; however, deviations from the default option and the motivation for the deviations are noted in the following sections.

2.1.4.3.2 CALMET

The CALMET model was run for three consecutive years in one model run (January 2011 to December 2013). The modelling domain was 250 km by 250 km and the modelling resolution was 1 km by 1 km. Due to the large domain size, use was made of Lambert Conic Conformal (LCC) coordinates in order to minimize map distortion. CALMET was run in hybrid mode making use of prognostic MM5 (short for Fifth-Generation Penn State/NCAR Mesoscale Model) data. The winds from the MM5/3D.DAT were used as initial guess field to the CALMET model. Default options for the setup of CALMET were mainly used. Those settings that were chosen to deviate from default options, and the motivations for the choices are summarized in Table 2-3.

Table 2-3: A summary of CALMET options selected that deviate from default options (Exponent, 2014).

Variable	Description	Default value	Used value	Motivation
PMAP	Map projection	UTM (Universal Transverse Mercator)	LCC (Lambert Conic Conformal)	To minimize map distortion over the large domain
NOOBS	No observation mode	0 (Observations only)	2 - No surface, overwater, or upper air observation. Use MM4/MM5/3D.DAT for surface, overwater, and upper air data.	Observational data was limited and confidence in observational data is low.
IEXTRP	Extrapolate surface wind observations to upper layers	-4 (similarity theory used except layer 1 data at upper air stations ignored)	1 - no extrapolation is done	No observations were included in the model run
IPROG	Use gridded prognostic wind field model output fields as input to the diagnostic wind field model.	0 (no)	14 (yes, use winds from MM5 model as initial guess field)	No observations were included in the model run
IRHPROG	3D Relative humidity from observations or from prognostic data	0 (Use observational data)	1 (use prognostic data)	No observations were included in the model run
ITPROG	3D Temperature from observations or from prognostic data	0 (use observational data)	1 (use prognostic data)	No observations were included in the model run

The MM5 prognostic data was purchased from Lakes Environmental Software Company as MM5 data is not available commercially in South Africa at present. The purchased MM5 data is therefore the best available option. The MM5 data model resolution is 12 km with 18 vertical levels using a LCC projection with a centre point at 26.47 South and 29.03 East (Figure 2-3).

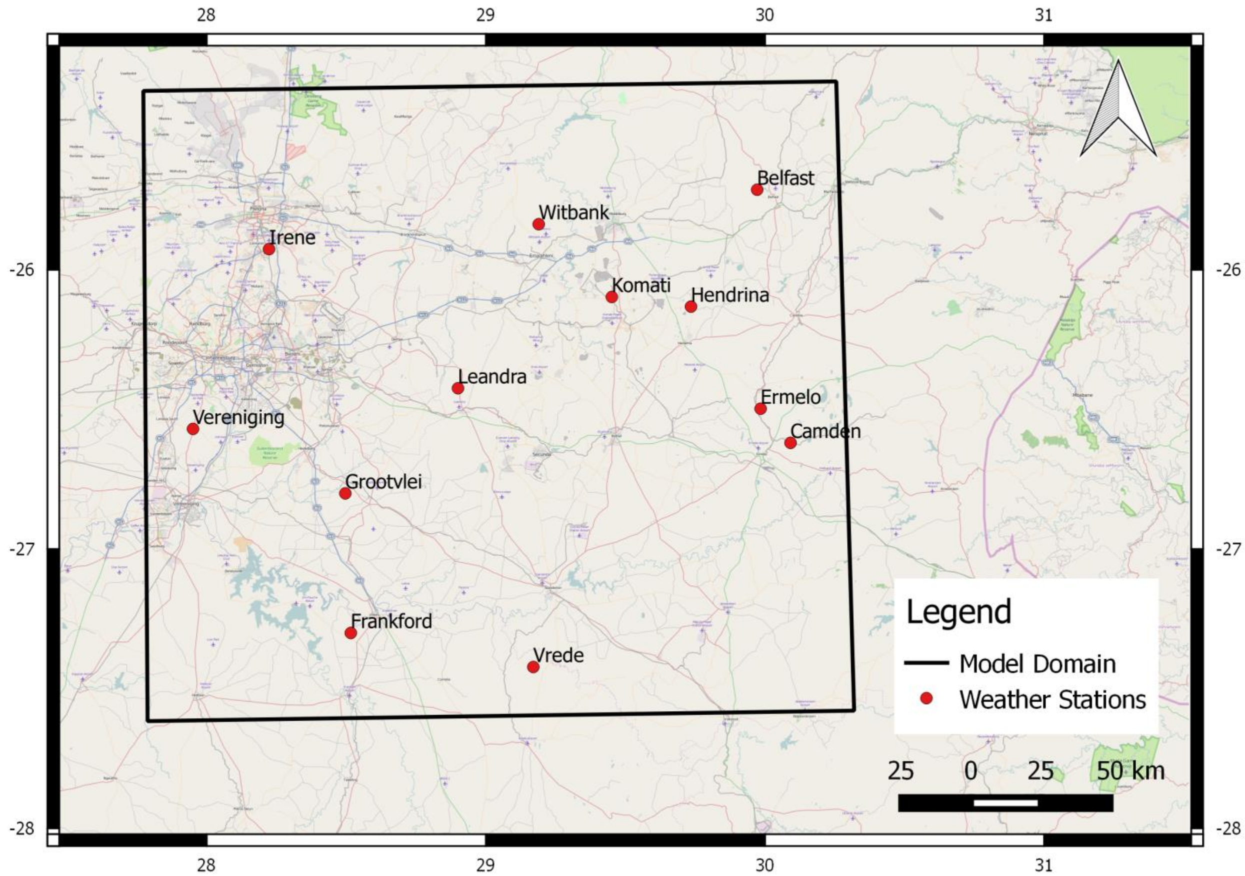


Figure 2-3: The area spanning the MM5 modelled domain. The locations of weather stations used to verify modelled MM5 data are also indicated.

The MM5 model was configured with Dudhia simple-ice microphysics, the Medium Range Forecast Planetary Boundary Layer scheme and the multi-layer soil model. Analysis nudging was performed; however observational nudging was not (Exponent, 2014). The model was initialized by means of National Center for Environmental Prediction (NCEP) Global Reanalysis data. The reanalysis data has a grid resolution of 2.5 by 2.5 degrees globally (Lakes Environmental, 2010).

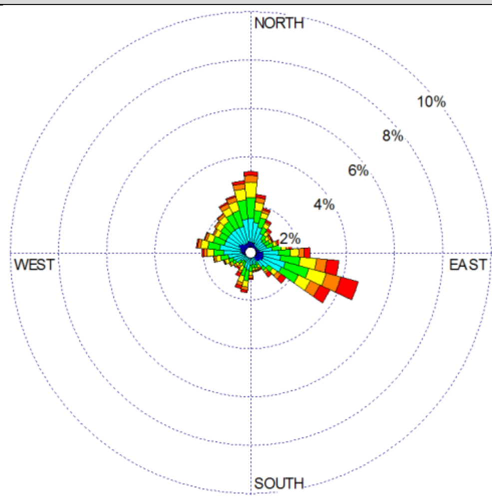
CALMET surface temperature, wind speed and wind direction data were extracted at the locations of 12 surface weather stations (which locations are indicated in Figure 2-3) in order to evaluate the CALMET model performance against observations. It is important to note that for the CALMET run in question, use was only made of MM5 prognostic data as input and no observational data was used. This evaluation therefore also serves as an evaluation of MM5 model data.

Observational and simulated wind roses are compared in Table 2-4 for 11 sites within the model domain for the period January 2011 to December 2013. Dark blue colours represent wind speeds between 1 and 2 metres per second (m/s), cyan wind speeds between 2 and 3 m/s, green wind speeds between 3 and 4 m/s, yellow wind speeds between 4 and 5, orange between 5 and 6 m/s and red wind speeds exceeding 6 m/s.

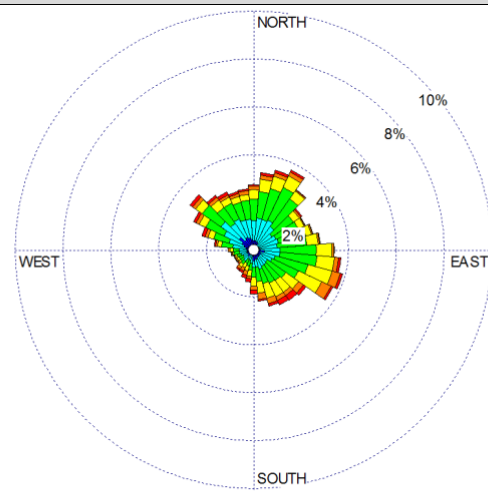
In general, wind direction was relatively well simulated. In most cases, simulated calm conditions were higher than those observed (with the exception of Vrede, Frankford, Camden and Belfast stations). The locations, mast height above ground level and data availability at each of the different weather stations are summarized in Table 2-5.

Table 2-4: A comparison of observed and simulated wind roses at 11 different locations within the model domain for the period January 2011 to December 2013.

<table>
<tr><th>Observation</th><th>Simulation</th></tr>
<tr><th colspan="2">Witbank</th></tr>
<tr><td>

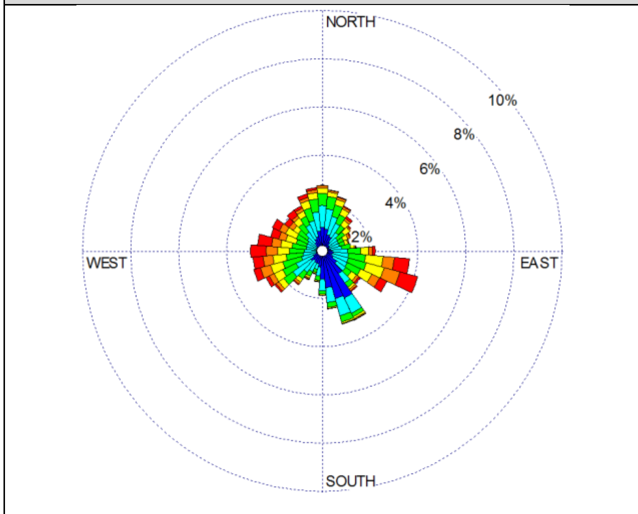


</td><td>

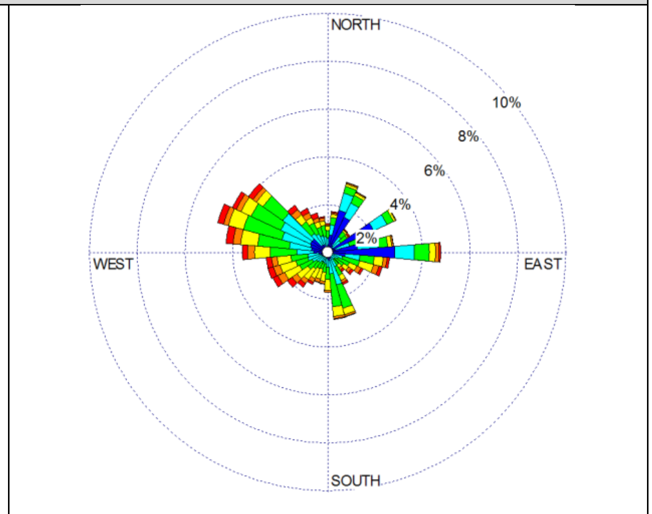


</td></tr>
<tr><td>Calms: 6%</td><td>Calms: 14%</td></tr>
<tr><td colspan="2"></td></tr>
</table>

Vrede

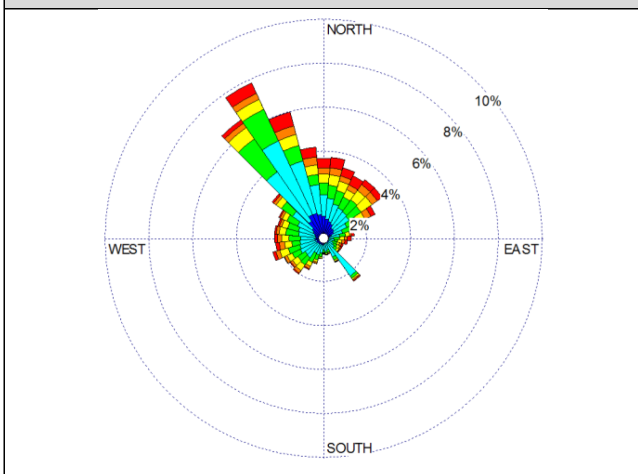


Calms: 17%

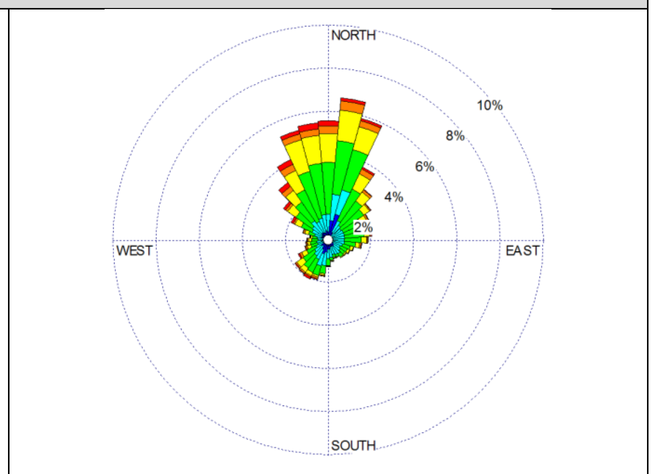


Calms: 14%

Vereniging

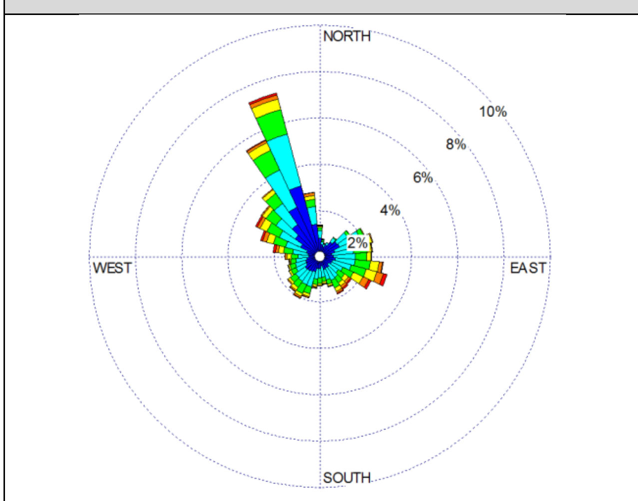


Calms: 4%

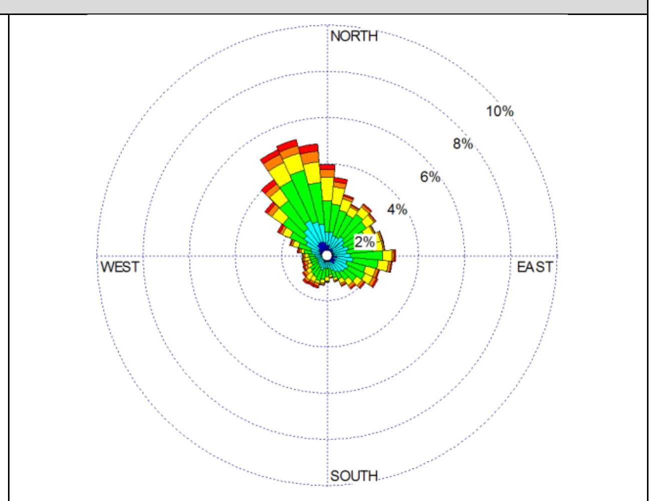


Calms: 15%

Leandra

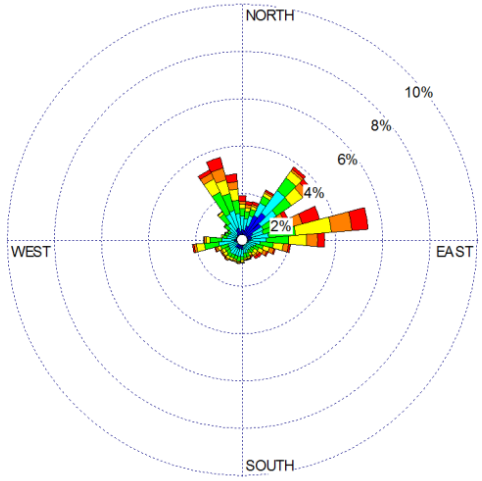


Calms: 13%

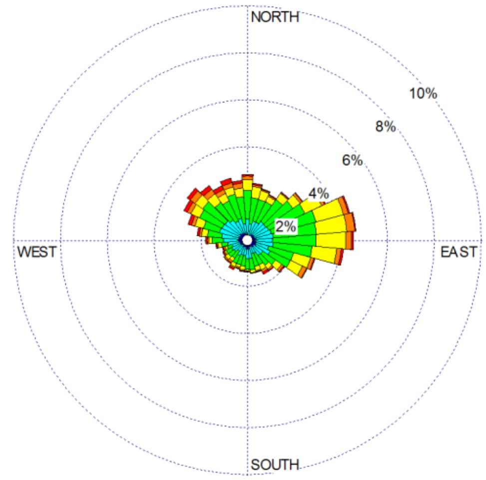


Calms: 15%

Komati

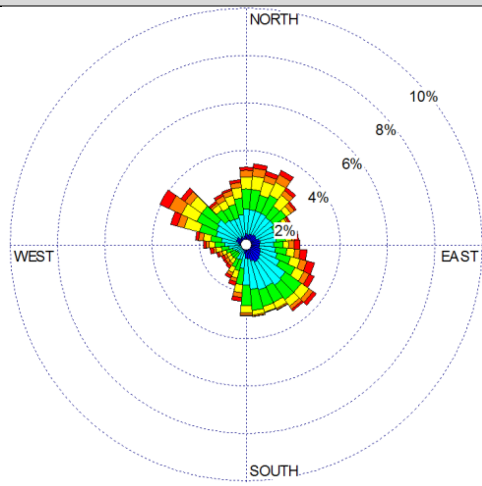


Calms: 9%

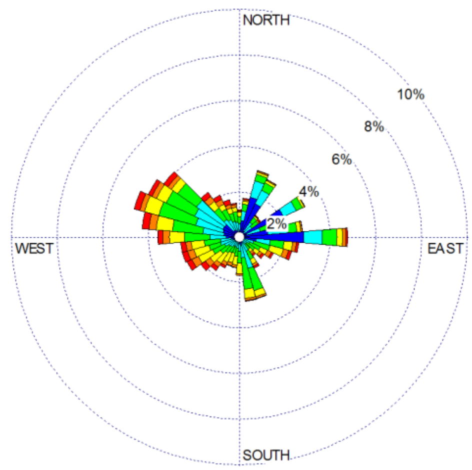


Calms: 14%

Irene

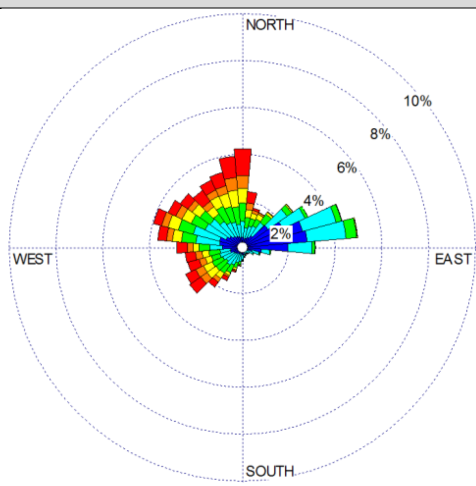


Calms: 5%

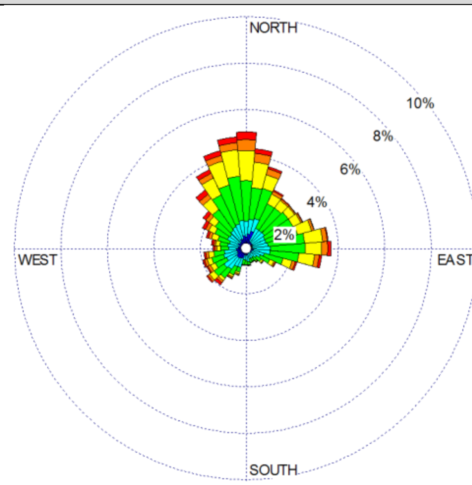


Calms: 14%

Grootvlei

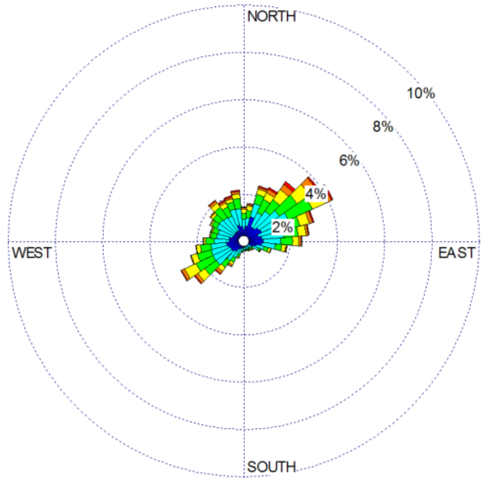


Calms: 16%

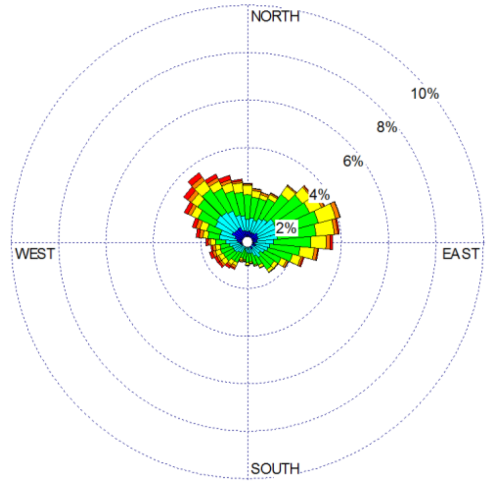


Calms: 16%

Frankfort

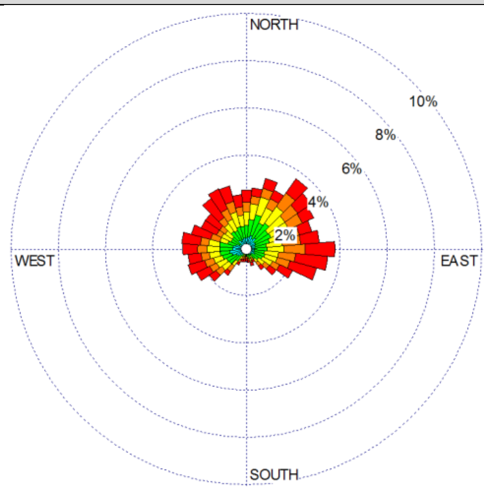


Calms: 35%

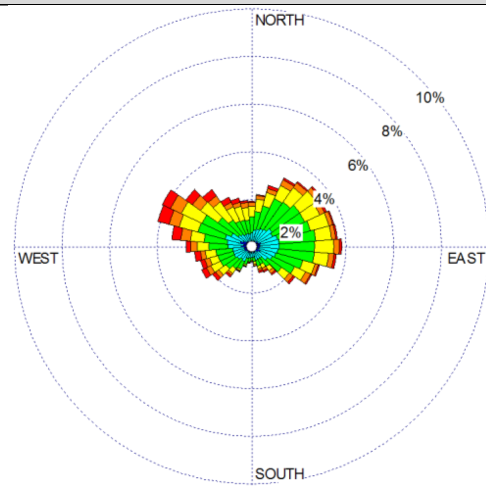


Calms: 18%

Ermelo

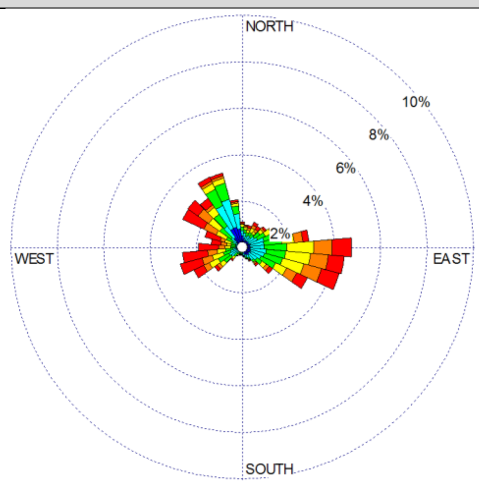


Calms:0 %

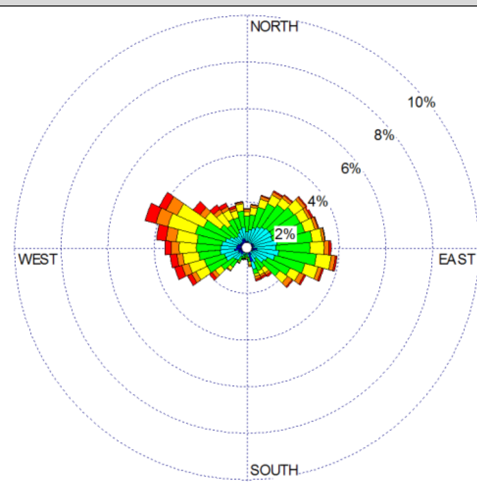


Calms: 11%

Camden

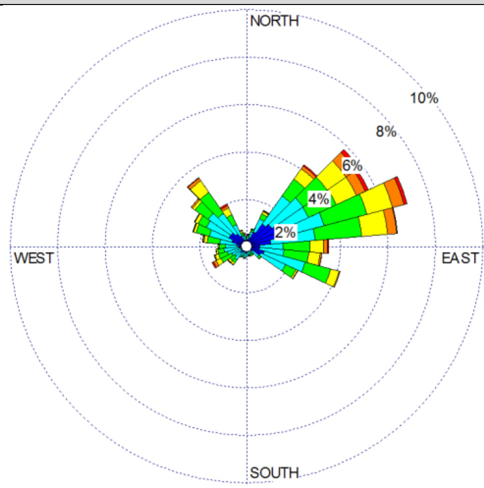


Calms: 15%

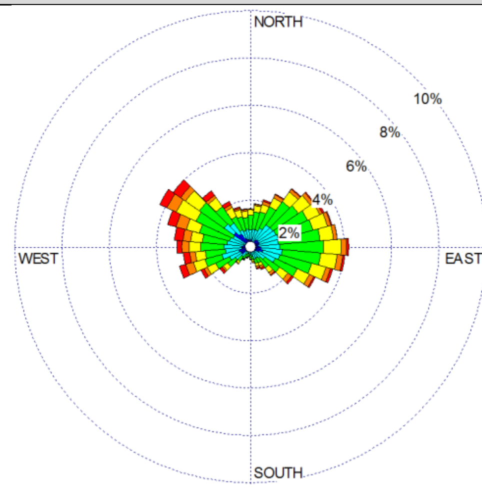


Calms: 11%

Belfast



Calms: 21%



Calms: 13%

Table 2-5: Data availability (%) at the 11 observational sites used for MM5 model evaluation.

Weather station	Lattitude (°S)	Longitude (°E)	Mast Height above ground (m)	Data availability (%)
Witbank	-25.837	29.189	10	73
Vrede	-27.423	29.169	10	99
Vereniging	-26.570	27.950	10	92
Leandra	-26.424	28.900	10	91
Komati	-26.097	29.451	10	75
Irene	-25.926	28.222	10	98
Grootvlei	-26.801	28.496	10	98
Frankfort	-27.301	28.516	10	80
Ermelo	-26.498	29.984	10	81
Belfast	-25.713	29.971	10	96
Camden	-26.620	30.091	10	100

At present, there are no accepted performance criteria for prognostic meteorological models. The reason for this is the valid concern that the establishment of such criteria, unless accompanied by careful evaluation, might lead to the misuse of such goals. However, there remains nonetheless the need for some benchmarks against which to compare new prognostic model simulations (Tesche *et al.*, 2002). Tesche *et al.* (2001) and Emery *et al*. (2001) formulated a set of model evaluation benchmarks based on MM5/RAMS meteorological model performance evaluation literature which are summarized in Table 2-6. The purpose of these benchmarks is to put modelling results into a useful context and should not be understood as the assignment of a passing or failing grade to these results (Tesche *et al.*, 2002).

Model observation benchmarks are based on statistical parameters including the root mean square error (RMSE), mean bias (MB), gross error (GE) and index of agreement (IOA). The RMSE and GE are both good overall measures of model performance. However, large errors are weighted heavily and therefore large errors in a small sub region may produce large RMSE and GE values even though the errors may be small elsewhere. MB is simply the average difference between modelled and observed results. The IOA is a measure of skill and gives one an idea of how well the model estimates departure from the observed mean matches, case by case, the observations' departure from the observed mean and it therefore condenses all the differences between model estimates and observations into one statistical quantity. The IOA has a theoretical range of 0 to 1, the latter score indicating perfect agreement. Similar statistical measures have also been used in other prognostic model testing (see, for example, Doty *et al.*, 2002; Tesche and McNally, 2001; Tesche *et al.,* 2002, Emery *et al.*, 2001).

It is important to note that the confidence in observational weather data in South Africa is sometimes relatively low as equipment are often vandalized and/or not calibrated at regular intervals. For this reason the model evaluation against observed data should be treated with caution.

Table 2-6: Model evaluation benchmarks; in m/s for wind speed; Kelvin (K) for temperature and degrees (°) for wind direction (Tesche et al., 2001; Emery et al., 2001; Tesche *et al.*, 2002).

Wind speed		
RMSE (m/s)	**MB (m/s)**	**IOA**
≤ 2	≤± 0.5	≥ 0.6
Temperature		
GE (K)	**MB (K)**	**IOA**
≤ 2	≤± 0.5	≥ 0.8
Wind direction		
GE (°)	**MB (°)**	
≤ 30	≤± 10	

One of the main problems of using statistical techniques in the model evaluation process is that outlying errors are often heavily weighted. It is therefore important to break data into shorter time periods and smaller areas in order to better understand error distribution. The stratification of the error statistics is essential in evaluating the overall performance of the simulation as it can be determined if one region or a specific time period has larger errors and biases than others (Tesche *et al.*, 2002). In the tables to follow (Tables 2-7, 2-8 and 2-9), simulated and observed wind speed (at a height of 10 m above sea level), temperature and wind direction results are compared in terms of period (the entire three year period), day-time, night-time and seasonal time periods. Where the benchmarks of Table 2-4 are not met, values are indicated in orange.

The model performance in the simulation of wind speed (Table 2-7) was superior relative to that of temperature (Table 2-8) and wind direction (Table 2-9). In general, the model tends to perform better during night-time and summer in simulating temperature, compared to other evaluated time periods. Wind speed and wind direction results did not show any improved results over specific evaluated time periods. Other studies which have incorporated observational data into their CALMET model did not necessarily show superior performance to those obtained here (see for example Hernandez-Garces *et al*., 2015 and Emery *et al*., 2001). It was therefore concluded that the model quality was adequate for this assessment.

Table 2-7: Statistical model evaluation of wind speed results for 11 sites within the model domain. Orange blocks indicate values not meeting the Tesche *et al*. (2001) and Emery *et al.* (2001) benchmarks summarized in Table 2-4.

Witbank							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.65	0.69	0.63	0.57	0.69	0.60	0.68
RMSE (m/s)	1.77	1.79	1.76	1.78	1.78	1.77	1.76
MB (m/s)	-0.08	-0.72	0.57	-0.37	0.31	0.07	-0.17
Vrede							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.68	0.73	0.56	0.64	0.68	0.64	0.70
RMSE (m/s)	1.92	1.88	1.95	1.63	2.19	1.83	1.97
MB (m/s)	0.20	-0.33	0.72	-0.32	0.80	0.26	0.03
Vereniging							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.63	0.69	0.57	0.47	0.69	0.55	0.65
RMSE (m/s)	1.80	1.94	1.64	1.87	1.72	1.70	1.90
MB (m/s)	-0.18	-0.79	0.43	-0.28	-0.02	0.00	-0.45

Leandra							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.62	0.69	0.54	0.56	0.63	0.63	0.60
RMSE (m/s)	1.77	1.71	1.82	1.66	1.94	1.51	1.92
MB (m/s)	0.68	0.30	1.05	0.57	0.87	0.46	0.80
Komati							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.69	0.73	0.65	0.60	0.69	0.67	0.69
RMSE (m/s)	1.71	1.70	1.71	1.63	1.92	1.50	1.82
MB (m/s)	-0.01	-0.55	0.52	-0.12	0.30	0.09	-0.19
Irene							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.56	0.60	0.52	0.49	0.55	1.77	0.53
RMSE (m/s)	1.97	1.92	2.01	1.80	2.14	0.56	2.12
MB (m/s)	-0.07	-0.06	-0.09	-0.25	0.17	-0.03	-0.18
Grootvlei							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.63	0.68	0.60	0.41	0.68	0.57	0.63
RMSE (m/s)	2.07	2.20	1.93	1.99	2.12	1.83	2.30
MB (m/s)	0.14	-0.71	0.98	0.46	0.15	0.40	-0.45
Frankfort							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.62	0.68	0.58	0.50	0.68	0.58	0.63
RMSE (m/s)	1.96	1.74	2.16	1.85	2.10	1.91	2.05
MB (m/s)	0.85	0.15	1.55	0.56	1.22	0.88	0.82
Ermelo							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.64	0.67	0.58	0.53	0.68	0.63	0.63
RMSE (m/s)	2.29	2.49	2.06	2.53	2.20	1.99	2.45
MB (m/s)	-1.45	-1.68	-1.22	-1.55	-1.37	-1.27	-1.66
Camden							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.65	0.65	0.66	0.60	0.67	0.64	0.61
RMSE (m/s)	2.15	2.41	1.85	1.86	2.39	1.99	2.35
MB (m/s)	-0.27	-1.11	0.57	-0.47	0.01	-0.16	-0.60
Belfast							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.63	0.65	0.60	0.56	0.67	0.62	0.59
RMSE (m/s)	1.93	1.76	2.08	1.66	2.09	1.79	2.10
MB (m/s)	0.83	0.28	1.38	0.51	1.15	0.72	0.91

Table 2-8: Statistical model evaluation of temperature results for 11 sites within the model domain. Orange blocks indicate values not meeting the Tesche *et al*., 2001 and Emery *et al*. benchmarks summarized in Table 2-4.

Witbank							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.92	0.87	0.94	0.88	0.85	0.88	0.89
GE (K)	2.74	3.54	1.93	2.18	3.27	2.82	2.82
MB (K)	-1.39	-2.85	0.07	-0.57	-2.54	-1.85	-0.95
Vrede							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.92	0.88	0.95	0.89	0.85	0.90	0.89
GE (K)	2.95	3.89	2.01	2.19	3.60	2.99	3.01
MB (K)	-1.62	-3.34	0.09	-1.10	-1.89	-2.01	-1.49
Vereniging							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.93	0.90	0.94	0.90	0.86	0.89	0.89
GE (K)	2.93	3.54	2.33	2.03	3.56	2.96	3.03
MB (K)	-1.20	-2.82	0.41	0.15	-1.63	-1.59	-1.57
Leandra							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.88	0.80	0.94	0.86	0.75	0.84	0.83
GE (K)	3.42	5.01	1.83	2.60	4.11	3.47	3.55
MB (K)	-1.99	-4.29	0.30	-0.59	-3.03	-2.53	-1.94
Komati							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.93	0.90	0.95	0.91	0.89	0.91	0.91
GE (K)	2.50	3.20	1.80	1.95	3.13	2.64	2.59
MB (K)	-0.99	-2.3333	0.35	-0.33	-1.88	-1.27	-0.91
Irene							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.75	0.81	0.70	0.62	0.53	0.73	0.56
GE (K)	4.60	4.21	4.99	3.37	5.71	3.95	5.32
MB (K)	-1.95	0.45	-4.35	-0.43	-3.16	-2.14	-2.06
Grootvlei							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.93	0.89	0.95	0.89	0.86	0.91	0.88
GE (K)	2.90	3.78	2.02	2.22	3.41	2.83	3.10
MB (K)	-1.51	-3.08	0.06	-0.28	-2.29	-1.69	-1.72

Frankfort							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.92	0.89	0.92	0.87	0.83	0.89	0.88
GE (K)	3.52	4.03	3.00	2.57	4.78	3.50	3.50
MB (K)	-0.54	-3.12	2.04	-0.59	0.18	-0.84	-0.75
Ermelo							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.94	0.91	0.95	0.93	0.87	0.91	0.91
GE (K)	2.34	3.00	1.66	1.58	2.81	2.36	2.48
MB (K)	-1.27	-2.20	-0.32	-0.38	-2.16	-1.63	-0.68
Belfast							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.91	0.84	0.93	0.89	0.84	0.87	0.86
Gross error (K)	2.67	3.46	1.89	1.85	3.31	2.71	2.87
Mean Bias (K)	-0.71	-2.03	0.60	0.11	-1.82	-1.12	-0.09
Camden							
	Period	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
IOA	0.88	0.81	0.88	0.85	0.75	0.86	0.87
GE (K)	3.59	4.48	2.71	2.59	4.96	3.37	3.22
MB (K)	-1.39	-2.64	-0.14	-1.26	-1.80	-1.40	-0.94

Table 2-9: Statistical model evaluation of wind direction results for 11 sites within the model domain. Orange blocks indicate values not meeting the Tesche *et al.*, 2001 and Emery *et al*. benchmarks summarized in Table 2-4.

Witbank							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	80	76	83	86	74	72	83
MB (º)	-7	0	-13	-19	8	9	-17
Vrede							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	89	77	101	83	96	92	85
MB (º)	29	8	49	-10	54	41	30
Verkykerkop							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	86	70	102	113	81	76	77
MB (º)	45	11	79	59	55	36	32

Vereniging							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	101	77	125	98	106	106	94
MB (º)	-24	-7	-40	-8	-49	-15	-20
Leandra							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	76	72	79	86	63	71	81
MB (º)	-23	-27	-20	-36	-23	-14	-18
Komati							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	67	61	72	66	64	65	72
MB (º)	10	10	9	2	13	15	12
Irene							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	109	106	112	110	105	95	123
MB (º)	-10	38	-58	-7	-17	-3	-14
Grootvlei							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	78	66	90	81	77	**75**	78
MB (º)	-14	-10	-18	-7	-29	-13	-7
Frankfort							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	97	82	112	80	112	104	94
MB (º)	60	36	84	32	80	79	49
Ermelo							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	67	62	73	63	61	75	70
MB (º)	5	1	9	-13	0	24	6
Belfast							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	94	73	99	68	106	105	95
MB (º)	64	30	115	36	82	82	53
Camden							
Parameter	**Period**	**Day**	**Night**	**Summer**	**Winter**	**Autumn**	**Spring**
GE (º)	70	62	79	71	70	69	72
MB (º)	-11	-15	-7	-24	-4	-4	-17

Contour maps indicate the spatial distribution of errors and can be used to determine whether model performance is spatially biased (Tesche, 2002). The spatial distribution of the three year period wind speed RMSE (m/s) is indicated in Figure 2-4, whereas that of the wind speed IOA is depicted in Figure 2-5, the temperature GE (K) distribution shown in Figure 2-6, the temperature IOA indicated in Figure 2-7 and the wind direction GE (ᴼ) is shown in Figure 2-8. In general (with the exception of the wind speed RMSE (Figure 2-4)), the model seems to perform worst in the north-west corner of the domain.

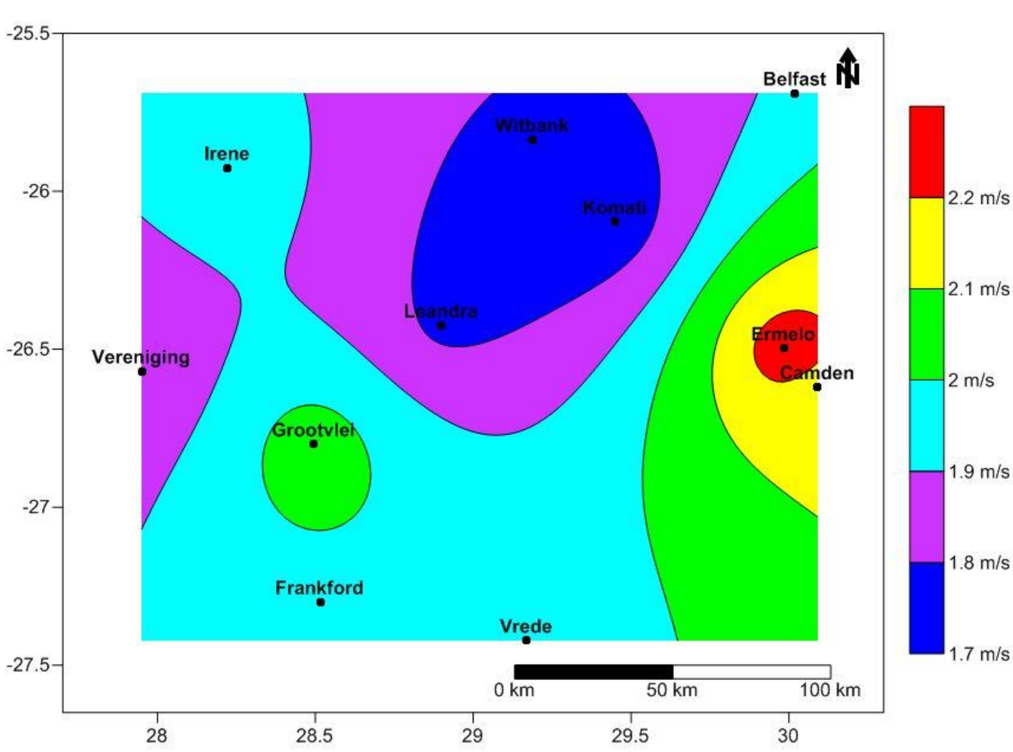


Figure 2-4: Spatial distribution of the wind speed RMSE (m/s).

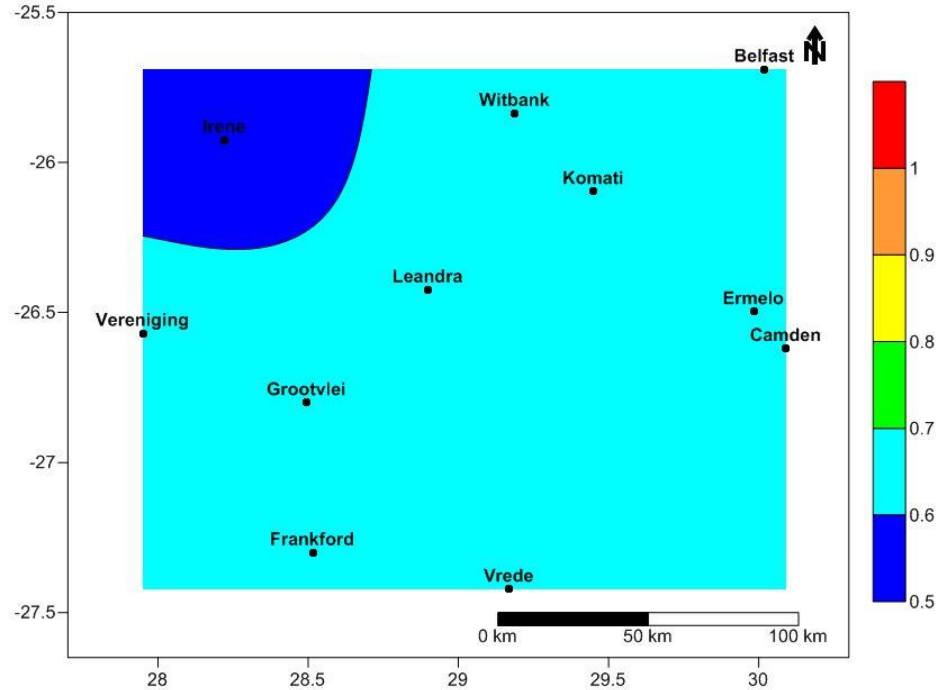


Figure 2-5: Spatial distribution of the wind speed IOA.

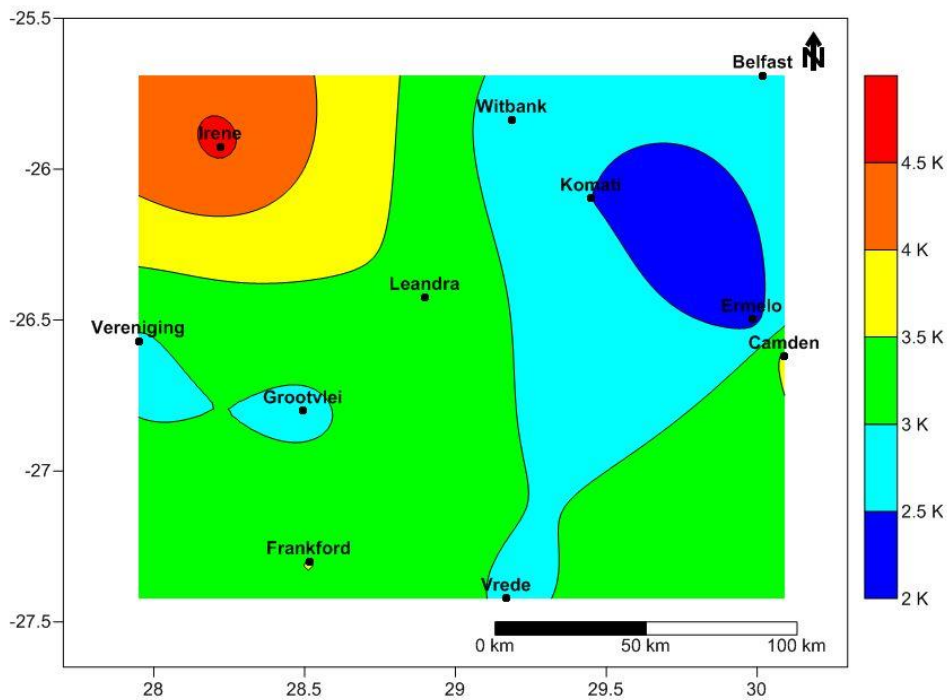


Figure 2-6: Spatial distribution of the temperature speed gross error (K).

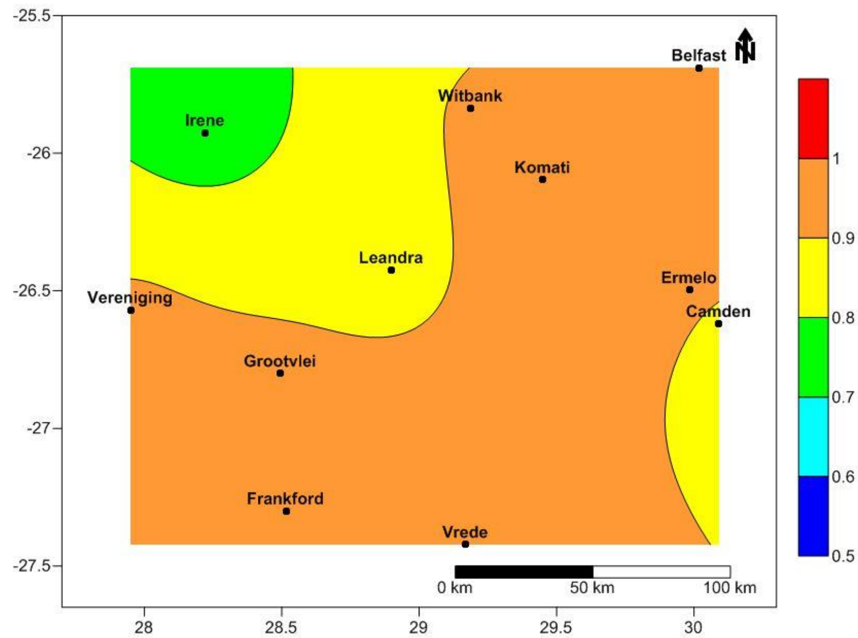


Figure 2-7: Spatial distribution of the temperature IOA.

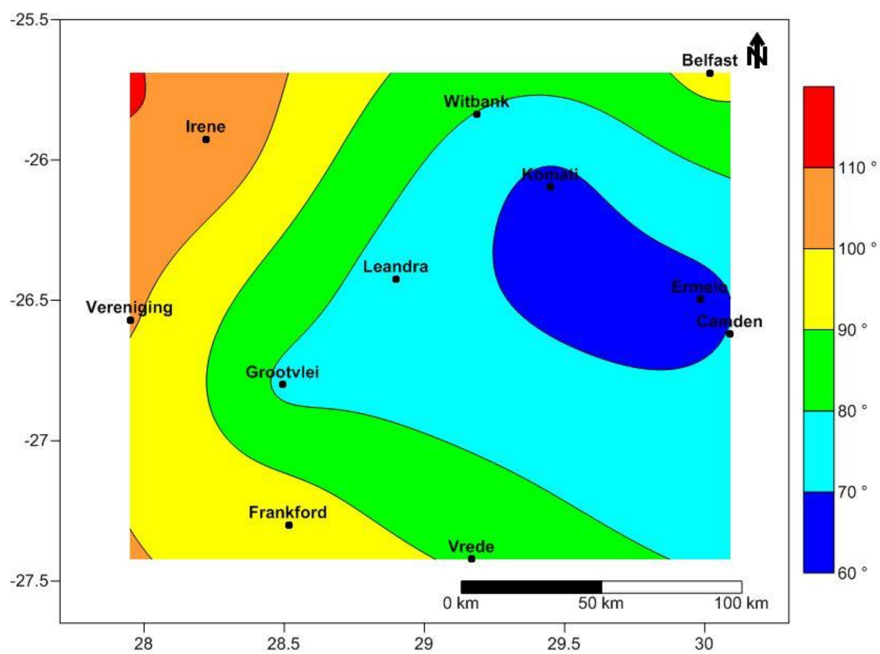


Figure 2-8: Spatial distribution of the wind direction gross error (degrees).

2.1.4.3.3 CALPUFF

CALPUFF version 6.42 was used for the purpose of this study. Use was made of the Mesopuff-II scheme for chemical transformation and six chemical species (SO_2, SO_4, NO_x, Ammonium Nitrate (HNO_3), NO_3 and PM_{10}) were modelled, however only three (SO_2, NO_x and PM_{10}) were emitted. The Mesopuff-II chemical transformation scheme makes use of parameterizations that were developed from chemical transformation rate expressions derived from the results of photochemical model simulations over a wide range of environmental conditions (US EPA, 1994). As part of this chemical transformation method, daytime SO_2 oxidation varies hourly based ozone concentration, solar radiation, atmospheric stability, and relative humidity, with a night-time conversion rate of 0.2 % per hour. Daytime NO_x oxidation values varies hourly as a function of background ozone concentration, atmospheric stability and plume NO_x concentration with a night time rate of 2 % per hour (Zhou *et al.,* 2003).

Monthly ozone (O_3) concentrations were calculated from the 3-year monthly averages of three monitoring stations (Grootvlei, Ermelo and Witbank) situated within the Highveld Priority Area. The monthly averaged ambient background ammonia (NH_3) concentrations were calculated by averaging monthly concentrations of three monitors within the Highveld Priority Area over the period of three years. Values were obtained from the Exponent, (2014) report and monitoring stations included Bosjesspruit, Secunda and Langverwacht. Monthly averaged NH_3 and O_3 concentrations used are summarized in Table 2-10.

Table 2-10: Monthly average monitored NH_3 and O_3 concentrations utilized in the CALPUFF modelling.

Month	NH_3 Average (ppb)	O_3 Average (ppb)
January	17.6	25.8
February	18.6	26.6
March	14.2	25.6
April	10.7	21.6
May	13.9	21.8
June	19.3	21.9
July	19.1	23.6
August	20.1	33.9
September	16.9	39.7
October	8.7	39.6
November	7.3	40.8
December	10.6	31.2

Turbulence-based dispersion (MDISP=2), the recommended setting for CALPUFF, was selected in conjunction with the Probability Density Function (PDF). The PDF function has been found in a number of model evaluation studies to be important for tall stack dispersion under convective conditions (Exponent, 2014).

As modelled emissions originate from tall power station stacks (most probably in compliance with good engineering practice stack heights), it was expected that building downwash would not have significant effects on the plume in question. For this reason building downwash was not included in the modelling endeavour. This argument was considered valid in the Exponent 2014 peer review. Dry and wet deposition options were activated for the modelling procedure in order to produce the most realistic results.

2.1.4.4 CALPOST

CALPOST model version 6.292 was used. Total sulphate and nitrate concentrations were estimated from ammonium sulphate and ammonium nitrate concentrations, respectively.

2.2 Conclusion

In conclusion, the articles "***A critical comparison of gaseous coal-fired large boiler emission estimation in South Africa***" (Chapter 3) and "***The impact of the South African energy crisis on emissions***" (Chapter 4) mainly adopt the form of review articles, with literature and desktop studies as their main methodology.

The methodology used in the article "***A perspective of South African coal-fired power station emissions***" (Chapter 5) relied mainly on calculations of future coal-fired power station emissions scenarios in South Africa. The last article entitled "***Emissions management and health exposure: Should all power stations be treated equal?***" (Chapter 6) made us of dispersion modelling and calculation of potential human health exposure to power station emissions in South Africa.

The purpose of this chapter is to provide background information on the methodology followed in each manuscript hereafter, however, more information can be found within each individual manuscript. The following chapters consist of individual manuscripts, each addressing a single study objective.

3 Journal article: *A critical comparison of gaseous coal-fired large boiler emission estimation in South Africa*

Authors:

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This paper has been submitted to the CLEAN - Soil, Air, Water Journal for review:

I. Pretorius, J.B. Keir, S.J. Piketh and **R. P. Burger, 2015**. A critical comparison of gaseous coal-fired large boiler emission estimation in South Africa.

Consent from co-authors is attached as an addendum.

Thesis objective:

To compare CEMS and mass balance coal-fired power station emission estimation methods.

All debates and studies concerning air quality ultimately rely on emission factors as input. When emission factors are faulty or associated with large uncertainties it can possibly lead to bad policy choices, such as the unnecessary instalment of costly emissions abatement or the warranting of pollution at the cost of human health. For this reason, knowledge of the process and data quality associated with emissions estimation is so important. Historically, use was made of plant-specific emission factors and mass balance calculations for estimating gaseous emissions from coal-fired boilers across all sectors in South Africa (including coal-fired power station boilers, smelters, furnaces and heaters). However, from 2015 onwards as a requirement of the National Environmental Management: Air Quality Act, 2004 (NEM:AQA) (Act No. 39 of 2004) CEMS needs to be utilized to measure emissions from all large boilers. This article compares the calculation and CEMS methods in terms of cost, ease of operation, calculation/measurement uncertainty, data quality and practicality for use in the South African context.

Abstract

Emissions information is key to understanding the impact of a source of air pollution on its surrounding environment and human health. Errors in emissions estimation from large stationary boilers such as coal-fired power stations can have major cost implications, such as the unnecessary installment of costly abatement technology. This publication looks at the different gaseous large stationary boiler emissions estimation techniques used in the past and at present in South Africa and compares them in terms of cost, complexity and data quality. Emissions estimation was mainly done by means of plant-specific emission factors and mass balance calculations in the past whereas there is currently a transition taking place to Continuous Emissions Monitoring Systems (CEMS) as a requirement of the South African National Environmental Management: Air Quality Act, 2004 (NEM: AQA NO. 39 OF 2004). Calculation methods are significantly more cost-effective than CEMS. Comparison tests between the two methods were conducted for CO_2, NO and SO_2 found that data quality of both methods is similar in South Africa and that the methods give very similar results. When CEMS

are not operated reliably and calibration and maintenance are not done routinely, CEMS will give inaccurate results. It is therefore recommended that calculation methods be used in combination with CEMS until it can be proven that CEMS provide quality measurements with lower uncertainties than calculation methods in South Africa.

3.1 Introduction

Emissions data is at the core of understanding environmental problems and have been collected and used in environmental policy making since the 1970's. The collection of emissions data in the form of emissions inventories has aided the understanding of emerging problems in highly industrialized areas (Pulles and Heslinga, 2010).

In South Africa, gaseous emissions from large coal-fired boilers (>100 MW) were required to be reported to the Department of Environmental Affairs (DEA) since the 1990's (Eskom, personal communication). Emission reporting is done on a monthly basis and is audited annually. Historically, usage was made of plant specific emission factors and mass balance calculations for estimating gaseous carbon dioxide (CO_2), sulphur dioxide (SO_2), and oxides of nitrogen (NO_x), reported as nitrogen dioxide; (NO_2) emissions from coal-fired boilers across all sectors (including coal fired power station boilers, smelters, furnaces, heaters). However, from 2015 onwards, as a requirement of the National Environmental Management: Air Quality Act, 2004 (NEM:AQA) (Act No. 39 of 2004), CEMS needs to be utilized to measure emissions from large boilers.

Plant-specific emission factors are developed by making use of spot-measurements (done once every couple of years) to estimate emissions associated with a normalised amount of coal consumption at a specific plant. Emissions from the plant are then calculated by multiplying emission factors with fuel usage over a specific period.

Mass balance calculations entails following the mass flow of an element through the combustion process. The general mass balance equation can be written as: Input = Output (Solid waste + Emissions) (Bader and Bleischwitz, 2009). CEMS, on the other hand, is an instrument (such as a gas analyser) used to continuously measure a gas concentration from a stationary source. Emissions are derived from CEMS by multiplying the concentration of the pollutant measured in the stack flue gas by the flow rate of the gas (Loreti *et al.,* 2000).

At present, only gaseous emissions of SO_2 and NO_x are regulated under the Minimum Emission Standards (MES) of NEM:AQA. However, CO_2 emissions also need to be quantified and reported in order to compare progress made against the South African formal climate change mitigation proposals with the United Nations Convention on Climate Change. It is expected that CO_2 tax will be implemented to regulate CO_2 emissions in the future (expectedly 2016) and this will further increase the need to estimate CO_2 emissions at high levels of certainty (Greve, 2013).

The aim of this paper is to critically compare calculation methods (mass balance and plant-specific emission factors) and CEMS in terms of cost, complexity of operation and accuracy for large (electricity generation) coal-fired boilers in South Africa.

3.2 Emission estimation techniques for large boilers

The description on historical gaseous emissions estimation techniques for large coal-fired boilers is largely based on the techniques employed by South African electricity public utility; Eskom, in the past. It is assumed that emissions from comparable sources not owned by Eskom were calculated in a similar manner.

3.2.1 Past plant-specific emission factor techniques (1982-1995)

A mobile gas laboratory was developed and built between the late 1970s and early 1980s. Flue gas analyses were conducted at every Eskom stack between 1982 and 1995. Plant tested emissions factors for CO_2, SO_2 and NO_x were then calculated from coal and flue gas analyses by making use of mass balance calculations. The emission equations were derived in the following steps:

Firstly, the mass of total carbon burnt (in kilograms (kg)) per kg of coal was calculated from coal analysis by means of the following equation:

$$C_{burnedAR} = \frac{C_{coalAR}}{100} - \frac{A_{coalAR}.C_{ash}}{100.(100-C_{ash})} \quad (1)$$

Where:

$C_{burnedAR}$: The mass (in kg) of total Carbon burned per kg coal as received

C_{coalAR}: The amount of total carbon per 100 kg coal as received

A_{coalAR}: The amount of ash per 100 kg coal as received

C_{ash}: The amount of carbon remaining per 100 kg of ash produced after combustion

Secondly, the mass of carbon present in one kg of flue gas was calculated from flue gas analysis. This is done by means of the following equation.

$$C_{Flue} = \frac{3.(10^4.CO_2+CO+THC)}{25.10^4.Z} \tag{2}$$

Where:

C_{Flue}: The mass (in kg) of carbon in one kg of flue gas

CO_2: Carbon dioxide (%) in flue gas

CO: Carbon monoxide (ppm) in flue gas

THC: Total Hydrocarbons (ppm) in flue gas

Z: Sum of proportional weights of all gasses in flue gas

Thirdly, the mass (in kg) of flue gas per kg of coal burned was calculated by dividing (1) by (2) in order to obtain (3).

$$\frac{10^4.Z.((100-C_{ash}).C_{coalAR}-A_{coalAR}.C_{ash})}{12.(100-C_{ash}).(10^4.CO_2+CO+THC)} \tag{3}$$

Fourthly, the emissions of gases (in kg per ton of coal burned) was calculated by multiplying the proportional weights of each gas in one kg of flue gas by Equation 3 and correcting it for a ton of coal burned (multiplying by a 1000). The following equations for E_{CO2} (the emission factor for CO_2 in kg per ton of coal burned) (4), E_{SO2} (the emission factor for SO_2 in kg per ton of fuel coal) (5) and E_{NO} (the emission factor for Nitric Oxide; NO, in kg per ton of coal burned) (6) can now be obtained:

$$E_{CO2} = \frac{CO_2.11.10^5.((100-C_{ash}).C_{coalAR}-A_{coalAR}.C_{ash})}{3.(100-C_{Ash}).(10^4.CO_2+CO+THC)} \tag{4}$$

$$E_{SO2} = \frac{SO_2.160.((100-C_{Ash}).C_{coalAR}-A_{coalAR}.C_{Ash})}{(100-C_{ash}).(10^4.CO_2+CO+THC)} \tag{5}$$

$$E_{NO} = \frac{NO.25.((100-C_{ash}).C_{coalAR}-A_{coalAR}.C_{ash})}{(100-C_{ash}).(10^4.CO_2+CO+THC)} \quad (6)$$

E_{NO} is multiplied by 46/30 (the molecular mass of NO_2 divided by the molecular mass of NO) in order to give the emissions of NO_2 (kg per ton of coal burned) to the air since NO changes rapidly to NO_2 in the atmosphere.

The main disadvantage of this approach was that emissions estimations were based on calculations derived from a relatively small number of stack tests conducted on every boiler in Eskom approximately once every two to three years. Emissions estimations therefore could not be adapted easily for changes in coal quality and operating conditions.

3.2.2 Mass balance techniques (1995-March 2015/Current)

After 1995 the technique for calculating CO_2 and SO_2 emissions has been changed. Comparisons were done between emissions estimations making use of the plant tested emission factors during the previous years and those making use of daily coal and ash analyses collected over a period of a month (where each month's analysis is made up of weighted daily coal analyses). The monthly weighted average coal analyses are produced from thirty plus daily coal samples with their respective mass flow tonnages (Keir, 2014).

It was found that basing emissions calculations on the latter method allowed for quicker adaption of emissions estimated for changes in coal quality. This technique is based on the assumption that when coal is combusted, the amount of CO_2 and SO_2 released is directly proportional to the amount of carbon and sulphur in the coal; taking any carbon and sulphur remaining in the ash after combustion into account (Loreti *et al.*, 2000). At present, mass balance calculations can only be calculated on a monthly basis due to logistical problems with coal sampling and analysis which is not continuous and instantaneous.

3.2.2.1 CO_2 emissions

Three pieces of information are required when estimating CO_2 emissions by means of the mass balance method used by Eskom, namely the amount of fuel burned, the carbon content of the fuel and the fraction of carbon left in the ash after combustion (Loreti et al., 2000). The total carbon content of the coal is obtained from coal analysis. The amount of carbon remaining in the ash post combustion is obtained from fly ash analysis. The carbon remaining in the ash is subtracted from the total carbon content of the coal. The analysis of carbon in the ash is done at an on-going basis at all power stations by means of ce-grits instruments. The formula

$C+O_2=CO_2$, is then used in order to calculate an emission factor for CO_2. In this formula C is the fraction of carbon in the coal that is converted to CO_2 (after the carbon remaining in the ash post combustion is subtracted from the total carbon content of the coal). The CO_2 emission factor is then multiplied by coal flow (measured by means of gravimetric conveyor belt scales) in a given time period in order to estimate CO_2 emission in tons for that specific period.

One challenge in using this method is that South African power stations only determine proximate coal analysis on site, on a daily basis. Proximate coal analyses only gives values for fixed carbon in coal. However, some of the carbon is present in the form of volatile matter, and a proximate analysis is not able to measure the amount of carbon in this form. In order to account for this, a part of the coal sample from each daily proximate analysis (sometimes up to three analyses per day) is collected over a month and sent to Eskom's central chemical laboratory for proximate and ultimate analyses. Annual regression curve factors are then determined from a number of monthly ultimate and proximate analyses. Calculated monthly station ultimate analyses are then determined from each stations monthly weighted average proximate analysis by using the annual regression curve factors (Keir, 2014).

3.2.2.2 SO_2 emissions

The same procedure used to calculate CO_2 emissions is utilized for the calculation of SO_2 emissions. The daily sulphur analysed at each power station is weighted with daily coal tonnages in order to give a monthly weighted average sulphur value. The sulphur value is then inserted into the formula $S+O_2=SO_2$; in order to calculate an SO_2 emission factor. The SO_2 emissions tonnage over a specific period of time is calculated by means of multiplying the coal mass flow by the SO_2 emission factor. South African power station coals have relatively low sulphur contents (approximately 1%). The amount of sulphur remaining in the ash post combustion was found to be negligibly low and is therefore not taken into account in the mass balance equation.

3.2.2.3 NO_x emissions

The formation of NO_x during the combustion process is a more complex process than that of CO_2 and SO_2. The major portion (approximately 98% - according to Eskom estimations (Eskom, 1993)) of NO_x emitted during the combustion process is in the form of NO. The combustible nitrogen needed for the formation of NO emissions is present in both the coal (namely chemically fuel bound nitrogen producing NO) and the air (called thermal NO). Most of the NO (approximately 80%) (Srivastava *et al*., 2005) is produced from the fuel nitrogen. Due to the complexity of NO_x formation, there is not a newer mass balance technique by which NO_x can be estimated and emissions are estimated by the past emission plant specific emission factor technique described in section 3.2.1. Every two to three years plant tests are conducted in order to update the NO_x emission factors for each power station.

3.3 CEMS

In accordance with NEM:AQA No. 39 of 2004, the South African DEA requires large stationary boiler SO_2 and NO_x emissions to be continuously monitored from 1 April 2015 onwards by means of CEMS; which are permanently installed in each stack. The CEMS need to be quality assured and controlled in South Africa according to the British standard BS EN 14181:2014: 'Stationary source emissions quality assurance of automated measuring systems'. The law makes provision for the use of a different method of estimating emissions if it can be proven that this method is equivalent to CEMS and with written consent of the relevant air quality officer. The averaging period of compliance monitoring by means of CEMS needs to be expressed on a daily average basis and the emissions monitoring system should yield a minimum of 80% valid hourly average values during the monitoring period.

In order to gain expertise in the use of this technology, Eskom started by installing one analyser per power station in 2007. At present, 31 analysers have been installed out of 54 stacks (excluding Kusile and Medupi power stations which are currently under construction). The analysers range between four types, namely Servomex (Straight extractive), Codel (in-situ), Sick (in-situ) and Procal (in-situ).

The CEMSs are required to be verified by South African National Accreditation System (SANAS) accredited laboratories at least once every two years. These mobile laboratories are accredited according to the ISO/IEC 17025 standard called 'General requirements for the competence of testing and calibration laboratories'. The majority of CEMS are expected to be installed by the 1st of April 2015, but not all verified. Eskom is therefore moving towards real time, on-line, in-situ (or extractive measurements) for gaseous monitoring of CO_2, SO_2 and NO_x emissions in the future.

3.4 Methods comparison

Calculation techniques and CEMS are each associated with different advantages and disadvantages. Most notably, the advantages and disadvantages are associated with capital and operational cost, different output periods, operational and maintenance factors. Table 3-1 summarizes these factors for each of the two methods.

Table 3-1: A comparison of the capital cost, operational cost, output periods as well as operational and maintenance complexity of calculation methods and CEMS.

Estimation technique	Capital cost ratio	Operation and maintenance cost ratio	Output period	Ease of operation	Equipment replacement
Calculation Methods / CEMS	For one CEMS 1 / 200 For fifty CEMS 1 / 10 000	For one CEMS 1 / 8 For fifty CEMS 1 / 50	Monthly / instantaneous to daily averages; subject to severity of stack stratification	Relatively simple / Complex	None / 10 to 15 years

From Table 3-1 it is clear that the capital, operational and maintenance costs of CEMS is significantly higher than those of calculation techniques. Operational costs of calculation methods include IT repair for the laptop, equipment costs for taking spot measurements of in-stack NO_x concentrations at each plant every two to three years, labour, travel and accommodation costs. The total CEMS operating and maintenance costs are made up of the following (Berry, 1997);

- 30% to 35% Data validation / reporting / record keeping
- 35% to 40% Training, daily checks and routine maintenance
- 20% Quality Assurance and Quality Control
- 10% to 15% Corrective maintenance

It is further believed that due to the fact that the use of CEMS technology is relatively new in South Africa, training costs are vastly underestimated. Mass balance equations make use of coal and ash analysis methods that are already conducted for other purposes at all stations. In-stack spot measurements required for the development of plant-specific emission factors are well understood and are required to be done on an infrequent basis (once every two to three years at each stack).

An advantage of CEMS is that emission output can be obtained in continuous real time, instantaneous to daily average values; which can be compared against short-term emission limits. Presently, calculation methods at South African coal-fired power stations can only give monthly average values, since daily coal analyses need to be weighted with the tonnage of coal and averaged over a month to reduce uncertainty caused by the variability of coal quality.

Calculation methods are relatively easy to implement and are operationally simple whereas CEMS are complex. CEMSs are replaced approximately every 10 to 15 years as a result of improvement in technology and the abrasive environment these systems operate in.

3.4.1 Data quality

In order to delineate whether the high costs and operational difficulty of CEMS are justified; the two emissions estimation methods further needs to be compared in terms of data quality. Data quality refers to the confidence one has in the reliability of the data originating from each technique. For data to be termed reliable one would expect the quality to be both known and documented (Evans *et al*., 2009). In order to assure good data quality, the following processes need to be in place (Evans *et al*., 2009).

- Those making use of the measurement procedure in order to generate data must be trained.
- Measurement equipment must be calibrated to traceable standards.
- The calibration must be inspected regularly to ensure continuing reliability.
- Laboratories that are used for fuel analysis must be accredited.
- Only validated sampling and analysis methods (e.g. ASTM, ASME, EN) must be used.
- A written quality assurance plan must be generated.
- Adherence to the quality assurance plan must be documented.
- Uncertainties need to be quantified.

At present, the data quality of both the calculation methods and CEMS at South African coal-fired power stations are theoretically similar as the current calculation techniques are audited annually in accordance with the International Standard on Assurance Engagements (ISAE 3000) (KPMG, personal correspondence) and CEMS methods are required, by law, to be assured and controlled according to international standards (although a massive knowledge gap on this currently exists in South Africa, which is explained later). Of all steps listed above, only the last step (namely the calculation of uncertainties) is not currently done for each method.

Due to the fact that overall uncertainties for both techniques are not currently calculated at South African coal-fired power stations, it is not possible to compare existing uncertainties of the two emissions estimation techniques. For the purpose of this study, use was made instead of allowed uncertainty values according to international standards and values published in literature, in order to compare the uncertainties of the two methods (Table 3-2).

Table 3-2: A comparison of allowed uncertainties for the mass balance calculation and CEMS emissions estimation approaches for gaseous emissions estimation from coal-fired power station boilers.

Technique	Uncertainty		
	CO_2	SO_2	NO_x
Mass Balance	+-2.5 (Tier 4) to +- 7.5% (Tier 1)[a]	+- 20 %[b]	- +20%[b]
CEMS	+-2.5 (Tier 4) to +- 10% (Tier 1)[c]	+- 20% [d, e]	+-10% [f]+-20% [e]

[a] Tiers of uncertainty according to the Monitoring and Reporting Regulation (MRR) – Guidance on Uncertainty Assessment. European Commission. Guidance Document No. 4.

[b] Based on a coal flow uncertainty of up to 20% (and assuming this is the highest uncertainty), (Evans *et al*, 2009).

[c] Tiers of uncertainty according to the MRR Guidance Document–Continuous Emissions Monitoring Systems (CEMS), Guidance Document No. 7.

[d] The permissible uncertainty according to the standard reference method BS EN 14791 for measuring emissions of SO_2.

[e] Maximum permitted uncertainty for a power plant which is categorized as large combustion plant under the EU Directive 2001/80/EC.

[f] The permissible uncertainty according to the standard reference method BS EN 14792 for measuring emissions of NO_x.

It is important to note that flue gas stratification within the power station stack makes it extremely difficult to measure gas concentrations and flow rates accurately, especially by means of single-point analysers (US Environmental Protection Agency (US EPA), 1994; Evans *et al,* 2009). As CEMS systems have only been in use relatively recently in South Africa, the flow stratification problem in stacks are not well understood and has not been documented or formally investigated (Eskom, personal communication).

From the information in Table 3-2 it is evident that calculation methods and CEMS can achieve similar uncertainties, however CEMS is generally considered to operate in a slightly higher reliability band than mass balance calculations when the appropriate Quality Control/Quality Assurance measures are in place (Figure 3-1) (US EPA AP42, 1995).

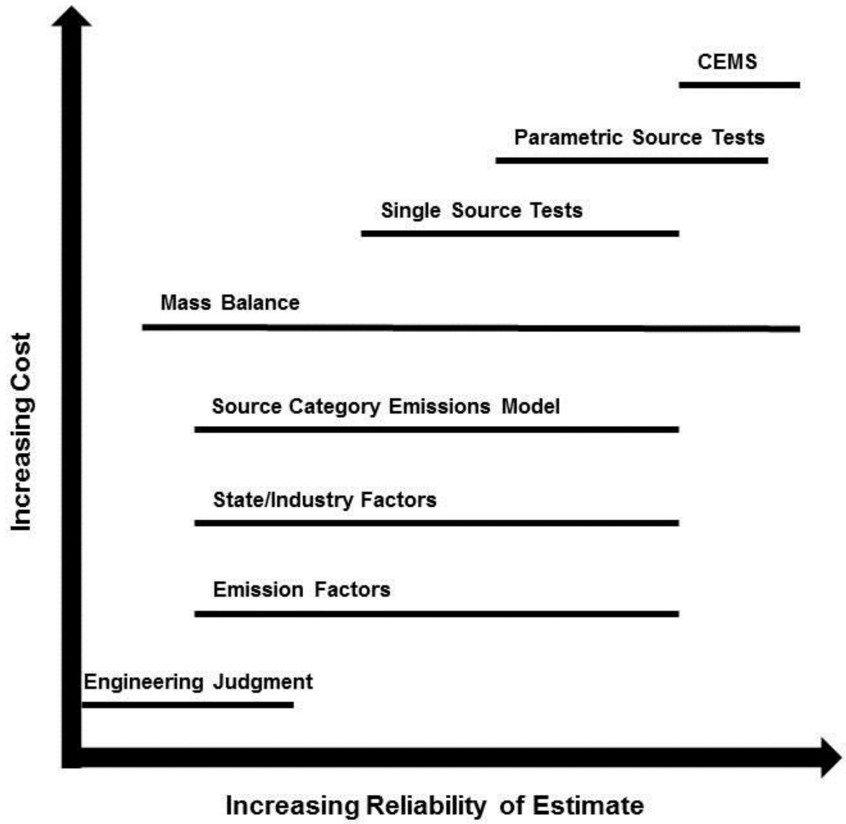

Figure 3-1: The risk associated with different emissions estimation techniques (adapted from US EPA AP42, 1995).

In some cases, mass balance calculations have been reported to yield better uncertainty values in estimating CO_2 emissions than CEMS (Loreti *et al*., 2000). For this reason, mass balance techniques are the preferred method for estimating CO_2 emissions in the European Union (EU) Monitoring and Reporting regulations. Overall uncertainties of ±1.6% can be achieved for large power station installations.

The main criticism against calculation methods is the poor data quality these methods often employ (Evans *et al*, 2009). When compared to CEMS, calculation methods are not nearly as well regulated and standardized. Only in a handful of cases, such as the example of the EU Monitoring and Reporting regulations mentioned in the previous paragraph, are strict quality assurance and quality control implemented. However, if calculation methods are presented with data to support their reliability and fulfill the same requirements that are in place for measured data, it can be an inexpensive and relatively simple tool for emissions estimation (Evans *et al,* 2009). Emissions calculation methods at South African coal-fired power stations follow strict documented procedures, are audited annually and therefore employ high data quality standards.

The main challenge in using CEMS in South Africa is the steep learning curve involved in operating these systems. It is believed that Eskom is still years away from achieving measurements with high confidence. At present, gas analysers are not performing optimally. This is illustrated by a comparison done in 2011 between the availability and reliability of analysers in the United Kingdom (97%) compared to that of Eskom (estimated to be between 45% and 79%) (Eskom, 2012a). The NEM:AQA No. 39 of 2004 requirement of 80% data availability is therefore unrealistic, at least in the short to medium term. Another important factor to take note of is that CEMS without regular maintenance and calibration will give poorer quality results than that of mass balance methods.

When gaseous emissions control is installed at a power station (such as Flue Gas Desulphurization systems (FGD) and Low NO_x Burners (LNB)), CEMS is the only gaseous emissions estimation technique that can be used – as mass balance calculations cannot be utilized if all input and output streams are not known, which is the case when emissions abatement is used. The advantages of implementing CEMS are that they can be used to estimate control equipment operation and for maintenance monitoring purposes – they can therefore be used to indicate how well the power station is functioning.

A study was conducted where gas analyser (CEMS) measurements were compared to calculated emissions at thirteen South African coal-fired power stations. Thirty seven comparison tests were conducted for CO_2, and forty five for SO_2 and NO. Coal sampling as an input to calculations were conducted concurrently with measurements. Measurements were taken at two units of each power station. Gas was sampled using a 3 metre stainless steel heated probe and filter. The gas was then passed through a peltier cooler; to extract flue gas moisture. The gas was analysed on a dry basis. The gas analyser was carefully calibrated before and after each test and small corrections were applied to the data in order to correct for any drift that occurred during the test period. The test was conducted over a time period of 2 hours to allow for variance in coal quality and flue gas stratification (Eskom, 2012b).

From the measured values, the median of both absolute and percentage differences between the two techniques were calculated with confidence intervals (Table 3-3). Flue gas stratification was not taken in account during these tests.

Table 3-3: The median of both absolute and percentage difference between mass balance calculated emissions and CEMS measurements.

Compound	Number of tests	Median of absolute difference between CEMS measurements and mass balance calculations (ppm). [a, c]	Median of percentage difference between measurements and calculations (%) [b, c]
CO_2	37	- 0.35 (±0.23)	-2.63 (±1.74)
SO_2	45	83.03 (±59.34)	9.30 (±6.80)
NO	45	40.19 (± 39.96)	5.30 (± 7.33)

[a] Brackets indicate 95% confidence interval (ppm) of absolute differences between CEMS measurements and mass balance calculations.

[b] Brackets indicate 95% confidence interval (%) of percentage differences between CEMS measurements and mass balance calculations.

[c] Confidence intervals were calculated by means of a Wilcoxon signed rank test.

The agreement between the calculated and measured emissions was relatively good for CO_2 with an average difference between measurement and calculation of -2.63 (± 1.74) %. For a similar study conducted in the US on a > 500 MW bituminous coal-fired boiler, the agreement was much lower (between 21% and 26%) (Evans *et al,* 2009). The good data quality of current mass balance methods at South African power stations may explain the good correlation between the two methods. The agreement between calculated and measured NO emissions were lower than that of CO_2, at 5.30 (± 7.33) % (which is within the allowed measurement uncertainty for NO (Table 3-2) and for SO_2 the agreement (9.3 ± 6.8 %) was also still within the measurement and calculation uncertainty described in Table 3-2. This proves that the quality and accuracy of mass balance calculations in South Africa is high and if coal-fired power station does not make use of gaseous emissions abatement, the additional costs and complexity of CEMS is not necessarily justified.

3.5 Methods used internationally

Internationally, developing countries mainly make use of calculation methods for estimating emissions from large boilers, whereas CEMS is generally the preferred method in the developed world (International Energy Agency, 2011).

EU member states are required to report CO_2 emissions to the EU emissions trading system based on emission factors, unless it can be demonstrate that CEMS produces more accurate data. The opposite is true for the United States of America, where CEMS for monitoring CO_2 are encouraged over the use of emission factors. However, for all other pollutants, CEMS is the preferred method used for compliance monitoring in these countries (International Energy Agency, 2011).

In India, greenhouse gas emissions are mainly estimated from Intergovernmental Panel on Climate Change (IPCC) default emission factors. In limited cases, plant specific emission factors have been developed (similar to those described in Section 3.2.1) and recently some efforts have been made to estimate emissions by means of mass balance and combustion principles (Mittal *et al.,* 2012). Similar to India, only a few of the power plants in Mexico have continuous emissions measuring capability; emissions are mainly estimated by means of emission factors, or periodically performed stack measurements (Vijay *et al.*, 2004). In China, CEMS monitoring is required for estimating SO_2 and NO_x emissions (Hsu, 2015).

3.6 Conclusions

In accordance with the NEM:AQA # 39 of 2004, the South African DEA requires large coal-fired boiler gaseous emissions to be continuously measured by means of CEMS from 1stApril 2015 onwards. Continuous and instantaneous data output from these systems; subject to stratification being taken into account, can be used to monitor how well abatement technology is functioning in real time and can be used as input into real-time dispersion models. For power stations making use of gaseous abatement technology, CEMS is the only method that can be used to estimate emissions.

At the moment there is still a void in CEMS operational and maintenance knowledge in South Africa as a whole. CEMS measurement data are not currently reliable and only a small number of installed CEMS instruments are functioning optimally. This knowledge gap needs to be filled before retro-fitments of gaseous abatement technologies are completed at South African Power Stations, as CEMS will be the only way to estimate emissions from these stations. It is believed that since this technology is relatively new in South Africa, training costs associated with CEMS might be vastly underestimated.

As a requirement of South African legislation, the averaging period of compliance monitoring by means of CEMS needs to be expressed on a daily average basis and the emissions monitoring system should yield a minimum of 80% valid hourly average during this period. A criticism against the legislation is that CEMS can output sub-daily measurements of emissions (subject to in-stack stratification) and one therefore does not make use of the full capability of the CEMS if compliance monitoring results are expressed on a daily average basis as prescribed by NEM: AQA # 39 of 2004. Measuring emissions at a sub daily level will enable problems with abatement technology to be identified sooner and will be able to establish whether diurnal trends in emissions exist. Another criticism is the high data availability requirement of the legislation. It is believed that this requirement is unrealistic, especially with such a new technology, as this data availability could not be achieved during a testing phase. The legislation further does not distinguish between simple and complex processes. The input and output streams of power stations not making use of gaseous emissions abatement is relatively simple and can be quantified by means of calculation methods with relative ease and high data quality.

In a method comparison study, it was shown that measured emissions did not differ significantly from emissions estimated by means of calculation methods. The difference between the two techniques was within the allowable uncertainty brackets of a number of international standards. The NEM: AQA # 39 of 2004 makes provision for the use of a different method of estimating emissions from CEMS if it can be proven that this method is equivalent to CEMS. If South African energy generators are not able to improve measurement quality from CEMS, this study (and/or similar studies) may be used in order to motivate the future use of calculation methods (which are well established) and more cost effective than CEMS – at least for power stations not making use of gaseous abatement.

It is recommended that calculations should be used concurrently with CEMS in the near future until such time as it can be proven that CEMS output is reliable and of high quality. Calculations can also be used as a simple and cost effective backup emissions estimation technique to CEMS.

Thesis conclusion

The objective of this paper is to compare CEMS and mass balance coal-fired power station emission estimation methods.

The following main conclusions can be drawn:

- *At present, the theoretical data quality of CEMS and calculation methods are similar in South Africa.*
- *The cost and complexity of CEMS is much higher than that of calculation methods.*
- *At the moment there is still a void in CEMS operational and maintenance knowledge in South Africa. The training costs associated with CEMS is most probably vastly underestimated.*
- *The high data availability requirement of the legislation (80%) for CEMS is unrealistic as this data availability could not be achieved during a testing phase.*
- *It is recommended that calculation methods be used concurrently with CEMS at least until such time as it can be proven that CEMS output is reliable and of high quality.*

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4 Journal article: *The impact of the South African energy crisis on emissions*

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Consent from co-authors is attached as an addendum.

Thesis objective

To investigate the effect of the South African energy crisis on emissions.

Since the middle 2000's, South Africa has been experiencing an electricity shortage. As a result, electricity outages became commonplace during the first quarter of 2008 with damaging effects on the South African economy. Three older power plants (Camden, Grootvlei and Komati) that were mothballed during the late 1980's and early 1990's had to return back to service during 2004 to 2013 in order to help alleviate the pressure on operational plants. Since the blackouts that occurred during 2008, electricity demand could be met by means of delaying maintenance on the generation fleet. A combination of the above factors led to the decline in performance and overall condition of the power station fleet which caused an increase in emissions. Apart from the increase in emissions from coal-fired power stations as a direct result of the energy crisis, the crisis also had (and has) effects on other sources of emissions. These include emissions from the domestic burning of solid fuels, emissions from Open Cycle Gas Turbines (OCGT's), and emissions from back-up generators and vehicle emissions. This article explores the effect the South African energy crisis had (and still has) on power station and other sources of emissions.

Abstract

Worldwide, the energy sector has a major environmental impact. Recent decades have seen exponential growth in population and therefore also in energy demand and environmental concerns. Many countries in the world are currently facing energy shortages, including major developing countries such as China and India. This paper evaluates the link between an energy restricted environment and emissions in South Africa, a country plagued by energy shortages since the middle 2000's. Lessons learned from the South African energy crisis hold important implications for countries facing similar challenges or those whose energy reserves are kept low in order to produce energy at competitive prices. It was found that the South African energy crisis had an undeniably negative impact on emissions from a range of sources, especially those with high human health impacts due to the fact that their emissions are emitted close to the ground and in close proximity to human populations. Examples of these type of sources include domestic burning (which increased as a result of dramatic increases in the South African electricity tariff during the energy crisis), backup generators (as higher income households and

businesses make use of diesel-fuelled back-up generators during times of planned electricity outages) and motor vehicles (traffic lights are out of order during times of planned electricity outages). Emissions from large power stations also increased due to lowered maintenance and deterioration of the condition of the stations. The removal efficiencies of emissions abatement technologies decreased due to the increased pressure on these systems and missed maintenance opportunities.

4.1 Introduction

Numerous countries in the world are currently experiencing energy shortages. Among these are some of the major economies in the world, including China and India (World Economic Forum, 2015). Numerous developed countries (such as the United States, Australia and European countries) keep energy reserves low in order to produce energy at competitive prices (International Energy Agency, 2007). An increase in emissions in China and India, for instance, will hold major implications for the global emissions scenario, and therefore the experience gained from the current energy crisis in South Africa can serve as an example of what may come if preventative measures are not taken.

Since 2007, South Africa has been experiencing energy shortages. The energy shortages led to electricity outages across the country and hence the term ‘the South African energy crisis’ was born. The reasons for the energy crisis are three-fold. Firstly, a dramatic increase in demand was experienced after 1994 when economic sanctions of the apartheid era were lifted and economic growth was high (Inglesi and Pouris, 2010). Secondly, the free basic energy policy was implemented in 2001 where 50 Megawatt-hour (MWh) of electricity was supplied to poor households free of charge. This was done as part of a drive to provide basic services to previously disadvantaged households (Inglesi and Pouris, 2010). Thirdly, in 2004 the government delayed making a decision to fund the building a new power station, when it became apparent that new energy capacity was needed (Inglesi and Pouris, 2010).

The aim of this paper is to investigate the effect the South African energy crisis had (and still has) on emissions. Direct impacts of the energy crisis on emissions include those associated with the decline in thermal efficiency of the coal-fired power stations, due to the increased pressure on the fleet, reduced maintenance and the return to service of older, less efficient stations. Increased emissions can also be expected from the increased use of diesel fuelled Open Cycle Gas Turbines (OCGT). Indirect impacts on emissions include the effect the energy crisis had on the use of solid fuel burning by poor households due to the increased price of electricity, the unreliability of electricity and low economic growth, the use of back-up generators by higher income households and business during planned electricity outages and an increase in traffic emissions during times of planned electricity outages when traffic lights are not working, thus increasing traffic congestion in the cities.

4.2 The energy crisis

Approximately 85% of South African energy is generated by large coal-fired power stations. Eskom, the South African public energy utility, is responsible for generating 95% of South African energy. The remaining 5% of energy is generated by privately owned and municipal energy installations (Ziramba 2009; Menyah and Wolde-Rufael, 2010).

Since 2007, the onset of the energy crisis, energy demand was met by means of delaying maintenance on the generation fleet. This 'Keeping the lights on' strategy led to the decline in performance of the fleet, which negatively impacted the effectiveness of the fleet to meet future demand (Department of Energy, 2013). Three older, less efficient, power stations that were decommissioned during the 1980's and early 1990's returned back to service to alleviate the pressure on existing stations. Diesel-fired OCGT was increasingly used, producing energy at exuberant costs. It is believed that the energy demand/supply balance will remain vulnerable until Medupi, a new power station currently under construction, comes fully online expectedly in 2018 (although uncertainty exists around the precise date) (Eskom, personal communication).

The energy crisis is characterised by a reduction in electricity reserve. Electricity reserve is the amount of reserve energy in an electric power system left after consumer supply has been met at all times. The electricity reserve is needed to operate reliably in the face of unplanned events, such as equipment outages, unplanned maintenance and fluctuations in demand due to occurrences such as unusually cold weather conditions (Pretorius *et al.,* 2015; Department of Energy, 2011). Electricity reserve can therefore be used as an indicator of how much pressure an electricity generation system experiences. When energy demand is greater than supply there will be very little spare energy in the system (Department of Energy, 2013).

The historical South African electricity reserve is illustrated in Figure 4-1 (Eskom, 2006-2013). During the period leading up to the energy crisis and during the energy crisis itself, the electricity reserve fell well below the South African aspiration of 15%. Internationally, electricity reserve requirements usually fall in the range of 15% to 25% (Pretorius *et al.,* 2015; Department of Energy, 2011). During the end of 2007 and beginning 2008, the energy system could not keep up with demand and planned electricity outages had to be implemented across the country for the first time. A number of planned electricity outages have followed since. From 2007 onwards the electricity reserve increased, however, it should be noted this increase was artificial as the reserve was managed by means of planned electricity outages, the application of a power buy-back program (where certain energy intensive consumers were paid not to use energy during this period) and the fact that large consumers were requested to reduce their consumption by 10%.

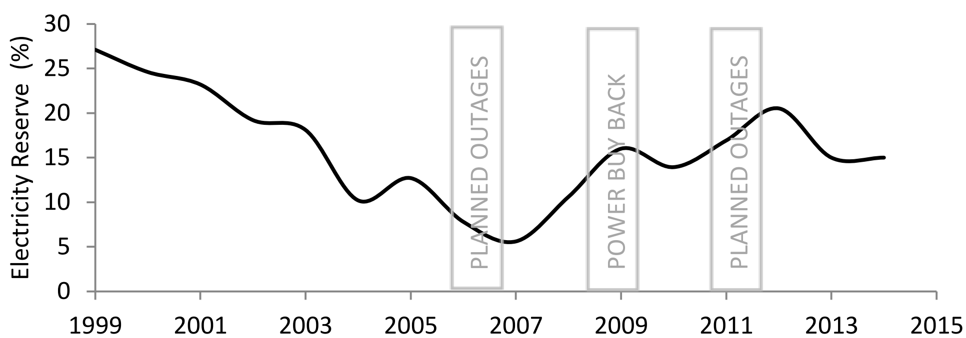

Figure 4-1: The South African electricity reserve (%) during the period 1999 to 2014 (Pretorius *et al.,* 2015)

As a result of a very thin electricity reserve, scheduled maintenance of power stations was deferred in 2008. This was done amidst the increasing pressure the South African government placed on Eskom to 'keep the lights on' at all costs. The maintenance backlog led to increased breakdowns of plants and therefore increased plant unavailability and the overall deterioration of the condition of the power stations. This is illustrated by the increase of the Unplanned Capability Loss Factor (UCLF) (a measure of the power lost due to the unplanned shutdown of power stations) after the deferral of maintenance in 2008 (Figure 4-2) (Matona, 2015). Early 2015, Eskom and the South African government acknowledged that the 'Keeping the lights on' strategy was unsustainable and the strategy was revoked. Eskom developed a maintenance regime in order to catch up the maintenance backlog (Matona, 2015).

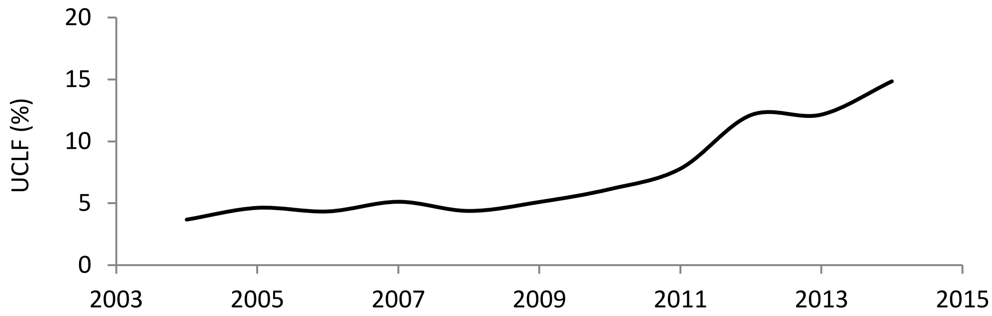

Figure 4-2: The Unplanned Capability Load Factor (UCLF) (%) for South African coal-fired power stations during the period 2004 to 2014 (Matona, 2015).

4.3 The impact on coal-fired power station emissions

The deterioration in the condition of the South African coal-power station fleet and the return to service of older, less efficient power stations, led to the decrease in overall thermal efficiency of the fleet (Figure 4-3) (Eskom, 2006-2013). A sharp decrease in the thermal efficiency of the fleet is evident from 2009 onwards.

When it is assumed that coal quality is stable (between 2005 and 2012., coal quality remained relatively stable with an average calorific value of 19.25 and a standard deviation of 0.34.) the decrease in thermal efficiency of the fleet essentially means that more fuel needs to be burned in order to produce the same amount of energy output. This is illustrated in Figure 4-4 where total coal consumption (Megatons (Mt)) and annual energy sent out (Terrawatt hour Sent Out (TWhSO)) by the South African coal-fired power station fleet is indicated from the period 1999 to 2012. Coal consumption and energy output curves follow the same trend until around 2006 where coal consumption starts to increase relative to energy output. During the period 2009 to 2012 coal consumption relative to energy output is around 8% higher than before the energy crisis.

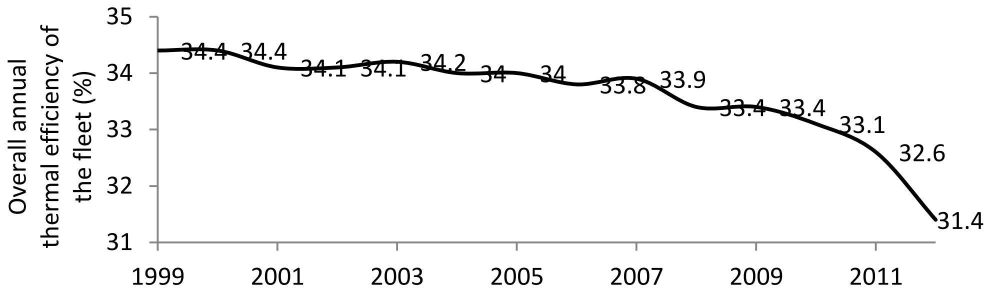

Figure 4-3: Overall thermal efficiency of the South African coal-fired power station fleet during the period 1999 to 2012.

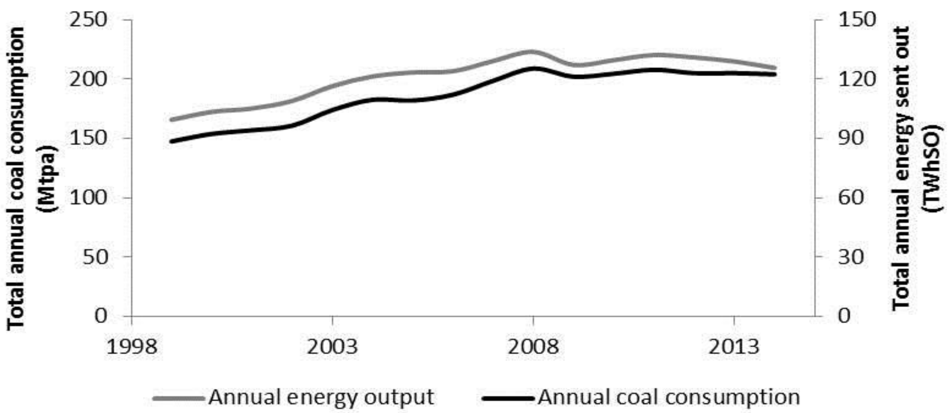

Figure 4-4: Coal consumption (Mt) and energy output (TWhSO) by the South African coal-fired power station fleet for the period 1999-2012 (Pretorius *et al.,* 2015).

As a result of the increase in relative coal consumption per energy output by the South African coal-fired power station fleet from the onset of the energy crisis period, it is expected that (if operating conditions remain constant) emissions will at least increase by roughly the same percentage. This was true for NO_x and CO_2 emissions, as relative emissions of these pollutants (emissions per energy output) increased proportionally to coal consumption (Figure 4-5). However, this was not true for emissions of SO_2 (Figure 4-5) as average sulphur contents of fuel burned during the energy crisis period decreased (Pretorius *et al*., 2015).

PM emissions were the most affected by the energy crisis. The reason for this is that PM is the only pollutant currently controlled by means of abatement at coal-fired-power stations in South Africa. Approximately two thirds of South African thermal power plants make use of Electrostatic

Precipitators for PM control and the other third make use of Fabric Filters. A sharp increase in relative PM emissions (emissions normalised for energy sent out) was experienced between 2007 and 2010 (Figure 4-5). Absolute PM emissions (total emissions in kilo-tons per annum (ktpa) almost doubled between 2007 and 2010 when energy output only increased by around 0.3% during the same period. This can be explained by the increase in relative PM emissions due to the increased pressure on PM abatement equipment and missed maintenance opportunity during this period. From 2010 onwards, relative PM emissions started to decline, albeit not to pre-energy crisis levels. This reduction is a result of the major modifications that were completed on particulate emission abatement equipment in 2010 (Pretorius *et al*., 2015; Eskom, 2007).

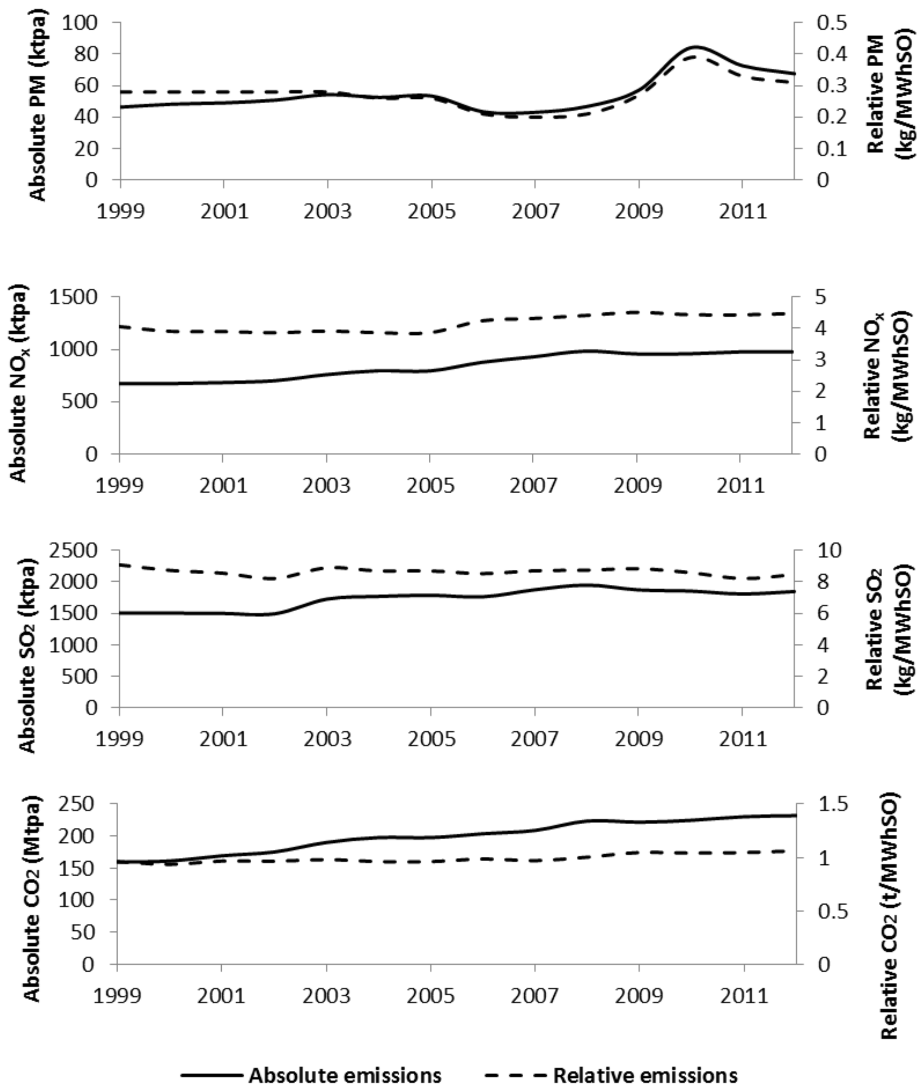

Figure 4-5: Absolute and relative emissions of PM, NO_x, SO_2 and CO_2 from South African coal-fired power stations during the period 1999 to 2012 (Pretorius *et al*., 2015).

4.4 The impact on OCGT emissions

During 2004 it became apparent that South Africa was heading for an energy crisis and that there was a very short lead time in order to invest in technology to have enough electricity to get through the winter peaks of 2007 (Eskom, 2014). After intensive investigations it was decided that the most viable technology was to invest in the building of OCGT's. Reasons for choosing this technology included the availability of the technology, the short lead times needed for installation and the proven track record of the technology (Eskom, 2014). Construction on two OCGT's started in 2006 and ended in 2009. These stations form part of peaking generation units and are indented to be used only at peak demand periods (mornings and evenings), however, the stations can be run up to eight hours a day should it be necessary. The cost of running OCGT's is extremely high compared to that of coal-fired power stations (approximately ten times higher than the cost of generating energy from coal) (Ndebele, 2015). Diesel usage by the OCGT plants (in Mega-Litres (ML)) increased drastically from 2009 to 2013, and expectedly, so did emissions (Figure 4-6) (Eskom, 2014; United States Environmental Protection Agency (US EPA), 1995; Australian Government, 2012).

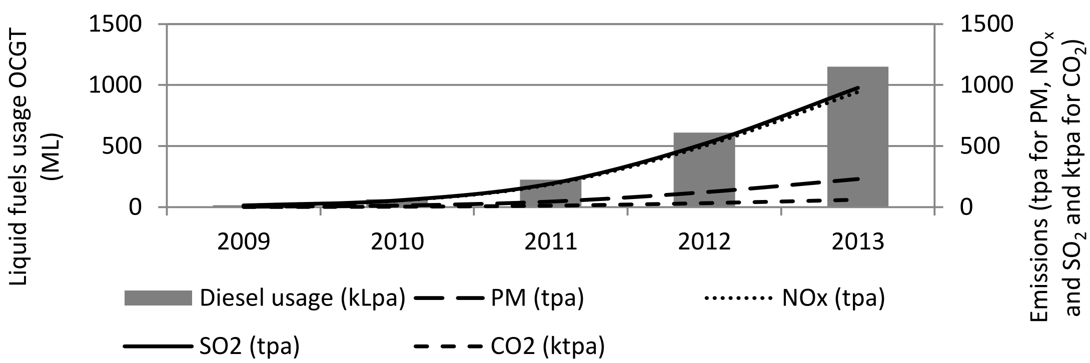

Figure 4-6: Fuel usage (ML) and emissions from OCGT's in South Africa for the period 2009 to 2013 (Eskom, 2014).

4.5 The impact on domestic burning emissions

Domestic burning of wood, coal and paraffin is practiced by the very poor, living in informal settlements, in South Africa. In 2011, the number of households living in informal settlements was in the order of 1.25 Million, of which 57% of these households did not have access to electricity. Of the 43% of households that did have access to electricity, many opted to still make use of domestic burning of wood, paraffin and coal for their cooking and heating needs (Housing Development Agency, 2013).

During the period 2008 to 2011, real electricity tariffs increased by 78% as Eskom embarked on a massive build programme as a result of the on-going energy crisis (Deloitte, 2012). The type of energy source used by households is strongly linked to per capita income (Figure 4-7) (Department of Energy (DOE), 2012). Electricity and gas usage increases with per capita income whereas candles, fuel wood and paraffin are used mostly by the poorest quintile in

South Africa (DOE, 2012). It can therefore be expected that when energy prices increase and economic growth is low, electricity will no longer be affordable to poor households (even if they are connected to the electricity grid) and more and more households will be forced to make use of domestic burning in order to fulfil their energy needs.

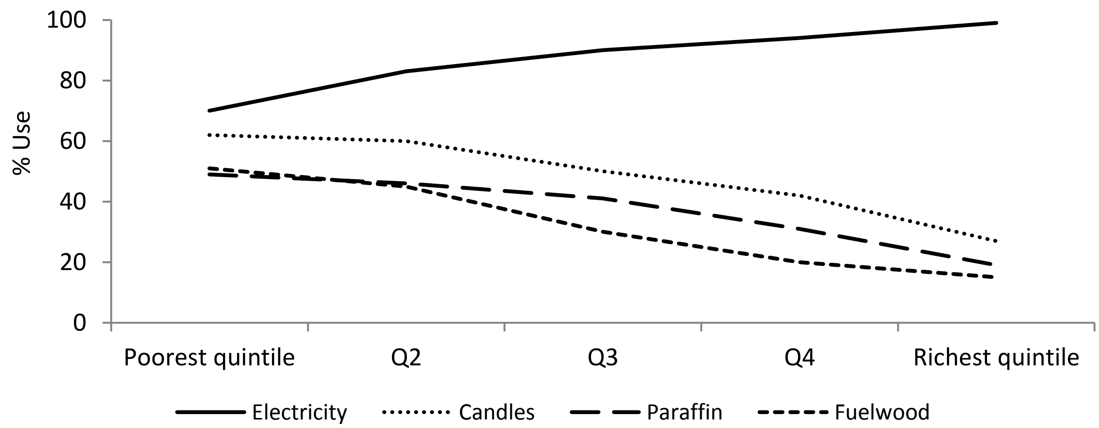

Figure 4-7: The use of energy sources (%) by quintiles of per capita monthly income (adapted from DOE (2012)).

Research has found that even though a significant number of households were connected to the electricity grid from the middle 1990's to middle 2000's, the increase in the price of electricity as well as the deterioration of the electricity redistributor are slowing down progress. New connection rates cannot keep up with current household formation let alone make up for backlogs. It now seems as if the number of household without electricity is on the increase (Trollip *et al.*, 2014).

Past studies have found that of all sources of air borne emissions in South Africa, domestic burning has by far the largest impact on human health (Friedl *et al.,* 2008; Fund for Research into Industrial Development Growth and Equity (FRIDGE), 2004). The reason for this is the close proximity of emissions to humans (at ground level), the concomitance of peak emissions with periods of poor atmospheric dispersion (early morning, night time and winter time) and the release of these emissions within areas of dense population exposure to both indoor and outdoor pollution concentrations (FRIDGE, 2004).

There are manifold health risks associated with domestic burning activities, which act on the respiratory system when high concentrations of PM and other pollutants are inhaled (Naidoo *et al.*, 2014). In poorly ventilated dwellings, indoor smoke can be 100 times higher than acceptable levels for PM (World Health Organisation (WHO), 2014). Main health risks include pneumonia, stroke, ischaemic heart disease, chronic obstructive pulmonary disease and lung cancer. The most affected population groups are women and young children as they spend the most time near the domestic hearth (WHO, 2014). When people fall ill as a result of exposure to domestic burning emissions, it impacts their ability to work as well as the country's health budget, thereby ultimately impacting negatively on a country's economy.

4.6 The impact on small backup generator emissions

Numerous businesses and private households (middle- and upper class) make use of small (<440 kW) diesel-fuelled back-up generators in the event of planned electricity outages. It is estimated that back-up generators with a total capacity in the order of 3500 Megawatt (MW) is currently installed in South Africa (Engineering News, 2012). During late 2014 and beginning 2015, planned electricity outages has taken place, on average, approximately 12.5 days a month for two and a half hours a day, throughout the country. When it is assumed that 3000 MW of back-up generators run for two hours every time planned outages occurs over the period of a year, an estimated 1500 tons (t) PM, 1400 t SO_2 and 800 kt CO_2 are emitted (US EPA, 1995). This is equal to the emissions of a 2000 MW coal-fired power station running for a period of a month. NO_x emissions are around 21 000 t, roughly equal to a 2000 MW coal-fired power station running for a period of six months. As in the case of domestic burning emissions, emissions from small back-up generators occur at ground level and often in relatively densely populated areas. It is estimated that planned electricity outages will continue in South Africa, at least for another two years, until the first units of new power stations that are currently under construction come online.

4.7 The impact on vehicle emissions

During periods of planned electricity outages, traffic lights are out of order. This causes havoc on the South African roads. Qualitative estimates indicated that during these periods travel times at least double, therefore it is expected that vehicle emissions will also at least double. Vehicle emissions, as in the case of domestic burning and backup generator emissions have especially high human health impacts because these emissions are emitted close to the ground and in close proximity to humans.

4.8 Conclusions

Lessons learned from South Africa show that there is an undeniable link between energy reserve and atmospheric emissions. These lessons are applicable to other countries currently facing energy shortages or to those whose energy reserve is kept low in order to produce energy at competitive prices.

Emissions from large scale coal-fired power stations increased due to decreased maintenance and the return to service of older, less efficient stations that were decommissioned. OCGT emissions increased as a result of increased usage, past their intended peak generating function. Small back-up generator emissions increased as businesses as well as middle- and upper class households utilise them to generate energy during periods of planned electricity outages.

The most worrying impact of the energy crisis is that of increased domestic burning. The reason for this being increased electricity tariffs, decreased economic growth, unreliability of electricity provision and a decrease in the grid connection rates. Emissions resulting from the domestic burning of solid fuels and paraffin result in significant human health exposure and impacts.

Proper planning could have prevented the energy crisis, as signs of the energy crisis approaching were apparent before the crisis struck. The famous 5-P acronym, namely ‘Proper Planning Prevents Poor Performance’ can therefore perhaps be rephrased in order to create a 4-P acronym for countries with low energy reserves: ‘Proper Planning Prevents Pollution’.

Thesis conclusion

The objective of this article is to investigate the effect of the South African energy crisis on emissions.

The following main conclusions can be drawn:

- *An energy restricted environment causes an increase in emissions.*
- *The deferral of maintenance on power stations let to the deterioration of the power station fleet which ultimately caused a systematic decrease in the thermal efficiency of power stations. The return to service of decommissioned stations further led to a decrease in the thermal efficiency of the fleet. This meant that more coal had to be burned in order to produce the same energy output as before the energy crisis. As a result, emissions per energy output of the South African fleet increased (with the exception of SO_2 due to a decrease in sulphur content of coals during the energy crisis period).*
- *Emissions of PM showed a significant increase compared to other pollutants during the energy crisis period, as a result of lowered maintenance on PM abatement, as PM was the only pollutant that was controlled at South African power stations at that stage.*

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5 Journal article: *A perspective on South African coal-fired power station emissions*

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Consent from co-authors is attached as an addendum.

Thesis objective

To make projections of future South African coal-fired power station emissions

Even though the South African government is trying to reduce the country's dependence on coal; it will remain a dominant source of energy in South Africa, at least in the medium term. Apart from the existence of 13 Eskom-owned power stations, two Sasol-owned stations, one privately owned station and two municipal-owned stations; two new power stations, namely Medupi and Kusile, are currently under construction. Numerous factors have an effect on the extent of power station emissions, including legislation governing emissions of coal-fired power stations, the retrofit rate of stations with emissions abatement and the persistence of the energy crisis (which has been shown earlier to have a largely negative effect on emissions from these sources). Power stations are a major source of emission in South Africa and for this reason it is important to understand how these emissions might change in the future. This article makes projections for future emissions from South African coal-fired power stations for the period 2015 to 2030 for different scenarios. The different scenarios are based on different retrofit rates of stations with new, more efficient emissions abatement technologies and different energy demand forecasts.

Abstract

This publication investigates trends of historical- and projected future South African coal-fired power station criteria- (total primary Particulate Matter (PM), Sulphur Dioxide (SO_2) and Nitrogen Oxides (NO_x)) and Carbon Dioxide (CO_2) emissions. It was found that an energy restricted environment has an increasing effect on emissions, as emissions per energy unit increased from the onset of the South African energy crisis. Especially PM emissions increased during the energy crisis period, due to increased pressure on PM abatement and lowered maintenance opportunity. Projections of future coal-fired power station criteria and CO_2 emissions are made for four different future scenarios for the period 2015 to 2030. Three of the four scenarios are based on the lower projected energy demand baseline case as published in the updated Integrated Development Plan (IRP). The difference between these three scenarios is different retrofit rates of power stations with emissions abatement technologies. The fourth scenario is a worst case scenario and assumes high energy demand (and therefore no decommissioning of power stations), high emission rates (similar to worst past emission rates

during the period 1999-2012) and no further abatement of emissions above and beyond current mitigation efforts. This scenario gives an indication of what South African coal-fired power station emissions could look like if the energy crisis persists. There is a marked difference between projected best- and worst case PM emissions during the entire projected period, but especially during 2030 when worst case PM emissions compared to a 2015 baseline value are expected to rise by 40% and best case PM emissions are projected to decline by 40%. Worst case NO_x emissions are expected to increase by 40% in 2030 from a 2015 baseline value whereas best case emissions are expected to decline 10% from the same level in 2030. Worst case SO_2 emissions are predicted to increase by around 38% in 2030 and best case emissions are expected to decrease by around 20% in 2030 from a 2015 baseline value. Relative emissions used in the projection of future CO_2 emissions in this publication differ from that used in the energy demand and energy mix modelling done for the updated IRP baseline case. The reason for this is that the modelling for the updated IRP assumed relative CO_2 emission factors for supercritical boilers whereas only Kusile and Medupi fall in this category and relative emissions from all other stations are, in fact, between 5% and 16% higher. For this reason it seems unlikely that the South African climate commitment target for 2030 will be made.

5.1 Introduction

The South African energy sector is currently faced with a number of challenges. Residential energy consumption dramatically increased (by 50%) during the period 1994 to 2007 due to the implementation of a Free Basic Electricity Policy in 2001 (Inglesi and Pouris, 2010). This meant that 50 kWh of electricity was supplied per household to poor households per month, free of charge (Inglesi and Pouris, 2010). Since 2007 the country has been experiencing an ongoing energy crisis. The main reason for this was the delay by government in making a decision to fund the building of a new power station after being warned of an energy crisis approaching in 1998, combined with an increase in demand as a result of economic growth and the implementation of the Free Basic Energy Policy (Department of Minerals and Energy (DME), 1998; Inglesi and Pouris).

During the energy crisis period, energy demand was met by means of delaying maintenance on the generation fleet. This led to the decline in performance of the fleet which in turn, negatively impacted the effectiveness of the fleet to meet future demand (Integrated Resource Plan for Electricity (IRP), 2013). Three older power stations that were mothballed during the 1980’s and early 1990 are returned back to service to alleviate the pressure on existing stations. It is believed that the energy demand/supply balance will remain vulnerable until Medupi and Kusile, two new power stations currently under construction, come fully online expectedly between 2018 and 2020 (Eskom, personal communication), although uncertainty still remains on the exact commissioning dates. In 2010 the South African Department of Environmental Affairs (DEA) promulgated a set of Minimum Emission Standards (MES) for criteria pollutants that will come into effect in 2015 and 2020, and is expected to decrease emissions (Department of Environmental Affairs (DEA), 2013). However, a number of industries, including Eskom and Sasol, the two major role players in the combustion of coal in South Africa have filed applications for the postponement of, and in some cases, exemption from the MES (Iliso Consulting, 2013; SRK Consulting, 2013). The reasons for this are the high cost of compliance with the MES (with a capital cost of around 6% of the South African nominal Gross Domestic Products (GDP) for 2013) (Eskom, personal communication, 2014; Statistics South Africa, 2014), and the inflexibility of the MES by not taking the ambient air quality and exposed population surrounding power stations into account. This means that stations are expected to comply with the MES even if the national ambient air quality standards are met before compliance. It is further envisaged that a Carbon tax as an instrument to encourage carbon mitigation will come into effect in 2016 (Greve, 2013).

The energy sector in South Africa is the biggest contributor to SO_2 and NO_x emissions and second highest contributor to PM emissions of all sources of air emissions in the country (70%, 55% and 36%, respectively) compared to industrial, commercial & institutional fuel burning (27%, 23% and 44%) , vehicle emissions (2%, 21%, 5%), biomass burning (0%, 0.3%, 6%) and domestic burning (0.8%, 0.2%, 9%) (DEA, 2012 after Scorgie *et al.,* 2004). However, several studies have shown that power station emissions are not the main cause of adverse health impacts from air quality in South Africa. Past studies have found that domestic burning has by far the largest impact on human health (Friedl *et al.,* 2008; Scorgie *et al*., 2004). Domestic burning of wood, coal and paraffin is practiced by the very poor, living in informal settlements, in South Africa. In 2011, the number of households living in informal households was in the order of 1.25 Million, of which 57% of these households did not have access to electricity. Of the 43% of households that did have access to electricity, many opted to still make use of domestic burning of wood, paraffin and coal for their cooking and heating needs (Housing Development Agency (HDA), 2013).The reason for the large negative impact of domestic burning emissions on human health is the close proximity of emissions to humans (at ground level), the concomitance of peak emissions with periods of poor atmospheric dispersion (early morning, night time and winter time) and the release of these emissions within areas of dense population exposure to both indoor and outdoor pollution concentrations (Scorgie *et al.*, 2004). On the other hand, power station emissions are emitted through tall stacks and therefore usually dilute in the atmosphere before reaching human lungs. It is believed that cost and unreliable supply are the main factors that keep the South African poor from switching to electricity (Friedl et al., 2008).

In the past, regional CO_2 and NO_x emission factors for the power sector in Southern Africa were determined both theoretically and from continuous in-stack measurements for comparison to the Intergovernmental Panel on Climate Change (IPCC) default emission factors (Zhou *et al.* 2009). It was found that Southern African CO_2 emission factors were on the upper end of the IPCC default emission range whereas NO_2 emission factors were below the low end of the range. In 2013, a document was published on the outlook of the coal value chain in South Africa. Emissions projections for South African coal-fired power stations were made until 2040 for four different future scenarios, namely a lag behind, more of the same, at the forefront and low carbon world scenario (South African Coal Roadmap (SACRM), 2013). However, this document is already outdated in terms of the decommissioning schedules of existing power stations and the projection of future South African energy demand (and therefore the building program of new power stations to meet this demand) (IRP, 2013). Currently there are no academic publications focusing on the current and future status of coal-fired power station emissions in South Africa – taking into account the effect the energy crisis had on emissions, the most updated information on the decommissioning schedules of stations, the commissioning of stations currently under construction, the building of new stations and the retrofitting of stations with new, more efficient, emissions abatement technologies in the future.

The aim of this paper is to give a perspective on the contribution of South African coal-fired power stations to a wide range of pollutants, including criteria pollutants (PM, NO_x, SO_2) and CO_2. Historical emissions were investigated in order to establish a relationship between an energy restricted environment and emission trends. Estimations of future coal-fired power plant criteria and CO_2 emissions from 2015 to 2030 in South Africa are made for worst case, business as usual, intermediate and best case scenarios which are based on different predicted future energy demand outlooks and retrofit scenarios of stations with emissions abatement technologies.

5.1.1 The South African power sector

South Africa generates 32% of total energy on the African continent. Eskom, one of the largest energy utilities in the world, is responsible for the generation of approximately 95% of South African electricity and 45% of Africa's electricity (Eskom, 2010). Eskom power is exported to Botswana, Lesotho, Mozambique, Namibia, Swaziland and Zimbabwe. Eskom-owned coal-fired power plants, all of which are base load plants, include Arnot, Duvha, Camden, Grootvei, Hendrina, Kendal, Komati, Kriel, Lethabo, Majuba, Matla, Matimba and Tutuka (Eskom, 2012). The remaining 5% of South African electricity is generated by coal-fired power plants owned by the private sector (Kelvin power plant), municipalities (Rooiwal, Pretoria West and Bloemfontein power plants) and Sasol. Currently two additional Eskom plants are under construction, namely Medupi and Kusile. It is expected that the first units of each will come online during 2015, although there is still uncertainty about the precise dates (Eskom, 2013a; Eskom, 2013b). It is evident that even though the South African government is trying to reduce the country's dependence on coal; it will remain a dominant source of energy in South Africa, at least in the medium term.

Most South African power plants consist of six to ten units with an average capacity of approximately 600 megawatt (MW) each. Eight of the thirteen base-load stations have generating capacities in excess of 3000 MW. When compared to the approximate average sizes of thermal power plants in the United States (737 MW) (US Energy Information Administration (US EIA), 2013a), it is clear that South African power stations are extremely large when compared to their international counterparts.

South Africa has been at the forefront in the developing world in recognizing climate change and its role in addressing carbon dioxide emissions. The latest developments include the commitments made by the presidency at the 2009 Climate Summit, to a "peak, plateau and decline" emissions path between 2010 and 2050. This means that carbon emissions are allowed to peak between 2020 and 2025 at 500 megatons (Mt) to 550 Mt CO_2 equivalent and then to remain constant at this level until 2035, where after it should decline to between 200 Mt and 400 Mt in 2050 (DEA, 2010 after Department of Environmental Affairs and Tourism (DEAT), 2009). In January 2010 the country formally notified its climate change mitigation proposals with the United Nations Convention on Climate Change. These included a 34% reduction of emissions below "Business as Usual" by 2020 and a 42% reduction by 2025. Whether or not these targets can be realistically met will be addressed in Section 5.3.2 of this paper when future CO_2 emissions projections for South Africa are discussed.

5.1.2 South African Coal Quality

South African coal has the general characteristics of the southern hemisphere Gondwana coal and therefore differs from northern hemisphere Laurasian coal in being variable between regions and seams and in possessing relatively high ash contents, low calorific values and low sulphur, sodium, potassium and chlorine contents (Falcon and Ham, 1988). The variability in the quality of South African coals is illustrated by the fact that the difference between the maximum and minimum ash contents, calorific values and sulphur contents burned at Eskom during the 1999 to 2012 historical period was 4%, 6 mega joules per kilogram (MJ/kg) and 19%, respectively (Eskom, 2006 -2012). The average ash content, sulphur content and calorific values of South African fuel coals compared to those of China, United States (US), India, Russia and Germany, the major coal consumers in the world, are shown in Figure 5-1 (Chandra and Chandra, 2004; Eskom, 2006; 2007; 2008; 2009; 2011; 2012; European Association for Coal and Lignite (EURACOAL), 2013; Podbaronova, 2010; Sun, 2010 and US EIA, 2013b). The annual coal consumption of each country is also indicated in megatons per annum (Mtpa) (US EIA, 2014).

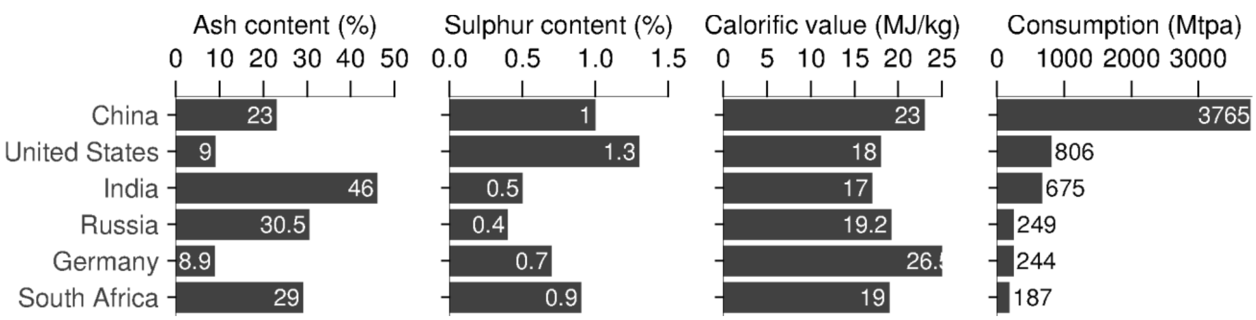

Figure 5-1: A comparison of average ash contents (%), calorific values (MJ/kg) and sulphur contents (%) of fuel coals from the major coal consumers in the world, namely China, US, India, Russia, Germany and South Africa (in descending order of coal consumption (Mtpa)).

5.2 Methods

5.2.1 Historical South African power station emissions

Historical South African coal-fired power station emissions were investigated in order to understand the effect of an energy restricted environment on emissions. Historical emissions and energy production information for Eskom power plants over the period 1999 to 2012 were obtained from the Eskom energy utility's annual reports (Eskom, 2006-2012). Total annual PM emissions reported in above reports were estimated by means of continuous opacity monitoring systems and estimated volumetric flow rates of flue gas in power station stacks. NO_x, SO_2 and CO_2 annual emissions were estimated from mass-balance equations and annual coal consumption tonnages. Although Eskom does not currently calculate uncertainties associated with their emissions estimation techniques, it is estimated from similar operations elsewhere in the world that uncertainties associated with PM, NO_x, SO_2 and CO_2 emissions estimation at Eskom is around 10%, maximum 20%, maximum 20% and maximum 7.5%, respectively (Source Testing Association, personal communication; European Commission, 2012; Evans *et al.,* 2009). It was assumed that the coal-fired power plants not owned by Eskom followed the same emissions trends as the Eskom plants during this period. This assumption is valid as Eskom plants generate the major share of South African electricity (95%). Relative emissions from coal-fired power stations were calculated by normalizing the absolute emissions (in units of mass per annum) for total electricity production per annum. It was assumed that all Eskom reported emissions originated from coal-fired power stations as gas turbine stations (the only emitters apart from coal-fired power stations) were responsible for only a fraction (<< 1%) of total energy production and therefore have a negligible effect on total criteria and CO_2 emissions.

5.2.2 Future emissions projections

Projections of future South African coal-fired power station emissions were made for the period 2015 to 2030. The decommissioning of power stations, the addition of Kusile and Medupi power stations and the building of new power stations in the future were included in the emissions projections. The decommissioning and new building schedules are strongly dependent on future energy demand, which in turn is dependent on numerous factors such as demand responses to higher electricity prices, structural changes in the economy, energy efficiency and population dynamics (Energy Research Centre, 2013; Department of Energy (DOE), 2012).

The projection of future South African energy demand is therefore associated with high relative uncertainties. However, the fact that this publication only looks at coal-fired power station demand projections simplifies this process to an extent. It is unlikely that Eskom will be able to construct another large scale coal-fired power station after the completion of Kusile and Medupi (Eskom, personal communication). Even if this is the case, the construction of such a power station will take time (Medupi and Kusile will take an estimated 15 years to be fully constructed) and therefore such a station will most likely only contribute to emissions after 2030 (the cut-off date of emissions projections in this publication). It is furthermore probable that the 50-year lifetimes of existing stations will be expanded instead of investing in new coal generating capacity as this will most likely be the more cost effective option. For this reason, the future coal-fired power station new building program and decommissioning schedules assumed in this study are based on the baseline projection as published in the updated IRP (IRP, 2013).

The baseline projection published in the IRP 2013 is the preferred power generation output of TIMES modelling done by the Energy Research Centre at the University of Cape Town (Energy Research Centre, 2013). The TIMES model makes use of a number of assumptions including demand projections, fuel prices and CO_2 emissions constraints in order to project the optimal energy mix to sustain future demand (Energy Research Centre, 2013). The baseline scenario published in the recently updated electricity resource plan (IRP, 2013) and based on above mentioned modelling, proposes that the lifetimes of existing coal-fired power stations (excluding the return-to-service stations) will be extended beyond their 50 year operational time period and that 2500 MW of new coal-fired capacity be added in the future. This is believed to be a more realistic scenario compared to an addition of 6500 MW and no extensions of the lifetimes of power stations as proposed in the IRP 2010. Business as usual, intermediate and best case future projections of criteria and CO_2 emissions were based on the updated IRP baseline scenario (Table 5-1, black text), but an additional worst case scenario was included where high energy demand was assumed (and therefore that no power stations will be decommissioned) (Table 5-1, grey text). The worst case emissions scenario can be seen as an estimation of an upper limit of emissions if rapid economic growth occurs and the pressure on the South African energy system remains high.

Table 5-1: A summary of the decommissioning-, commissioning- and new build schedules for South African coal-fired power stations for the period 2015 to 2030. The total nominal capacity assumed in the worst case projected scenario (which assumes no decommissioning of power stations) is indicated in grey text whereas black text indicates the energy outlook as indicated by the IRP (2013) baseline case.

Term	Decommissioning Schedule (MW)	Commissioning Schedule (MW)	Total Nominal Capacity (MW)
Short-term 2015-2020	Non Eskom (-180) Non Eskom (-90)	Medupi (+4800) Kusile (+4800)	49000, 49000
Medium-term 2020-2025	Non-Eskom (-170) Komati (-90) Camden (-1500)		46000, 49000
Long-term 2025-2030	Grootvlei (-1200)	New Coal (+2500),	48000, 49000

The business as usual, intermediate and best case scenarios are based on different retrofitting rates of power stations with newer, more efficient abatement technologies. Mitigation strategies for different pollutants are independent of one another and are all tied with different technologies, capacities and infrastructure development pathways. The abatement technologies include the retrofitting of Electrostatic Precipitators (ESPs), the current abatement technologies used at around half of the existing power stations with Fabric Filter Plants (FFP's) (which have higher efficiencies than ESPs) for reducing PM emissions, Low NO_x Burners (LNB) for reducing NO_x emissions, and Flue Gas Desulfurization Plants (FGD) for SO_2 emissions reductions. The business as usual scenarios assume retro-fitments only on new stations whereas the intermediate and best case scenarios assume less aggressive and aggressive retro-fitment rates, respectively. There is no emissions abatement planned for CO_2 emissions reductions at present; however CO_2 emissions are influenced by the FGD retrofit scenario as CO_2 is a direct byproduct of the wet FGD process and the additional auxiliary power requirements of the FGD system of around 1% of annual power generation by the station (E-ON Engineering, 2007). CO_2 emission scenarios are therefore slightly influenced by the SO_2 retrofit scenario. The effect of LNB's on CO_2 emissions was considered to be negligible (there are some who believe it will impact CO_2 emissions by changing the thermal efficiency of a power station, but information on this is scarce). A summary of the retrofit schedules assumed in the business as usual, intermediate and best case scenarios are given in Table 5-2. Retrofit rates and schedules were possible scenarios proposed by Eskom (Eskom, personal communication).

Table 5-2: A summary of the business as usual, intermediate and best case scenarios, used to make future projections of PM, SO_2, NO_x and CO_2 emissions. The worst case scenario assumes no retrofits and high energy demand.

Pollutant	Abatement technology required to comply with 2020 MES	Scenarios		
		Business as usual	Intermediate	Best case
PM	Fabric Filter Plant (FFP).	No FFPs are retrofitted on existing stations in the future. Medupi, Kusile and new stations make use of FFPs.	FFPs are retrofitted at Duvha (the remaining 3 units) 2021-2023, Grootvlei (remaining 3 units) 2015-2017, Kriel (6 units), Matla (6 units) 2019-2024 and Tutuka (6 units) 2018-2023 at a reduced retrofit rate. Medupi, Kusile and new stations make use of FFPs.	FFPs are retrofitted at Duvha (the remaining 3 units) 2018-2020, Grootvlei (remaining 3 units) 2015-2016, Kendal (5 units) 2020-2025, Kriel (6 units) 2016-2020, Lethabo (6 units) 2015-2021, Matla (6 units) 2013-2017 and Tutuka (6 units) 2014-2019, at an aggressive retrofit rate. Medupi, Kusile and new stations make use of FFPs
NO_x	Low NO_x burner (LNB). Emissions are assumed to average 700 mg/Nm^3 at 10% O_2 after retrofits.	No existing stations are retrofitted with LNB's. Medupi, Kusile and new stations make use of LNB's.	LNBs are retrofitted at 3 existing stations, namely Tutuka 2020-2025, Matla 2012-2015 and Majuba 2020-2025. Medupi, Kusile and new stations make use of LNBs.	LNBs are retrofitted at 4 existing stations, namely Tutuka 2020-2025, Matla 2021-2015 and Majuba 2020-2025 and Kriel 2020-2025. Medupi, Kusile and new stations make use of LNBs.
SO_2	Flue Gas Desulfurization Plant (FGD). It was assumed that a dry FGD has 40% removal efficiency and a wet FGD 90%[1].	No FGDs are retrofitted on existing stations. Kusile makes use of a wet FGD. Medupi is retrofitted with a dry FGD. New stations make use of dry FGDs.	Dry FGDs retrofitted at Medupi 2019-2022 and Kendal 2021-2026. Kusile makes use of a wet FGD. New stations make use of dry FGDs.	Dry FGDs retrofitted at Kendal 2021-2026, Majuba 2028-2030, Lethabo 2024-2028, Tutuka 2027-2032, Duvha 2025-2030, Matla 2022-2027, Kriel 2023-2028 and Medupi 2019-2022. Kusile makes use of a wet FGD. New stations make use of dry FGDs.
CO_2	None	Dry FGD's retrofitted at Kendal 2021-2026, Majuba 2028-2030, Lethabo 2024-2028, Tutuka 2027-2032, Duvha 2025-2030, Matla 2022-2027, Kriel 2023-2028 and Medupi 2019-2022.	Dry FGD's retrofitted at Medupi 2019-2022 and Kendal 2021-2026. Kusile makes use of a wet FGD. New stations make use of dry FGD's.	No FGD's are retrofitted on existing stations. Kusile makes use of a wet FGD. New stations make use of dry FGD's.

[1] According to the United States Environmental Protection Agency (US EPA) (2003) removal efficiencies of calcium-based dry FGD systems are in the order of 50% to 60% and wet FGDs in excess of 90%. In order to be conservative it was assumed that the removal efficiency of dry FGDs are 40% and that of wet FGDs 90%.

Intermediate- and best case emissions were calculated by making use of relative emissions for the different retrofit scenarios (Table 5-3) based on the efficiency of emissions abatement technology and projected future load factors (Eskom, personal communication). Retrofits of FFP's, LNB's and FGD's take place at a rate of one unit per year and therefore relative emissions were allowed to gradually decrease during the retrofit period. Business as usual criteria emissions projections were calculated from the current emission limits to which stations adhere (provided in Table 5-4) (Eskom, personal communication). Relative CO_2 emissions for the business as usual, intermediate and best case scenarios were assumed to be 1000 kg/MWSO for all power stations were no FGD retrofits take place (Eskom, personal communication). The annual increase in CO_2 emissions that would result due to the installation of an FGD plant at a given power station wes obtained from Eskom's applications for postponement or exemption from the MES (Eskom, 2013c; 2013d; 2013e; 2013f; 2013g; 2013h; 2013i). Worst case scenarios were calculated by making use of the highest relative emissions of the power generation fleet during the historical period 1999 to 2012 (see Figure 5-4) and the projected generating capacity based on a high future energy demand scenario assuming that no power stations are decommissioned during the projected period (grey values in Table 5-1).

Table 5-3: Relative emissions and average load factor values used for the projection of intermediate- and best case emissions scenarios before and after the installment of emissions abatement.

Station	PM Relative emissions (kg/MWh)		NO_x Relative emissions (kg/MWh)		SO_2 Relative emissions (kg/MWh)		Average load factor
	Before FFP	After FFP	Before LNB	After LNB	Before FGD	After FGD	
Arnot	0.13-0.2		4300		6600		70
Duvha	0.25-0.33	0.07-0.12	4300		7200	720	80
Hendrina	0.08-0.09		4300		10300		72
Kendal	0.2	0.12	3600		8100	820	83
Kriel	0.8-1	0.12	6200	3600	6600	660	76
Lethabo	0.35-0.44	0.15	4500		7900	790	79
Majuba	0.09-0.11		5500	3300	6800	680	62
Matimba	0.12-0.19		2500		11500		85
Matla	0.45-0.69	0.12	5200	3900	8400	840	81
Tutuka	0.75-0.83		5300	4000	9400	940	72
Camden	0.12		4300		9500		52
Grootvlei	1.06-1.44	0.2	4400		8600		57
Komati	0.35-0.65		5600		6900		55
Medupi		0.09-0.12		1700	10700	1000	81
Kusile		0.09		1700		900	80
New Coal		0.09		1700		900	86

Table 5-4: Pre-2015 emission limits for Eskom power stations (mg/Nm^3) under normal conditions of 10% O_2, 273 Kelvin and 101.3 kPa.

Power Station	PM (mg/Nm^3)	NO_x (mg/Nm^3)	SO_2 (mg/Nm^3)
Arnot	50	760	1400
Duvha	75	1100	2100
Hendrina	50	1100	2700
Kendal	100	860	2100
Kriel	125	1100	2100
Lethabo	100	900	2100
Majuba	50	1100	1900
Matimba	100	760	3300
Matla	175	1100	2400
Tutuka	250	1100	2100
Camden	50	990	2400
Grootvlei	300	1500	3000
Komati	100	1200	1600
Medupi	50	750	750
Kusile	50	750	750

The formula used to calculate total emissions from relative emissions is as follows:

$$E = h \sum_i \sum_j R_{ij} . C_j L_j$$

Where *E* is total annual emissions of a specific pollutant, *i*, in tons/year, *h* is the total hours in a year, *R* is the relative emission in tons per megawatt hour sent out (t/MWhSO), C_j is the total nominal capacity of power station *j* (MW), and L_j is the generation load factor of power station *j* (%) as planned by Eskom (Eskom, personal communication). The following formula was utilized to calculate total emissions from emission limits and the volumetric flow rates of power stations:

$$E = h \sum_i \sum_j V_j . L_j . EL_{ij} . n_j . 10^{-9}$$

Where V_j is the specified gas volume flow rate in normal cubic metres per hour (Nm^3/h) for a single boiler at power station *j*, EL_{ij} is the emission limit of pollutant *i* in milligrams per normal cubic metre (mg/Nm^3) with which power station *j* comply and n_j is the number of boilers at power station *j*.

Even though South African legislation dictates that emissions information should be available to the public of South Africa, the reality is that information is relatively inaccessible. It was therefore not possible to obtain current information from Sasol, Kelvin power station and the municipal power stations. Emissions estimations for these non-Eskom plants were made by assuming that they have similar emissions to Eskom plants of similar ages and operational conditions, making use of similar emissions abatement technologies. This is the same approach taken in the SACRM (2013). The future energy projections further assumed that future fuel coal quality will remain constant and similar to current values.

5.3 Emissions trends and projections

5.3.1 South African power plant emissions during the energy crisis

Electricity reserve is the amount of reserve energy in an electric power system left after consumer supply has been met at all times. The electricity reserve is required in order to operate reliably in the face of possible unplanned equipment outages and fluctuations in demand due to occurrences such as unusually cold weather conditions (DOE, 2010). Electricity reserve can therefore be used as an indicator of how much pressure an electricity generation system is under. When electricity demand is greater than supply, there will be very little spare electricity in the system. The decline in the electricity reserve of the South African energy system from 1999 to 2007 marks the approach of the energy crisis (Figure 5-2) (Eskom, 2006-2012; Eskom 2014). During the period leading up to the energy crisis and during the energy crisis itself, the electricity reserve fell well below the Eskom aspiration of 15%. Internationally, percent electricity reserve requirements usually fall in the range of 15% to 25% (DOE, 2010). The electricity reserve curve was skewed after 2008, when the implementation of load shedding increased the electricity reserve artificially. During 2011 and 2012 the reserve was increased by means of the application of power buy-backs by Eskom, in which certain energy intensive consumers were paid not to use energy during this period. From the end of 2014 onwards, the reserve was again increased by means of the implementation of load shedding and Eskom urging large consumers to cut back their electricity consumption by 10%.

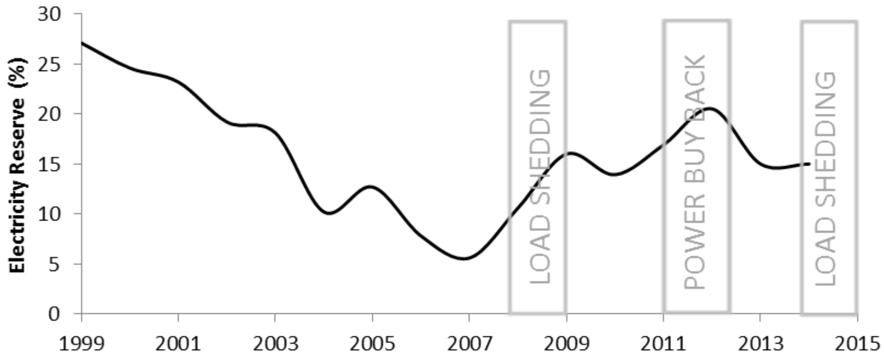

Figure 5-2: The electricity reserve (%) of the South African coal-fired power station fleet during the period 1999 to 2014.

Three older power plants (Camden, Grootvlei and Komati) that were mothballed during the late 1980's and early 1990's had to return back to service during 2004 to 2013 in order to help alleviate the pressure on operational plants. These older plants have lower thermal efficiencies and, in most cases, make use of older, less effective particulate matter abatement technologies. Since the load shedding that occurred during 2008, electricity demand could be met by means of delaying maintenance on the generation fleet, which led to the decline in performance of the fleet (IRP, 2013). This deteriorating effect is evident in the fact that the IRP (2011) assumed the fleet to have an average availability of 86%, but in reality the actual performance declined to less than 80% (IRP, 2013). The combination of the above mentioned factors contributed to the decline of approximately 3% in the overall thermal efficiency of the fleet between 2007 and 2012 (Eskom, 2006; 2007; 2008; 2009; 2011; 2012). The energy crisis therefore had a negative effect on the overall thermal efficiency of South African power plants, which meant that more coal had to be burned in order to produce the same amount of energy. The decline in the thermal efficiency of the fleet led to an increase in coal burn of approximately 8% per annum relative to energy output from 2008 onwards as indicated in Figure 5-3 (Eskom, 2006-2012; Eskom 2014).

The relative (emissions per energy output) and absolute (total annual emissions) criteria- and CO_2 emissions for South African power plants for the period 1999 to 2012 are shown in Figure 5-4 (Eskom, 2006-2012). Absolute emissions are a multiplication function of the relative emissions and annual energy sent out. Therefore it is important that absolute emission trends be seen against the annual energy sent out (Figure 5-3).

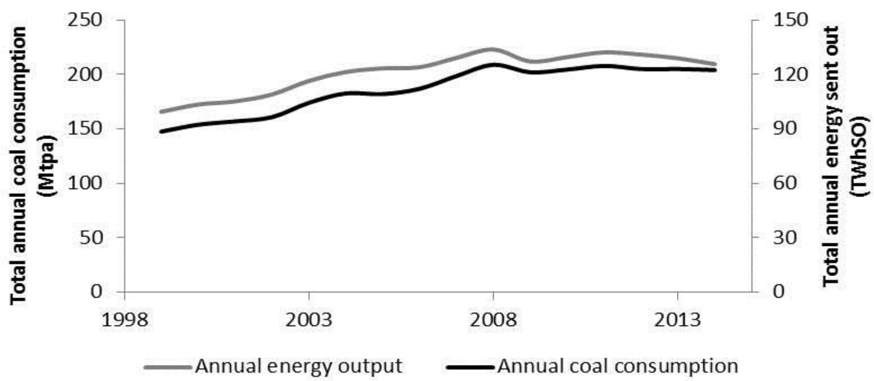

Figure 5-3: The total annual coal consumption (Mtpa) and annual energy output in terawatt hour sent out (TWhSO) of the South African coal-fired power station fleet during the period 1999 and 2014.

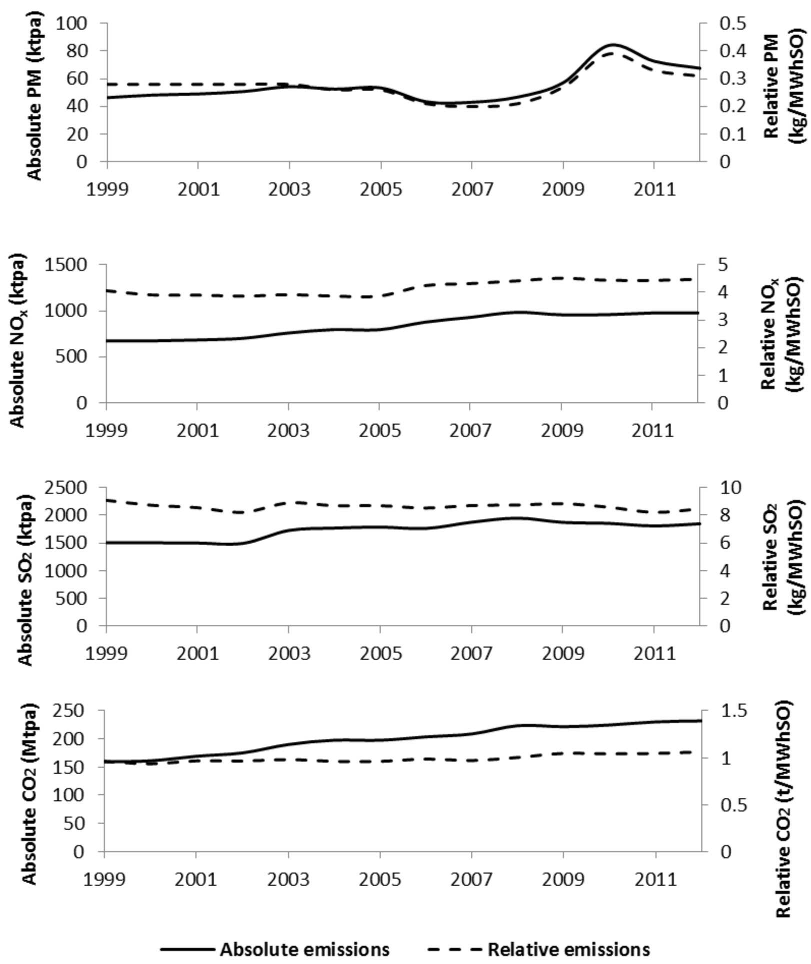

Figure 5-4: Absolute criteria- (ktpa) and CO_2 (Mtpa) as well as relative criteria- (kg/MWhSO) and CO_2 (t/MWhSO) emissions from South African coal-fired power stations for the period 1999 to 2012.

PM emissions are mainly a function of the ash content of the coal burned and the efficiency of the PM abatement technology used (United States Environmental Protection Agency (US EPA), 1993). Approximately half of South African thermal power plants currently make use of ESPs for PM control and the other half make use of FFP's. In general, the FFP removal efficiencies are higher than those of ESP's, by design. In South Africa plants making use of ESP's experience additional difficulties associated with the low sulphur content of coal fuels (and therefore low resistivities of fly ash), and various operational and maintenance challenges. In order to mitigate the problem of high resistivity fly ash, flue gas conditioning (by means of SO_3 injection) is done at the majority of plants that make use of ESPs.

The sharp increase in relative PM emissions from 2007 to 2010 is explained by the increase in relative PM emissions due to the increased pressure on PM abatement equipment during this period. From 2010 onwards, relative PM emissions started to decline, albeit not to pre-energy crisis levels. This reduction is explained by the major modifications that were completed on particulate emission abatement equipment in 2010 (Eskom, 2010). The modifications included the installation of an SO_3 injection plant at Matimba, refurbishment work done on the SO_3 injection plants at Kriel and Matla, the completion of the short-term ESP improvement plan at Tutuka and the replacement of pulse jet fabric filters at Majuba and Hendrina. Absolute emissions mainly followed the same trend as that of relative emissions, thereby showing that the absolute emissions were strongly affected by the increase in relative emissions during the energy crisis period. Absolute PM emissions almost doubled between 2007 and 2010 (from 43 ktpa to 84 ktpa) when energy output only increased by approximately 0.3% during the same period. It is therefore clear that PM emissions were highly affected by the energy crisis. The reason for this is the fact that abatement technology experienced tremendous strain during the energy-restricted period and maintenance opportunity was low. PM is the only pollutant that is currently controlled by means of abatement, but in the future FGD's and LNB's maybe installed to control SO_2 and NO_2 emissions, respectively. It can be argued that, if the energy crisis persists in the future, removal efficiencies of these abatement technologies will probably be lower than expected, as in the case of PM abatement during the historical energy crisis period (2007 to 2012).

The absolute and relative NO_x emissions during the period 1999 to 2012 are indicated in Figure 5-4. NO_x emission factors are governed by a number of different factors, including the thermal efficiency of the plant, fuel quality, boiler type and emission control level (US EPA, 1993). Currently none of the South African thermal power plants make use of NO_x abatement technologies. From 2006 onwards absolute (total) NO_x emissions increased by 10% (from 877 ktpa to 977 ktpa) whereas energy output only increased by 6%. This was most probably as a result of the decreasing thermal efficiency of the power station fleet.

Uncontrolled SO_2 emissions from conventional pulverized combustion are almost exclusively a function of the sulphur content in the fuel and SO_2 abatement (US EPA, 1993). Currently there are no operational power stations using SO_2 abatement. The absolute and relative SO_2 emissions from the South African coal-fired power station fleet during the period 1999 to 2012 are shown in Figure 5-4. Relative SO_2 emissions (kg/MWhSO) remained relatively stable during the energy crisis period, and absolute emissions mainly followed the energy sent out trend of Figure 5-3. This can be explained by a decrease in average sulphur content in coals burned during the period 2007 to 2012 of around 10% (Eskom 2007-2012).

The amount of CO_2 emitted by a thermal power plant depends on the thermal efficiency of the plant and the extent to which the energy content of the coal can be converted into electrical energy without losses. Absolute CO_2 emissions increased by 15% (from 200 Mtpa to 230 Mtpa) during the 2006-2012 period (Figure 5-4) whereas energy output only increased by 6% (Figure 5-3). The reason for this increase was the reducing effect the energy crisis had on the overall thermal efficiency of the fleet.

5.3.2 Emissions projections

Future projections of absolute criteria coal-fired power station emissions indicated as a percentage growth against a 2015 baseline are depicted in Figure 5-5. It is important to note that projections for 2015 differ and that for this reason not all projections intercept zero. Real projected values (not normalized for a 2015 baseline case) are tabulated in Table 5-5 and are supplied for input to prospective modelling endeavors.

There is a marked difference between projected best- and worst case PM emissions during the entire projected period, but especially during 2030 when worst case PM emissions are expected to rise by 40% from a 2015 baseline value and best case PM emissions are projected to decline by 40% from the same value (Figure 5-5). Eskom plans to retrofit FFP's at five existing stations and Medupi and Kusile will also make use of FFP's (Eskom, 2013c; 2013d; 2013e; 2013f; 2013g; 2013h; 2013i). If this plan goes forward, future PM emissions will most probably follow the intermediate scenario trend which means that PM would have decreased by around 28% in 2030 compared to a 2015 baseline value (Figure 5-5). However, if pressure on the energy system remains high and maintenance opportunities are continually missed, retrofits may not be possible and emissions may follow the business as usual or even the worst case scenario trends.

Worst case NO_x emissions are expected to increase by 40% in 2030 from a 2015 baseline value whereas best case emissions are expected to decline 10% from the same level in 2030. There is not a marked difference between predicted best case and intermediate emissions trends. Eskom undertakes to install LNB's at four of its existing stations (Medupi and Kusile will both also make use of LNB's) (Eskom, 2013c; 2013d; 2013e; 2013f; 2013g; 2013h; 2013i), if this is done and if the current pressure on the energy system decreases, emissions will follow the approximate best case NO_x emissions trend, which means that emissions are expected to decline by approximately 10% between 2015 and 2030.

There is a marked difference between worst- and best case SO_2 emissions during 2030 (Figure 5-5), where worst case emissions are predicted to increase by around 38% from a 2015 baseline in 2030 and best case emissions are expected to decrease by around 20% in 2030 from the same baseline value. Eskom undertakes to retrofit one FGD at Medupi power station (although some uncertainty exists on this). FGD systems are major infrastructure investments with high complexity of operation and are associated with high capital and operational costs. This means that the most probable SO_2 emissions trend is the business as usual scenario (which is projected to stay relatively constant between 2015 and 2030) or the worst case scenario, if pressure on the energy system persists.

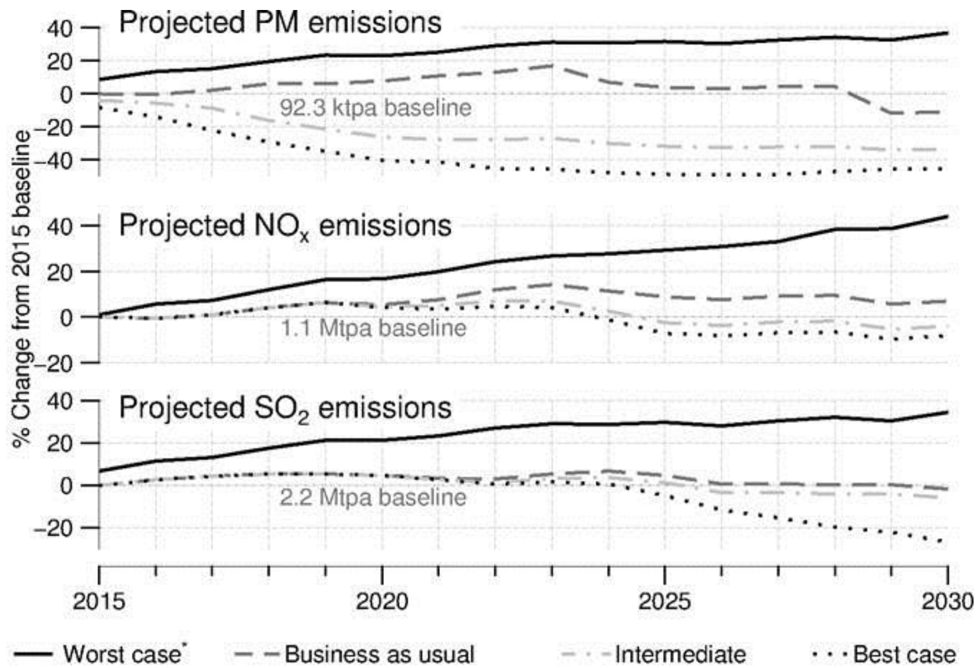

Figure 5-5: Future projections (in % change from a 2015 baseline) of absolute criteria emissions for 2015 to 2030 for four different future scenarios, namely worst case, business as usual (BAU), intermediate and best case scenarios. *The worst case scenario is based on a higher energy demand forecast than other scenarios.

Table 5-5: Absolute emissions projected for criteria pollutants (ktpa) for different scenarios in 2015, 2020, 2025 and 2030.

Scenarios	Worst case	Business as usual	Intermediate	Best case
PM (ktpa)				
2015	100	92	89	85
2020	115	97	68	55
2025	127	96	63	47
2030	135	82	62	50
NO_x (ktpa)				
2015	1160	1094	1094	1094
2020	1334	1155	1145	1139
2025	1470	1192	1067	1017
2030	1559	1172	1052	1005
SO_2 (ktpa)				
2015	2336	2186	2186	2186
2020	2652	2295	2295	2295
2025	2839	2293	2216	2086
2030	2946	2155	2063	1605

5.3.2.1 CO_2 emissions projections and South African climate commitments

Absolute emission projections for CO_2 are given in Table 5-6 whereas CO_2 projections in % change from a 2015 baseline value are shown in Figure 5-6. The difference between CO_2 scenarios assuming different retrofit rates of FGDs (business as usual, intermediate and best case scenarios) was negligibly small and was therefore indicated as a single line in Figure 5-6 (namely IRP Baseline, because of the fact that these scenarios assume the updated IRP baseline future energy demand and energy mix). The worst case- and IRP baseline projected CO_2 emissions in 2015 differ because of the fact that they have assumed different relative CO_2 emissions, and for this reason both lines do not intercept zero.

One of the assumptions of the TIMES energy demand/energy mix modelling was that CO_2 emissions are capped at 275 Mtpa from 2025 onwards in order to follow a peak, plateau and decline trajectory (Energy Research Centre, 2013). However, use was made of relative CO_2 emissions for supercritical boilers in the modelling (IRP, 2013). Only Medupi and Kusile fall in this category, whereas all 13 other base load stations as well as Sasol and municipality-owned stations do not. Relative CO_2 emissions assumed for supercritical boilers in the TIMES modelling and IRP (2013) are 947 kg/MWhSO, whereas the Eskom average for the period 2002 to 2012 was 1002 kg/MWhSO and projections in this publication assumed 1000 kg/MWhSO. This means that CO_2 emissions were underestimated during the energy forecast modelling for the updated IRP.

When a 45% contribution of the electricity sector (and specifically coal-fired power stations) to total carbon emissions in South Africa is assumed, the upper limit carbon emissions of the electricity sector, according to South Africa's climate change commitments, should be in the order of 280 Mt by 2030 (IRP, 2013). From the CO_2 projections in this study (Table 5-6) it is clear that it is unlikely that this target will be met, unless economic growth and energy demand dramatically decrease in the future.

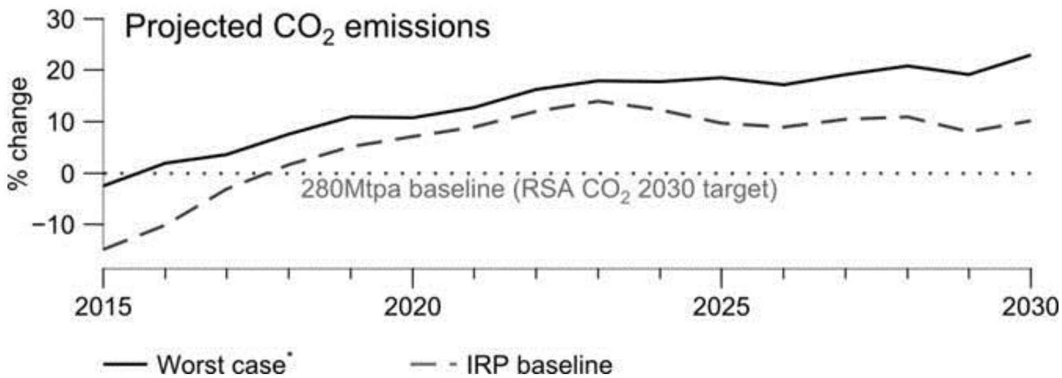

Figure 5-6: Future projections of absolute CO_2 (in % change from a baseline) emissions for a worst case, and IRP baseline scenario during the period 2015 to 2030. *The worst case scenario is based on a higher energy demand forecast than other scenarios.

Table 5-6: Absolute emissions projected (Mtpa) CO_2 for different scenarios in 2015, 2020, 2025 and 2030.

Scenarios	Worst case	Business as usual	Intermediate	Best case
CO_2 (Mtpa)				
2015	273	239	239	239
2020	314	300	300	300
2025	346	307	307	306
2030	367	308	306	306

5.4 Conclusion

South African coal is variable between regions and seams and has relatively high ash contents, low calorific values and characteristically low sulphur contents. The difference between the maximum and minimum ash contents, calorific values and sulphur contents during the historical period 1999 to 2012 is 4%, 6 MJ/kg and 19%, respectively. The implication of this is that emissions from South African coal-fired power stations may vary only based on the variability of fuel coals. This is especially true for uncontrolled SO_2 emissions as sulphur contents showed large variability during the historical period.

An energy-restricted environment has an increasing effect on emissions. This is especially true for pollutants controlled by means of abatement as increased pressure on abatement technology and low maintenance opportunity reduce removal efficiencies. Absolute PM emissions doubled between 2007 and 2010, the height of the energy crisis, when energy output only increased by around 0.3% during the same period. There is a marked difference between projected best- and worst case PM emissions during the 2015 to 2030 projected period, but especially during 2030 when worst case PM emissions are expected to rise by 40% from a 2015 baseline value and best case PM emissions are projected to decline by 40% from the same value.

NO_x emissions increased by 10% during the 2006-2012 energy crisis period whereas energy output only increased by 6%. The reason for this increase was the reducing effect the energy crisis had on the overall thermal efficiency of the coal-fired power station fleet. Worst case NO_x emissions are expected to increase by 40% in 2030 from a 2015 baseline value whereas best case emissions are expected to decline 10% from the same level in 2030.

SO_2 emissions did not increase during the energy crisis because the sulphur content in fuel coals decreased. There is a marked difference between worst- and best case SO_2 emissions during 2030, where worst case emissions are predicted to increase by around 38% from a 2015 baseline in 2030 and best case emissions are expected to decrease by around 20% in 2030 from the same baseline value. The best case SO_2 scenario (eight stations being retrofitted with FGD's) is highly improbable as FGD systems are major infrastructure investments with high complexity of operation and are associated with high capital and operational costs. At best Eskom undertakes to retrofit one FGD at Medupi power station (although some uncertainty exists on this). This means that the most probable SO_2 emissions trends are the business as usual scenario (which is projected to stay relatively constant between 2015 and 2030) or the worst case scenario (projected to increase by around 20% during the 2015 to 2030 period), if pressure on the energy system persists.

CO_2 emissions increased by 15% during the 2006-2012 period whereas energy output only increased by 6%, as a result of the decline of power station thermal efficiencies during the energy restricted period. Relative emissions used in the projection of future CO_2 emissions in this publication differs from that used in the energy demand and energy mix modelling done for the updated IRP baseline case. The reason for this is that the modelling for the updated IRP assumed a relative CO_2 emission for supercritical boilers whereas only Kusile and Medupi fall in this category. The relative CO_2 emissions for the rest of the South African coal-fired power station fleet are between 5% and 16% higher than that of supercritical boilers. From projections of future CO_2 emissions in this study it seems unlikely that the South African climate commitment target of 280 Mt in 2030 will be made, unless energy demand dramatically decreases in the future.

Thesis conclusion

The objective of this article is to make projections of future South African coal-fired power station emissions.

The following main conclusions can be drawn:

- *South African coal-fired power station emissions may vary substantially only based on the variability of fuel coals. This is especially true for uncontrolled SO_2 emissions as sulphur contents showed large variability during the investigated historical period.*
- *There is a marked difference between projected worst- and best case SO_2 emissions during 2030, where worst case emissions are predicted to increase by around 38% from a 2015 baseline and best case emissions are expected to decrease by around 20% in 2030 from the same baseline value.*
- *Projected best- and worst case PM emissions differ markedly for the different scenarios. During 2030, worst case PM emissions are expected to rise by 40% from a 2015 baseline value whereas best case PM emissions are projected to decline by 40% from the same value.*
- *Worst case NO_x emissions are expected to increase by 40% in 2030 from a 2015 baseline value whereas best case emissions are expected to decline 10% from the same level in 2030.*
- *From projections of future CO_2 emissions in this study it seems unlikely that the South African climate commitment target of 280 Mt in 2030 will be made, unless energy demand dramatically decreases in the future.*

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6 **Journal article:** *Emissions management and health exposure: Should all power stations be treated equal?*

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Consent from co-authors is attached as an addendum.

Thesis objective

To develop a coal-fired power station emissions management strategy for the Highveld of South Africa.

In South Africa, air quality is regulated by means of both ambient air quality standards and minimum emission standards (MES) - similar to many developed and developing countries in the world. The listed activities and associated MES identified in terms of section 21 of the NEM:AQA sets blanket MES for all large boilers (>100 MW) including coal-fired power stations. Tension sometimes arise between the ambient air quality standards and MES, as power stations are expected to comply with MES irrespective of whether ambient air quality standards in their vicinity are met and of their potential human health exposure. This may lead to the unnecessary instalment of costly abatement technology, the funding which may have been applied with greater effect to health exposure reduction elsewhere. This study proposes an alternative emissions management approach where potential human health exposure is used as a decision making basis on which an emissions management strategy for power stations is based.

Abstract

At the centre of all air quality regulation stands the right of humans to an environment that is not harmful to health and well-being. In many developing countries, including South Africa, coal-fired power station emissions are managed both from an ambient air quality and minimum emissions standpoint. Ambient air quality standards and Minimum Emissions Standards (MES) are often in conflict with one another, as power stations in which vicinity ambient air quality standards are met still have to comply with a blanket set of MES. In developing countries this often leads to the unnecessary incurrence of already constrained financial resources. This study proposes an alternative emissions management strategy where potential human health exposure is used as a decision making basis on which power station emissions control is founded. The potential human health exposure of population groups to primary Particulate Matter with a diameter of 10 micron or less (PM_{10}), secondary sulphurous and nitrous Particulate Matter (PM), sulphur dioxide (SO_2) and oxides of nitrogen (NO_x) emissions are calculated and compared for thirteen power stations in the Highveld of South Africa. It was found that the potential human health exposure to individual power stations differ substantially.

It is suggested that it makes more sense both from both a human health and fiscal perspective that emissions from coal-fired power stations be managed on an individual power station basis, especially in developing countries.

6.1 Introduction

To live within an environment that is not harmful to health and well-being is a constitutional right in South Africa. This also forms the basis of environmental legislation across the globe. In many countries in the world, including South Africa, air quality is regulated from two main perspectives, namely through ambient air quality standards (which establish the highest allowable concentration in the ambient air for each conventional pollutant) and MES (which set a limit to the concentration of a pollutant that may exit the stack of a polluting industry). Interestingly, these two regulation methods are often in conflict with one another, as sources which are compliant with ambient air quality standards within their vicinity are still expected to comply with MES. This leads to the unnecessary instalment of costly emissions abatement equipment, the funding of which could possibly have been applied with more useful effect in reducing human exposure to pollutants elsewhere.

In South Africa, MES were promulgated in 2005 to take effect in April 2015. During 2013 many industries, including Eskom (the South African public energy utility) and Sasol, both which own the vast majority of South Africa's coal-fired power stations, applied for postponement, and in some cases, exemption from the standards. Cost was cited as the major hurdle preventing compliance.

Previous international studies show that the health exposure of humans to coal-fired power station emissions can vary substantially with the geographical location of the power station (Zhou *et al.*, 2006). If this is the case, then it makes sense from both a financial and health exposure perspective to manage coal-fired power station emissions on an individual power station basis, especially in developing countries where financing for emissions control is limited. In this way the emissions management strategy can be optimized for reduced cost and health impacts.

The aim of this paper is to test this hypothesis by comparing potential human health exposure to primary PM_{10}, SO_2, NO_x, as well as secondary PM in the form of sulphate (SO_4) and nitrate (NO_3) emissions from thirteen coal-fired power stations in the Highveld of South Africa. The Highveld Priority Area (HPA) was identified as an area within South Africa that has a degraded airshed, often in exceedance of the National Ambient Air Quality Standards, and where immediate air quality management needs to take place. Potential human health exposure is determined by means of two methods, namely intake (the total amount of pollutant from a specific source that enters human lungs) and intake fraction (the mass fraction of a pollutant from a specific source that enters the lungs of humans). The long-term coal-fired power station emission concentrations to which population groups living in the Highveld Priority are exposed were obtained by means of dispersion modelling whereas population data was obtained from the latest 2011 South African census database (Statistics South Africa, 2012). At present, this technique has never been used to estimate potential health exposure to power station emissions within South Africa.

6.2 Methods

6.2.1 Population data

Population data for the purpose of calculating intake and intake fraction values were obtained from 2011 Census data (Statistics South Africa, 2012). A map indicating the population density as determined by the 2011 census within the study domain as well as the locations of the power stations investigated is given in Figure 6-1.

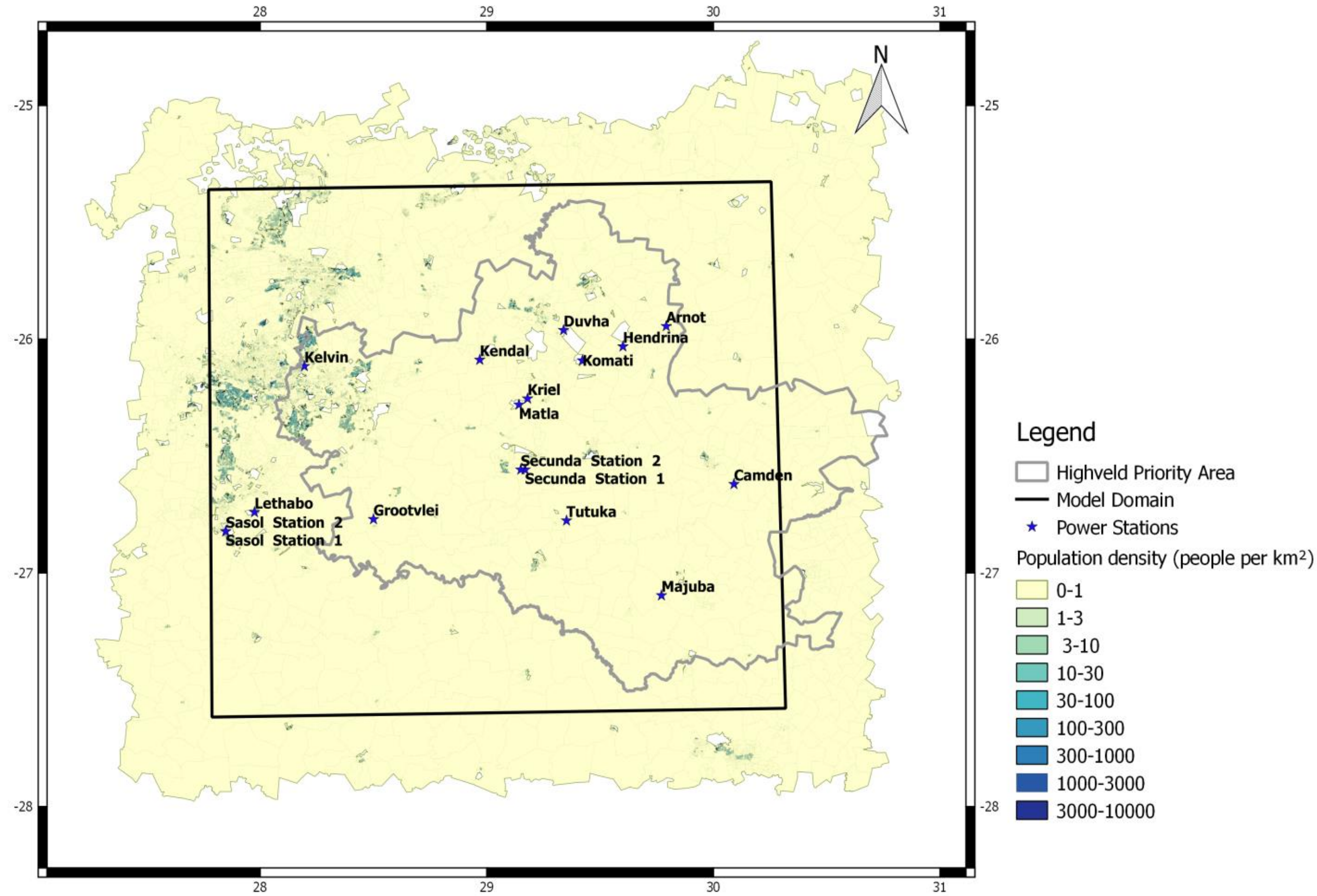

Figure 6-1: The population density within the study area as derived from 2011 Census data as well as the locations of the different power stations investigated.

6.2.2 Intake and intake fraction

Potential human health exposure to power station emissions is measured against two separate entities, namely intake (*I*) in kilograms (kg) and intake fraction (*iF*), a dimensionless number. Intake and intake fraction for a population exposed to the emissions of a single coal-fired power station over a specific time period are closely related and defined as follows (Lu and Fang, 2015; Bennet *et al.*, 2002; Zhou *et al.*, 2006):

$$I = \sum_{i}^{N} P_i \times C_i \times BR$$

$$iF = \frac{\sum_i^N P_i \times C_i \times BR}{Q}$$

Where *i* is a single census block for which the size of the population is known and P_i is the population in this census block. C_i is the long term average concentration at location *i* (in grams per cubic metre (kg/m^3)) that is determined by means of dispersion modelling, whereas *BR* is the population average breathing rate for which a nominal value of 20 m^3/day was assumed (Hao *et al.,* 2007 and Zhao *et al.* 2006). *Q* is the total emission rate during the study period of the pollutant in question, or in the case of secondary pollutants, its precursor (kg/s).

The intake and intake fraction formula can only be directly applied to human health risk assessment if risk can be represented as a linear function with respect to ambient concentration changes. Previous studies have indicated that for the incremental changes in pollution associated with realistic policy alternatives, the possible existence of thresholds or other non-linearities in the exposure-response function does not pose a major concern (Zhou *et al.*, 2003; Zhou *et al.*, 2006).

6.2.3 Pollutants investigated

The focus of this study is on particulates as well as their precursor gases. PM emissions can be divided into two classes, namely primary and secondary PM. Primary PM is emitted directly into the atmosphere while secondary PM is formed in the ambient air by means of chemical reactions of gaseous precursors (e.g., SO_2, NO_x) during atmospheric transport (Zhou *et al.,* 2003).

Secondary SO_4 intake values are defined as the mass of ammonium sulphate ($(NH_4)_2SO_4$) inhaled by the Highveld population whereas the secondary SO_4 intake fraction can be described as the mass of ammonium sulphate ($(NH_4)_2SO_4$) inhaled per unit mass of SO_2 emissions. In the same way the secondary NO_3 intake value is the mass of ammonium nitrate (NH_4NO_3) inhaled whereas the secondary NO_3 intake fraction is simply defined as the mass of ammonium nitrate (NH_4NO_3) inhaled per unit mass of NO_x emissions (Zhou *et al.,* 2003).

6.2.3.1 Domain and modelling approach

The CALMET/CALPUFF version 6 modelling suite was used for the dispersion modelling purposes of this study. CALPUFF is a multi-layer, multi species non-steady-state Lagrangian Gaussian puff model that is able to handle complex terrain effects, overwater transport, coastal interaction effects, building downwash, wet and dry removal, as well as simple chemical transformation and is recommended by the U.S. Environmental Protection Agency (US EPA) for simulating long-range transport (US EPA, 1998). This model was decided to be best suited for this study due to a number of reasons, including its ability to model dispersion impacts over a large domain and the fact that both primary and secondary pollutant concentrations can be estimated (Hao *et al.,* 2007). It has been applied in numerous power station intake fraction studies elsewhere in the world (see Evans *et al.*, 2002; Levy *et al.*, 2002, Levy *et al.,* 2003; Wolff, 2000; Hao *et al.*, 2003; Li and Hao, 2003; Zhou *et al.*, 2003; Zhou *et al.*, 2006).

6.2.3.1.1 CALMET

The CALMET model was run for three consecutive years in one model run (January 2011 to December 2013). The modelling domain was 250 km by 250 km (Figure 6-1) and the modelling resolution 1 by 1 km. Due to the large domain size, use was made of Lambert Conic Conformal (LCC) coordinates in order to minimize map distortion. CALMET was run in hybrid mode making use of prognostic data from the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). The winds from the MM5 model were used as initial guess field to the CALMET model.

The MM5 model with a grid resolution of 12 km by 12 km was configured with Dudhia simple-ice microphysics, the Medium Range Forecast Planetary Boundary Layer scheme and the multi-layer soil model. Analysis nudging was performed; however observational nudging was not (Exponent, 2014). The model was initialized by means of National Centre for Environmental Prediction (NCEP Global Reanalysis data) with a grid resolution of 2.5 by 2.5 degrees globally (Lakes Environmental, 2010).

CALMET surface temperature, wind speed and wind direction data was extracted at the locations of 12 surface weather stations in order to evaluate the CALMET model performance against observations. It is important to note that for the CALMET run in question, use was only made of MM5 prognostic data as input and no observational data was used. The reason for this is that observational data was limited and often of poor quality.

At present, there are no accepted performance criteria for prognostic meteorological models. However, Tesche, (2002), Tesche *et al.* (2001) and Emery *et al*. (2001) formulated a set of model evaluation benchmarks based on MM5/RAMS performance evaluation literature which are summarized in Table 6-1. The purpose of these benchmarks is to put modelled results into a useful context and should not be understood as the assignment of a passing or failing grade

(Tesche, 2002). Model observation benchmarks are based on statistical parameters including the root mean square error (RMSE), mean bias (MB), gross error (GE) and index of agreement (IOA). The average of each statistical parameter for long-term predictions of wind speed, temperature and wind direction for the twelve sites are given in Table 6-2. Those statistical parameters meeting the Tesche, (2002), Tesche *et al.* (2001) and Emery *et al*. (2001) criteria, on average, were marked in green. On average, the majority of the statistical benchmarks were met at the 12 sites. The long-term modelled results were evaluated as, for the purpose of this study, only long term dispersion modelling predictions were of interest.

Table 6-1: Prognostic meteorological model evaluation benchmarks; in meters/second (m/s) for wind speed; Kelvin (K) for temperature and degrees (^{O}) for wind direction (Tesche *et al.*, 2001; Emery *et al.,* 2001; Tesche, 2002).

Wind speed		
RMSE (m/s)	MB (m/s)	IOA
≤ 2	≤± 0.5	≥ 0.6
Temperature		
GE (K)	MB (K)	IOA
≤ 2	≤± 0.5	≥ 0.8
Wind direction		
GE (^{O})	MB (^{O})	
≤ 30	≤± 10	

Table 6-2: The MM5 modelled and observational meteorological data evaluation averaged over 12 observational sites.

Wind speed		Temperature		Wind Direction	
RMSE (m/s)	1.84	GE (K)	3.11	GE (^{o})	64.63
MB (m/s)	0.21	MB (K)	-1.32		
IOA	0.64	IOA	0.90	MB (^{o})	10.33

6.2.3.1.2 CALPUFF

Use was made of the Mesopuff-II scheme for chemical transformation and six chemical species (SO_2, SO_4, NO_x, Ammonium Nitrate (HNO_3), NO_3 and PM_{10}) were modelled, however only three (SO_2, NO_x and PM_{10}) were emitted. The Mesopuff-II chemical transformation scheme makes use of parameterizations that were developed from chemical transformation rate expressions derived from the results of photochemical model simulations over a wide range of environmental conditions (US EPA, 1994). As part of this chemical transformation method, daytime SO_2 oxidation varies hourly based ozone concentration, solar radiation, atmospheric stability, and relative humidity, with a night-time conversion rate of 0.2% per hour. Daytime NO_x oxidation varies hourly as a function of background ozone concentration, atmospheric stability and plume NO_x concentration with a night time rate of 2% per hour (Zhou *et al.,* 2003). Monthly background ozone (O_3) and ambient background ammonia concentrations were calculated from the 3-year monthly averages of three monitoring stations situated within the model domain.

Dry and wet deposition options were activated for the modelling procedure in order to produce the most realistic results. Default CALPUFF settings for these were used. Concentration and deposition were modelled for all the centre points of 2011 South African census data small area blocks in the model domain (Figure 6-2) as discrete receptors (Statistics South Africa, 2012).

Turbulence-based dispersion, the recommended setting for CALPUFF, was selected in conjunction with the Probability Density Function (PDF). The PDF function has been found in a number of model evaluation studies to be important for tall stack dispersion under convective conditions (Exponent, 2014).

The modelling domain includes the heavily populated areas of the Highveld of South Africa, an area that was declared a priority area for air quality management due to the fact that it is a degraded Airshed (Department of Environmental Affairs and Tourism, 2007). The main sources within the Highveld Priority area include industry, electricity generation, domestic burning and vehicle emissions (Department of Environmental Affairs, 2011). Although populations in other areas of South Africa are most probably also affected by power station emissions, the modelling domain was restricted to the Highveld of South Africa to provide the information most directly relevant to Highveld Priority Area policy analyses. A map indicating the modelling domain, the Highveld Priority area boundary, the census block centre points modelled as discrete receptors (the density of points are directly proportional to population density), the locations of each power station investigated and observational and background monitors used for model evaluation are shown in Figure 6-2.

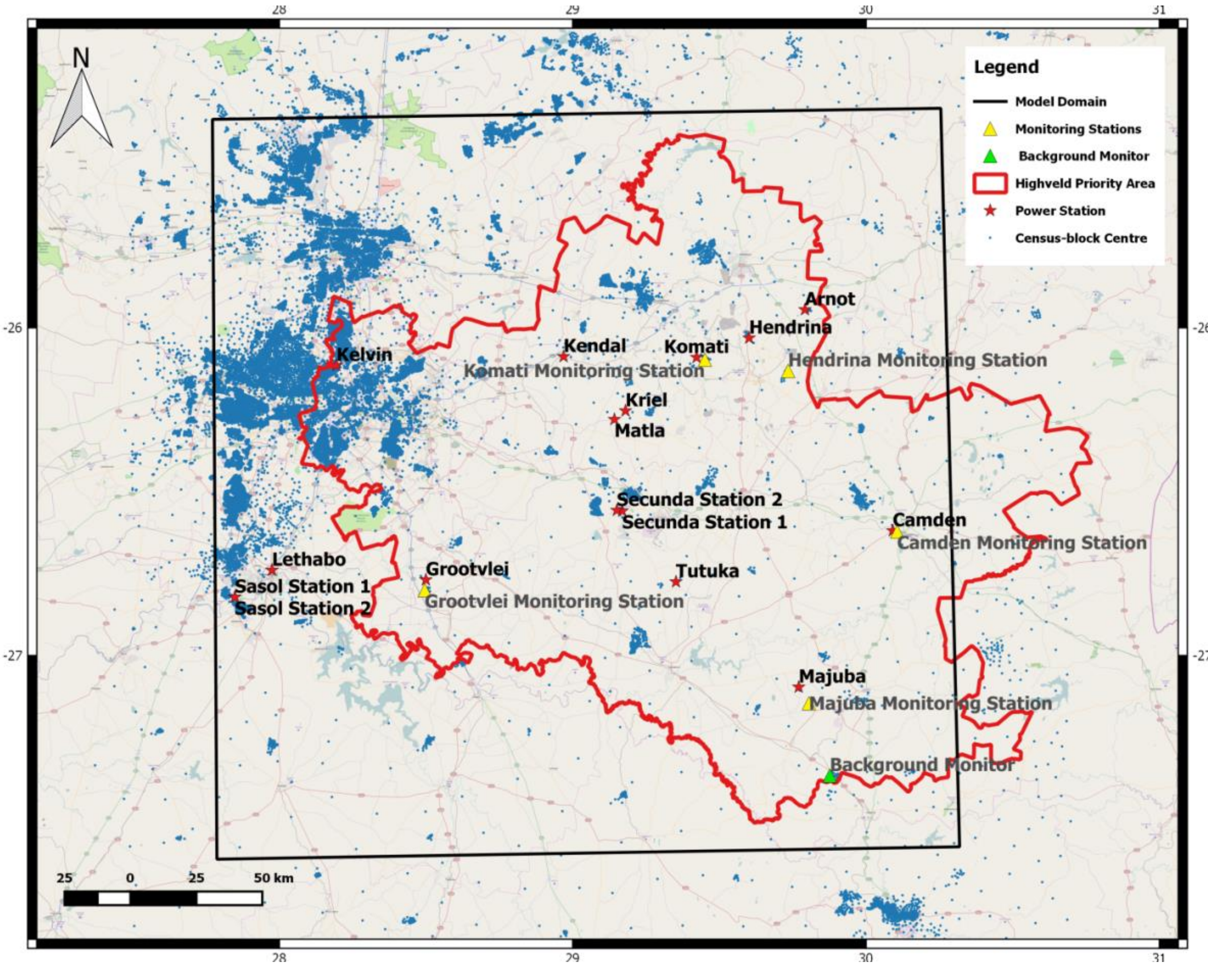

Figure 6-2: A map of the model domain, the Highveld Priority Area boundary, census data block centre points, the power stations investigated and observational and background monitors.

6.2.4 Source characteristics and emissions

Source characteristics and emission factors for the purpose of dispersion modelling were obtained directly from the utility (in the case of Eskom-owned power stations) and from past atmospheric impacts reports (in the case of Sasol-owned power stations). Information for the only privately owned power station, namely Kelvin, was unavailable and therefore estimated from other power stations of similar age and generating capacity. At present, and during the modelling period, South African power stations only made use of Particulate Matter (PM) emissions control. Approximately two thirds of the power stations within the Highveld make use of Electrostatic Precipitators (ESP) for PM control, whereas the remaining third makes use of Fabric Filter Plants (FFP). The annual average PM_{10}, SO_2 and NO_x emission factors and type of PM control used at each of the power stations investigated are summarized in Table 6-3. Each power station is associated with a different seasonal diurnal energy output trend. Emissions change diurnally proportionally to energy output. The normalized diurnal trends in energy output of all Eskom-owned power stations are shown in Figure 6-3 and were incorporated in the dispersion modelling. Diurnal trends were not available for the two Sasol-owned and privately owned power stations. A single, constant emission factor for these stations was utilized in the dispersion modelling process.

Table 6-3: The total annual PM_{10}, SO_2 and NO_x emission rate in tons per annum (tpa) as well as PM emissions control installed per power station.

Power station	Emissions abatement installed	Total annual emission rate (tpa)		
		PM_{10}	SO_2	NO_x
Arnot	FFP	750	64000	52500
Camden	FFP	1300	78700	31200
Duvha	FFP (Units 13); ESP(Units 4-6)	3100	134000	75300
Grootvlei	ESP (Units 2-4); FFP (Units 1,5-6)	4900	41800	27100
Hendrina	FFP	910	128000	49400
Kendal	ESP	5000	208000	98900
Komati	ESP	2100	15100	13300
Kriel	ESP	11200	136000	94600
Lethabo	ESP	8500	186000	108300
Majuba	FFP	2800	181000	138600
Matla	ESP	13000	187000	108400
Tutuka	ESP	16000	175000	109300
Kelvin	FFP	*1250*	*20900*	*8000**
Secunda Station 1	ESP	5200	184000	57900
Secunda Station 2	ESP	4700	164000	51500
Sasol Station 1	ESP	740	5300	7300
Sasol Station 2	ESP	850	7030	8830

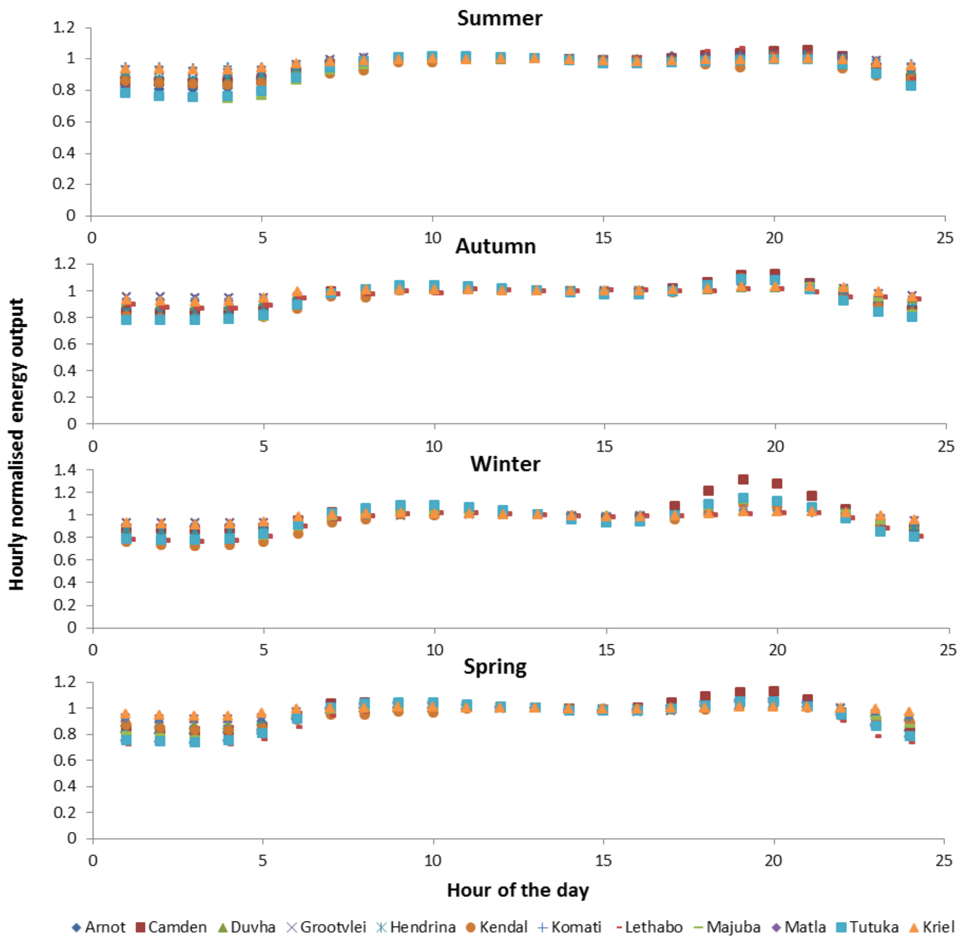

Figure 6-3: Normalized seasonal diurnal energy output profiles per power station.

The positions, generating capacities, stack heights, stack diameters, flow rates and exit temperatures of each power station investigated are summarized in Table 7-4. The locations of each of the power stations with respect to the Highveld Priority area and the dispersion modelling domain are shown on the map (Figure 7-2) in the previous section.

Table 6-4: Source characteristics of each power station investigated in this study.

Power station	Position		Generating Capacity (MW)	Stack height (m)	Effective stack diameter (m)	Flow rate (m/s)	Exit temperature (K)
	Latitude	Longitude					
Arnot	-25.944	29.792	2100	195	16	25	418
Camden	-26.62	30.091	1600	155	17	14	423
Duvha	-25.961	29.339	3600	300	18	27	413
Grootvlei	-26.77	28.5	1200	152	13	22	418
Hendrina	-26.031	29.601	2000	155	16	22	411
Kendal	-26.088	28.969	4100	275	19	24	413
Komati	-26.091	29.422	1000	220	17	10	418
Kriel	-26.254	29.18	3000	213	20	19	413
Lethabo	-26.740	27.975	3700	275	17	28	433
Majuba	-27.096	29.771	4100	250	17	35	398
Matla	-26.28	29.142	3500	275	19	26	408
Tutuka	-26.776	29.352	3600	275	17	29	413
Kelvin	-26.115	28.195	600	220	17	10	418
Secunda Station 1	-26.558	29.169	600	301	14	25	458
Secunda Station 2	-26.558	29.15		250	14	25	458
Sasol Station 1	-26.822	27.848	140	75	9	6	433
Sasol Station 2	-26.822	27.848		145	8	10	433

6.3 Results and discussion

The spatial distribution of modelled SO_2, NO_x and total (primary and secondary) PM_{10} concentrations in micrograms per cubic metre (µg/m³) as a result of all power stations investigated in this study are shown in Figures 6-4, 6-5 and 6-6. Concentrations of all pollutants investigated are generally highest in the central part of the modelling domain. It is important to note that the concentrations presented in these figures are from power station emissions only and does not include any background values. It can be seen that concentrations are relatively low and below national and international ambient air quality standards (a summary of South African National Ambient Air Quality Standards (NAAQS) and World Health Organisation Air Quality Guidelines (WHO AQG) annual average standards for SO_2, NO_2, PM_{10} and $PM_{2.5}$ are given in Table 6-5 for comparison) (Department of Environmental Affairs, 2012; World Health Organisation, 2005). However, the population exposed to these emissions is large (in the order of millions) and for this reason the potential human health impacts from these power stations may be large.

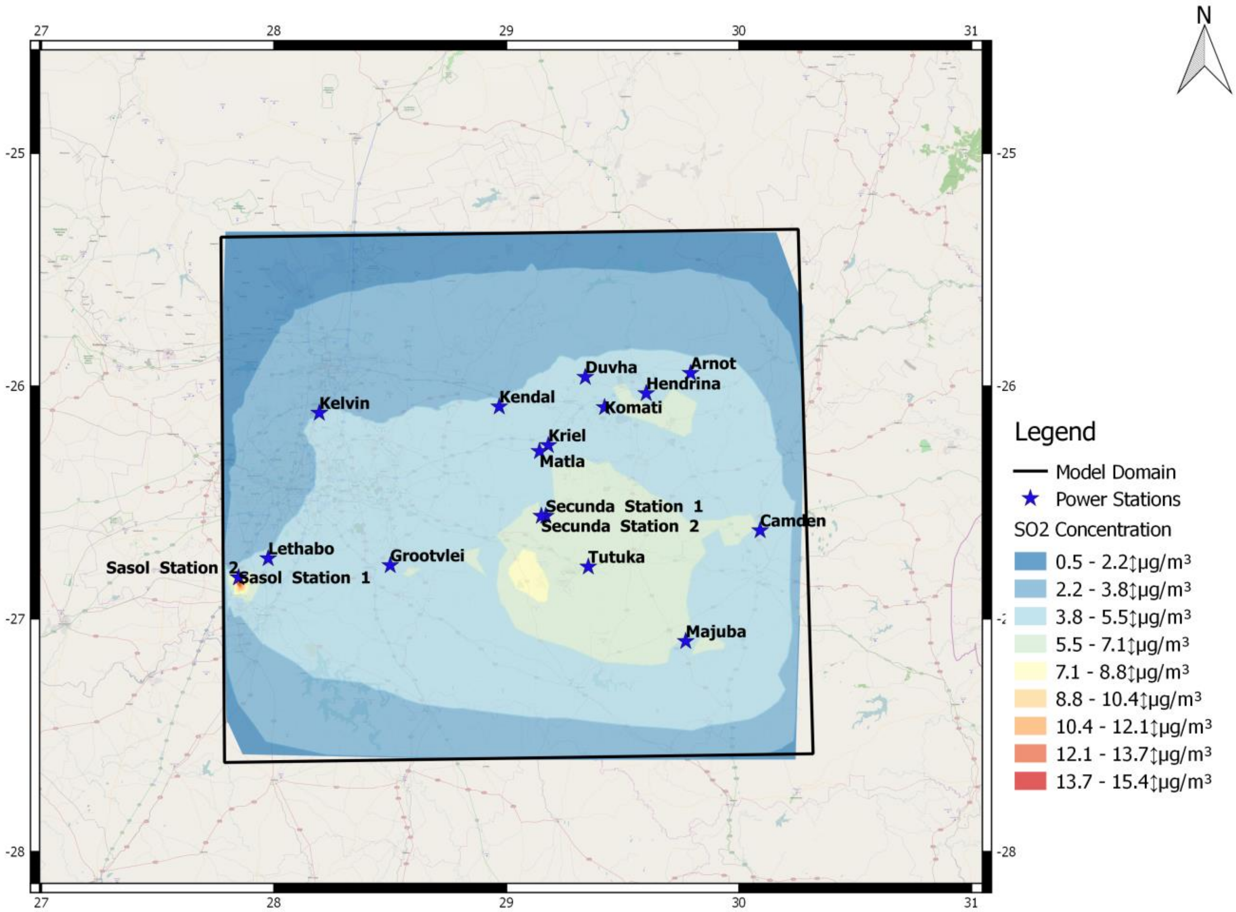

Figure 6-4: The spatial distribution of modelled three year average SO_2 concentrations (µg/m³) as a result of power station emissions in the Highveld of South Africa.

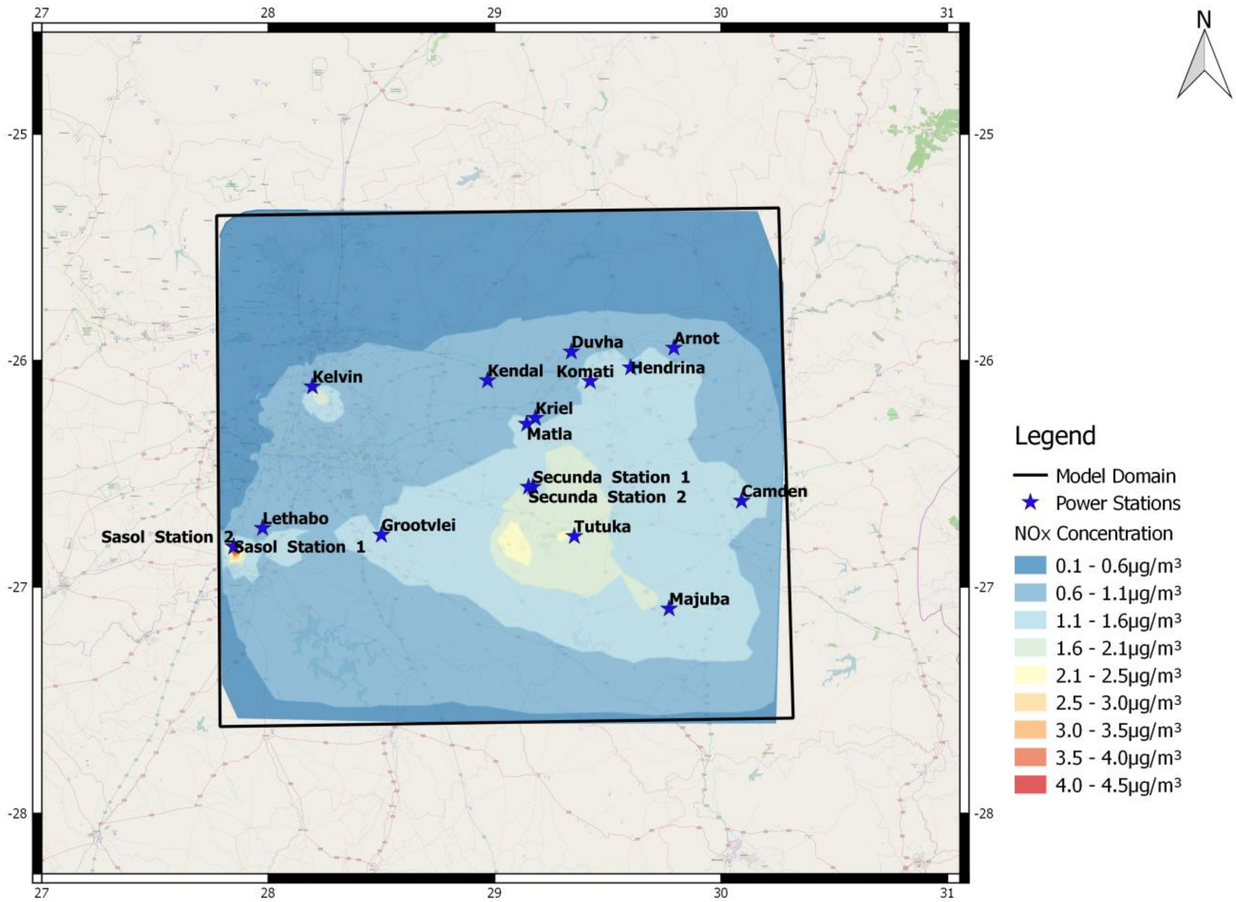

Figure 6-5: The spatial distribution of modelled three year average NO_x concentrations (µg/m³) as a result of power station emissions in the Highveld of South Africa.

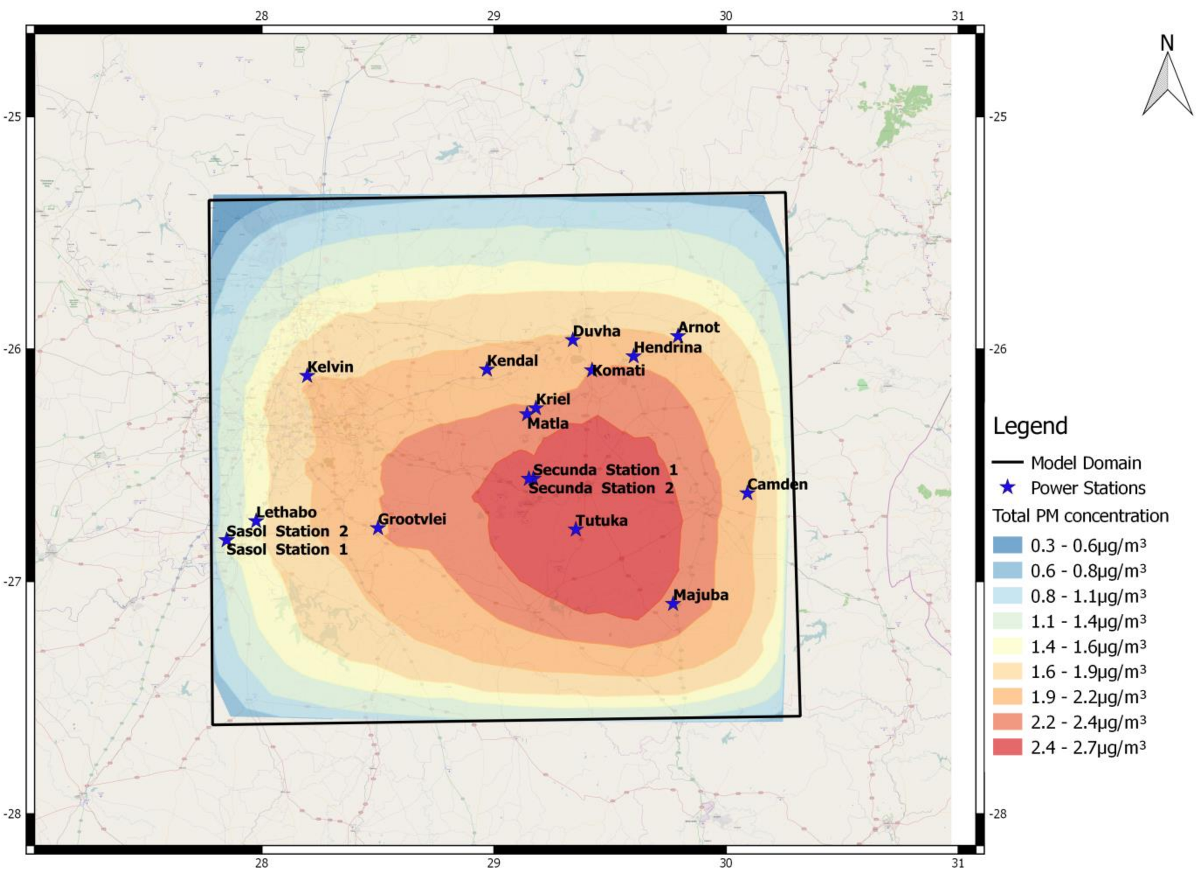

Figure 6-6: The spatial distribution of modelled three year average (primary and secondary) PM_{10} concentrations (µg/m³) as a result of power station emissions in the Highveld of South Africa.

Table 6-5: Long-term national and international ambient air quality standards for SO_2, NO_2, PM_{10} and $PM_{2.5}$.

Pollutant	South African NAAQS	WHO AQG
	Concentration µg/m³	Concentration µg/m³
SO_2	50	-
NO_2	40	40
PM_{10}	40	20
$PM_{2.5}$	20 (Jan 2016 to Dec 2029)	10
	10 (Jan 2030 onwards)	

6.3.1 Model evaluation

It is relatively easy to model the air quality impacts of individual power stations, but difficult to validate these results using monitoring data. It would be ideal if it was possible to obtain atmospheric monitoring results with and without the various power stations operating as modelling results could have been easily validated in such a way (Hao *et al.,* 2007 and Zhao *et al.* 2006). However, such monitoring results are unfortunately not available. Instead long term average (2011-2013) background concentrations of SO_2 and NO_x were calculated for a monitoring station (called Verkykerkop) that is situated relatively far away (35 km) from a prominent source of emissions (this monitor is indicated as the Background Monitor in Figure 6-2). The long term background concentrations were then added to long term averaged model results for the same period and compared to observational results of five different monitoring stations that are situated in close vicinity to power stations and relatively far away from other prominent sources (Table 6-6). The locations of the observational monitoring stations are shown in the map indicated in Figure 6-2. As suggested by Kumar *et al.* (1993) an air quality model can be considered to perform well when the Fractional Bias (FB) is between -0.5 and 0.5 and the Normalised Mean Square Error (NMSE) ≤0.5. These statistical parameters were calculated for the modelled results (added to a background concentration) and the observational results. The observational monitors for which these statistical requirements were met are indicated in green in Table 6-7. It is evident that the model performed relatively well at the majority of the monitoring stations. Only long term average modelled results were evaluated as this study is concerned with three-year average concentrations for the purpose of intake and intake fraction calculations.

Table 6-6: A comparison of observed and modelled (added to background) concentrations (μg/m³) as well as statistical verification in the form of Fractional Bias (FB) and Normalised Mean Square Error (NMSE) for SO_2 and NO_2 at five different observational sites for the period 2011-2013.

SO_2				
Monitoring Station	**Long term (2011-2013) average concentration (μg/m³)**		**Statistical comparison**	
	Observation	**Modelled plus background value**	**FB**	**NMSE**
Hendrina	13.7	7	0.65	0.47
Komati	13.1	5.34	0.84	0.86
Camden	11.1	5.53	0.67	0.5
Grootvlei	8.9	5.62	0.45	0.21
Majuba	4.6	5.7	-0.21	0.05
NO_x				
Hendrina	6	5.05	0.17	0.03
Komati	5.8	4.63	0.22	0.05
Camden	6.8	4.54	0.4	0.16
Grootvlei	13.7	4.64	0.99	1.29
Majuba	3.66	4.78	-0.27	0.07

6.3.2 Intake and intake fraction

The resulting intake (kg per year) and intake fraction values for each power station located within the Highveld of South Africa are given in Table 6-8. Intake and intake fraction values from individual power stations for SO_2 and NO_x are depicted in the graphs shown in Figures 6-7 and 6-8, respectively. The contribution of primary PM_{10} and secondary PM (SO_4 and NO_3) to total intake is shown in Figure 6-9, whereas intake fraction values for primary PM_{10}, SO_4 and NO_3 are shown in Figure 6-10. It is clear from the results that the potential health exposure to power stations in this area is highly variable from station to station.

Annual SO_2 intake values range between a maximum of 74.5 kg per year for Kendal power station to a minimum of 3.3 kg per year for Komati, an order of magnitude difference. Intake fractions for SO_2 differ by three orders of magnitude between a maximum of 1.9E-5 for Kelvin and a minimum of 6.4E-8 for Secunda.

NO_x intake and intake fraction values also differ extensively for the power stations investigated. Intake values range between a maximum of 12.8 kg per year for Kelvin and a minimum of 1kg per year for Komati. NO_x Intake fraction values range between 1.6E-6 for Kelvin and 1.9E-8 for Majuba, a difference of two orders of magnitude.

Human health exposure to primary PM_{10} is also highly variable between the different power stations and Secunda contributes to the highest intake of an estimated 6.1 kg per year whereas Majuba contributes the least at only 0.1 kg per year. Intake fractions vary between a maximum of 3.0E-06 for Kelvin power station and a minimum of 3.7E-08 for Majuba, a difference of two orders of magnitude.

Secondary PM intake values in the form of SO_4 (ammonium sulphate) range between a maximum and minimum of 22.4 and 0.8 kg whereas NO_3 intake values (ammonium nitrate) range between 9 and 0.9 kg. Intake fraction values for SO_4 differ up to two orders of magnitude between 2.2E-06 and 1.8E-08 and that for NO_3 differs one order of magnitude between 3.4E-07 and 2.4E-08. An important finding is that the secondary PM contribution to the intake value (kg per year) from total fine particulates is more prominent than that of primary PM_{10} (Figure 6-9).

The differences in intake and intake fraction values of all emissions but primary PM_{10} emissions are explained by the proximity of the station in question to human populations and the emission rate of the station, as none of these emissions are currently abated at South African power stations. The primary PM_{10} intake fraction, however also depend on the type of emissions abatement that is installed whereas secondary PM values depend additionally on atmospheric conversion rates from precursor gases.

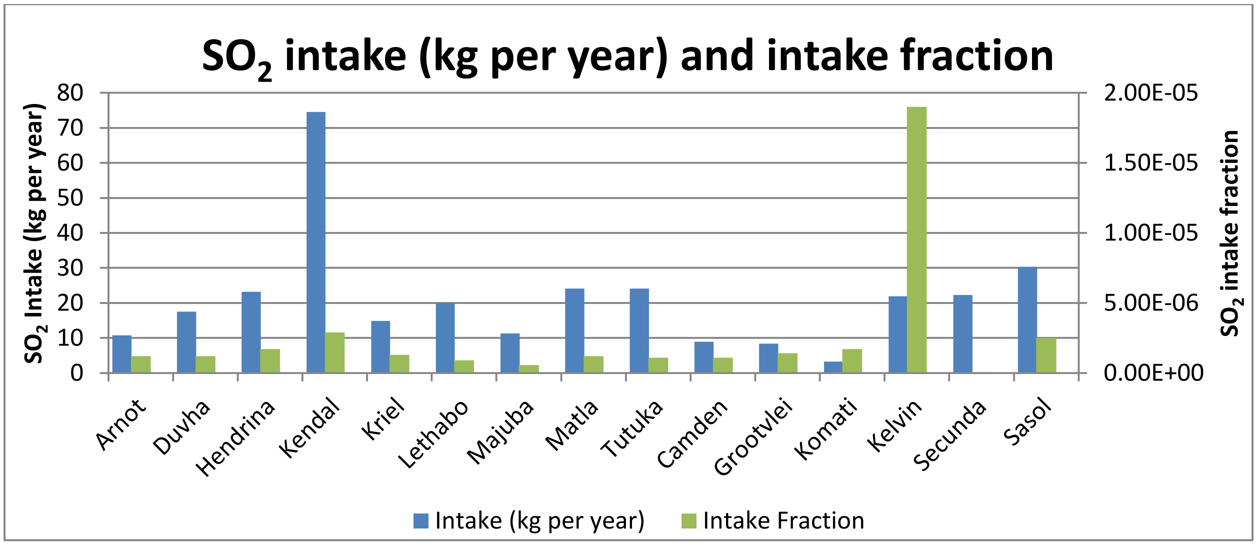

Figure 6-7: A graph indicating intake (kg per year) and intake fraction values for SO_2 from individual power stations.

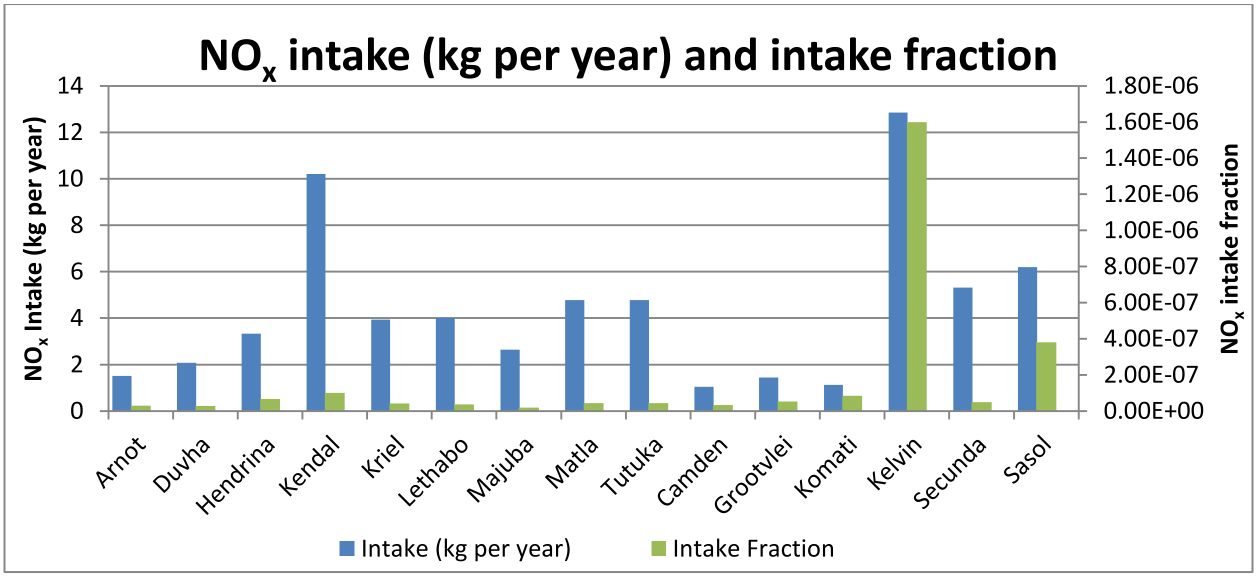

Figure 6-8: A graph indicating intake (kg per year) and intake fraction values for NO_x from individual power stations.

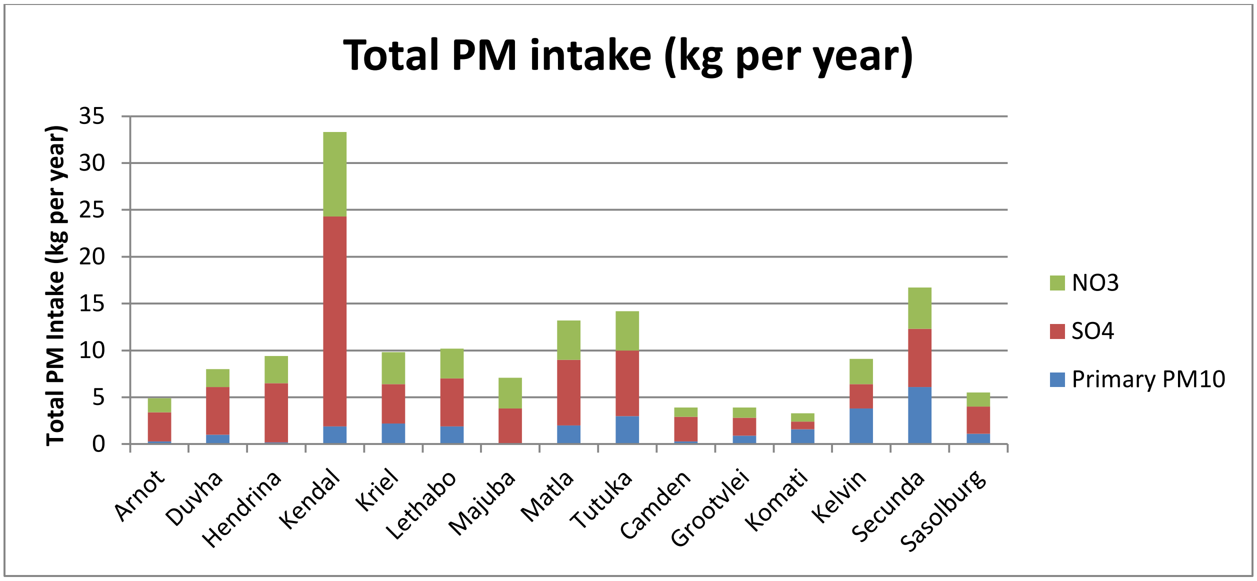

Figure 6-9: A graph indicating total PM intake (kg per year) from individual power stations as fractions of secondary and primary PM.

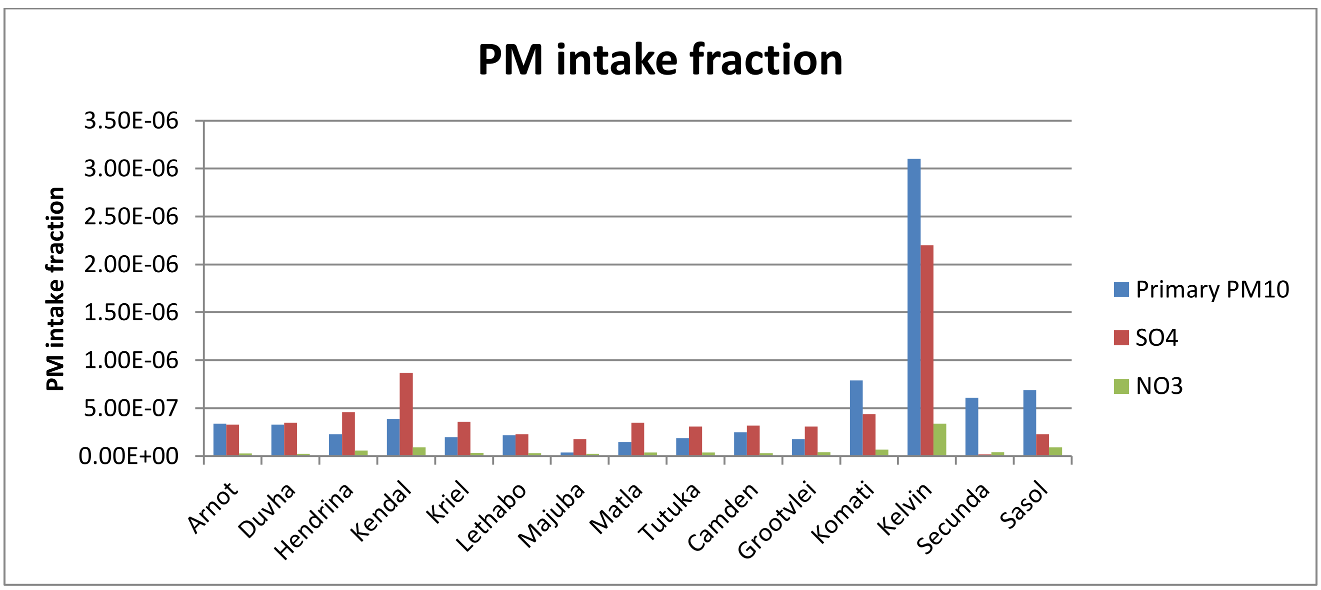

Figure 6-10: A graph indicating total PM intake fraction values individual power stations.

Table 6-7: Intake (kg per year) and intake fraction values from individual coal-fired power station emissions by the population of the Highveld of South Africa.

Power Plant	SO_2		NO_x		PM_{10}		SO_4		NO_3	
	Intake (kg)	Intake Fraction	Intake (kg)	Intake Fraction	Intake (kg)	Intake Fraction	Intake (kg)	Intake Fraction	Intake (kg)	Intake Fraction
Arnot	10.8	1.2E-06	1.51	2.9E-08	0.3	3.4E-07	3.1	3.3E-07	1.5	2.9E-08
Duvha	17.5	1.2E-06	2.08	2.8E-08	1.0	3.3E-07	5.1	3.5E-07	1.9	2.5E-08
Hendrina	23.2	1.7E-06	3.33	6.7E-08	0.2	2.3E-07	6.3	4.6E-07	2.9	5.8E-08
Kendal	74.5	2.9E-06	10.21	1.0E-07	1.9	3.9E-07	22.4	8.7E-07	9.0	9.1E-08
Kriel	14.9	1.3E-06	3.94	4.2E-08	2.2	2.0E-07	4.2	3.6E-07	3.4	3.6E-08
Lethabo	20.0	9.0E-07	4.00	3.7E-08	1.9	2.2E-07	5.1	2.3E-07	3.2	3.0E-08
Majuba	11.3	5.6E-07	2.64	1.9E-08	0.1	3.7E-08	3.7	1.8E-07	3.3	2.4E-08
Matla	24.1	1.2E-06	4.78	4.4E-08	2.0	1.5E-07	7.0	3.5E-07	4.2	3.9E-08
Tutuka	24.1	1.1E-06	4.78	4.4E-08	3.0	1.9E-07	7.0	3.1E-07	4.2	3.8E-08
Camden	8.9	1.1E-06	1.04	3.3E-08	0.3	2.5E-07	2.6	3.2E-07	1.0	3.3E-08
Grootvlei	8.4	1.4E-06	1.44	5.3E-08	0.9	1.8E-07	1.9	3.1E-07	1.1	4.1E-08
Komati	3.3	1.7E-06	1.12	8.4E-08	1.6	7.9E-07	0.8	4.4E-07	0.9	6.9E-08
Kelvin	21.9	1.9E-05	12.85	1.6E-06	3.8	3.1E-06	2.6	2.2E-06	2.7	3.4E-07
Secunda	22.3	6.4E-08	5.32	4.9E-08	6.1	6.1E-07	6.2	1.8E-08	4.4	4.0E-08
Sasol	30.3	2.5E-06	6.20	3.8E-07	1.1	6.9E-07	2.9	2.3E-07	1.5	9.0E-08
Mean	21.0	2.5E-06	4.3	1.7E-07	1.8	5.1E-07	5.4	4.7E-07	3.0	6.5E-08
Standard Deviation	16.0	4.5E-06	3.3	3.9E-07	1.5	7.1E-07	4.9	5.1E-07	2.0	7.5E-08
Maximum	74.5	1.9E-05	12.8	1.6E-06	6.1	3.1E-06	22.4	2.2E-06	9.0	3.4E-07
Minimum	3.3	6.4E-08	1.0	1.9E-08	0.1	3.7E-08	0.8	1.8E-08	0.9	2.4E-08
Total	315.5	3.8E-05	65.2	2.6E-06	26.4	7.7E-06	80.8	7.0E-06	45.1	9.8E-07

6.3.3 Comparison to international studies

International intake fraction values for PM emissions from power stations are widely available. Smith (1993) estimated that it is approximately in the order of 10E-5 for developing countries and 10E-6 for developed countries. The total intake fraction calculated for all power stations in the Highveld of South Africa in this study is 7.7E-06 for primary PM and 1.57E-05 for total PM (primary plus secondary PM), in line with Smith's estimations. Using a similar methodology as this study, Zhou *et al.* (2006) estimated fine primary PM intake fractions from power plants in China to be in the order of 10E-5 and that of SO_4 and NO_3 to be in the order of 10E-6. US estimates for fine primary PM intake fractions are in the order of 10E-6 and 10E-7 for fine secondary PM (Evans *et al.,* 2002; Levy *et al.,* 2002; Wolff, 2000). The total SO_4 intake fraction for all power stations estimated in this study is 7.0E-06, a value similar to the Zhou *et al.* (2006)

findings, whereas the total NO_3 intake fraction value estimated in this study (9.8E-07) is similar to the US findings.

6.3.4 Emissions management strategy for the Highveld of South Africa

Based on the estimated intake and intake fraction values in Table 6-8, an emission management strategy for power station emissions in the Highveld of South Africa can be developed. Those power stations presenting the highest potential human health exposure can be identified and targeted for emissions interventions. For the management of both SO_2 and secondary PM emissions in the form of SO_4 it is proposed that SO_2 emissions control be considered at Kendal, Kelvin and Sasol power stations. For primary PM_{10} emissions control it is advised that ESP's be retrofitted with FFP's at Kelvin, Komati, Sasol, Secunda, Kendal and Tutuka power stations. NO_x emissions control for the reduction of both NO_x emissions and secondary PM in the form of NO_3 should be considered at Kelvin, Kendal and Sasol power stations and possibly also at Secunda, Matla and Tutuka.

6.4 Conclusions

The results of this study show that the health exposure of population groups to individual power station emissions differ substantially from power station to power station. Differences in intake fraction values of up to three orders of magnitude were estimated for SO_2, whereas NO_x, primary PM_{10} and SO_4 values differed by up to two orders of magnitude. Intake values in the case of all pollutants investigated differed by up to an order of magnitude. The answer to the question "should all power stations be treated equal?" as put in the title of this paper can therefore be answered with a definite "No". It makes more sense both from a cost and a human health standpoint that emissions from power stations be managed on an individual power station basis and not by means of blanket minimum emission standards.

It is believed that the methodology used in this study can be implemented to identify those power stations that contribute to highest human health exposure in order to target them for emissions management interventions. In this case, fiscal resources can be optimally utilized to reduce emissions at these stations where state of the art emissions control can be installed, whereas stations contributing to low human health exposure can be left to pollute. In developing countries, where financial resources for the control of pollution from power stations are limited, the methodology proposed in this study may be extremely useful in reducing human health impacts and saving lives.

Thesis conclusion

The objective of this article is to develop a coal-fired power station emissions management strategy for the Highveld of South Africa.

The following main conclusions can be drawn:

- *The potential health exposure of population groups to individual power station emissions* differ substantially from power station to power station and from pollutant to pollutant.
- The secondary PM contribution to total annual intake (kg per year) from total fine particulates is more prominent than that of primary PM_{10}
- *It makes more sense both from a cost and a human health standpoint that emissions from power stations be managed on an individual power station basis and not by means of blanket minimum emission standards.*
- *The intake and intake fraction methodology proposed in this study can be used to identify individual power stations that contribute to the highest potential human health exposure. These power stations can then be targeted for emission reduction interventions.*

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7 Conclusions

Coal-fired power stations are responsible for the highest CO_2, SO_2 and NO_x emissions and second highest PM emissions of all sources of air emissions in South Africa. These emissions are not only prominent locally but also play a regional and global role where South Africa has a large carbon footprint with respect to the size of its economy. For this reason it is so important to understand power station emissions holistically, taking in account the uncertainties associated with their emissions estimation as well as the different factors that can impact these emissions at present and in the future. Often it is necessary to look at past emissions trends in order to predict what may happen in the future. This study investigated coal-fired power station emissions following a bottom-up approach. The first step in this approach was to compare the traditional approach of estimating coal-fired power station emissions (mass balance calculations) with the new approach as required by legislation (CEMS). The influence of the South African energy crisis on coal-fired power station emissions was then investigated, followed by a prediction of how these emissions will change in the future based on different scenarios. Lastly, an alternative coal-fired power station emissions management strategy is proposed in order to achieve optimal human health outcomes at lowest cost.

7.1 Study objective 1

The objective of the first article, entitled "***A critical comparison of gaseous coal-fired large boiler emission estimation in South Africa***" was to compare CEMS and calculation-based coal-fired power station emission estimation methods. Calculation-based emissions estimation techniques and CEMS were compared in terms of cost, ease of operation/calculation, data quality and practicality in the South African context. The most important findings of this study are that calculation methods are the simplest, most cost effective methods to use whereas CEMS are both expensive and complex. The data quality of both methods is currently similar in South Africa. If operated properly, and if proper quality assurance/quality control measures are in place, CEMS can obtain emissions measurements with lower uncertainties than that of calculation methods. However, there is still a knowledge-gap in operating these systems in South Africa and the data availability requirements of the legislation cannot currently be achieved.

The main thesis conclusions that can be drawn from this study are summarised as follow:

- *At present, the data quality of CEMS and calculation methods are similar in South Africa.*
- *The cost and complexity of CEMS are much higher than that of calculation methods.*
- *At the moment there is still a void in CEMS operational and maintenance knowledge in South Africa. The training costs associated with CEMS are most probably vastly underestimated.*
- *The high data availability requirement of the legislation (80%) for CEMS is unrealistic as this data availability could not be achieved during a testing phase.*
- *It is recommended that calculation methods be used concurrently with CEMS in at least until such time as it can be proven that CEMS output is reliable and of high quality.*

7.2 Study objective 2

The objective of the second paper of this study, namely "***The impact of the South African energy crisis on emissions***" was to investigate the impact of the South African energy crisis on emissions. The study showed that the energy crisis had, and still has, a negative impact on emissions. Coal-fired power station emissions increased as a result of the decrease in thermal efficiency of the fleet due to low maintenance opportunity and increased pressure on emissions abatement equipment. This shows that if the energy crisis persists, emissions from power stations may be much higher than expected and this should be taken in account in future planning.

The main findings of the study are summarised below:

- *An energy restricted environment causes an increase in emissions.*
- *The deferral of maintenance on power stations let to the deterioration of the power station fleet which ultimately caused a systematic decrease in the thermal efficiency of power stations. This meant that more coal had to be burned in order to produce the same energy output as before the energy crisis. As a result, emissions per energy output of the South African fleet increased (with the exception of SO_2 due to a decrease in sulphur content of coals during the energy crisis period).*

- *Emissions of PM showed a significant increase compared to other pollutants during the energy crisis period, as a result of lowered maintenance on PM abatement, as PM was the only pollutant that was controlled at South African power stations at that stage.*

7.3 Study objective 3

Even though the South African government is trying to move away from coal as the country's dominant energy source, coal will remain the main source of energy at least in the medium term. In the near future, Medupi and Kusile, two new power stations that are currently under construction, will be added to the fleet and it is envisaged that the lifespans of existing power stations will be extended beyond the planned 50 years. The third research paper of this study, called "***A perspective of South African coal-fired power station emissions***" predictions are made of future coal-fired power stations emissions for different scenarios during the period 2015 to 2030. The scenarios differ in terms of different retrofit rates of power stations with emissions abatement technologies and different energy demand outlooks. Emissions projections for the different scenarios differ substantially for all pollutants. The worst case scenario assumes a relatively high energy demand outlook and further assumes that the energy crisis persists over the next 15 years whereas the best case scenario assumes lower energy demand and abatement retrofits at some stations. Worst case emissions are roughly double that of best case emissions during 2030 for PM, SO_2 and NO_x. Another important finding is that it is unlikely that the South African climate commitment target of 280 Mt CO_2 in 2030 will be made, unless energy demand dramatically decreases in the future.

The main findings of this article can be summarised in the following way:

- *South African coal-fired power station emissions may vary substantially only based on the variability of fuel coals. This is especially true for uncontrolled SO_2 emissions as sulphur contents showed large variability during the investigated historical period.*
- *There is a marked difference between projected worst- and best case SO_2 emissions during 2030, where worst case emissions are predicted to increase by around 38% from a 2015 baseline and best case emissions are expected to decrease by around 20% in 2030 from the same baseline value.*
- *Projected best- and worst case PM emissions differ markedly for the different scenarios. During 2030, worst case PM emissions are expected to rise by 40% from a 2015*

baseline value whereas best case PM emissions are projected to decline by 40% from the same value.

- *Worst case NO_x emissions are expected to increase by 40% in 2030 from a 2015 baseline value whereas best case emissions are expected to decline 10% from the same level in 2030.*
- *From projections of future CO_2 emissions in this study it seems unlikely that the South African climate commitment target of 280 Mt in 2030 will be made, unless energy demand dramatically decreases in the future.*

7.4 Study objective 4

The objective of the last paper of this study, entitled "***Emissions management and health exposure: Should all power stations be treated equal?***" was to develop an alternative emissions strategy for coal-fired power stations in South Africa. The study showed that the health exposure to power station emissions varies greatly from station to station and from pollutant to pollutant. Potential human health exposure in the form of intake fractions estimated in this investigation differed up to two orders of magnitude for SO_2, NO_x and primary PM_{10}. Secondary PM emissions differed less, due to the fact that these pollutants form away from the source and are therefore able to disperse more evenly in the atmosphere. As a result of the findings presented in this study, the authors believe that a more logical solution to the effective management of power station emissions, with optimal human health and reduced cost as end goal, may be to address power station emissions on an individual power station basis. The methodology developed in this study may be followed in order to identify power stations contributing to high potential human health exposure in order to target them for emissions reduction interventions.

The main conclusions of this paper are summarised as follow:

- *The potential health exposure of population groups to individual power station emissions differ substantially from power station to power station and from pollutant to pollutant.*
- *The secondary PM contribution to total annual intake (kg per year) from total fine particulates is more prominent than that of primary PM_{10}*
- *It makes more sense both from a cost and a human health standpoint that emissions from power stations be managed on an individual power station basis and not by means of blanket minimum emission standards.*

- *The intake and intake fraction methodology proposed in this study can be used to identify individual power stations that contribute to the highest potential human health exposure. These power stations can then be targeted for emission reduction interventions.*

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9 Addendum: Co-author consent letters

29 September 2015.

To whom it may concern.

Dear Sir/Madam.

We, the undersigned and co-authors of the manuscript,

> **I. Pretorius, J.B. Keir, S.J. Piketh** and **R. P. Burger**, 2015. A critical comparison of gaseous coal-fired large boiler emission estimation in South Africa. Submitted to the *CLEAN – Soil, Air, Water* Journal.

Herewith give permission that this manuscript can be submitted as part of Ilze Pretorius's PhD thesis. Although we were involved with the conceptualization of this work, Ilze Pretorius was primarily responsible for the execution and documentation of this research.

Sincerely

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29 September 2015.

To whom it may concern.

Dear Sir/Madam.

We, the undersigned and co-authors of the manuscript,

> **Pretorius, S.J. Piketh** and **R. P. Burger**, 2015. The impact of the South African energy crisis on emissions. *WIT Transactions on Ecology and The Environment*, Vol 198, ISSN 1743-3541 (on-line). ***Published with open access. Used with kind permission from WIT Press.***

Herewith give permission that this manuscript can be submitted as part of Ilze Pretorius's PhD thesis. Although we were involved with the conceptualization of this work, Ilze Pretorius was primarily responsible for the execution and documentation of this research.

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29 September 2015.

To whom it may concern.

Dear Sir/Madam.

We, the undersigned and co-authors of the manuscript,

> **I. Pretorius, S.J. Piketh, R.P. Burger** and **H. Neomagus** 2015. A perspective of South African coal fired power station emissions. *Journal of Energy in Southern Africa,* 26(3). **Published. Used with permission.**

Herewith give permission that this manuscript can be submitted as part of Ilze Pretorius's PhD thesis. Although we were involved with the conceptualization of this work, Ilze Pretorius was primarily responsible for the execution and documentation of this research.

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29 September 2015.

To whom it may concern.

Dear Sir/Madam.

We, the undersigned and co-authors of the manuscript,

> **I. Pretorius, S.J. Piketh** and **R. P. Burger**, 2015. Emissions management and health exposure: Should all power stations be treated equal?

Herewith give permission that this manuscript can be submitted as part of Ilze Pretorius's PhD thesis. Although we were involved with the conceptualization of this work, Ilze Pretorius was primarily responsible for the execution and documentation of this research.

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