The Minimum Emission Standard (MES) Health Benefit Cost Analysis (BCA) Study at Medupi Power Station

DRAFT
FOR STAKEHOLDER COMMENT

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PRIME AFRICA CONSULT

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For Stakeholder Comment

Contract No.: GXHO-1075983762

Prepared for:

Eskom Holdings SOC Ltd

Eskom Holdings SOC Ltd

Megawatt Park

Sunninghill, 2157

Johannesburg, South Africa

Prepared by:

The Factory, 274 Brander Street,
Jan Niemand Park
0186 Pretoria, South Africa
+27 (0)12 348 0317

www.primeafrica.net

Project Manager Contact: Dr Jackie Crafford

j.crafford@primeafrica.net

Authors: Dr Karen Eatwell, Dr Jackie Crafford, Christian Griffiths, Ntlale Mohumutji, Sean Bennett, Valmak Mathebula, Isabella Selzer, Atham Raghunandan*, Dr Mark Zunckel*, Dr Magretha Pierce**

* uMoya-NILU Consulting (Pty) Ltd responsible for CALPUFF modelling and air quality analyses

** BioSwitch Africa provided health evidence advisory and exposure-response functions technical memoranda

PREAMBLE

This study was conducted to comply with the Department of Forestry, Fisheries and the Environment (DFFE) Minister's Record of Decision section 7.3 of 31 March 2025 in respect of the exemption applications submitted by Eskom in terms of Section 59 of the National Environmental Management: Air Quality Act (NEMA: AQA), 2004 (Act No. 39 of 2004). The Decision requires additional analyses from Eskom that include:

The completion of a revised and expanded plant-specific benefit-cost-analysis (BCA) regarding installing flue gas desulphurisation (FGD) at Medupi. Specific requirements addressed include those listed in the table below with an indication of where it is addressed in the report:

Clause Number	Section	Clause	Report Section where it is addressed
7.29	Conditions - Technology Retrofit Abatement - Medupi CBA & Power Modelling	I note the concerns regarding the CBAs undertaken by Prime Africa for purposes of Eskom's exemption application: i) The issue of airshed saturation (cumulative impact) is not accounted for, and this is an important determinant of health impacts. For example, in a saturated airshed, asthmatics respond to lower emission levels more quickly and intensely than healthy, unexposed individuals. ii) The use of Exposure Response Functions from other countries likely underestimates South Africa's baseline TB and HIV concerns, which impact on respiratory, cardiovascular and immunological response. iii) Synergistic pollutant interactions were not incorporated, which contribute to cumulative impacts. iv) The value of abating additional pollutants to PM, NOx and SOx were not included.	i) Section 2.3.3: The study assessed the Waterberg-Bojanala Priority Area (WBPA) airshed and it is not a saturated airshed. The exposure response functions (ERFs) applied in this assessment have been selected with consideration of the relevant ambient concentrations. ii) Section 2.3.1 and Table 2-8: The study conducted a comprehensive review of ERFs, taking consideration of South Africa's baseline health concerns. iii) Section 2.3.1 Box 1: Synergistic effects were accounted for via ERF selection process. iv) Section 2.3.1 Box 1: The value of additional pollutants was accounted for via ERF selection process. Please also refer to comment 7.32 which limits the assessment of SO_2 and please see notes in Box 1 on how this was addressed.

Clause Number	Section	Clause	Report Section where it is addressed
		v) Morbidity impacts were not included (cost of medical treatment, loss of employment, impacts of health risk on households, employers, the health care and insurance industries, educational impacts for vulnerable populations, (children, elderly, those with chronic health conditions). vi) Environmental aspects such as infrastructure and services to provide water and waste management (sorbents) associated with the FGD were not included.	v) The BCA has been expanded to assess morbidity impacts. Refer to section 2.3.1 and sub-heading morbidity for detailed explanations. vi) The BCA has been expanded to assess costs of implementation of these environment aspects. See Section 2.3.4.
7.3	Conditions - Technology Retrofit Abatement - Medupi CBA & Power Modelling	A revised and expanded plant-specific CBA must therefore be undertaken regarding installing FGD at Medupi within six (6) months of the exemption decision and submitted to me.	This study was conducted and the results are provided in the current report.
7.31	Conditions - Technology Retrofit Abatement - Medupi CBA & Power Modelling	To respond to the concerns articulated above, the following must be included in the quantitative assessment: (i) Health costs (addressing all concerns cited above); (ii) Technology costs (construction, maintenance and operation); (iii) Energy efficiency penalty; (iv) CO_2 costs; (v) Cost of sorbent supply, including infrastructure costs; (vi) Waste treatment; and (vii) Cost of water supply, including infrastructure costs.	All aspects listed are included in the expanded CBA study reported on here. Refer to Section 2.3.2 for health costs and Section 2.3.4 for technology and other costs as listed here.
7.32	Conditions - Technology Retrofit Abatement - Medupi CBA & Power Modelling	The CBA must be limited to SO_2 health impacts, holding all other pollutants constant and consider plant closure dates of 2045, 2055 and 2071 in separate scenarios. The report must further provide commentary on construction and operational risks, timing and duration of outages required to install the FGD, finance availability, project status currently, and the plant emission levels post the retrofit.	The expanded BCA analysis focused on SO_2 as explained in Box 1. Three alternative station/plant closure dates for Medupi power station were included in the BCA analysis separately as required here. The required commentary on aspects as listed here for Condition 7.32 is covered in Section 2.3.3.4.

Clause Number	Section	Clause	Report Section where it is addressed
		Implications for SO_2 emissions and the FGD plant of running Medupi at reduced utilisation rates must also be commented upon.	Commentary is provided in Section 2.3.3.1.
7.33	Conditions - Technology Retrofit Abatement - Medupi CBA & Power Modelling	Further, the CBA must consider two scenarios: (i) Compliance with new plant MES for SOX on a daily basis (i.e., wet-FGD), and (ii) Scenarios with appropriate abatement retrofits that do not necessarily comply with new plant MES but significantly reduce SOX emissions.	The expanded BCA considered three technical scenarios: (i) Scenario C with wet FGD to comply with new plant MES; and (ii) Two scenarios which would significantly reduce SO_2 but not necessarily comply with new plant MES (Scenario D with semi-dry FGD and Scenario E with dry FGD).
7.34	Conditions - Technology Retrofit Abatement - Medupi CBA & Power Modelling	Eskom must further commission independent power system modelling to explore alternatives to installing FGD at Medupi. The following scenarios must be compared: (i) Installing wet-FGD at Medupi; (ii) Scenarios with appropriate abatement retrofits that do not necessarily comply with new plant MES but significantly reduce SOx emissions; and (iii) Spending the CAPEX instead on flexibilising Mpumalanga coal units to displace a similar amount of health cost. The choice of plant must be guided by the Forum Report's 2024 Plant Baseline Assessment to target the poorest performing plants across multiple criteria.	Wrt items (i) and (ii), the current work assesses the technical scenarios of installing wet FGD at Medupi and other FGD technical alternatives (also see comment above). In addition, the work also evaluates several alternative scenarios to installation of FGD that assess health benefits that may result from options supporting flexibilising Mpumalanga coal units Refer to section2.4.
7.35	Conditions - Technology Retrofit Abatement - Medupi CBA & Power Modelling	The modelling output that must be compared across the two scenarios includes: electricity adequacy, cost, GHG emissions, and NOX, PM and SOX emissions.	The BCA assessed the technical and alternative scenarios for electricity adequacy, cost, GHG emissions, and air emissions (as explained above). These analyses may lead into further investigations related to power system modelling that fall outside the scope of this BCA.

EXECUTIVE SUMMARY

The purpose of the current study was to conduct a "revised and expanded" Benefit-Cost Analysis (BCA) for the Medupi power station to comply with the Department of Forestry, Fisheries and the Environment (DFFE) Minister's Decision of 31 March 2025. The BCA estimates the incremental health benefits resulting in the Waterberg-Bojanala Priority Area (WBPA) from:

- Three Flue Gas Desulphurisation (FGD) abatement technology options at Medupi power station
- Six alternative scenarios that may reduce emissions or mitigate health impacts resulting from different possible emission reduction approaches (not limited to WBPA).

Methodology

An integrated Air Pollution Health Risk Benefit-Cost Analysis (APHR-BCA) model was developed to model the impacts of three different abatement scenarios as developed by Eskom. The APHR-BCA was developed following the General Principles of the World Health Organisation, WHO (WHO, 2016a), for performing air pollution health risk assessments (AP-HRA). The detailed methodology and assumptions are set out in section 2 below. In summary, the methodology proceeded through several steps, as set out in the schematic Figure 2-1.

Health benefits resulting from air pollution abatement

Methodologically, this benefit-cost analysis builds on the 2024 Eskom assessment by broadening the scope of health impacts associated with air pollution to include both premature mortality and a range of morbidity outcomes estimated using exposure-response functions (ERFs). In the APHR-BCA the mortality effects are valued using an income-adjusted value of a statistical life (VSL), while morbidity effects are valued using a cost-of-illness (COI) approach that captures direct medical costs as well as costs associated with productivity and welfare losses. Key uncertainties in health risk and valuation parameters are explicitly explored through sensitivity analysis. The revised analysis therefore provides a more comprehensive estimate of the net benefits of emission reduction interventions, while remaining consistent with the structure of the 2024 study. More detail is provided in section 2.3.

This study evaluates the alternative emission reduction scenarios with respect to their potential impacts on air emissions. No additional dispersion modelling was done to evaluate the health benefits of these scenarios, rather, existing modelled data and literature was used to estimate the relative health benefits of the scenarios. To this end, the risk assessment methodology of the International Finance Corporation (IFC) Introduction to Health Impact Assessment (2009) was applied. The cost of implementation of these alternate scenarios has also been done at a concept level. Refer to section 2.4.

Technical Scenario Assessment

The three technical scenarios evaluated in the BCA study, against a baseline included:

- Scenario C: Wet FGD at Medupi power station
- Scenario D: Semi-Dry FGD at Medupi power station
- Scenario E: Dry FGD at Medupi power station

In addition, the analysis considered the alternative plant closure dates of 2045, 2055 and 2071 separately as required in condition 7.32 in the DFFE Minister's Decision. The detailed emission abatement measurements relevant to the scenarios above are set out in Table 2-9 in section 2.3.3. The scenarios evaluate the SO_2 reduction technology in the form of wet FGD, semi-dry FGD and dry FGD installation at the Medupi power station. The focus on SO_2 reduction is important given the extent to which it is anticipated to impact on air quality and public health and the very significant cost of SO_2 reduction. The Matimba power station, without any additional abatement technologies, was included in the modelling analysis due to its close proximity to Medupi and its contribution to the cumulative air quality impact on the region.

With respect to earlier shutdown dates, it is important to note that the early shutdown scenarios assessed in this report were based on timelines that respond to the Minister's request for additional analysis, but they do not imply that the earlier shutdown dates are technically or financially feasible for Eskom. Eskom generation planning is guided by the Integrated Resource Plan (IRP) 2025 (DMRE, 2025) to determine shutdown dates. It is further to be noted that earlier shutdown periods would impact on the Eskom electricity tariffs and would likely result in increased tariffs as Medupi investment costs would have to be recovered over a significantly shorter time period. These additional costs were not assessed as part of this study.

Health benefits associated with each scenario were calculated against a baseline that considered the anticipated increase in population growth, future loads, assumed no abatement technologies installed, and both stations would continue to emit air pollution at their full rates until shutdown.

The BCA ratios need to be interpreted with care. They are meant only to provide a perspective on and to inform the decision-making process underlying the scenarios. They are not meant to be interpreted as a definitive answer to making abatement decisions. Decisions involving human health must be informed by non-economic criteria as well. In addition, with uncertainty inherent in the analysis, the benefit-cost ratio should not be viewed as absolute, but rather as a relative value from which to compare scenarios.

The BCA results are provided in the Table 0-1 below. In the upper estimates, the lower costs and higher VSL and COI are used and in the lower estimates, the higher costs and lower VSL and COI are used as recommended by Robinson et al. 2018.

- The benefit-cost ratios (calculated using Eskom's WACC of 10.8%) of all the scenarios are significantly less than 1, even under the most optimistic (upper bound) parameters of the sensitivity analysis. The upper range ratios do not exceed approximately 0.05, implying that less than five cents of quantified health benefit is generated per rand of expenditure.
- Evaluation of the BCA ratios at a social discount rate of 2% delivers similar results, with all three scenarios ratios remaining less than 1.
- Scenario C (wet FGD) generates the largest absolute health benefits and BCA ratio, consistent with higher SO_2 removal efficiency. These gains are however outweighed by the significantly higher capital, operational and retrofit-related costs, leading to the largest negative Net Present Values (NPVs) among the scenarios.
- Scenarios D (semi-dry FGD) and E (dry FGD), although having lower lifecycle costs as expressed by "NPV of Costs", result in BCA ratios that are even less favourable than Scenario C (wet FGD).

When early shutdown of Medupi power station is considered (closure by 2055 or earliest by 2045), the overarching conclusion remains the same. The patterns in terms of all aspects observed in the timeline of full station lifetime remain the same, including the substantially lower NPV of benefits compared to NPV of costs; the BCA ratios being less than one and remaining so, even with the most optimistic parameters of the sensitivity analysis; scenario E (dry FGD) having the lowest NPV of costs compared to scenario C (wet FGD) and D (semi-dry FGD); and the pattern of the central BCA ratios. While early shutdown does result in a reduction in total health impact it is associated with negative impacts on funding viability, electricity provision and electricity tariff levels.

Table 0-1: BCA ratios (lower and upper) for each scenario (discounted at Eskom WACC) in the 2025 - 2071 period

	Scenario C Wet FGD		**Scenario D Semi-dry FGD**		**Scenario E Dry FGD**	
Million Rands	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
NPV of Costs	-36,190	-25,635	-34,126	-24,173	-21,983	-15,571
NPV of Benefits	172	954	149	828	63	351
NPV of Benefits minus Costs	-36,018	-24,681	-33,977	-23,345	-21,919	-15,220
Benefit:Cost Ratio (*range*)	0.0048	0.0372	0.0044	0.0342	0.0029	0.0226
Benefit:Cost Ratio (*central*)	0.0210		0.0193		0.0127	

Alternative Scenario assessment

Eskom formulated six alternative scenarios that would result in health benefits not limited to the WBPA only. It is to be noted that the alternative scenario results are not intended to be directly comparable to those of the technical scenarios modelled. The purpose of the alternative scenarios is to demonstrate the relative potential for achieving health benefits, at different levels of scale, while comparing relative cost structures of these alternative scenarios. The six alternative scenarios evaluated in the BCA study, against a baseline included:

- Eskom's AQO Programme: Eskom's air quality offset programme including a clean cooking programme is to be expanded to cover approximately 96,000 households by 2030. The programme has been partially implemented, with 5,991 households completed to date. The remaining households are expected to be addressed by the target date. Interventions include ceiling insulation, electrical rewiring, clean cooking interventions (stove installations, and the introduction of LPG heating), at an estimated cost of approximately R56,769 per household.
- Coal beneficiation: This is the process of improving raw coal by removing impurities before combustion. Methods include wet washing, dry cleaning, crushing and separation, fine-coal cleaning, and more advanced chemical/thermal/biological treatments.
- High Efficiency, Low Emissions (HELE): Circulating Fluidised Bed Combustion (CFBC) involves in-furnace sulphur capture through limestone injection during the combustion process, reducing SO_2 emissions without reliance on post-combustion control technologies such as FGD.
- Carbon Capture, Utilisation and Storage (CCUS): This comprises technologies that capture CO_2 emissions from large point sources and either utilise the captured CO_2 or store it permanently in geological formations. SO_2 polishing is a process requirement of CCUS and results in an air quality co-benefit.
- Long Duration Energy Storage (LDES): This refers to energy storage technologies capable of storing electricity for extended periods, typically ranging from several hours to multiple days, and discharging it when required.
- Small Modular Reactor (SMR): High Temperature Gas-Cooled Reactor - Pebble-Bed Module (HTR-PM) is a nuclear reactor that produces heat through controlled nuclear fission and converts that heat into electricity using conventional power-generation equipment.

To ensure maximum comparability with the technical scenarios assessed, the health benefits were estimated using all-cause mortality projections available to 2045. While decommissioning scenarios extend to 2055 and 2071 for consistency in the temporal framing of emission reductions and associated benefits with the Minister's request for the technical scenarios at Medupi, health benefits beyond 2045 were extrapolated using projected coal

burn values and assumed emissions reductions in order to extend the analysis horizon. This limitation applies to all alternative scenarios assessed in the analysis, with the exception of the AQO programme. In addition to SO_2-related health impacts, $PM_{2.5}$-related health benefits were also quantified for the AQO Programme only, as this intervention directly targets household-level exposure pathways. For coal beneficiation, the reported results exclude the Waterberg Priority Area (WBPA), as coal supplied to this region is already beneficiated and cannot be further beneficiated within the scope of the intervention.

The BCA results for the 2025 to 2071 (Table 0-2) assessment:

- The Eskom AQO Programme delivers substantial net benefits across both $PM_{2.5}$ and SO_2 reductions. The value of health benefits associated with $PM_{2.5}$ reductions ranges from approximately R53 to R233 billion, while benefits from SO_2 reductions range from R10 to R25 billion, compared to implementation costs of R3.4 billion. The resulting BCA ratios are consistently above 1 for both pollutants, indicating that benefits outweigh costs and highlighting the strong economic case for targeted household-level air quality interventions.
- SMR and LDES are both expected to generate significant health benefits, with SMR health benefits significantly larger than that of LDES due to the scale of SMR implementation possible. In both cases, there are no additional costs required to achieve health benefits and thus BCA ratios are not relevant.
- Coal beneficiation yields benefits in the range of R1 to R5 billion, but these are outweighed by significantly higher implementation costs resulting in a BCA ratio of approximately 0.04, indicating that the intervention is not cost-effective from a health benefit perspective.
- HELE shows benefits of approximately R1.4 billion with BCA ratios below 1, indicating that implementation costs outweigh the associated health benefits received.
- CCUS generates benefits of approximately R9 to R11 billion, but these are small relative to high costs, resulting in low BCA ratios. Moreover, CCUS technology has not been technically proven and is likely to be prohibitively expensive. This suggests that CCUS is not cost-effective from a health benefit perspective, even over the long term.

It is important to note that benefit-cost ratios are not directly comparable across interventions that differ in scope and function. Some alternative scenarios exhibit higher BCA ratios than the technical abatement options primarily as a result of more direct health benefits (as is the case in the AQO programme), lower absolute costs or due to different population sizes in different areas. These results should therefore be interpreted as indicative, showing the possibility of alternative scenarios to compliment certain technical compliance measures such as FGD.

Conclusion

The Waterberg-Bojanala Priority Area (WBPA) in the analysed period (2022 - 2024) is found to be materially in compliance with the National Ambient Air Quality Standards (NAAQS). It is expected that with the continued operation of the Medupi and Matimba power stations it will not result in non-compliance with these national standards. In the modelled domain (108,900km^2), in 2025 an estimated 1.5 million people out of the total 1.67 million people are expected to be exposed to more than an additional 1 µg/m^3 of SO_2.

The benefit-cost analysis (BCA) for the three technical scenarios comparing wet, semi-dry and dry FGD to the baseline shows BCA ratios that are considerably less than 1. This implies that there are significant financial costs for a relatively limited health benefit across all three scenarios. The early shutdown of the stations was modelled to comply with the Minister's requirements. This produces similar BCA ratios as operation to the planned end of life (2071), While early shutdown does result in a reduction in total health impact it is associated with negative impacts on funding viability, electricity provision and electricity tariff levels.

Overall, the alternative scenarios assessed indicate that a range of interventions can deliver health benefits; however, for most scenarios these benefits are either low relative to costs or subject to significant uncertainty due to early-stage development, high capital requirements, or implementation risks. In addition, previous assessments have shown that the early shutdown of coal-fired power stations delivers substantial air quality and health benefits. Any alternative scenario that extends the operational life of coal stations beyond planned decommissioning dates would therefore reduce these potential benefits. As a result, the realisation of these benefits remains contingent on further planning, technological maturity, and implementation certainty, and should therefore be regarded as probable rather than confirmed. Eskom is already involved in investigations into these alternatives to better asses these in support of national energy planning. In contrast, the Eskom Air Quality Offset (AQO) clean cooking programme consistently demonstrates substantial net health benefits, very high benefit-cost ratios, and a high likelihood of implementation.

Table 0-2: BCA ratios (lower and upper) for each alternative scenario (discounted at Eskom WACC) in the 2025 - 2071 period

	Eskom AQO Programme ($PM_{2.5}$)		Eskom AQO Programme (SO_2)		Coal beneficiation		HELE		CCUS		LDES		SMR	
Million Rands	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
NPV of Costs	3,426	3,426	3,426	3,426	42,847	128,540	5,634	7,300	196,592	1,489,712	-	-	-	-
NPV of Benefits	53,305	233,281	10,571	25,475	1,746	5,238	1,282	1,453	9,985	11,036	84.1	126.2	261	3,920
NPV of Benefits minus Costs	49,879	229,855	7,145	22,049	-41,100	-123,300	-4,350	-5,845	-186,600	-1,478,669	84.1	126.2	261	3,920
Benefit:Cost Ratio (*range*)	15.6	68.1	3.1	7.4	0.041	0.041	0.228	0.199	0.051	0.007	n/a	n/a	n/a	n/a
Benefit:Cost Ratio (*central*)	35.2		5.1		0.041		0.212		0.012		n/a		n/a	

ACRONYMS AND ABBREVIATIONS

AEL	Atmospheric Emissions Licence
AP-HRA	Air Pollution Health Risk Assessment
AQA	Air Quality Act
AQMS	Air Quality Monitoring Station
AQO	Air Quality Offsets
BCA	Benefit-Cost Analysis
CBA	Cost-Benefit Analysis
CFBC	Circulating Fluidised Bed Combustion
CCUS	Carbon Capture, Utilisation, and Storage
CFOI	Census of Fatal Occupational Injuries (USA)
COI	Cost of Illness
CREA	Centre for Research on Energy and Clean Air
DEA	Department of Environmental Affairs (now DFFE)
DEFRA	Department for Environment, Food & Rural Affairs (UK)
DFFE	Department of Forestry Fisheries & Environmental Affairs
DTIC	Department of Trade, Industry and Competition
ELV	Emission Limit Value
ERF	Exposure Response Function
EU	European Union
FEED	Front-End Engineering Designs
FGD	Flue Gas Desulphurisation
GBD	Global Burden of Disease
GNI	Gross National Income
HELE	High Efficiency Low Emissions
HIA	Health Impact Assessment
HPA	Highveld Priority Area
ICD	International Classification of Diseases
IFC	International Finance Corporation
kW	Kilowatt

kWh	Kilowatt Hour
LDES	Long Duration Energy Storage
LPG	Liquefied Petroleum Gas
MES	Minimum Emissions Standards
MW	Megawatt
MWg	Megawatt gross
NAAQS	National Ambient Air Quality Standard
NAQI	National Air Quality Index
NDoH	National Department of Health
NEMA	National Environmental Management Act
NO_2	Nitrogen Oxide
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PAF	Population attributable Fraction
PM	Particulate Matter
RR	Relative Risk
SAAQIS	South African Air Quality Information System
SANAS	South African National Accreditation System
SAWS	South African Weather Service
SDL&I	Supplier Development, Localisation and Industrialisation
SMR	Small Modular Reactors
SO_2	Sulphur Dioxide
USA	United States of America
VSL	Value of a Statistical Life
WACC	Weighted Average Cost of Capital
WBPA	Waterberg-Bojanala Priority Area
WHO	World Health Organisation
WTP	Willingness to Pay
YLD	Years Lived with Disability

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1 INTRODUCTION

The Earth Summit[1] in Rio de Janeiro in 1991 raised the awareness of the linkages between environmental health and human wellbeing to a global agenda. In the three and half decades since the Summit, significant effort has gone into methods for quantifying these linkages, in all environmental spheres, and informing policy development. During the same period, we have seen an information technology revolution, which has radically improved our ability to collect and analyse large data sets. In the field of air quality health risk assessment specifically, there has been a rapid and continuously improving set of methodologies through which to analyse the linkages between air pollution and health risk.

The World Health Organisation (WHO) has been leading the development of health risk assessment methodology. Formally, air pollution health risk assessments (AP-HRA) are performed to provide quantifiable information for informing public policy decisions. The general principles for AP-HRAs have been published by the WHO (WHO, 2016a). An AP-HRA proceeds through three steps.

Firstly, it assesses the exposure of the target population to specific air pollutants. This requires a quantification of constituents in the atmosphere that are associated with human health risks. The atmosphere we breathe contains various such constituents, both from natural sources (e.g., sea salt and bio-aerosols) and anthropogenic sources (e.g., fuel combustion, suspension of fine particles, and industrial emissions) (refer to FRIDGE (2004) for a comprehensive discussion of pollution sources). When a particular policy option is analysed, specific indicator constituents need to be selected, and the incremental effect of the policy option needs to be estimated in terms of population exposure. In this study, incremental population exposure to ambient pollutant concentrations resulting from emissions from Eskom's coal-fired power plants was estimated. Ambient pollutant concentrations were estimated through the use of dispersion modelling.

Secondly, the AP-HRA estimates the resultant incremental change in health risk. This requires the application of exposure-response functions (ERFs). ERFs quantify the incremental change in health outcomes (compared to the baseline incidence), based on changes in exposure to pollutants. ERFs are derived from epidemiological studies, which are large-scale population health studies that compare health outcome incidence between populations exposed to different concentrations of pollution. In this study, ERFs from the latest systematic reviews from 2020 and 2021 that were conducted for the update of the WHO Global Air Quality guidelines were used (WHO 2020, 2021) and a 2024 updated review for particulate matter ($PM_{2.5}$ and PM_{10}). ERFs for morbidity were sourced from various cohort or systematic review studies. AP-HRA results can be reported in terms of mortality indicators (e.g., premature mortality) and/or morbidity indicators (e.g., cost of medical treatment and lost economic productivity). These indicators can be converted to monetary impacts by applying cost-of-

[1] http://www.un.org/geninfo/bp/enviro.html

illness (COI) methodologies. In this study, premature mortality was evaluated, using a value of a statistical life (VSL) COI methodology. In the case of morbidity, the evaluation was done using a general COI methodology.

Thirdly, the AP-HRA process requires the quantification and expression of the uncertainty of the estimated health effects. The WHO states that this step is "*an important and integral component of the results, and … vital to ensure both that the main message is not lost and that the results produced are understandable by policy-makers and others who do not necessarily have a technical background or expertise in AP-HRA.*" This step requires "*the use of expert judgement (consensus) on the level of confidence of the results*".

This study is a new plant-specific Benefit Cost Analysis (BCA) expanding on the 2024 assessment to investigate the health effects of air pollution with a focus on SO_2 resulting from the Medupi coal-fired power station and additionally takes into consideration that from the Matimba coal-fired power station located in close proximity to Medupi in the Waterberg-Bojanala Priority area. The BCA applies the AP-HRA methodology.

The pollutants modelled included sulphur dioxide (SO_2), particulate matter ($PM_{2.5}$ and PM_{10}) and nitrogen dioxide (NO_2). These pollutants have several negative impacts on public health (WHO, 2016b). In the final BCA assessment only SO_2 and fugitive emission ($PM_{2.5}$) were included.

The Department of Forestry, Fisheries and the Environment (DFFE) under the National Environmental Management Act (NEMA: AQA, 2004) sets ambient air quality standards. Where ambient air quality standards are exceeded, specific air quality mitigation actions would be required. Power generation is a Listed Activity in terms of Section 21 of the National Environmental Management: Air Quality Act (NEMA: AQA) and Minimum Emission Standards (MES) are prescribed for existing and new stations. In 2018, amendments were made to the list of activities and associated MES in terms of Section 21 (4)(a). Eskom was granted MES postponements for SO_2 at Medupi and Matimba to 2025 (DEA, 2018 a & b). In 2024, according to the May 2024 ruling by the Minister of the DFFE requirement, Eskom submitted applications in terms of Section 59 of the NEMA: AQA, for the exemption of the MES for eight power stations that will continue to operate beyond 2030. An analysis of Matimba and Medupi stations were included in the application. On 31 March 2025, the Minister's Decision in respect of the above exemption applications submitted by Eskom, grants Eskom exemption from SO_2 compliance until 2030 and requires Eskom to comply with several conditions including the requirement for the completion of a "revised and expanded" plant-specific BCA regarding installing flue gas desulphurisation (FGD) abatement technology at Medupi.

This study investigates three air pollution technical mitigation scenarios and six alternative scenarios for Eskom, through a BCA. The BCA uses the AP-HRA methodology to estimate the likely changes in health costs resulting from each scenario. The BCA compares these benefits against the costs of the mitigation options (this includes the incorporation of additional cost items as per the Minister's Decision) for each technical scenario (refer to section 2.3).

The Minister's Decision also requires Eskom to undertake independent power system modelling in respect of SO_2 reduction alternatives. The assessment of technical and other alternatives in this report will provide a basis for these further investigations.

1.1 Other Applicable South African Studies

Other studies have previously been conducted to estimate the health impacts of either fossil fuel power stations, air pollution in general or specific sources in South Africa. They estimated morbidity and mortality, and in some instances attributed costs to these health impacts. Studies of this nature can take either bottom-up (deterministic) approaches or top-down (stochastic) approaches to modelling pollution exposure, with the latter usually preferable in data poor environments or large spatial domains (Dios et al., 2012). These studies also varied in geographic scale, ranging from selected areas to a national scale.

Several of the studies reviewed adopt methodological components similar to the current BCA, particularly those that apply bottom-up, source-specific health risk assessment (HRA) frameworks. Our study follows a deterministic, bottom-up approach, using CALPUFF dispersion modelling to simulate population-level exposure to SO_2 emissions from coal-fired power stations. This is aligned with internationally recognised methods, particularly the WHO AP-HRA frameworks, in estimating both mortality and morbidity endpoints. Notably, our analysis focuses on SO_2 as the primary pollutant of concern while holding other pollutant exposures constant (in alignment with the Minister's requirements).

This approach shares strong methodological parallels with studies such as CREA (2023), Myllyvirta (2019), and the Scorgie (2006) regional health risk assessments and the recently published Naidoo et al. (2024) co-benefits study. These studies combine atmospheric dispersion modelling or photochemical modelling with WHO- or GBD-based exposure-response functions to estimate attributable health burdens. In some cases, studies proceed to quantify economic damages using VSL, COI, or related methods. Naidoo et al. (2024) focuses on future energy transition scenarios using the CAMx model and quantifies avoided premature mortality from SO_2, NO_2, and $PM_{2.5}$; it, however, does not monetise health impacts. While our BCA is more tightly scoped around SO_2, its structure, which integrates exposure modelling, attributable health burden estimation, and valuation, makes it a comprehensive study. The choice to isolate SO_2 impacts ensures compliance with regulatory expectations while still leveraging a full impact pathway methodology comparable in rigour to international best practice.

The methodology used for the completion of the expanded Medupi BCA is discussed in detail in section 2 below.

Table 1-1: A comparison of studies on health impacts of coal-fired power stations in South Africa

Study Reference	Study Type	Pollutants Assessed	Study Modelling Approach	Exposure Assessment Method	Population Studied	Health Outcomes (Mortality/Morbidity)	Core Equation Used	Valuation Method	Key Assumptions	Main Results (Health and Economic Impacts)
Naidoo et al., 2024	Air Quality Co-benefits Assessment (HIA)	SO_2, NO_2, $PM_{2.5}$	Bottom-up	• CAMx regional photochemical air quality model • Driven by SATIMGE energy-economic scenario modelling and gridded emission inventory	National-scale model domain centred on Highveld; health impact estimated by municipality using Stats SA data	All-cause premature mortality, all ages	Population-weighted exposure × RR × mortality rate = premature deaths avoided	N/A	Mortality rate held constant; only 3 simulation years modelled (2023, 2033, 2050); static meteorology and emissions outside energy sector	• 8Gt scenario (high GHG reduction) yields ~12,987 SO_2-related deaths avoided, ~6,031 $PM_{2.5}$-related, and ~5,821 NO_2-related between 2023 and 2050
Myllyvirta & Kelly, 2023	HIA Cost-Benefit Analysis (CBA)	SO_2, $PM_{2.5}$, NO_2, Hg	Bottom-up	• CALPUFF dispersion modelling and emissions inventory • Annual average concentrations (µg/m³, ppm) • Scenarios modelled to post 2031	South African national population (spatial distribution from GBD/Gridded Population datasets)	All-cause mortality, stroke, COPD, asthma (incidence, ER visits), diabetes, LRI, preterm birth, work absence, YLD	Standard RR-based attributable fraction formula for each outcome and exposure bin	VSL, YLD (DEFRA-based), COI	Emission control scenarios; population projections; international RR applied to SA; no-harm thresholds	• Non-compliance scenario: up to 79,500 deaths projected • MES compliance: 34,400 deaths and ZAR 617bn avoided • Morbidity impacts: include asthma, preterm births, work absence
Myllyvirta, 2019a	HIA	SO_2, NOx, $PM_{2.5}$, Hg	Bottom-up	• CALPUFF dispersion modelling with grid-level emissions and meteorology • µg/m³)Annual and hourly average concentrations (	South African national and sub-national (municipality-level), with population data from UN and NASA SEDAC	Premature mortality: LRI, COPD, stroke, diabetes, lung cancer, ischaemic heart disease	GBD-style attributable fraction formula: Pd = PAF × DR × pop × AF	N/A	All plants run to 50-year lifespan; no economic valuation; spatial health impact attribution down to municipal level	• Non-compliance: 16,267 premature deaths projected from excess emissions • Compliance: 3,100 deaths avoided in Gauteng
Myllyvirta, 2019b	HIA with emissions policy modelling	SO_2 (converted to secondary $PM_{2.5}$), Hg, NOx	Bottom-up	• CALPUFF dispersion model across national domain with stack-level parameters and projected emissions • $PM_{2.5}$ µg/m³ attributable to SO_2 emissions • Grid-level concentrations at 1 km² resolution	National population with focus on Gauteng and Highveld	Premature mortality: LRI, COPD, stroke, diabetes, IHD, lung cancer; also, mercury-related neurotoxicity risk	Population Attributable Fraction = 1 - 1/RR(concentration); Attributable deaths = PAF × incidence × population	N/A	Power stations operate 50 years; scrubbers avoided in weakened MES case; $PM_{2.5}$ effects dominant; GBD IER applied with population weighting	• 3,316 premature deaths projected from doubling MES SO_2 limit vs current • Annual peak: 170 deaths (2025-26)

Study Reference	Study Type	Pollutants Assessed	Study Modelling Approach	Exposure Assessment Method	Population Studied	Health Outcomes (Mortality/Morbidity)	Core Equation Used	Valuation Method	Key Assumptions	Main Results (Health and Economic Impacts)
Langerman & Pauw, 2018	Systematic review of HIA/HRA	PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3	Bottom-up and Top-down in review	• Review of model-based dispersion (CALPUFF, CAMx, EXMOD) • Ambient data comparison (daily and annual averages)	Includes South African Highveld and national scale	Premature mortality, respiratory and cardiovascular admissions, DALYs	Standard RR = exp[β(x - x0)]; AF = (RR - 1)/RR; I = AF × incidence × pop	N/A	Comparison of exposure models, counterfactuals, RR assumptions across 5 studies; proposes IER approach as best suited to SA	• Synthesised estimates range from 10 to +2,200 deaths/year across studies
Steyn & Kornelius, 2018	HIA CBA	SO_2 (primary and secondary sulphates)	Bottom-up	• Dispersion modelling focused on the Highveld Priority Area • Change in ambient SO_2 and secondary sulphate concentrations	Populations residing within the Highveld Priority Area	Premature mortality; comparison of CRFs for SO_2 and sulphates	Standard CRF application with monetisation via VSL	VSL based on US EPA guidance (adjusted)	Wet FGD assumed as control tech; focus on one facility with highest impact; includes secondary sulphates in main estimates	• Largest benefit was reduction in premature mortality • SO_2 control had net benefit under some assumptions • Benefits could outweigh costs if plant is high impact
Myllyvirta, 2014	HIA Economic externality estimation	SO_2, NOx, $PM_{2.5}$, PM_{10}, Hg	Bottom-up	• $PM_{2.5}$ regression models calibrated with emission inventories • Annual average concentration from power plants (modelled) and population-weighted exposure	South African national population. Sub-national level, 0.1x0.1 degree resolution	Premature mortality: lung cancer, IHD, COPD, stroke, LRI; IQ loss from Hg exposure	Attributable fraction: AF = (RR - 1)/RR; applied to cause-specific mortality	OECD income-adjusted VSL; Spadaro & Rabl damage cost for Hg	Regression model approximates dispersion; national population baseline; income elasticity of 0.8	• Premature mortality: 2,200-2,700 annually • ZAR 30bn annual cost • MES non-compliance: 20,271 cumulative deaths (ZAR 231bn cumulative external cost) • IQ points lost (Hg): 280,000
Holland, 2017	HIA Economic valuation	$PM_{2.5}$, SO_2, NOx	Bottom-up	• Dispersion and impact pathway modelling, emissions allocation and extrapolated impact estimation • Annual average $PM_{2.5}$ exposure and secondary aerosols • Power station-level disaggregation	National and sub-national (provincial aggregation). Exposure-weighted estimates based on local dispersion (facility-level)	Premature mortality (lung cancer, IHD, COPD, stroke, LRI); chronic bronchitis, asthma, hospital admissions, lost workdays	Impact = Ci × Pa × Pr × R × CRF (from IPA model); costs from OECD/WHO VSL & COI	OECD-based income-adjusted VSL, productivity losses, healthcare costs	Uses Myllyvirta 2014 as base; aggregates and extrapolates using OECD CIRCLE multipliers; no original dispersion modelling done	• Attributable deaths: 2,239 /year • Chronic bronchitis: 2,781 cases • Lost workdays: ~1 million • Restricted activity days: >3.9 million • Total health damage cost: Int$2.37 billion/year

Study Reference	Study Type	Pollutants Assessed	Study Modelling Approach	Exposure Assessment Method	Population Studied	Health Outcomes (Mortality/Morbidity)	Core Equation Used	Valuation Method	Key Assumptions	Main Results (Health and Economic Impacts)
McDaid, 2014	Desktop HIA with burden estimation	PM_{10}, SO_2, NO_2, Hg	Top-down	• Ambient air monitoring data and emissions attribution (indirect modelling) • Annual and seasonal average concentrations • Monitoring site data (2008-2012)	Mpumalanga Highveld, comparisons to Tshwane and Cape Town	Premature childhood and cardiovascular mortality; minor restricted activity days (MRADs); mercury-related IQ loss	Burden attributed using % contribution from Scorgie (2012) to cause-specific deaths	Qualitative and selective quantification	Apportions burden using source contributions; limited direct modelling; illustrative only	• Childhood respiratory deaths: 15/year • Preventable deaths: 70-165 (under WHO PM10 levels) • Estimated 50% of ambient air-related health burden in HPA attributed to Eskom • External cost ranges R3.5-230 billion • R200bn for Eskom abatement cost vs R5trn health benefit (EPA ratio)
Riekert & Koch, 2012	CBA of projected health externalities	PM_{10}, SO_2, NOx	Top-down	• Regression model linking emissions to exposure and emissions intensity estimates • Exposure increases in µg/m³ $PM_{2.5}$ equivalent from projected emissions	Residents within 100 km radius of Kusile Power Station	Premature mortality from $PM_{2.5}$ exposure	AF = (RR-1)/RR; DALYs and death valuations applied	VOLY (converted from EU VSL to SA GNI context)	Linear dose-response; no threshold; static population; long-term exposure	• Projected external cost: R29.5 billion • Annual health damages: R720m/year • Net cost to society under most scenarios • Air pollution externalities exceed abatement cost
Dios, 2012	Estimates of emissions inventory, dispersion and impact estimate	NOx, SO_2, PM_{10}, $PM_{2.5}$, CO, Hg	Bottom-up	• CALPUFF dispersion modelling with emissions inventory (based on stack heights, flow rate, plant-specific data) • Annual average concentrations over 500x500 km grid	National grid-level population linked with modelled exposure fields	Premature mortality; LRI, cardiovascular, lung cancer; morbidity: asthma, bronchitis, hospital days	Impact = pop × incidence × CRF × ΔC (concentration change)	ExternE unit damage costs (€2010/tonne pollutant); COI for morbidity	Power stations operate full time; constant emissions; conversion of all SO_2 to sulphate; fixed meteorology from TAPM	• Coal power plant air pollution: ~2,500 attributable deaths/year • External costs: €3.6 billion/year (mainly from mortality)
WHO, 2009	Burden of disease estimation	PM_{10}, indoor solid fuel smoke	Top-down	• Mean annual PM_{10} urban exposure • % households using solid fuels	National population	Mortality and DALYs from indoor and outdoor air pollution	DALYs = Exposure × Risk × Pop burden	N/A	Exposure estimates based on national urban PM10 means and SFU household fraction	• Outdoor air pollution: 1,100 deaths/year • Indoor air: 3,200 deaths/year

Study Reference	Study Type	Pollutants Assessed	Study Modelling Approach	Exposure Assessment Method	Population Studied	Health Outcomes (Mortality/Morbidity)	Core Equation Used	Valuation Method	Key Assumptions	Main Results (Health and Economic Impacts)
Scorgie & Thomas, 2006a	Health risk assessment	PM_{10}, SO_2, NO_2	Bottom-up	• CALPUFF dispersion modelling • Existing and proposed power stations at 50x50 km grid resolution • Predicted ambient concentrations and population overlays for cumulative exposure	Populations in Lephalale municipality, focusing on Marapong and surrounding communities	Premature mortality; respiratory hospital admissions	Risk = Exposure × Dose-Response × Population	N/A	Linear risk function; population static over time; background emissions excluded	• Deaths from Matimba emissions: 1-1.5 deaths/year • Respiratory admissions: 140 respiratory admissions/year • Project Alpha would add 1.5-3 deaths/year and ~300 hospital cases/year
Scorgie & Thomas, 2006b	Health risk assessment (cumulative)	PM_{10}, SO_2, NO_2	Bottom-up	• CALPUFF dispersion modelling • Seven Eskom stations on the Mpumalanga Highveld at 50x50 km resolution • Annual average and 99th percentile hourly concentrations	Populations within and adjacent to the Highveld Priority Area (Ermelo, eMalahleni, Bethal and Delmas)	Premature mortality; hospital admissions; respiratory outcomes (chronic bronchitis, asthma)	Standard risk = Pop × CRF × ΔC	N/A	No background concentrations included modelled stack emissions only; health response based on international CRFs	• Premature deaths (PM_{10}): 17-23/year • Hospital admissions (SO_2 and PM_{10}): ~1,500 hospital admissions • Most affected areas: eMalahleni and Middelburg
FRIDGE, 2004	Risk assessment Policy strategy	PM_{10}, SO_2, NOx, CO, benzene, lead, O_3	Top-down	• Compilation of national and regional monitoring data, ambient air quality review • Ambient concentrations at monitoring sites (Highveld, eThekwini, Cape Town)	Urban and peri-urban residents (vulnerable groups) across major metros	Childhood asthma, bronchitis, cardiovascular and respiratory diseases, lead neurotoxicity	Not explicit; referenced guideline exceedances and linked health outcomes	N/A	Assumes exceedance of WHO/SA guidelines corresponds with increased morbidity	• Air pollution levels often exceed WHO guidelines in major urban areas • PM_{10} dominant concern for health burden
Spalding-Fecher & Matibe, 2003	External cost analysis (hybrid CBA)	PM_{10}, SO_2, NOx, CO_2	Top-down	• EXMOD pathway model • Weighted average emission impact (11% increase) • Ambient concentration estimation via simplified dispersion	National (general population exposure)	Premature mortality; respiratory illness; morbidity from paraffin and coal exposure	Damage cost per unit = CRF × ΔC × valuation per impact	VSL and COI (adjusted for local GNI); climate damages equity-weighted	Coal-fired power dominant; uses benefits-transfer; includes benefits from electrification	• 852-1,450 deaths/year; • Additional benefits: 173-2,324 million R/year from avoided household air pollution • Total external cost: R2.3-15.4 billion/year

Study Reference	Study Type	Pollutants Assessed	Study Modelling Approach	Exposure Assessment Method	Population Studied	Health Outcomes (Mortality/Morbidity)	Core Equation Used	Valuation Method	Key Assumptions	Main Results (Health and Economic Impacts)
Van Horen, 1996	CBA of health and environmental externalities	SO_2, PM_{10}, NOx, CO, CO_2, Pb	Top-down	• EXMOD impact pathway model • Transfer coefficients from European studies • Population-weighted exposure to annual mean concentrations from emission scenarios	National (urban and rural populations affected by electricity generation)	Mortality (cardio-respiratory), respiratory hospital days, asthma, bronchitis, neurodevelopmental toxicity (Pb)	Impact = emissions × transfer coefficient × health response × unit cost	COI for morbidity; VSL based on European WTP studies; DALY approach used for sensitivity	European transfer coefficients; uses linear dose-response; health valuation adapted from ExternE	• 700-1,000 deaths/year from electricity generation emissions • External costs: R1.2-5.1 billion/year

2 METHODOLOGY AND INPUTS

2.1 Overview

An integrated Health BCA Model was developed that combined an AP-HRA with a BCA to assess three technical and six alternative air pollution mitigation scenarios for the Medupi coal-fired power station in the Waterberg region. The Matimba coal-fired power station (in its current operations state) was also taken into account in the model, due to its close proximation to Medupi power station and contribution to the overall air quality impact within the region.

Figure 2-1 below provides an overview of the methodology, and sections 2.2 to 2.5 provide a more detailed discussion of each component.

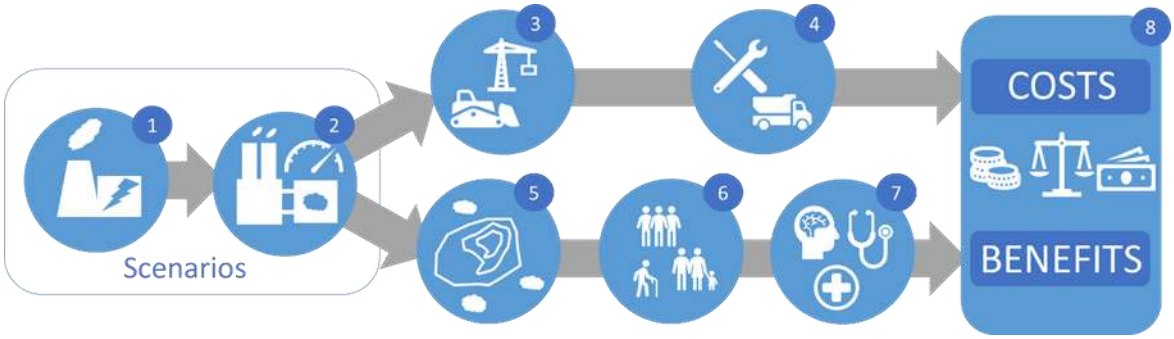

Figure 2-1: Overview of methodology and model architecture.

With reference to Figure 2-1, the integrated Health BCA Model includes the following components:

1. Station lifetimes were described for two coal-fired power stations, Medupi and Matimba, and included commissioning and shutdown (provided by Eskom).
2. Flue Gas Desulphurisation (FGD) abatement technologies for SO_2 reduction at Medupi power station were evaluated as per the Minister's Decision. These were defined by type and likely implementation schedule (refer to section 2.3.3). No additional abatement technologies were considered for the Matimba power station.
3. & 4. The model includes all the costing elements associated with each scenario. Costs that are taken into account in the quantitative assessment in the model include, as per condition 7.3.1 of the Minister's Record of Decision, all technology costs (construction, maintenance and operation), energy efficiency penalty, CO_2 costs, costs of sorbent supply and its infrastructure, waste treatment and cost of water supply and its infrastructure. (refer to section 2.3.4).
5. Dispersion modelling was done by uMoya-NILU Consulting (Pty) Ltd. This data was then segregated spatially by municipal ward boundaries to align with gridded population data. The dispersion modelling performed included

modelling of the individual power station predicted ambient concentrations of SO_2, $PM_{2.5}$, PM_{10}, and NO_2 per scenario from the stacks and the other the cumulative predicted ambient concentrations of SO_2, $PM_{2.5}$, PM_{10}, and NO_2 stacks at both power stations per scenario. Note that for PM, the dispersion modelling predicted primary PM and secondary PM effects, resulting from NO_2 and SO_2 reactions in the atmosphere (ammonium nitrate, NH_4NO_3 and ammonium sulphate, $(NH_4)_2SO_4$). In addition, dispersion modelling was done separately for the fugitive emissions (refer to section 2.2).

6. Population exposure was estimated at a spatial resolution of municipal wards. At each municipal ward, the number of people exposed to different ambient concentration ranges were determined per scenario per year, based on the latest 2025 spatially gridded total population data (Bondarenko et al., 2025) The growth factor for growing the population across the timeline into the future was determined using the latest Stats SA Census 2022 data and that from the United Nations population growth forecasts (refer to section 2.2).
7. Health impacts were determined by using the AP-HRA methodology. Epidemiological evidence, for mortality and morbidity, in the form of exposure-response functions (ERFs) was obtained from global studies. Those for mortality were obtained from the World Health Organisation (WHO) systematic reviews (2020 & 2021) conducted by various researchers for the WHO as part of the WHO update to the Global Air Quality Guidelines (released in late of September 2021) and a 2024 updated review for PM (refer to section 2.3). Those for morbidity were sourced from various cohort or systematic review studies. To quantify the economic burden of a disease or premature mortality, the Cost of Illness (COI) methodology was used. Mortality cost used the value of a statistical life (VSL). This method estimates the willingness to pay (WTP) of an individual for reducing their health risk and should not be interpreted as the intrinsic value of a life. Morbidity cost estimates made use of the general COI methodology. Refer to section 2.3.2 for a more detailed discussion.
8. The BCA compares the overall scenario health benefits achieved through abatement at Medupi power station to the costs of implementation of the abatement technology. The outputs of the AP-HRA, i.e., the health cost savings of each scenario, were used as the benefit. As per the Minister's requirements, the model considers three alternative shutdown dates for Medupi which are 2045, 2055 and 2071. The analysis timeline starts in 2025. (Refer to section 2.3). Finally, an assessment of uncertainty of the results and a sensitivity analysis was conducted (refer to Section 2.6). A similar approach was followed for the alternative scenarios, and this is described in section 2.4.

2.2 Exposure of the target population to specific air pollutants

2.2.1 Overview

This section comprises the first step of the AP-HRA and assesses the exposure of the target population to specific air pollutants.

This requires an incremental effects quantification of constituents in the atmosphere that are associated with human health risks. The focus or indicator pollutant was ambient SO_2, however the effects of $PM_{2.5}$, PM_{10}, and NO_2 emitted by the two coal-fired power stations were also included in the investigation. The emissions from these stations impact the Waterberg-Bojanala Priority area (WBPA) in the Limpopo province of South Africa.

Dispersion modelling combined with population distribution provided an estimate of the exposed population.

2.2.2 Pollutants analysed

The Waterberg-Bojanala Priority Area (WBPA) has three ambient Air Quality Monitoring Stations (AQMS), Marapong, Medupi and Lephalale stations, equipped for continuous monitoring of air quality and meteorological parameters. Marapong AQMS and Medupi AQMS were established by Eskom in 2006 and 2014 respectively and Lephalale is a SAWS-DEA owned NAQI (National Air Quality Index) station that was established by DEA (now DFFE) in 2012.

The sections that follow provide a summary of the ambient concentrations of SO_2, NO_2 and PM in the period of 2022 to 2024 at the AQMS near the Matimba and Medupi power stations. Each of these stations is exposed to multiple SO_2 sources, both nearby and more distant. Depending on their location and proximity to emission sources, they are influenced to varying degrees by power station emissions, residential and domestic fuel burning and motor vehicle emissions. In terms of proximity to the power stations, Marapong AQMS and Medupi AQMS are close to Matimba and Medupi power stations respectively, whereas the Lephalale AQMS is much further from the power stations.

2.2.3 Airshed saturation

The WBPA is not considered to be a saturated airshed and the exposure response functions applied in this assessment have been selected with consideration of the relevant ambient concentrations.

An airshed may be described as saturated (for a given pollutant) when monitored ambient concentrations exceed the applicable ambient air quality standard, as defined by that standard's averaging period and allowable exceedance frequency, over a specified period of time, indicating limited or no remaining capacity for additional emissions. The WBPA airshed demonstrates an ability to disperse pollutants efficiently. Monitoring stations do record exceedances of the 1-hr limit value of the NAAQS, but the exceedances do not occur consistently.

2.2.4 Data quality

The South African Air Quality Information System (SAAQIS) adheres to a guideline, derived from the South African National Accreditation System (SANAS) requirements, which mandates a minimum data capture/collection efficiency of 90% for data to be considered acceptable and valid (SANAS TR 07-03 2012). The data capture rates for the three AQMSs, expressed as the percentage of valid hourly measurements obtained over the three-year assessment period (i.e., 26,304 hours) are shown in

Table 2-1. Data recovery at all three AQMSs is below the minimum requirement of 90%. It is evident on review of the data at the three AQMSs that data quality assurance and quality control have not been undertaken at any of the three stations prior to uploading to the SAAQIS (https://saaqis.environment.gov.za/home/index). The data therefore contains negative concentrations, zeros and concentration spikes which influence averages. Missing data has a bearing on the number of exceedances. Data cannot be cleaned by an independent party. The data presented here may therefore not be accurate.

Table 2-1: Percentage data recovery at Lephalale, Marapong and Medupi AQMSs for the three year period 2022 to 2024

AQMS	Year	SO_2	NO_2	$PM_{2.5}$	PM_{10}
Lephalale	2022	73.2	71.0	7.0	34.1
	2023	57.9	74.8	57.6	59.5
	2024	74.5	85.8	71.7	74.2
Marapong	2022	44.7	44.7	42.0	44.7
	2023	0.0	0.0	0.0	0.0
	2024	47.1	47.1	47.1	47.1
Medupi	2022	71.3	71.3	71.1	71.4
	2023	37.3	37.3	37.3	37.8
	2024	70.2	71.1	71.3	71.3

2.2.5 Pollutant concentrations at the AQMSs

2.2.5.1 Sulphur dioxide (SO_2)

Industrial processes and power generation are the main source of SO_2 in the atmosphere through the combustion or refining of sulphur containing fuels.

During the analysis period from 2022 to 2024 the average annual ambient SO_2 concentrations were low relative to the National Ambient Air Quality Standards (NAAQS) of 50 µg/m^3 at all three monitoring stations (Table 2-2) and thus compliant with the NAAQS. Exceedances of the 1-hour limit value of 350 µg/m^3 occurred at Marapong and Medupi AQMS. At Medupi the

tolerance of 88 per year was exceeded in 2022 when 100 exceedances were recorded. In comparison to the NAAQS limits, the WHO Air Quality Guidelines (AQGs) recommended levels for SO_2 are only set for short-term 24-hour averages of SO_2 at 40 µg/m^3 and no annual AQG is set due to insufficient evidence of long-term effects of SO_2 at low concentrations (WHO, 2021).

Table 2-2: Annual average SO_2 concentrations at the Marapong, Medupi and Lephalale AQMS in µg/m^3 and the number of exceedances of the 1-hour limit value per year. Exceedances above allowable shown in bold font

AQMS	Year	Annual average SO_2	Number of exceedances (1-hour limit)
Lephalale	2022	5.2	0
	2023	7.7	0
	2024	7.3	0
Marapong	2022	10.6	19
	2023	-	-
	2024	10.4	15
Medupi	2022	17.6	**100**
	2023	*	21
	2024	21.5	29
NAAQS		50.0	88
* Negative concentrations resulted in a negative average			

2.2.5.2 Nitrogen dioxide (NO_2)

Industrial processes and power generation are the main source of NO_2 in the atmosphere through the combustion or refining of fossil fuels, with some contribution from motor vehicle emissions, residential fuel burning and biomass burning.

During the analysis period from 2022 to 2024 the average annual ambient NO_2 concentrations were low relative to the NAAQS of 40 µg/m3 at all three stations and in compliance with the NAAQS. Exceedances of the NAAQS 1-hour limit value of 200 µg/m^3 occurred at Marapong in 2022 and Medupi AQMS in two years following. At Medupi the tolerance of 88 per year was exceeded in 2022 and 2024 (Table 2-3). The annual recommended limit from the WHO for NO_2 is much more stringent at 10 µg/m3, however the hourly limit is the same as the NAAQS limit of 200 µg/m3 (WHO, 2021).

Table 2-3: Annual average NO_2 concentrations at the Marapong, Medupi and Lephalale AQMS in µg/m^3 and the number of exceedances of the 1-hour limit value per year. Exceedances above allowable shown in bold font

AQMS	Year	Annual average NO_2	Number of exceedances 1 hour limit
Lephalale	2022	12.8	0
	2023	16.1	0
	2024	16.0	0
Marapong	2022	17.2	11
	2023	-	-
	2024	3.8	0
Medupi	2022	21.0	**92**
	2023	15.3	36
	2024	37.1	**225**
NAAQS		200	88

2.2.5.3 Particulate matter (PM)

There are numerous sources of primary particulate matter, including power generation, industry, mining, biomass burning and agricultural activities, as well as natural sources such as wind entrainment. In addition, secondary PM is produced by NO_2 and SO_2 reactions in the atmosphere.

During the analysis period from 2022 to 2024 the average annual ambient PM_{10} concentrations were low and in compliance relative to the NAAQS of 40 µg/m^3 at Lephalale AQMS. It was also below the NAAQS at Marapong and Medupi in 2024. However, PM_{10} concentrations were relatively high at Marapong and Medupi, exceeding the NAAQS (Table 2-4). Exceedances of the 24-hour limit value of 75 µg/m^3 occurred at Marapong AQMS in 2022 and 2024, and Medupi AQMS in all three years. The tolerance of 4 per year was exceeded in all three years at Medupi and in 2022 at Marapong (Table 2-4).

During the analysis period from 2022 to 2024 the average annual ambient $PM_{2.5}$ concentrations were low relative to the NAAQS of 20 µg/m^3 except at Marapong in 2022 (Table 2-5). Exceedances of the 24-hr limit value of 40 µg/m^3 occurred at Lephalale in 2024 , Marapong in 2022 and 2024 (no data was available for 2023), and Medupi AQMS in AQMS in all three years (Table 2-5). The NAAQS does not provide any tolerance for exceedances of the 24-hour limit value for $PM_{2.5}$.

The WHO recommended AQG levels for $PM_{2.5}$ and PM_{10} are more stringent with annual recommended limits of 5 µg/m^3 and 15 µg/m^3 respectively (WHO, 2021).

Table 2-4: Annual average PM_{10} concentrations at the Marapong, Medupi and Lephalale AQMS in µg/m³ and the number of exceedances of the 24-hour limit value per year. Exceedances above allowable shown in bold font

AQMS	Year	Annual average PM_{10}	Number of exceedances
Lephalale	2022	22.7	0
	2023	17.8	0
	2024	27.4	0
Marapong	2022	**42.0**	**28**
	2023	-	-
	2024	19.0	2
Medupi	2022	**127.0**	**79**
	2023	**66.0**	**19**
	2024	20.0	**10**
NAAQS		40	4

Table 2-5: Annual average $PM_{2.5}$ concentrations at the Marapong, Medupi and Lephalale AQMS in µg/m³ and the number of exceedances of the 24-hour limit value per year. Exceedances above allowable shown in bold font

AQMS	Year	Annual average $PM_{2.5}$	Number of exceedances
Lephalale	2022	13.4	0
	2023	12.6	0
	2024	14.4	2
Marapong	2022	28.0	23
	2023	-	-
	2024	-	-
Medupi	2022	-	-
	2023	15.0	13
	2024	8.0	9
NAAQS		20	0

2.2.5.4 Comparison between modelled and monitored data

Several important considerations must be taken into account when comparing dispersion model predictions with ambient monitoring data:

- Continuous measurements at an AQMS using analysers are fundamentally different from concentrations estimated by a dispersion model; differences in results are therefore expected.
- A monitoring station represents a single point, whereas a dispersion model generates an average concentration for an entire grid cell.
- A monitoring station is influenced by multiple emission sources, while the model only reflects the sources explicitly included in the modelling exercise.
- The model uses hourly average meteorological inputs for predictions, while actual ambient conditions at the station can fluctuate over much shorter timescales.
- The 99th percentile modelled concentrations are used, i.e., the highest 1% of the predictions are excluded, while in the ambient data short-term peaks are included.

Given these factors, it is expected that dispersion modelling results will be conservative and that predicted concentrations may be lower than those measured. This is consistent with the findings: at all three AQMS locations, the average measured SO_2 concentrations exceed the corresponding modelled values (Table 2-6). At Lephalale, the model underpredicts by approximately 25%, while underprediction is more pronounced at Marapong (70% lower) and Medupi (44% lower).

Table 2-6: Comparison of average and maximum measured (AQMS) and predicted (CALPUFF) concentrations in µg/m³ at the three AQMS locations

Station		AQMS	CALPUFF
SAWS Lephalale-NAQI	Average	6.7	5.9
	Maximum	464.4	200.2
Eskom Marapong	Average	15.2	4.4
	Maximum	1,693.3	216.0
Eskom Medupi	Average	22.8	12.7
	Maximum	1,892.4	414.8

The difference between measured and modelled maximum concentrations is also notable, with measured values substantially higher at all stations. However, these maximums do not necessarily occur at the same time for the model and the monitoring stations. At Lephalale, the four highest measured SO_2 concentrations occurred between 13:00 and 15:00. Similarly, the highest concentrations at Marapong and Medupi occurred between 13:00 and 16:00. This timing suggests that these elevated concentrations are most likely due to power station

plumes being mixed down to ground level by afternoon atmospheric convection, rather than emissions from residential fuel-burning, which typically peaks later in the day.

The following conclusions are drawn:

- The dispersion modelling was conducted in accordance with the DFFE Regulations for Dispersion Modelling.
- All reasonable steps were taken to minimise uncertainties in both input data and model parameterisation. This included using representative and accurate input data, preparing input files correctly, cross-checking for errors, and performing iterative corrections and model reruns.
- Data recovery at all three AQMS are poor relative to SAAQIS guidelines and the SANAS minimum requirement of 90% for acceptable data quality assurance and valid data capture.
- As might be expected, the dispersion modelling results are conservative, with predicted concentrations generally lower than measured concentrations at all three AQMSs. Sensitivity analysis was conducted in the BCA analysis (see section 2.5).
- Based on these findings, uMoya Nilu has a high level of confidence in the reliability of the modelled results.

2.2.6 Description of power stations

The Eskom power stations forming part of this study in the Waterberg-Bojanala Priority Area are Matimba and Medupi. The two power stations are in the Waterberg District Municipality approximately 6 km from each other and are located near the town of Lephalale. These power stations have a combined installed capacity of 8,754 MW and are listed in Table 2-7.

Table 2-7: Eskom coal-fired power stations, used in this study, and their installed capacity (Eskom, 2024a)

Power Station	Province	Installed capacity (MW)
Matimba	Limpopo	3,990
Medupi	Limpopo	4,760

2.2.7 Dispersion modelling

Dispersion modelling is required to estimate the effects of stack emissions on ambient concentrations of pollutants and to describe them spatially.

Dispersion modelling for this study was conducted by uMoya-NILU Consulting (Pty) Ltd and followed the requirements of the Code of Practice for Air Dispersion Modelling, DEA guideline (DEA, 2014).

The work modelled the dispersion of sulphur dioxide (SO_2), primary particulate matter ($PM_{2.5}$ and PM_{10}), secondary PM (sulphates and nitrates) and nitrogen dioxide (NO_2) for the Medupi and the Matimba power stations. Dispersion modelling was performed using the CALPUFF suite of models. CALPUFF is a multi-layer, multi-species non-steady-state puff dispersion model that simulates the effects of time and space-varying meteorological conditions on pollution transport, transformation and removal. It includes algorithms for sub-grid scale effects, such as terrain effect, as well as longer range effects, such as pollutant removal due to wet scavenging and dry deposition, chemical transformation, and the formation of secondary particulate matter. The Air Pollution Model (TAPM) was used to model surface and upper air meteorological data for the study domain.

Two types of analysis were performed, individual and cumulative models. The CALPUFF modelling domain covers 108,900 km^2, with the domain extending 330 km (west-east) by 330 km (north-south) consisting of uniformly spaced receptor grid with a grid resolution of 1.25 km by 1.25 km, giving 69,696 grid cells (264x264 grid cells). The analysis included a further 51 sensitive receptors within a 50 km radius of Medupi and Matimba and 13 AQMS within the modelled domain (Appendix A).

This domain was larger than the domain modelled in the 2024 study (108 km × 108 km). The modelling domain extended beyond the area of peak concentrations (within approximately 25 km from source region) and includes regions where concentrations approach low thresholds (up to about 1 µg/m^3). For health benefit assessments, low concentrations over large populations can contribute meaningfully to total health impacts. It was therefore scientifically justified to expand the domain to ensure that:

- All spatially relevant exposure contributing to health outcomes is captured.
- By extending the modelling domain, population exposure at low but meaningful concentration levels is not excluded.
- Exposure estimates are spatially complete for subsequent health and economic valuation.

The domain size and resolution were selected to remain within known CALPUFF technical limitations and represents the largest feasible domain while maintaining an acceptable spatial resolution.

There were two baseline scenarios modelled in CALPUFF that are used in the study. The first one (Scenario A - historical baseline) represents the actual historical emissions for the period 2022-2024. The second baseline (Scenario B - future baseline) accounts for all six units in operation at Medupi, at the forecasted load factor and is a better representation of what will be happening in future years. Scenario B future baseline was used for comparison with the different scenarios in the BCA. Matimba is included in the dispersion modelling for the cumulative impact in the region.

Individual power station models: Five technical emissions scenarios have been modelled for Matimba and Medupi Power Stations individually. These include (1) Scenario A: historical baseline of actual monthly tonnage emitted per stack per station for 2022 to 2024; (2) Scenario B: future baseline of monthly tonnage emitted per stack per station accounting for all six units in operation at Medupi; (3) Scenario C: with predicted monthly tonnage emitted per stack with wet FGD installed at Medupi; (4) Scenario D: with predicted monthly tonnage emitted per stack with semi-dry FGD installed at Medupi; (5) Scenario E: with predicted monthly tonnage emitted per stack with dry FGD installed at Medupi.

Cumulative impact: The same scenarios listed above have been modelled for Matimba and Medupi Power Stations to assess the combined effect of these power stations on the ambient air quality.

Other detailed modelling inputs and parameters are included in the Dispersion modelling Technical Memorandum (uMoya Nilu, 2025).

2.2.7.1 Isopleth Maps

National Ambient Air Quality Standards (NAAQS) (DEA, 2009, 2012) apply to the pollutants emitted by stations. The NAAQS consists of a “limit value” and a permitted frequency of exceedance. The limit value is the fixed concentration level aimed at reducing the harmful effects of a pollutant and the permitted frequency of exceedance represents the acceptable number of exceedances of the limit value expressed as the 99th percentile[2]. In the context of the South African NAAQS, the 99th percentile is the statistical mechanism used to define compliance for pollutants, and it represents a permitted frequency of exceedance. It acknowledges that due to rare meteorological conditions or extreme operational events at facilities such as Medupi and Matimba, pollutant concentrations may sometimes exceed the prescribed “limit value” without constituting non-compliance. Statistically, the limit value must not be exceeded for more than 1% of the monitoring period, typically over a calendar year.

[2] The 99th percentile in a dataset is the value below which 99% of all data points fall – it marks the boundary for the top 1% of model predictions and separates it from the bottom 99% of the data. Therefore, in the model datasets, the top 1% of the highest values are excluded.

Compliance with the ambient standard implies that the frequency of exceedance of the limit value does not exceed the permitted tolerance. The NAAQS limits for the averaging period of 1 year for SO_2 is 50 µg/m^3, for NO_2 is 40 µg/m^3, for PM_{10} is 40 µg/m^3 and for $PM_{2.5}$ is 20 µg/m^3 (from 2030 is 15 µg/m^3). The South African NAAQS permits 4 exceedances of the 24-hour or daily limit value per annum, implying up to 12 permitted exceedances in a three-year modelling period. The South African NAAQS also permits 88 exceedances of the 1-hour or hourly limit value per annum, implying up to 264 permitted exceedances in a three-year modelling period.

Isopleth maps of predicted ambient SO_2 concentrations are presented in Figure 2-2 to Figure 2-6. The predicted concentrations are shown as isopleths, lines of equal concentration, in µg/m^3 for the respective NAAQS averaging periods. The isopleths are depicted as coloured lines on the maps, corresponding to a particular predicted ambient concentration. Areas within red isopleths indicate an area where exceedances of the respective NAAQS limit value are predicted to occur. Sensitive receptors are represented by green squares and AQMS are represented by white squares on the maps.

The isopleth maps showing the predicted annual average SO_2 concentrations clearly demonstrate the influence of the predominant northeasterly winds, with dispersion generally occurring to the southwest of the power stations. In all scenarios, the highest predicted annual average SO_2 concentrations occur between 10 and 20 km from the power stations, predominantly to the southwest. Predicted annual ambient SO_2 concentrations are relatively low and remain below the NAAQS limit values across the entire modelling domain in all scenarios. For SO_2, the predicted concentrations are attributed solely to stack emissions. For SO_2, exceedances of the 24-hour and 1-hour standards are predicted in the domain under the historical (Scenario A), future baseline (Scenario B) and dry FGD scenario (Scenario E); however, the number of exceedances remains within allowable limits, and compliance with the NAAQS is maintained in all scenarios.

The CSIR WBPA baseline assessment (CSIR, 2025) indicates apparent non-compliance for 1-hour and 24-hour SO_2 NAAQS at certain receptors on a regional scale. While the CALPUFF dispersion modelling results above demonstrate compliance with NAAQS, the results are not inconsistent with the findings from the CSIR WBPA study. The CSIR WBPA results represent a conservative, screening-level regional assessment (using CAMx modelling at 2 km resolution), whereas the CALPUFF dispersion modelling is a higher-resolution, source-specific compliance assessment, undertaken using regulator-approved methodology and conservative emission inputs. The apparent differences in SO_2 compliance outcomes arise mainly from model purpose, spatial resolution and treatment of short-term peaks, rather than from contradictory conclusions. The CSIR notes that the CAMx regional modelling has limited ability to resolve near-field plume behaviour and it exhibits “peak smearing” particularly for 24-hour averages due to grid resolution effects.

The reduction in SO_2 emissions at Medupi in Scenarios C and D results in a marked reduction in SO_2 concentrations in the affected area. Conversely, the increase in SO_2 emissions at

Medupi from Scenario D to Scenario E is reflected in an increase in the affected area. Compliance with the NAAQS is maintained in Scenarios C, D and E.

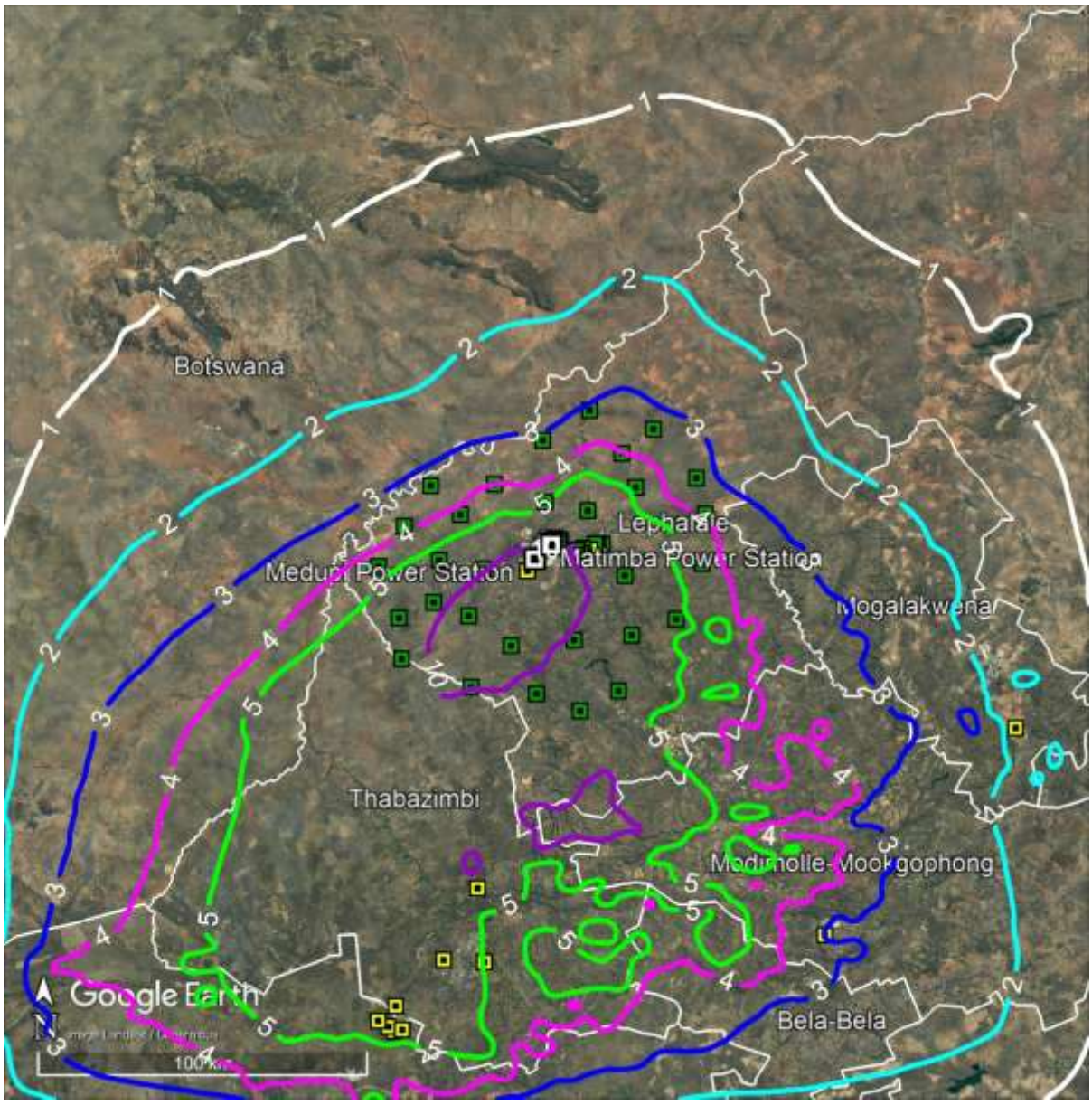

Figure 2-2: Predicted annual average SO_2 concentrations (µg/m³) for Scenario A historical baseline (NAAQS Limit is 50 µg/m³).

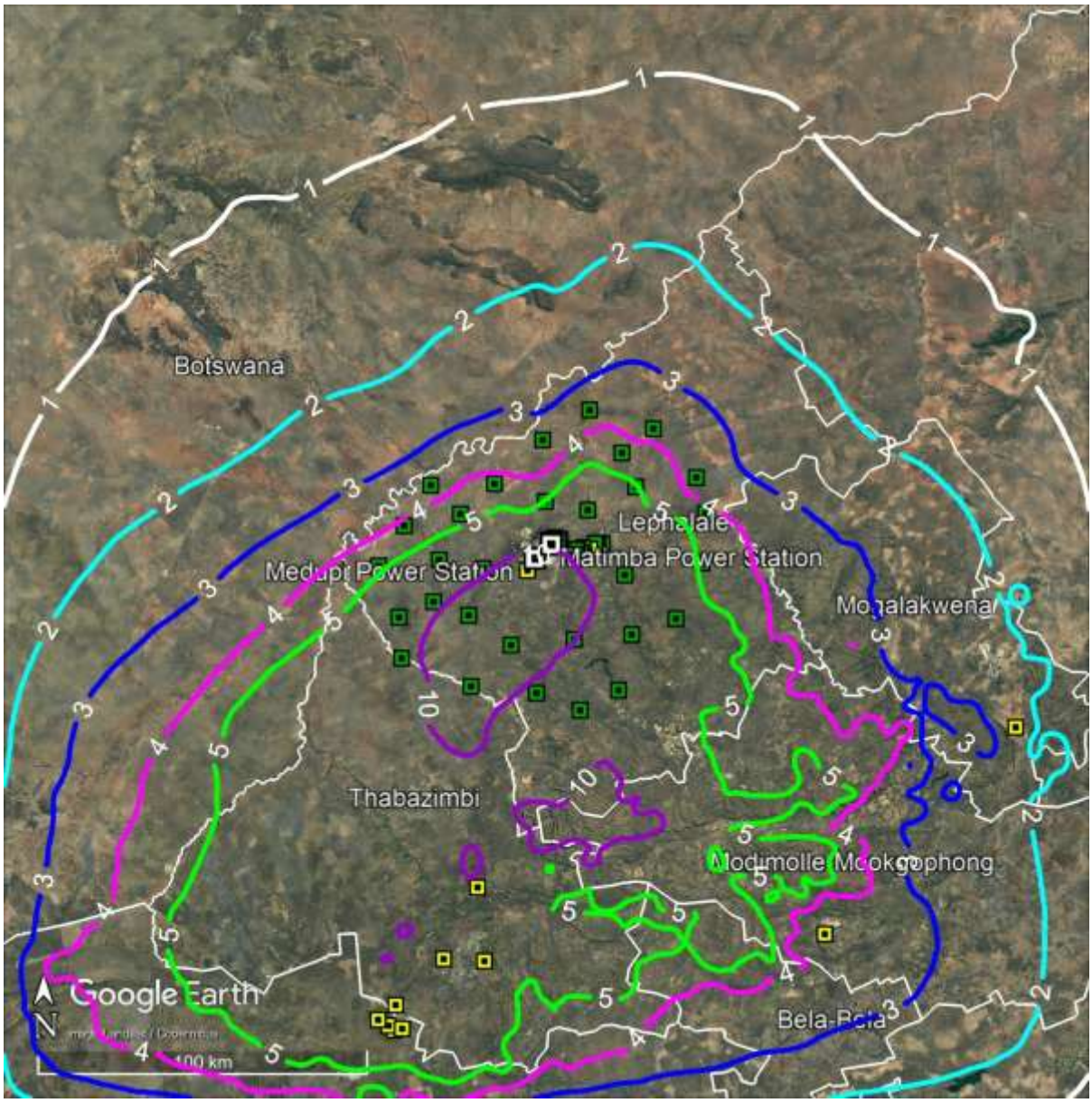

Figure 2-3: Predicted annual average SO_2 concentrations (µg/m³) for Scenario B future baseline (NAAQS Limit is 50 µg/m³).

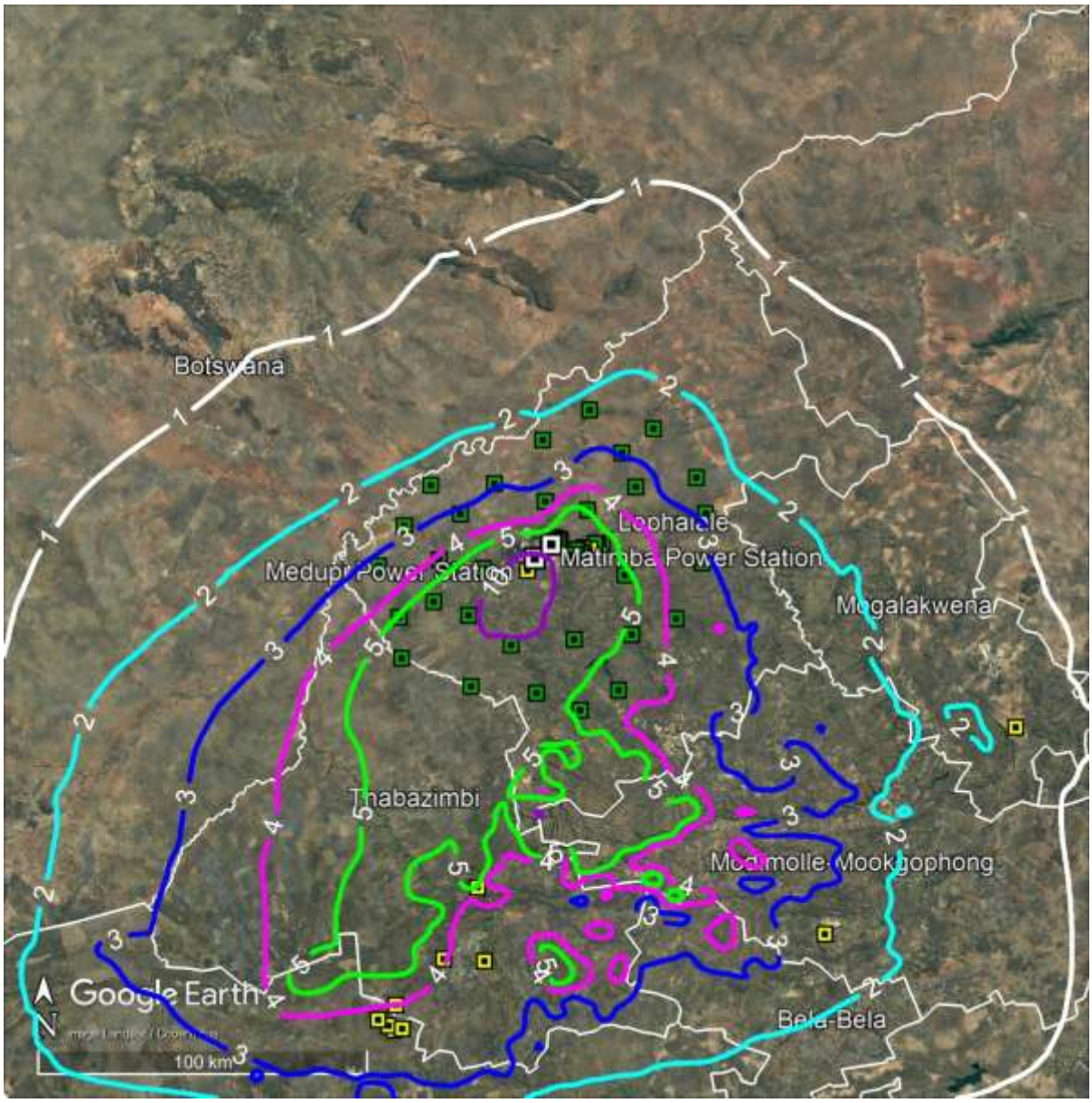

Figure 2-4: Predicted annual average SO_2 concentrations (µg/m³) for Scenario C wet FGD (NAAQS Limit is 50 µg/m³).

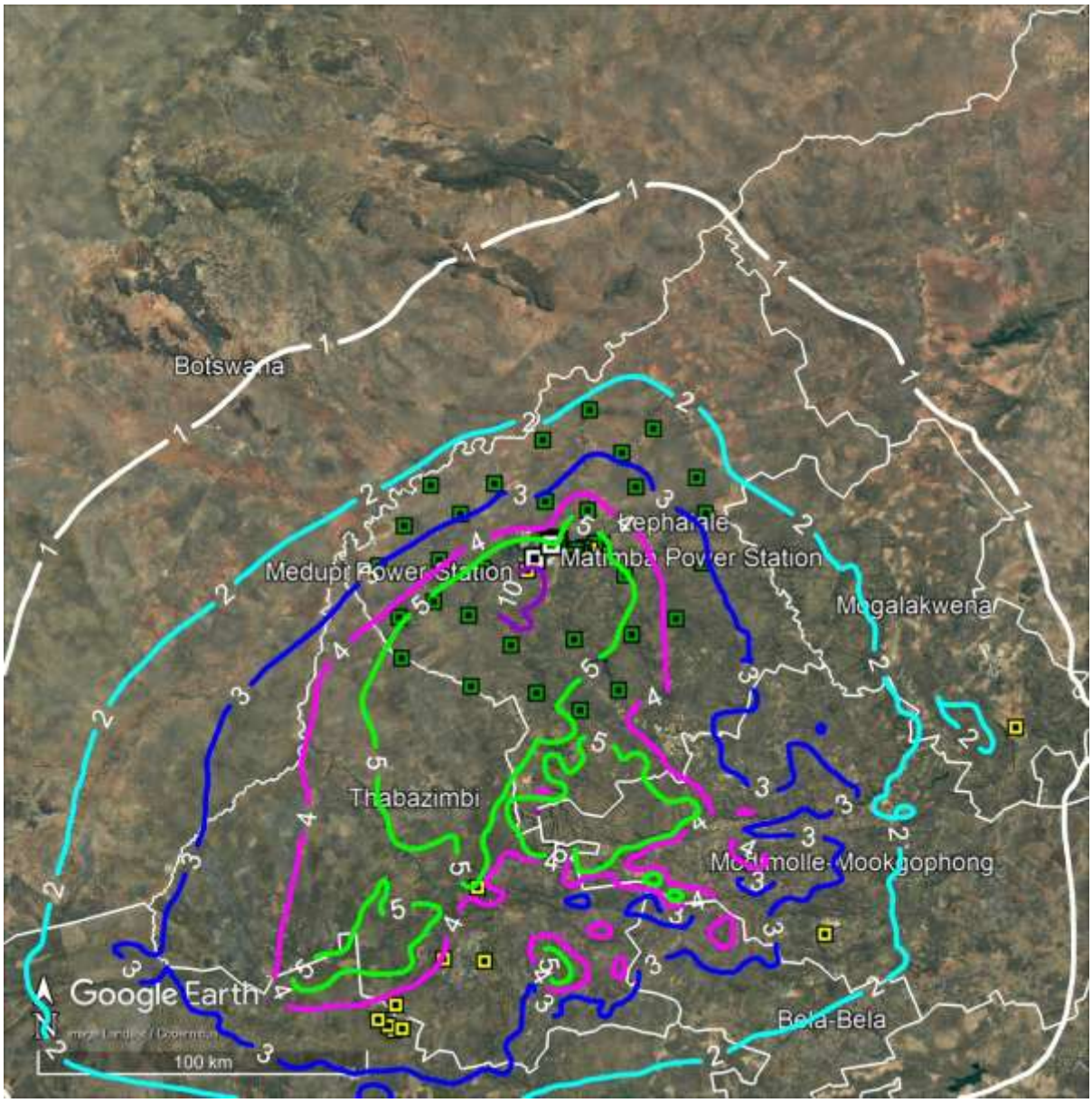

Figure 2-5: Predicted annual average SO_2 concentrations (µg/m³) for Scenario D semi-dry FGD (NAAQS Limit is 50 µg/m³).

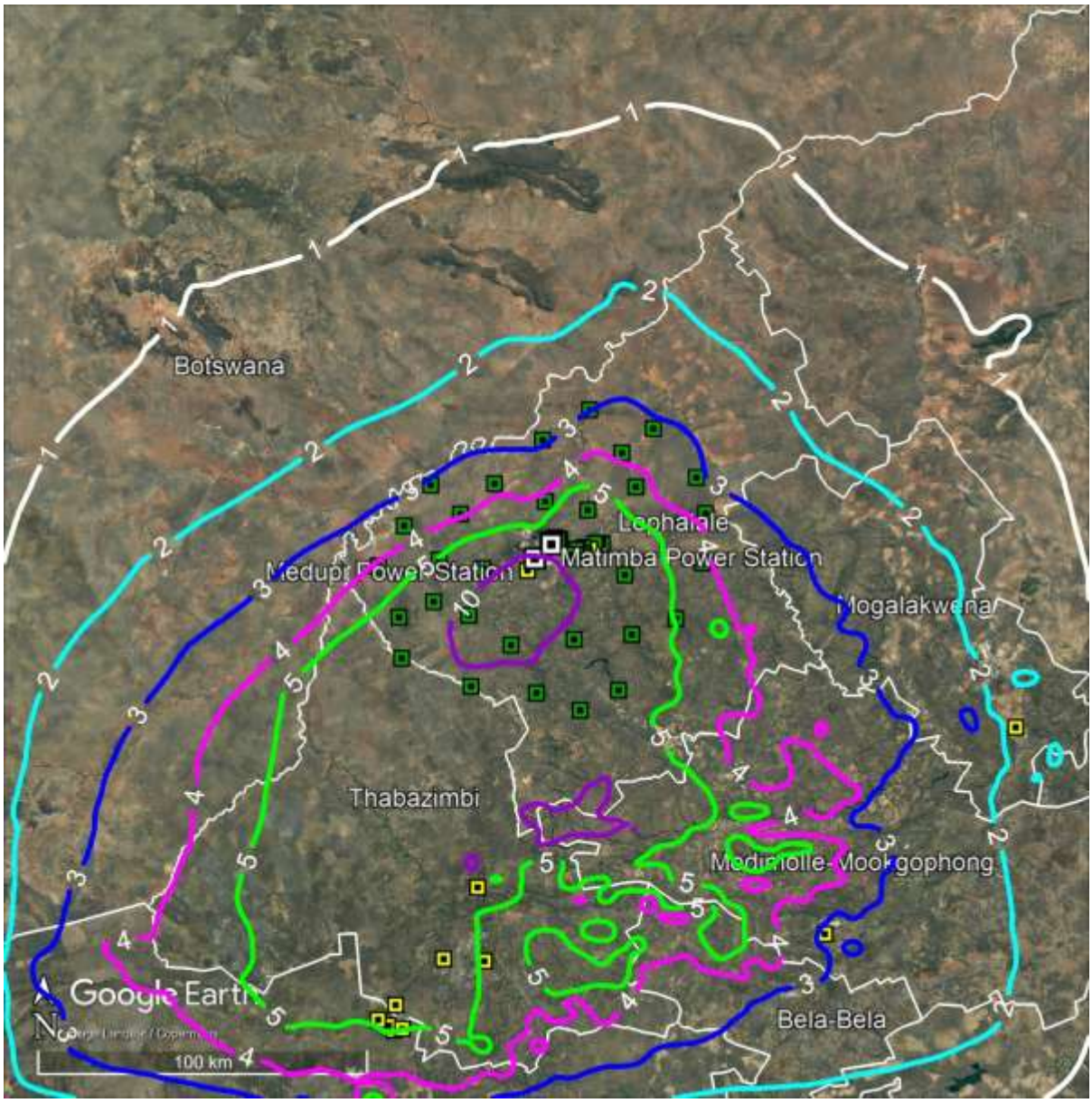

Figure 2-6: Predicted annual average SO_2 concentrations (µg/m³) for Scenario E dry FGD (NAAQS Limit is 50 µg/m³).

The isopleth maps for $PM_{2.5}$ and PM_{10} are in uMoya Nilu, 2025. The predicted $PM_{2.5}$ and PM_{10} concentrations are attributed to stack emissions, low-level fugitive sources (including coal stockyards, ash dumps and gypsum disposal facilities), and contributions from secondary particulate formation.

2.2.8 Population exposure

Population exposure was estimated at a spatial resolution of municipality and municipal wards, at each municipality or ward, the number of people exposed to different concentration ranges were determined taking into account where the population resides within each ward in the modelled domain by using the gridded population of 2025 (Bondarenko et al. 2025). The growth of the population for the modelled timeline was predicted based on a growth factor per year which was determined using the Stats SA Census 2022 (Stats SA, 2024) and the latest United Nations population prospects growth forecasts (United Nations, 2024).

Population exposure was estimated at a spatial resolution of municipal wards for the data from the dispersion model runs. At each modelled grid cell, the number of people exposed to different concentration ranges for each pollutant were determined per scenario per year. Part of the model domain falls within Botswana and the number of people exposed within this area was also estimated using the 2025 gridded population (Bondarenko et al. 2025) and growth factors determined using Botswana Census 2022 (Statistics Botswana, 2025) and the latest United Nations population prospects growth forecasts and included in the model runs.

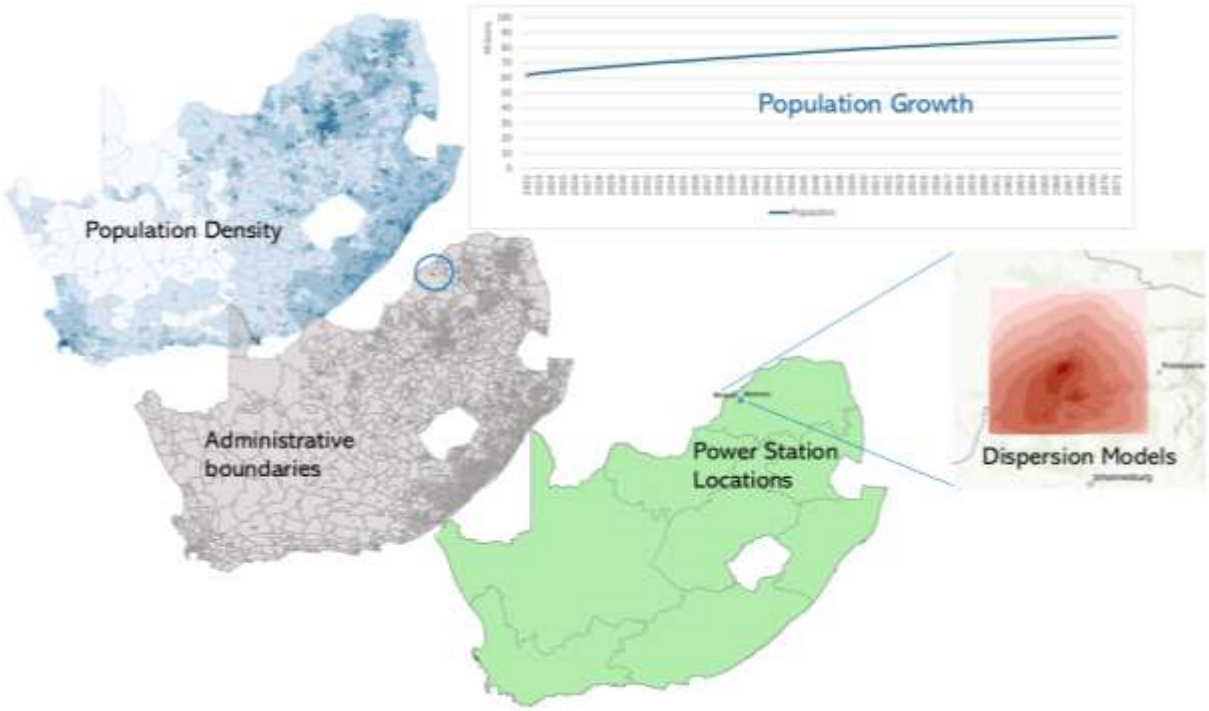

Figure 2-7: Overview of population exposure calculation.

The integrated Health BCA model calculated ambient exposure as follows:

- Dispersion Model outputs were used to spatially apportion ambient concentrations. The co-ordinates (x; y) of receptors from the output files were attributed to specific administrative boundaries.
- Administrative boundaries used were municipalities, municipal wards and the gridded population count within these boundaries. The predicted ambient concentrations for each pollutant were weighted based on the population count.
- Population counts for South Africa and Botswana were obtained from the gridded population datasets released in September 2025 by WorldPop (Bondarenko et al., 2025).
- Population growth forecasts were used to determine the growth in population exposure over time (Stats SA Census 2022; United Nations, 2024). This was used to grow the population numbers in each year following 2025 to the end of the modelled timeframe years of 2071, 2055 and 2045 (representing the alternative shutdown dates for Medupi).
- Power station locations were used to determine the wards which were affected by each station, to estimate relative impacts of each power station to the cumulative impact modelled.

In the modelled domain (108,900 km^2), approximately 1.67 million people are potentially exposed to the air pollution from Medupi and Matimba power stations in 2025, with an exposure profile as set out in Figure 2-8 below.

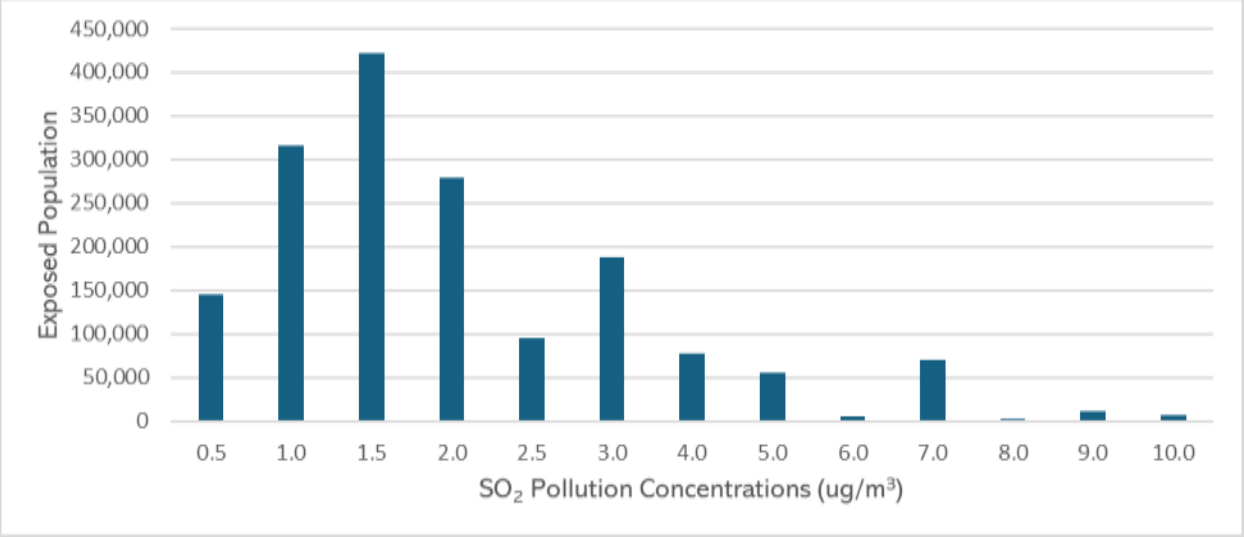

Figure 2-8: Population exposure to SO_2 annual average concentration ranges (2025).

2.3 Assessment of Technical Scenarios

2.3.1 Health impacts

The WHO (2016a) recommends the health risk to a population from air pollution to be estimated using exposure-response functions (ERFs). ERFs are based on Relative Risk (RR) estimates derived from primary epidemiological studies. Exposure to air pollution is the intersection in time and space between a concentration of air pollution and the presence of a human being. For benefit analyses, exposure is typically assessed at the population level by geographically linking estimates of outdoor pollution concentrations with projected population numbers; these together constitute the necessary inputs to exposure- or concentration-response functions for calculating health impacts.

The RR functions estimate the likelihood of health outcomes in a population exposed to a higher level of air pollution compared with a population with lower exposure (WHO, 2016a). RR is usually expressed as the proportional increase in the assessed health outcome associated with a given increase in pollutant concentrations, measured in $\mu g/m^3$. The WHO (2016a) notes that "*the RR estimate cannot be assigned to a specific person; it describes risk in a defined population, not individual risk.*"

Epidemiological studies are mostly based on evidence from population health studies that compare the incidence of health outcomes in populations exposed to higher levels of air pollution with those exposed to lower levels. Most of these studies have been done in Europe and North America. Prospective cohort studies examine differences between cities in mortality among individuals followed over an extended period and the variations in annual (or longer) mean outdoor pollutant concentrations. These studies are believed to address the relationship between chronic exposure and mortality. Epidemiological cohort studies consistently find associations between long-term exposure to outdoor air pollution and a range of morbidity and mortality endpoints (Brunekreef et al., 2021).

Ideally, ERF studies and their RRs should be determined based on primary epidemiological studies focussing on the exposed population. Updates to the WHO (2024) guidelines showed that the bulk of studies covered the European, American, and Western Pacific regions, with none from Southern Africa (Orellano et al., 2024). The ERF is specific to the joint distribution of covariates in the population from which it was derived and may not apply to populations with different demographics. Individual susceptibility/covariates such as age, sex, pre-existing health conditions (co-morbidities), genetics, lifestyle (smoking status, diet) and socioeconomic status (income, education) can modify the individual response to a given exposure level. In the absence of such studies, as in South Africa, the WHO (2016a) recommends using ERFs from other countries.

It is worth noting that there are inherent limitations to transferring ERF studies from other countries. Pollution levels, chemical composition and health care systems are typically very different in other settings, which affects the accuracy of the ERFs. Direct epidemiological evidence for an association between long-term pollutants is mostly based on studies from

high-income countries. Compared with low-income and middle-income countries (LMICs), exposure to air pollution is substantially lower in high-income countries and the distribution of co-morbidities and risk factors also differs, limiting direct extrapolation of relative and absolute risks from high-income countries to LMICs. Africa currently has the highest Human Immunodeficiency Virus (HIV) and second highest Tuberculosis (TB) burdens globally. Significant associations between exposure to air pollution mixtures and HIV/AIDS incidence and mortality rates, with $PM_{2.5}$ and PM_{10} being the primary drivers are evident. The relationship between Pulmonary TB risk and environmental factors, including air pollutants and meteorological conditions, is well-established (You et al., 2016; Popovic et al., 2019; Huangfu et al., 2020).

In the AP-HRA, a health outcome must be attributed to an individual indicator pollutant. Several studies warn against potential double counting of pollutant effects when estimating or quantifying health impacts. While health outcomes can be attributed to many different indicator pollutants, using all of them would result in double counting mixture effects in health impacts as these pollutants are associated with each other (WHO, 2013a, WHO2013b, WHO, 2016a, Malmqvist et al., 2018). Synergistic pollutant interactions reflect real biological amplification of harm, but in applied air pollution CBAs, they are already embedded in epidemiological risk functions. If one were to attempt to account for them, explicitly by combining pollutant-specific impacts it almost always results in double counting rather than in improved accuracy. The current study as required by the Minister's Decision is limited to SO_2 health impacts holding all other pollutants constant. Refer to Box 1 below for additional discussion.

The health outcomes for the expanded Medupi AP-HRA and benefit-cost analysis included all-cause mortality and morbidity.

All-cause mortality: This measures all deaths within the population from any natural causes. It includes natural deaths from all causes of death as provided in the WHO (2016b) International statistical classification of diseases and related health problems (IDC-10). In South Africa all-cause mortality makes up 87% of total deaths (Stats SA, 2025a). Positive associations of all-cause mortality and exposure to ambient SO_2, $PM_{2.5}$ and PM_{10} have been shown.

Morbidity: Morbidity refers to the burden of disease, including incidence and prevalence of illness within a defined population. Morbidity captures the full spectrum of non-fatal health outcomes that affect population health and wellbeing, including new diagnoses, hospitalisations, symptom exacerbations, disability and loss of function (WHO, 2019). Morbidity is typically measured as:

- Incidence: The number of new cases of disease arising in a defined population within a specified period (e.g., new pneumonia diagnoses per 1,000 children under 5 years annually).

- Prevalence: The total number of existing disease cases at a particular point in time (e.g., the proportion of adults living with a disease at the time of survey).
- Hospitalisation rates: The frequency of inpatient admissions, discharges, and transfers for specific diagnoses.
- Outpatient attendance: The number of primary health care clinic visits for acute or chronic disease management.

The ERFs used in the AP-HRA and benefit-cost analysis for all-cause mortality and the ERFs for several morbidity outcomes are provided in Table 2-8. The Relative Risk and the baseline incidence are provided in the table.

Table 2-8: Indicator pollutants, baseline incidence, and relative risks of each health outcome (Sources indicated in the table)

Indicator Pollutant	Health Outcome	Baseline Data	Source (Reference and Country)	Relative Risk or Hazard Ratio per 10 µg/m^3	Source (Reference and Country)
SO_2	All-cause Mortality	0.695%	Stats SA, 2025a (South Africa)	1.0059 (95% CI: 1.046,1.0071)	Orellano et al., 2021 (Global)
$PM_{2.5}$	All-cause Mortality	0.695%	Stats SA, 2025a (South Africa)	1.095 (95% CI: 1.064, 1.127)	Orellano et al., 2024 (Global)
PM_{10}	All-cause Mortality	0.695%	Stats SA, 2025a (South Africa)	1.081 (95% CI: 1.052, 1.110)	Orellano et al., 2024 (Global)
SO_2	Children <5 acute respiratory disease - pneumonia incidence	0.02139* 0.00501*	Zar et al., 2020 NDoH, 2026 (South Africa)	1.28 (95% CI: 1.22-1.34)	Nascimento et al., 2020 (Brazil)
SO_2	Acute myocardial infarction incidence	0.00388%	Heart and Stroke Foundation, 2016 (South Africa)	1.010 (95% CI: 1.003-1.017)	Mustafić et al., 2012 (Global)
SO_2	Asthma ED visits / hospital admissions	0.17	Econex, 2015 (South Africa)	1.010 (95% CI: 1.001, 1.020)	Zheng et al., 2021 (Global)
SO_2	Respiratory inpatient admissions	0.01428	OHID, 2025 (UK)	1.006 (95% CI: 1.0011, 1.0014)	Cao et al., 2022 (China)
$PM_{2.5}$	All cardiovascular hospital admissions	25%	Engelbrecht, 2025 (South Africa)	1.010 (95%CI: 1.006, 1.014	Ru et al., 2023 (Global)
$PM_{2.5}$	Asthma ED visits	0.17	Econex, 2015 (South Africa)	1.043 (95% CI: 1.026, 1.062)	Zheng et al., 2021 (Global)
$PM_{2.5}$	Work-loss days	13.46 days	PSC, 2002 (South Africa)	1.047	Ostro, 1987 (USA)
$PM_{2.5}$	All respiratory hospital admissions	0.01428	OHID, 2025 (UK)	1.014 (95% CI: 1.010, 1.017)	Ru et al., 2023 (Global)

* Data for the Limpopo region was received from the National Department of Health (NDoH) in January 2026. This data together with literature source for national baseline incidence was used for lower and upper limits for this morbidity outcome in the BCA model respectively.

Box 1: Notes on Synergistic effects and ERF selection.

Synergy (or interaction) occurs when the combined effect of two or more exposures exceeds the sum of their individual effects.

In real-world cohort studies, health outcomes observed arise from exposure to complex **pollution mixtures**, and not from isolated single pollutants. Thus, ERFs are derived from populations chronically exposed to mixtures of pollutant emissions. Furthermore, the estimated coefficients of reported single-pollutant emissions implicitly reflect correlated co-pollutant and synergistic effects of the study area. As a result, pollutant-specific ERFs represent marginal associations under correlated co-exposures rather than fully separable causal effects.

Therefore, so-called "single-pollutant ERFs" do not represent pollutant-specific causal effects. Applying additional pollutant-specific ERFs in such contexts would result in double counting and results in over-attribution of health impacts due to overlapping exposure pathways.

Consequently, estimated health impacts reported as single pollutant ERFs should be interpreted as summary effects of ambient mixtures rather than isolated causal effects of single pollutants, with the single pollutants serving as measurable indicators of these impacts.

Conversely, where ERFs are sourced from multi-pollutant models or from exposure environments with materially different source profiles, synergistic effects are unlikely to be fully internalised, and damage estimates should be interpreted as conservative.

Our study conducted a thorough literature review and selected a set of ERFs, linked to specific mortality and morbidity outcomes, that best approximate health impacts in the study area. Refer to Table 2-8.

The ERFs recommended by the WHO and other literature sources using in this study are robust for policy and risk assessment and should be interpreted as reflecting effects of ambient pollution mixtures rather than mechanistically isolated pollutant effects.

The Minister's Comment 7.32 (refer to Preamble) requested the CBA to be limited to SO_2 health impacts. For this reason, appropriate SO_2 ERFs were selected to represent the health impacts arising from the various FGD options and other alternative scenarios. In the case of the FGD scenarios, $PM_{2.5}$ effects resulting from the gypsum disposal pathways were assessed using $PM_{2.5}$ ERFs.

The baseline incidence rates for mortality health outcomes were determined based on published data from the year 2022 from Stats SA (Stats SA, 2025a). The ERFs describing the change in incidence in relation to changes in exposure (RRs) were obtained from the WHO latest systematic reviews for the update of the WHO Global Air Quality guidelines (WHO, 2020, 2021) and an updated systematic review publication for PMs of 2024.

To determine the baseline incidences for the selected morbidity health outcomes, best available literature was consulted and official statistics from the Department of Health (DoH). Provincial and national level data was obtained from published studies and reports based in Limpopo, preferably, to calculate the baseline incidences for the area of interest for most of the health outcomes (see Table 2-8). In exceptional cases where no local data was available, global sources were used to infer baseline incidences. Similarly, given the data gaps in the South African context (Glenn et al., 2022), the ERFs applied to health outcomes were mostly derived from literature from other parts of the world.

2.3.2 Health costs

The detrimental effects of air pollution on human health are borne in the economy by households, insurance companies, employers and public health programs (Romley et al., 2010).

The fundamental goal of health cost or cost of illness (COI) studies is to evaluate the economic burden that illness imposes on society (Jo, 2014). Rice (1967) and Rice et al. (1985), were instrumental in standardising methodologies for estimating COI, which continue to be used internationally and are periodically updated (Rice, 1996; Rice, 2000).

COI studies contextualise adverse health effects in monetary terms to inform decision-making. Such decisions could include (a) to simply present the magnitude of disease in monetary terms; (b) to comparatively evaluate intervention programs; (c) to assist in the allocation of research funding on specific diseases; (d) to provide a basis for policy and planning relative to mitigation initiatives; and (e) to provide an economic framework for program evaluation (Rice, 2000).

COI studies typically stratify costs into two categories: direct and indirect costs. Direct costs relate to the cost of medical treatment. This would include costs of visiting healthcare facilities, medicine and hospitalisation. Indirect costs comprise the morbidity costs (the cost of lost economic productivity due to absenteeism or temporary or permanent disability) and the mortality costs. With respect to mortality costs, valuing human life is contentious, as it can be seen as a judgement on the intrinsic value of life and involves complex ethical considerations. Often, cost-effectiveness analysis is used as an alternative (Muchapondwa, 2009). This side-steps the complexity of life valuation and uses disease or fatality incidence indicators to compare effectiveness of different policy or spending options.

The health impact or health risk, associated with air pollution, is estimated using ERFs as described in section 2.3.1 above. In this study, the ERFs discussed included both mortality and morbidity, sourced from the latest WHO systematic reviews and other cohort or systematic reviews; thus, a monetary measure was required for these ERFs to perform the benefit-cost analyses.

In air pollution benefit-cost analyses, the concept of value per statistical life (VSL) is commonly used to monetise mortality-related benefits of air pollution reduction. The concept of a VSL is frequently misunderstood. It does not measure the intrinsic value of a human life, and nor does it value a person's economic productivity. Rather, VSL is estimated by dividing an individual's willingness to pay (WTP) to reduce health risk by the likelihood of risk reduction. Robinson and Hammitt (2009) defines VSL to represent the rate at which an individual is willing to exchange their own income for a small reduction in their own mortality risk over a particular period. VSL is not the value that a person, society or the government would place on reducing the relative risk of mortality with certainty, but it is rather a representation of the rate at which a person views a change in the money available for spending as equivalent to a small change in their own mortality risk (Robinson et al., 2018).

Ideally, one would use a VSL calculated specifically for a South African context. However, primary WTP studies for mortality risk reductions have not been done in South Africa. Most countries lack reliable estimates of the VSL based on revealed or stated preferences (Viscusi and Masterman,2017) and primary research studies require considerable time and expense (Robinson et al., 2018). In these cases, a "benefit transfer" method is used to transfer values from other studies. Both the aforementioned authors recommend using a United States of America (USA) base VSL (calculated using labour market estimates from their Census of Fatal Occupational Injuries (CFOI) data) and then further adjusting it for differences in income between the USA and the country of interest.

The VSL estimate in this study is determined by the following equation (from Viscusi and Masterman (2017) and Robinson et al. 2018):

$$VSL_{target} = VSL_{base} \times \left(\frac{Income_{target}}{Income_{base}}\right)^{\text{elasticity}}$$

In the above equation the base country is the United States. The VSL is transferred using the income measure of GNI (Gross National Income) per capita from the World Bank which utilises the Atlas method based on exchange rates and inflation rates.

Data for the US base VSL was obtained from the US Economic Research Service and the Federal Register, the GNI per capita value was sourced from the World Bank. Exchange rates to convert the dollar value of the South African VSL into rands were taken from the annual average exchange rates from the South African Reserve Bank.

A sensitivity analysis was conducted in the BCA according to the recommendations of Robinson et al. 2018. The default values include:

- VSL = 160 * GNI per capita of the target country
- VSL = 100 * GNI per capita of the target country
- VSL extrapolated from USA estimate to target country using an elasticity of 1.5.

Additionally, the sensitivity analysis uses the Masterman and Viscusi (2017) income elasticity of 1.0. A higher elasticity is generally recommended when transferring VSL values from high-income to low-income countries (Hammitt and Robinson, 2011).

Although the income adjustment and income elasticity do not fully account for the differences in healthcare access and other indicators of population health, these differences are implicitly captured in the baseline incidences, which are ultimately multiplied by the VSL. The benefit-transfer approach is therefore widely applied in contexts where locally derived VSL estimates are unavailable and is generally regarded as a practical and transparent method currently for incorporating mortality risk reductions into economic appraisal across countries with differing income levels.

A COI approach was also applied in the costing of morbidity health outcomes. Aside from the costs directly incurred, including hospital fees, doctor visits and/or medication, COI also comprises indirect costs. Since morbidities have impacts far beyond the costs of treatment, indirect costs such as transport and loss of workdays to both the patient and caregiver were also considered. The value of workdays lost was calculated as the average salary in South Africa (Stats SA, 2025b), whilst the average cost of transport was derived from literature (Chimbindi et al., 2016, Morrow and Laher, 2022). The average length of stay in a hospital is approximately five days (Olukoga and Harris, 2005, Ramjee, 2013), and was applied as such, and taken into account alongside the average cost of hospital or emergency admission (Ramjee, 2013). Treatment costs specific to each health outcome were also determined. Once the COI per patient per health outcome was calculated, this was multiplied by the relevant baseline incidences and the RRs to gauge the total cost of morbidity attributed to the emissions, as seen in the equation:

$$Morbidity = COI \times baseline\ incidence \times RR$$

2.3.3 Pollution abatement options

2.3.3.1 Summary

Table 2-9 sets out the detailed abatement options for Medupi per scenario assessed.

The abatement options include the installation of technologies to reduce SO_2 emissions. The technologies investigated for this expanded Medupi BCA study include wet flue gas desulphurisation (wet FGD), semi-dry FGD and dry-FGD.

Lower load operation will also result in a reduction of absolute SO_2 emissions (i.e., tonnes). However, the MES and AEL is based on SO_2 emissions concentrations (i.e., mg/Nm^3) which does not change as the load changes. A load-based emissions limit (i.e., tonnes) will only work if the concentration limit is removed. Removing the concentration limit requires a revision of the MES regulations. Medupi is a super-critical higher cycle efficiency plant and has one of the lower OPEX costs in the Eskom coal fleet. It therefore does not make economic sense to run this plant at lower load in favour of less efficient and more expensive power plants in the fleet.

The BCA model was set up to compare three different scenarios in terms of the above abatement technology implementation for the Medupi power station. The dispersion modelling was done for each of these scenarios and the results were used in the BCA model. The model was constructed to allow for a gradual change in pollutant emission concentrations over several years based on the capital and operational expenditure timeframe. This was done to reflect that not all retrofitted units will be operational at the same time. When the abatement technology of all units is operational the model then reflects the final emission concentration values related to the specific scenario.

2.3.3.2 Station shutdown

Station lifetimes were described for the two power stations that were modelled. The shutdown dates affect (reduce) the emissions per year in the years that the station units are being shutdown. The Matimba power station shutdown date is from 2039 to 2043. The model considered three alternative shutdown dates for Medupi power station (as required in the Minister's Record of Decision (RoD) with respect to Generation MES exemption applications) which included, 2071 (current planned and at full station lifetime), 2055 and 2045. The full lifetime shutdown dates are in Eskom's present planning and technical requirements dates are subject to review based on national energy requirements. Eskom will follow all necessary regulator and stakeholder engagement process prior to station shutdown.

It is therefore important to note that the early shutdown scenarios assessed in this report were based on timelines that respond to the Ministers request for additional analysis, but it does not imply that the earlier shutdown dates are technically or financially feasible for Eskom. Eskom generation planning is guided by the Integrated Resource Plan (IRP) 2025 (DMRE, 2025) to determine shutdown dates. It is further to be noted that earlier shutdown periods would impact on the Eskom electricity tariffs and would likely result in increased tariffs as Medupi investment costs would have to be recovered over a significantly shorter time period. These additional costs were not assessed as part of this study.

2.3.3.3 Flue Gas Desulphurisation (FGD) for SO_2 reduction

FGD is a set of technologies used to reduce SO_2 emissions. FGD systems typically include a fly ash removal and SO_2 removal. SO_2 (an acid gas) removal is facilitated by alkaline sorbents such as limestone to react with the gas. The FGDs considered in different scenarios at Medupi power station for the model included, wet FGD, semi-Dry FGD and dry FGD. These

technologies differ in various ways especially such as capital and operational costs, resultant flue gas temperatures and their dependence on water requirements. FGDs typically can reduce SO_2 emissions by up to 90%.

The detailed summary of the technical scenarios is provided in Table 2-9.

Table 2-9: Detail Summary Table of Scenarios (Source: Eskom)

Scenario	Description, Abatement and Additional Information
Scenario A: Actual historical emissions	Modelling based on actual monthly tonnage emitted per stack per station for the period 2022-2024: • The "as is" baseline scenario • In the case of Medupi, the historical baseline reflects mostly 5 out of the 6 units in operation (Unit 4 had extended inoperability due to the turbine-generator explosion incident). As such, a future baseline assessment accounting for all six units in operation at the forecasted load factor was created. • The historical (Scenario A) and future baseline (Scenario B) also reflect the actual SO_2 emissions (i.e., plant operating without FGD), which are lower than the requested and modelled emission limit values. • Matimba is included in the modelling for the cumulative impact in the region.
Scenario B: Future baseline	• In the case of Medupi, the historical baseline reflects mostly 5 out of the 6 units in operation (Unit 4 had extended inoperability due to the turbine-generator explosion incident). As such the future baseline assessment accounts for all six units in operation at a forecasted load factor (upper load forecast (long term tax plan) of 70%). • The historical (Scenario A) and future baseline (Scenario B) also reflect the actual SO_2 emissions (i.e., plant operating without FGD), which are lower than the requested and modelled emission limit values. • Matimba is included in the modelling for the cumulative impact in the region.
Scenario C: Medupi wet FGD	Predicted monthly tonnage emitted per stack post 2033 assuming: • Medupi has been retrofitted with Wet FGD complying to the Emission Limit Value (ELV) of 1,000 mg/Nm^3 new plant standard but modelled at 80% of the ELV (800 mg/Nm^3). • Matimba is included in the modelling for the cumulative impact in the region. • As per Ministers Decision condition 7.32 all other pollutants constant
Scenario D: Medupi semi-dry FGD	Predicted monthly tonnage emitted per stack post 2035 assuming: • Medupi has been retrofitted with semi-dry FGD complying to the ELV of 1,000 mg/Nm^3 new plant standard but modelled at 80% of the ELV (800 mg/Nm^3)

Scenario	Description, Abatement and Additional Information
	• Matimba is included in the modelling for the cumulative impact in the region. • As per Minister's Decision condition 7.32, all other pollutants constant.
Scenario E: Medupi dry FGD	Predicted monthly tonnage emitted per stack post 2034 assuming: • Medupi has been retrofitted with dry FGD complying to an alternate ELV of 2,500 mg/Nm^3 but modelled at 80% of the proposed limit value (2,000 mg/Nm^3) • Matimba is included in the modelling for the cumulative impact in the region. • As per Minister's Decision condition 7.32, all other pollutants constant
Note: The dates for the commissioning and installation of the different FGD technology in Scenario C, Scenario D and Scenario E differ. The retrofit of FGD technology at Medupi is already in approved plans for the station with wet FGD technology as the main option (Eskom, 2024a). Thus, the dates in the modelling have wet FGD to be completed at an earlier date than the options of the alternative semi-dry and dry FGD technologies of Scenario D and E respectively as these would still need to go through a planning and approval stage prior to potential installation at Medupi.	

Three scenarios (C, D and E) as described above were evaluated against the future baseline (scenario B) of anticipated emissions post 2025. The tables below show the anticipated abatement commissioning schedule and the shutdown schedule for Matimba and Medupi. As described in Table 2-9, Matimba is included in the modelling for the cumulative impact in the region.

Table 2-10: Scenario C Wet FGD at Medupi: power plant commissioning and shutdown periods, and abatement technology installation schedules (Source: Eskom)

Scenario C Wet FGD	Plant Commissioning Period		Plant Decommissioning Period		Abatement Technology Commissioning Period	
Plant	COD start	COD end	S1DS	S1DE	FGD-S	FGD-E
Matimba	1987	1991	2039	2043		
Medupi	2015	2024	2065	2071	2030	2033
Medupi Alternate plant closure 1:			2050	2055	2030	2033
Medupi Alternate plant closure 2:			2040	2045	2030	2033
S-suffix denotes the start of an activity E-suffix denotes the end of the activity Abatement technologies assumed to run as units are retrofitted from technology commissioning date to continue until shutdown date of power plant						

Table 2-11: Scenario D Semi-dry FGD at Medupi: power plant commissioning and shutdown periods, and abatement technology installation schedules (Source: Eskom)

Scenario D Semi-dry FGD	Plant Commissioning Period		Plant Decommissioning Period		Abatement Technology Commissioning Period	
Plant	COD start	COD end	S1DS	S1DE	FGD-S	FGD-E
Matimba	1987	1991	2039	2043		
Medupi	2015	2024	2065	2071	2032	2035
Medupi Alternate plant closure 1:			2050	2055	2032	2035
Medupi Alternate plant closure 2:			2040	2045	2032	2035
S-suffix denotes the start of an activity E-suffix denotes the end of the activity Abatement technologies assumed to run as units are retrofitted from technology commissioning date to continue until shutdown date of power plant						

Table 2-12: Scenario E Dry FGD at Medupi: power station commissioning and shutdown periods, and abatement technology installation schedules (Source: Eskom)

Scenario E Dry FGD	Plant Commissioning Period		Plant Decommissioning Period		Abatement Technology Commissioning Period	
Plant	COD start	COD end	S1DS	S1DE	FGD-S	FGD-E
Matimba	1987	1991	2039	2043		
Medupi	2015	2024	2065	2071	2031	2034
Medupi Alternate plant closure 1:			2050	2055	2031	2034
Medupi Alternate plant closure 2:			2040	2045	2031	2034
S-suffix denotes the start of an activity E-suffix denotes the end of the activity Abatement technologies assumed to run as units are retrofitted from technology commissioning date to continue until shutdown date of power plant						

2.3.3.4 FGD Construction, operation and potential risks

Medupi has been built wet FGD-ready to minimise the outage duration. It is anticipated that the construction of the plant will continue while the units are operational and the tie-in will occur during the normal GO (Go Out) duration.

Design deficiencies of the boiler, draught and fabric filter plants have resulted in the boundary conditions for the FGD plant to be revised. This may require further modifications to the upstream plants and/or additional equipment to be installed that was not in the original wet FGD-ready concept. For example, the fabric filter plant will need to be modified to ensure sustainable bag life and PM emissions. Furthermore, there is a view that additional booster Induced Draft (ID) fans may be required to deal with the higher flue gas volumes. The implication of these is that the outage duration may need to be extended and these modifications and additions will increase the project costs.

The project is currently in the Commercial Phase, due to required extension in tender submission dates it is likely that outage start dates will be moved out.

This is the first FGD retrofit of its kind on a 6 x 800 MW plant in South Africa and is subject to technical risk. Skills in executing this type of project, both locally and internationally, is limited, which will impact the project.

The Operational, Maintenance and Engineering personnel will need to undergo extensive training and re-skilling in preparation for this plant. This further depends on the technology that will eventually be employed. For example, currently, the Kusile power station personnel are undergoing training at a similar FGD plant operating in India. Furthermore, there are support contracts in place with the various Original Equipment Manufacturers (OEMs) to augment the skills at the Kusile FGD plant.

The FGD plants have specialised equipment which are imported. This limits localisation and often requires a Sole/Single Source contract to be in place with the international vendors. This process is very bureaucratic and often requires Supplier Development, Localisation and Industrialisation (SDL&I) and/or Department of Trade, Industry and Competition (DTIC) Designation concessions.

Any change to other FGD technologies (i.e., semi-dry or dry) will result in further delays to the project. While these technologies are relatively cheaper in CAPEX than the Wet FGD, they are more OPEX intensive. Since these technologies have not been evaluated beyond a pre-concept stage, front-end engineering designs (FEED) studies will still need to be done and considering that the power plant has been built wet FGD-ready, the risk remains very high of not meeting the current projected completion dates.

2.3.4 Costs of implementation

The total costs of implementation for the three FGD options at Medupi power station are summarised in Table 2-13. The costs include capital costs of the abatement technology retrofits, all associated operational costs (including sorbents and water consumption), the total carbon costs associated with CO_2 (due to increased energy use associated with SO_2 reduction) and the opportunity costs related to the potential number of outage days required during the retrofit of abatement technology at Medupi.

Table 2-13: Summary of costs of implementation of FGD abatement for the Medupi power station per scenario and alternative station shutdown dates (Nominal costs Rand billion)[3] Source: Eskom

	Scenario C Wet FGD	**Scenario D Semi-Dry FGD**	**Scenario E Dry FGD**
CAPEX (all timelines)	56.2	48.7	15.4
OPEX*:			
2025-2071	286.2	446.7	368.2
2025-2055	90.8	136.0	114.2
2025-2045	17.0	46.9	91.1
Total Carbon Costs**:			
2025-2071	29.2	0	0
2025-2055	9.3	0	0
2025-2045	1.7	0	0
Total Opportunity costs due to outages (all timelines)	11.4 (43 days per unit)	38.9 (129 days per unit)	24.5 (86 days per unit)

*OPEX-associated costs include:

- Auxiliary power per unit (61,505 MWh (wet FGD); 78,667 MWh (semi-dry FGD); 30,667 MWh (dry FGD)
- Additional water consumption per unit (1.6Mm^3 (wet FGD), 756,000 m^3 (semi-dry FGD), 567,000 m^3 (dry FGD)
- Additional sorbent consumption per unit (250,000 tonne (wet FGD), 146,361 tonne (semi-dry FGD), 71,791 tonne (dry FGD)

**For the carbon costs, the current carbon tax price of R236/tonne (CO_2e) was applied to the total CO_2e emissions provided.

Note:
In the 2024 MES exemption applications, the Capex costs for the BCA analysis for (ERP 2024 A) (which included PM projects at Matimba and wet FGD at Medupi) were:
Capex (nominal):

- PM projects at Matimba (R1.4 billion)
- Wet FGD at Medupi (R57.3 billion)
- Total cost (up to 2045) of R58.7 billion

The Opex costs for the 2024 MES exemption applications for the BCA analysis included all costs associated with wet FGD operations. It did not include carbon costs or opportunity costs.
Opex (nominal):

- Total cost (up to 2045) of R25.7 billion (FGD operational costs)

[3] The cost estimates presented are not of uniform accuracy. The wet FGD (Scenario C) estimate is based on a higher level of definition (minimum Class 3), while the semi-dry and dry FGD estimates (Scenarios D and E) are screening-level estimates (Class 5). The estimates should therefore be compared and interpreted with this difference in estimate class in mind.

2.4 Assessment of Alternative Scenarios

2.4.1 Background

In response to the DFFE Minister's Record of Decision section 7.3 (specifically 7.34) of 31 March 2025, in respect of the exemption applications submitted by Eskom that requests for independent power system modelling that explores alternatives to installing FGD at Medupi, several alternative scenarios have been explored in this study in addition to the technical alternatives for SO_2 and health impact reduction at Medupi and in the WBPA. Multiple alternative approaches which could result in a similar level of emission reduction and/or health benefit in the WBPA or nationally exist. For example, previous studies have shown that the early shutdown of coal stations and their replacement with alternative energy supply options such as renewables, gas or nuclear will result in significant decrease in health costs. Implementing alternatives which increase coal generation or delay coal station closure will reduce the air quality benefit of coal station shutdown.

Possible alternative energy supply options are identified in the Integrated Resource Plan (IRP) 2025 (DMRE, 2025) which provides a framework for energy planning for the country. The IRP is a multifaceted exercise balancing energy supply (ESKOM and non-Eskom, coal, gas, renewables and nuclear), capital and operations costs, and environmental requirements.

Considering the IRP and international trends, a number of possible alternative health impact reduction activities were assessed for this study. In terms of the IRP Eskom is committed to implementing technology pilots by 2030 with the outcome of these being considered in future energy planning initiatives. The alternatives identified do not constitute a commitment by Eskom and are provided for illustrative purposes.

The alternative scenarios assessed contain uncertainty, particularly with regards to project design, implementation, emissions reductions and other cost-benefit parameters. Key limitations include:

- Accurate capex and operational cost assessment are not available at present.
- For Circulating Fluidised Bed Combustion (CFBC) specifically, system planning has not been conducted yet, and thus the reduction in relative emissions associated with substitution of coal-fires power stations has not been modelled.
- Alternative scenario investment decisions will not only be governed by air emissions impacts, but also by technology maturity, the IRP and technical and financial feasibility. For instance, the benefits of Long Duration Energy Storage (LDES) are limited in terms relative generation capacity; and it is likely to be an enabler of additional renewable energy rather than a direct substitute for coal-fired power station air emissions. Moreover, Eskom has limited funds for investment in LDES at present.

Given the uncertainty, the analysis applies a risk-based proportional assessment approach aligned with International Finance Corporation (IFC) risk assessment approaches. This means the depth of modelling and evidence collected were scaled to the materiality of potential health impacts.

2.4.2 Alternative scenarios identified for preliminary analysis

The alternatives identified are based on presently available information. Alternatives were scoped based on expected influence on key exposure pathways (such as SO_2), affected population size and potential severity of outcomes. Initiatives with highly speculative exposure outcomes were treated qualitatively. This aligns with the IFC risk assessment approach.

Costs used are indicative based on publicly available information.

Table 2-14 provides a description of each alternative scenario, outlining the locality, estimated cost, associated consequences/benefits and potential environmental and socio-economic impact of each scenario. The assessment aims to identify feasible options that could reduce emissions or mitigate impacts while considering practicality, benefits and cost.

Table 2-14: Scoping of alternative scenarios (Source: Eskom and publicly available information)

Alternative Scenario	Description	Risk/Uplift Impact Description	Locality	Theory of change	Consequence/ Benefit	Cost to Eskom
1. Eskom AQO Programme	Eskom expands its AQO programme to 96,000 households, effectively addressing the issue of residential fuel-burning. This involves improving practices or transitioning households to cleaner fuels.	Significant improvements in ambient air quality in the local airshed results. The benefits have been modelled based on two case study communities by ARM, focusing on coal stove replacement.	Households identified via an Eskom-protocol, situated in close proximity to coal-fired power stations within the Highveld Priority Area	Clean cooking interventions (ceiling retrofits, rewiring, stove replacements, introduction of LPG heating) demonstrated a real, quantifiable and verifiable reduction in PM emissions	WHO AP-HRA methodology can be applied at a per community level and scaled up to 96,000 households using assumptions extracted from ARM studies.	Eskom has accurate costing for the AQO programme
2. Coal beneficiation	Coal beneficiation and efficiency improvements (see MES application) is the process of improving raw coal (run-of-mine) by removing impurities (ash, moisture, non-combustible minerals, inorganic sulphur (e.g., pyrite), and other contaminants) before combustion. Methods include "wet washing" (dense-medium separation), dry cleaning, crushing + separation, fine-coal cleaning, and more advanced chemical/thermal/biological treatments.	The result is a "cleaner coal", higher calorific (energy) value per mass, lower ash content, more consistent combustion properties, and reduced impurity load.	All Eskom power stations excluding WBPA	Coal beneficiation reduces SO_2 emissions by between 1 and 5% Note: reduction potential is very low in addition, discard is generated which causes additional environmental risk	WHO AP-HRA methodology can be applied by evaluating the relative benefit achievable, based on uMoya NILU dispersion modelling. t	US $5-15/tonne cost reference (mostly North America, Europe, etc.) Additional indirect costs: water scarcity (if wet beneficiation), tailings/slime disposal, energy use, dewatering, environmental compliance, and transport

Alternative Scenario	Description	Risk/Uplift Impact Description	Locality	Theory of change	Consequence/ Benefit	Cost to Eskom
3. High Efficiency Low Emissions (HELE)	Circulating Fluidised Bed Combustion (CFBC) can remove over 90% of SO_2 (depending on limestone quality; Ca/S ratio (sorbent dosage); bed temperature; residence time of particles). It therefore avoids the need for flue-gas desulphurisation (FGD) units. CFBC has lower combustion temperatures which favour SO_2-CaO reactions; high turbulence and long solids residence time ensure very good mixing between fuel and sorbent; the continuous recirculation loop increases sorbent utilisation, improving capture efficiency.	CFBC results in lower SO_x and NO_x emissions.	Hendrina (3*200 MWg) Grootvlei (3*200 MWg) Duvha U3 (600MWg)	Can remove 90-98% of SO_2. PM not quantified	WHO AP-HRA methodology can be applied by evaluating the relative benefit achievable, based on uMoya NILU dispersion modelling.	R18 - R36 bn Hendrina and Grootvlei CAPEX: 1,700-2,200 USD/kW Fixed O&M: 35-45 USD/kW Duvha CAPEX: 2,500-3,300 USD/kW Fixed O&M: 45-60 USD/kW The difference between the cost of conventional pulverised coal boilers and CFBC was considered for the purposes of the BCA.
4. Carbon Capture Utilisation and Storage (CCUS)	Post-combustion Chemical Absorption Amine-based. It involves carbon capture, utilisation and storage.	SO_2 polishing is a process requirement of CCUS	Kusile I Unit (Demo) Grootvlei I Unit (Pilot) Kusile I Unit Medupi I Unit (Linked to coal-fired units - Up to 9,984MW)	CCUS can remove over 3.01 Mtpa of CO_2. It also reduces SO_2, NO_x and PM by > 91%, 93%, 80% respectively through the inclusion of compulsory MES reduction plant prior CO_2 capture.	WHO AP-HRA methodology can be applied by evaluating the relative benefit achievable, based on uMoya NILU dispersion modelling.	CAPEX: Total R390M - R500M (Kusile Demo). (Grootvlei Pilot). CAPEX: Total: R4bn - R6bn (Medupi & Kusile). OPEX: (R1,150.66/tCO_2 - R8,791.1/tCO_2

Alternative Scenario	Description	Risk/Uplift Impact Description	Locality	Theory of change	Consequence/ Benefit	Cost to Eskom
5. Long Duration Energy Storage (LDES)	New renewable capacity displaces coal generation in the merit order: Solar PV → displaces coal during daylight hours; Wind → displaces coal whenever wind resource is available; Storage (batteries/pumped hydro) → smooths variability, further displacing coal. As the share of variable renewable energy (VRE) rises, average coal load factors decrease.	Effect on SO_2 & Other Emissions; every MWh supplied by renewables results in: ~100% reduction in SO_2, NOx, PM, and Hg relative to coal-fired generation; thus, renewables achieve far larger reductions than coal-beneficiation (5%) or in-stack technologies (e.g., efficiency upgrades).	Standalone at generation sites (Camden / Komati / Kriel / Hendrina / Arnot / Grootvlei)	212 tonnes (for a 200 MWh system) to 1,272 tonnes (for a 1,200 MWh system) Enable increased and accelerated penetration of renewable energy (Wind/PV) into the energy mix. No direct CO_2 reduction	WHO AP-HRA methodology can be applied by evaluating the relative benefit achievable, based on uMoya NILU dispersion modelling.	The cost to Eskom is incurred for the purposes of transitioning away from coal. These costs are not solely incurred for the benefit of emission reductions. The emission reductions are an implicit benefit.
6. Small Modular Reactors (SMR)	High Temperature Gas-Cooled Reactor - Pebble-Bed Module (HTR-PM) is a nuclear reactor that produces heat through controlled nuclear fission and converts that heat into electricity using conventional power-generation equipment.	Nuclear development achieves near-zero operational emissions and may result in substitution of coal-fired power resulting in direct comparative air emission benefit	Arnot 1 - 6 Camden 1 - 8 Grootvlei 1 - 3 Hendrina 1 - 10 Kriel 1 - 6	Total 42.6 Mtpa. reduction for CO_2 Reduces SOx, NOx and PM by 100%	WHO AP-HRA methodology can be applied by evaluating the relative benefit achievable, based on uMoya NILU dispersion modelling.	The cost to Eskom is incurred for the purposes of transitioning away from coal. These costs are not solely incurred for the benefit of emission reductions. The emission reductions are an implicit benefit.

2.4.3 Costs of implementation

The total costs of implementation for the alternative scenarios, including alternative shutdown options, are summarised in Table 2-15. The costs include scenario-specific capital expenditure where applicable, together with the associated operating and programme costs required to deliver each intervention. Where relevant, costs also reflect coal-related costs associated with changes in fuel consumption or coal quality, as well as carbon-related costs linked to emissions. The cost estimates are presented to provide a consistent basis for comparison across the alternative scenarios.

Table 2-15: Summary of costs of implementation of alternative scenarios for Medupi Power Station per scenario and alternative station shutdown dates (Nominal costs Rand billion)

	Eskom AQO Programme ($PM_{2.5}$)	Eskom AQO Programme (SO_2)	Coal beneficiation	HELE	CCUS	LDES	SMR
CAPEX (all timelines)	5.1	5.1	-	11	5	-	-
OPEX:							
2025 - 2071			128.8 - 386.5	8.1 - 10.6	1,811 - 13,837	-	-
2025 - 2055			113.4 - 340.3	5 - 6.3	1,058 - 8,086	-	-
2025 - 2045			97.2 - 291.7	3 - 3.6	588 - 4,492	-	-

2.5 Benefit-cost Analysis

A BCA is a widely used approach employed for decision-making support. This approach was formalised in the United States in 1958 with the purpose of justifying public expenditures on alternative investment options competing public funds such as water, roads, and other public utilities' networks construction projects. BCA methodology broadly advises on the treatment of income benefits and costs; externality costs; how to measure them conceptually; how future prices should be treated; the importance of using a discount rate; the proper period of analysis; and cost allocation procedures for projects.

The World Bank[4] defines a Social BCA as an extension of a financial analysis. Ideally, in extending the financial analysis, all relevant economic costs and benefits are quantified and analysed. The BCA pulls together the component analyses of the study to assess the overall impact for a set of scenario options (emission reduction measures).

The objective of the BCA is to comparatively analyse investments or scenarios (in this case interventions in air quality management). The BCA achieves this end by identifying and monetising the costs and benefits and predicting the timing thereof over the same horizon as the projects' economic lifetime (National Treasury, 2017).

A BCA allows scenarios to be objectively compared according to the benefit-to-cost relationship to analyse the relative efficiency of various interventions and the magnitude of the benefits to identify the interventions that will have the largest impacts.

In this analysis, the BCA methodology is used to compare the scenario health benefits to the costs associated with abatement or mitigation for three technical scenarios and six alternative scenarios. (Refer to section 2.6.1 below for a discussion of BCA limitations.)

2.5.1 Technical Scenarios

There are three analysis timelines that are analysed separately within the BCAs to address the Minister's Decision requirement to consider plant closure dates of 2045, 2055 and 2071 in separate scenarios. The base year was 2025, due to the dispersion modelling timeframe. The BCA was performed in an Excel spreadsheet, which consolidated all data sources and contains all calculations, to run the large spatial exposure estimates for each scenario for the review period. The benefit-cost analysis apportioned costs (all costs as described in section 2.3.4) and benefits (health benefits) to the years in which they would be realised. Because costs and benefits are accrued in different years according to the intervention schedules, the net present values of costs and benefits, using Eskom's weighted average cost of capital (WACC) rate of 10.8% (Eskom, 2024b) as the discount rate allows an objective comparison of scenarios.

The health cost benefits were estimated based on the outputs of the AP-HRA and followed the steps below (section 3.1.1 provides the BCA results for the technical scenarios).

[4] http://documents.worldbank.org/curated/en/445971468767366310/pdf/multi-page.pdf

1. Each of the assessed scenarios implemented an abatement schedule at Medupi power station only (refer to section 2.3.3.3 for details)
2. The dispersion effects modelled by uMoya-NILU (Pty) Ltd were used to estimate the change in population exposure over the three timeline spans (2025 to 2071; 2025 to 2055; 2025 to 2045).
3. The change in population exposure resulting from step 2 above was applied to the ERFs identified in section 2.3.1 to estimate health impact outcomes of mortality and morbidity (sensitivity analysis was performed in the BCA to develop a view on the uncertainty inherent in the ERFs, also refer to section 2.6.1)
4. The VSL and COI (refer to section 2.3.2) was applied to the mortality and morbidity health impact outcomes respectively for each scenario, to estimate the total change in health cost benefits.
5. The costs in the BCA included all technology costs, energy efficiency penalty, CO_2 costs, costs of sorbent supply and its infrastructure, waste treatment and cost of water supply and its infrastructure (refer to section2.3.4).
6. Sensitivity analyses were performed on the VSL, COI, the health benefit and abatement cost estimates.

2.5.2 Alternative Scenarios

This study considered three separate analysis timelines for the BCAs of the alternative scenarios. Although the Minister's Decision requirement to consider plant closure dates of 2045, 2055 and 2071 was specified for the technical scenarios at Medupi, the same timelines were applied to the alternative scenarios. This was done to ensure consistency in the temporal framing of emission reductions and associated health benefits across all options assessed, thereby enabling the comparison of the different alternative scenarios BCA outcomes over equivalent time horizons. The costs and benefits are indicative figures used to provide early-stage BCA results

1. Each of the scenarios consider the decommissioning dates for the power stations considered for the implementation of alternatives.
2. A minimum, central and maximum value were calculated for the benefits and costs because of variability and uncertainty in emission reductions for all the alternatives.
3. The BCA of the AQO programme considered the health impacts of $PM_{2.5}$ and SO_2, keeping all other pollutants constant in each set of analysis.
4. The BCA ratio is a comparison of the cost of household interventions to the increase in mortality baseline incidence as a result of the improvement in ambient air quality for each pollutant.

5. The coal beneficiation BCA uses a researched cost reference applied to the quantity of coal burned across Eskom's power station fleet in the Highveld Priority Area (HPA). Benefits are estimated based on reductions in all-cause mortality values in the HPA, reflecting a 1 - 5% reduction in SO_2 emissions resulting from beneficiation.
6. For the CCUS, health benefits were modelled to reflect a 90% reduction in SO_2 emissions. For the costs, amounts provided by Eskom were evenly distributed over the implementation period. These amounts were then used to compute the BCA ratio. It is to be noted that this represents an extremely ambitious target, for a technology that has not been technically proven and that is likely to be very costly.
7. For CFBC, benefits were calculated by phasing in a 94% reduction in SO_2 emissions over a five-year implementation period. Indicative cost figures for CFBC technology were provided by Eskom. For the purposes of the BCA, the CFBC portion of the costs were isolated. This was done using a researched cost percentage. Literature suggests that there is a cost premium of 17.5% for CFBC technology relative to conventional boilers.
8. The benefits for LDES considers the 100 - 150 MW project capacity indicated by Eskom and then converts the MWs into electricity generation (MWh). A health cost per coal generation figure was calculated and applied to the renewable electricity generation. This means the renewable energy generation 100% offsets the emissions from the coal generation.
9. The benefits for SMR considers the 20 - 300 MW per unit project capacity indicated by Eskom and then converts the MWs into electricity generation (MWh). A health cost per coal generation figure was calculated and applied to the generation from the High Temperature Gas-Cooled Reactor - Pebble-Bed Module (HTR-PM). This means the cleaner energy generation substituting coal-fired power effectively enabling a 100% comparative reduction in air emission where coal-fired power is offset. Eskom is currently progressing from demonstration to commercial phase with SMR as part of a longer-term plan to replace coal with nuclear.

Although not assessed directly in this study, two additional system-level initiatives are expected to have a specific impact on ambient air quality outcomes in South Africa. These include the progressive shutdown of coal-fired power stations, for which previous reports have shown measurable improvements in ambient air quality, and system flexibilisation options that reduce coal station utilisation by increasing renewable dispatch where possible. Investigations into implementing flexibilisation within the Eskom coal fleet are underway.

2.6 Uncertainty of the estimated health effects

2.6.1 Sources of uncertainty and limitations

The WHO (2016a) advises performing an assessment of the uncertainty of the analysis; in this case, therefore, this requires an assessment related to a lack of knowledge about one or more components of the integrated Health BCA Model. The sections below discuss each source of uncertainty and related limitations.

Air pollutants exist as a complex mixture: Despite improvements in the science underlying AP-HRAs, it is still not possible to estimate with complete certainty the effects of air pollution on health (WHO Regional Office for Europe, 2014 cited in WHO, 2016a). The observed adverse effects attributed to an individual air pollutant may well be (partly) attributable to other pollutants in the mixture which are correlated with the assessed pollutant (WHO Regional Office for Europe, 2013 cited in WHO 2016a). It is not possible to assess the uncertainty relating to this (WHO, 2016a).

Pollutants modelled: The analysis considered sulphur dioxide (SO_2), primary particulate matter ($PM_{2.5}$ and PM_{10}), secondary PM (sulphates and nitrates) and nitrogen dioxide (NO_2) for the Medupi and the Matimba power stations. These are the criteria pollutants managed under South African air quality legislation and of most recognised significance in the Priority Area. Other pollutants may also contribute to health risk, and these were not modelled in the dispersion modelling. This may underestimate health risks and thus benefits of health risk mitigation. However, no data or other information exists through which to assess this limitation. Furthermore, the Minister's Decision required analyses of only SO_2 health impacts in the BCA.

Exposure response functions: ERFs are derived from epidemiological studies, in which the parameters of the epidemiological experiment and assumptions made during the experiment introduce some uncertainty into the results. More significantly, because primary epidemiological evidence on air pollution is not available for South Africa. This is a key limitation. As a result, inference must be drawn from studies in other parts of the world. It is worth noting that health response per unit change in air pollution in environments with high ambient levels (such as the HPA) may differ from that observed in countries with lower pollution levels. In summary, the WHO (2016a) notes that extrapolated ERF information may not accurately reflect the exposure-response relationship in the region being assessed, leading to uncertainties in the results. To address these uncertainties, we used variances in ERF outcomes as a measure of BCA ratio variation. The exposure-response functions applied in this assessment reflect the current state of the epidemiological evidence, as synthesised in major international reviews at the time of analysis.

Dispersion model accuracy (uMoya-Nilu, 2024): Air quality models attempt to predict ambient concentrations based on "known" or measured parameters, such as wind speed, temperature profiles, solar radiation and emissions. There are, however, variations in the parameters that are not measured, the so-called "unknown" parameters as well as unresolved details of atmospheric turbulent flow. Variations in these "unknown" parameters can result in deviations of the predicted concentrations of the same event, even though the "known" parameters are fixed.

There are also "reducible" uncertainties that result from inaccuracies in the model, errors in input values and errors in the measured concentrations. These might include poor-quality or unrepresentative meteorological, geophysical, and source-emission data; errors in the measured concentrations used to compare with model predictions; and inadequate model physics and formulation for predicting concentrations. "Reducible" uncertainties can be controlled or minimised. This is done by using accurate input data, preparing the input files correctly, checking and re-checking for errors, correcting for odd model behaviour, minimising the errors in the measured data and applying appropriate model physics.

Models recommended in the DEA dispersion modelling guideline (DEA, 2014) have been evaluated using a range of modelling test kits (http://www.epa.gov./scram001). CALPUFF is one of the models that have been evaluated; therefore, it is not mandatory to perform any modelling evaluations. Rather, the accuracy of the modelling in this assessment is enhanced by every effort to minimise the "reducible" uncertainties in input data and model parameterisation.

The model incorporates actual monthly average emission rates for the full three-year assessment period. It is important to note that the modelled ambient concentrations reflect only these stack emissions; no other SO_2 sources are included.

Baseline disease burden: The baseline cases of mortality used were for 2022, based on latest available Stats SA data. The data for this year is therefore accurate. Stats SA data for 2020 was not used as these numbers may be skewed by COVID-related effects. Uncertainty arises, however, because projections of future population growth are made under the assumption that the relative mortality rate remains constant. Baseline data for morbidity was obtained from literature sources. Baseline estimates used for both mortality and morbidity were aggregated at the provincial or national level. While obtaining data at the facility level is possible, it requires a lengthy process and was not feasible within the timeline provided. Data acquisition has been approved by the Department of Health and may be made available at a later stage if still relevant.

Value of a statistical life (VSL) and other Cost of Illness (COI) costing: VSLs are accurate when estimated from primary data collected through willingness to pay studies specific to the exposed population. All VSL estimates for South Africa are derived from studies done in the United States of America and transferred to South Africa. This introduces uncertainty in the BCA results. Similarly for the COI, the best available data from South Africa was used,

however, in cases of data gaps, other global data was used. This may also introduce uncertainty in the BCA results. As before, within the BCA, this uncertainty remains constant across all scenarios, enabling inter-scenario evaluation and comparison. Transferred VSL estimates may also not fully capture South Africa-specific disease burden patterns and population vulnerability, which should be considered when interpreting absolute cost estimates, while relative differences between scenarios remain robust.

Timeline of dispersion modelling predicted concentrations: The data from the dispersion modelling in CALPUFF is from a specific point in time and is then interpolated for the timeline values that are required to run a benefit-to-cost analysis. Ideally, the BCA model should have a CALPUFF run for each year used in the model timeline, however, to do this is not practical. This causes uncertainties in the results.

Cost uncertainty: Eskom uses a cost estimate classification matrix which has different estimate classes associated with different expected accuracy ranges for making project cost estimations (Eskom, 2020). Based on these classes the sensitivity analysis for costs estimates varied by +20% or -15%. Eskom is constantly working to refine the accuracy of the emission-reduction costing, which may result in internal costing updates. Anticipated changes in cost are anticipated to fall within the range of variance (-15% and +20%).

The BCA does not capture all economic externalities. These include both benefits and costs. The benefits of reduced health risk on households, employers and the health care and insurance industries were not assessed. The costs of implementation of abatement technologies would put additional pressure on Eskom capital (and debt) requirements, and further on electricity price escalations. These would result in additional economic costs, and these were not assessed. It is specifically to be noted that earlier shutdown periods assessed would impact on the Eskom electricity tariffs and would likely result in increased tariffs as Medupi investment costs would have to be recovered over a significantly shorter time period. These additional costs were not assessed as part of this study.

As above, within the BCA, this uncertainty remains constant across all scenarios and thus enables inter-scenario evaluation.

Level of acceptable risk not quantified: The health benefits assessed are the total health benefits associated with all reductions in modelled ambient air quality as a result of abatement technology. It is to be noted however that the MES implies a level of acceptable health risk, and the quantum of the health costs associated with this level of acceptable risk were not assessed in the BCA.

Uncertainties and limitations regarding alternative scenarios:

Alternative Scenario cost uncertainty: The alternative scenarios modelled are still at research or pre-feasibility stage and may be modified, scaled, or discontinued as research and testing progresses. The literature-based costs used in the modelling may not be directly applicable in the South African context and may therefore result in an under- or overestimation of actual implementation costs.

Benefits modelled beyond 2045: All-cause mortality values from the previous air quality and health impact model were used to calculate benefits, but these were only modelled to 2045. Benefits beyond 2045 were extrapolated using forecast coal burn values and assumed emissions reductions. This approach introduces additional uncertainty, as future ambient air quality, exposure patterns, and baseline mortality rates may change over time.

Performance assumptions: The SO_2 reduction efficiencies applied in the modelling were based on the best available technical inputs and were used to ensure consistency across the alternative scenarios. CCUS was modelled assuming a 90% reduction in SO_2, aligned with Eskom's stated expectation of >91% reduction achievable through the inclusion of compulsory MES abatement plant prior to CO_2 capture. CFBC was modelled assuming a 94% SO_2 reduction, which falls within the range indicated in the technical inputs (90-98%) and reflects high-performance operation. Coal beneficiation was modelled assuming a 3% reduction in SO_2, reflecting the modest reductions achievable through removal of residual pyritic sulphur. Actual SO_2 reductions may vary depending on final project scope, coal characteristics, sorbent quality and dosing, and operational performance.

Implementation scale: Several alternatives rely on assumed implementation scale (e.g., household reach targets or capacity proportions). Changes in rollout pace, targeting, or achievable coverage would affect both total costs and total benefits.

2.6.2 Dealing with the uncertainties and limitations in the assessment of results

There are several important considerations to take when interpreting the results of the integrated Health BCA.

Interpretation of premature mortality must be done with care. It is worth noting that these numbers are indicators of health risk at a population level. The relative risk estimate inherent in the ERF is a metric of the likelihood of an adverse health outcome and cannot be attributed to an individual. It can thus be used to quantify risk to a defined population (and not to an individual) (WHO, 2016a), and how this risk would vary between various policy options of scenarios.

The various sources of uncertainty discussed above, affect the accuracy of the absolute values of the assessments. In the absence of primary ERF studies, it is not possible to judge the accuracy of the absolute values of the assessment with a high level of confidence. However, this report uses ranges to reflect uncertainty.

Despite the various sources of uncertainty discussed above, the analysis still provides valuable insights into the comparison of the scenarios tested in the BCA. This is because the uncertainty inherent in the analysis remains constant across all scenarios.

The description of uncertainty sources also serves as a basis for prioritising further work to improve future integrated Health BCAs.

3 RESULTS AND DISCUSSION

3.1 Summary of results

3.1.1 Technical Scenarios

In 2025, within the modelled domain (108,900 km^2), approximately 1.67 million people are exposed to the air pollution from Medupi and Matimba power stations. The additional annual average exposure to air pollution of the population within this modelled domain, resulting from the coal-fired power station emissions, was estimated by averaging the dispersion modelling results for the population residing within each of the model grid cells. Out of the total population approximately 1.5 million people (91%) were exposed to more than an additional 1 $\mu g/m^3$ (mean annual) of SO_2 within the modelled domain. Similarly, 203,000 were exposed to an additional 1 $\mu g/m^3$ (mean annual) of $PM_{2.5}$ (including secondary nitrates and sulphates). Within the modelled domain no people were exposed to more than an additional 1 $\mu g/m^3$ (mean annual) of NO_2.

Health benefits associated with each scenario were calculated against the future baseline that considered the anticipated increase in future loads, assumed no abatement technologies installed and that both stations would continue to emit air pollution at their current rates until shutdown. Results are presented separately for the three alternative shutdown dates of 2071, 2055 and 2045 as per the Minister's Decision requirements.

The three technical scenarios (Scenario C wet FGD, Scenario D semi-dry FGD and Scenario E dry FGD) were compared in a benefit-cost analysis (BCA). The BCA apportioned costs (all capital and operational expenditure on abatement technologies) and benefits (health benefits - avoided premature mortality and morbidity effects) to the years in which they would be realised. Because costs and benefits are accrued in different years according to the intervention schedules, the net present values of costs and benefits, used Eskom's weighted average cost of capital (WACC) rate of 10.8% as the discount rate (Eskom, 2024b), and additional sensitivity analysis testing using a social discount rate of 2% (Stern, 2006), allowing for an objective comparison of scenarios. Separate analyses were conducted for each of the alternative shutdown dates and are presented as part of the sub-sections 3.1.1.1 to 3.1.1.3 below.

In the upper estimates of the BCA ratios, the lower costs and higher VSL and COI are used and in the lower estimates, the higher costs and lower VSL and COI are used as recommended by Robinson et al. 2018.

The BCA ratios need to be interpreted with care. They are meant only to provide a perspective on and to inform the decision-making process underlying the scenarios. They are not meant to be interpreted as a definitive answer to making abatement decisions. Decisions involving human health must be informed by non-economic criteria as well. In addition, with uncertainty inherent in the analysis, the benefit-cost ratio should not be viewed as absolute, but rather as a relative value from which to compare scenarios.

3.1.1.1 BCA Timeline 2025 - 2071

The **health benefits** over the 2025-2071 timeline period are summarised in Figure 3-1:

- The health benefits have an impact from the year that the specific abatement technology starts to be commissioned. The commissioning start dates differ for the three different abatement technologies in each of the scenarios. Wet FGD (Scenario C) is commissioned at Medupi from 2030 to 2034, semi-dry FGD (Scenario D) is commissioned at Medupi from 2032 to 2035 and dry FGD (Scenario E) is commissioned at Medupi from 2031 to 2034. While there are no abatement technologies being commissioned at Matimba, the station's shutdown schedule results in health benefits without the associated abatement costs. These benefits are seen in all scenarios as Matimba is decommissioned from 2039 to 2043. The health benefits from the wet, semi-dry and dry FGD at Medupi continue until Medupi shutdown, with full station lifetime shutdown being from 2066 to 2071.
- The overall highest associated health benefits across the modelled timeline are seen in Scenario C with wet FGD.
- In some years Scenario C with wet FGD delivers slightly lower associated health benefits in comparison to Scenario D. This is likely due to the different stack velocities and the dispersion patterns resulting when comparing semi-dry and wet FGD technologies.
- The lowest associated health benefits are seen in Scenario E with the dry FGD being installed at Medupi.
- It is further noted that health benefits increase over time post-retrofit until station shutdown due to population growth across the timeline and not due to changes in the emission impact.

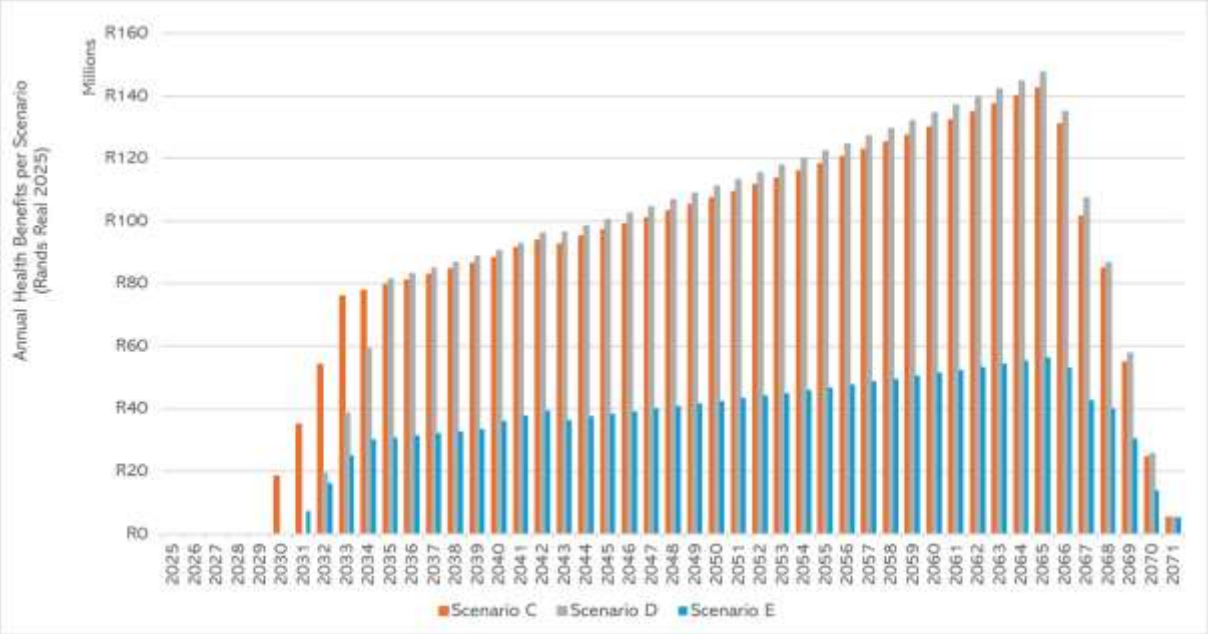

Figure 3-1: Annual health benefits per scenario illustrating the timeline of cumulative health benefits from 2025 to 2071.

The **abatement costs** associated with each scenario are set out in Figure 3-2:

- Wet FGD (Scenario C): Capex costs for implementation of wet FGD at Medupi start in 2027, with operational costs kicking in with the first two retrofit units in 2030, followed by a single unit in 2031 and 2032 and the final two units in 2033 During this period there are additional opportunity costs due to outages (43 days per unit) for the unit retrofits from 2030 to 2033. Once all retrofits are completed, operational costs continue until plant shutdown growing annually with Producer Price Index (PPI) escalation. The operational costs then decrease as units are shutdown from 2066 to 2071. The additional carbon costs associated with the additional direct process-related CO_2 emissions from the sorbent used in the wet FGD process are also reflected across the operational timeline and decrease as units are shutdown.
- Semi-dry FGD (Scenario D): Capex costs for implementation of semi-dry FGD start in 2032 and continue until retrofit completion in 2035. One unit is retrofitted per year in 2032 and 2033, followed by two units in each year in 2034 and 2035. The operational costs start with the first unit retrofit in 2032 and opportunity costs due to outages (highest outage days at 129 per unit) occurring during the retrofit period from 2032 up to 2035. Semi-dry FGD is not expected to have any associated additional carbon costs as the sorbent used in the semi-dry process does not produce any process-related CO_2. Operational costs (with annual PPI increases) continue until the Medupi shutdown from 2066 to 2071.

- Dry FGD (Scenario E): Capex costs for implementation of dry FGD start in 2031 and continue until the completion of retrofits in 2034. One unit is retrofitted per year in 2031 and 2032, followed by two units in each year in 2033 and 2034. As each unit retrofit is completed the operational costs start as from 2031 and continue (with annual PPI increases) until the Medupi plant shutdown from 2066 to 2071. During unit retrofits there are 86 days per unit outage days and the associated costs. As with semi-dry FGD, the dry FGD process sorbents do not produce any additional process-related CO_2 and thus no additional carbon related costs.

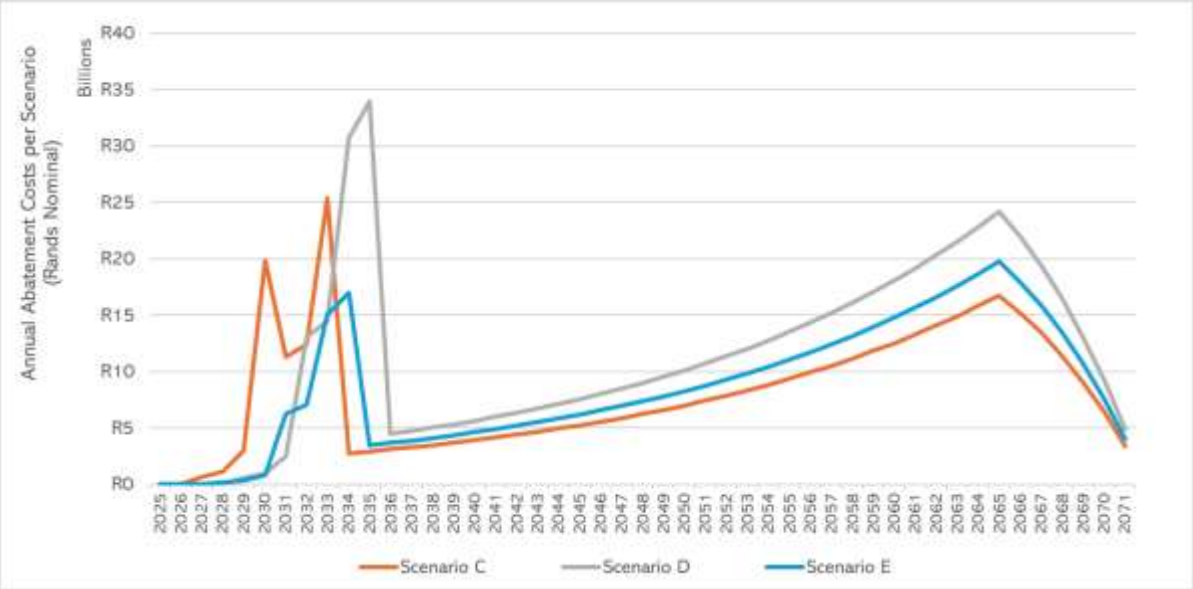

Figure 3-2: Total abatement costs (CAPEX, OPEX, carbon and opportunity costs) associated with each scenario's specific FGD abatement retrofits from 2025 to 2071.

The BCA results for the 2025 to 2071 timeline are provided in Table 3-1:

- The benefit-cost ratios of all the scenarios are significantly less than 1, even under the most optimistic (upper bound) parameters of the sensitivity analysis. The upper range ratios do not exceed approximately 0.05, implying that less than five cents of quantified health benefit is generated per rand of expenditure.
- Evaluation of the BCA ratios at a social discount rate of 2% delivers similar results, with all three scenarios ratios remaining less than 1.
- Scenario C (wet FGD) generates the largest absolute health benefits, consistent with higher SO_2 removal efficiency. These gains are however outweighed by the significantly higher capital, operational and retrofit-related costs, leading to the largest negative NPVs among the scenarios.
- Scenarios D (semi-dry FGD) and E (dry FGD), although having lower lifecycle costs as expressed by "NPV of Costs" result in BCA ratios that are even less favourable than Scenario C (wet FGD).

Table 3-1: BCA ratios (lower and upper) for each scenario (discounted at Eskom WACC) in the 2025 - 2071 period

	Scenario C Wet FGD		**Scenario D Semi-dry FGD**		**Scenario E Dry FGD**	
Million Rands	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
NPV of Costs	-36,190	-25,635	-34,126	-24,173	-21,983	-15,571
NPV of Benefits	172	954	149	828	63	351
NPV of Benefits minus Costs	-36,018	-24,681	-33,977	-23,345	-21,919	-15,220
Benefit:Cost Ratio (*range*)	0.0048	0.0372	0.0044	0.0342	0.0029	0.0226
Benefit:Cost Ratio (*central*)	0.0210		0.0193		0.0127	

In the analyses above, the health benefits associated with closure of power stations form part of the baseline. Thus, the cumulative health benefits over time are not reflected in the BCA ratios presented above.

- The power stations planned shutdown schedule (section 2.3.3.2 for the years in which this occurs) results in health benefits without associated abatement costs. These benefits, which are dependent on the timing of the shutdown schedule, have been assumed to form part of the BCA baseline and have therefore not been quantified directly in the BCA.
- To contextualise the three scenarios that were analysed with respect to the baseline, a visual representation (Figure 3-4, Figure 3-5, Figure 3-6) shows how each of these scenarios contributes to the cumulative health benefits over the analysed timeframe (full-term power station lifetime). The green area illustrates the health benefits realised as a result of station shutdowns relative to the baseline emission impact, showing that as stations shut down, the population is exposed to less pollution, and the health benefits increase. The orange, grey and blue areas indicate the additional health benefits of the scenarios described above. The figures show the effectiveness of station shutdowns in decreasing health impacts and increasing of health benefits.
- The health benefits from the respective scenarios contribute up to an additional 2.7 times the health benefits of the baseline (estimated on a net present value basis).
- To better demonstrate the relative benefit for scenarios C, D and E and the plant closures of Matimba and Medupi, the figures are presented in Real Rand terms.

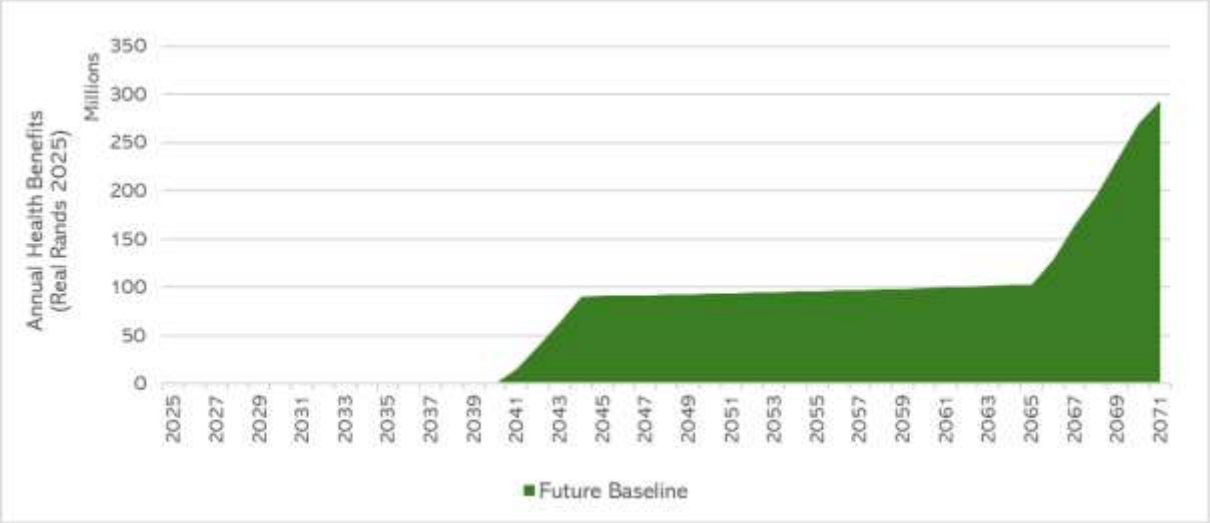

Figure 3-3: Cumulative annual health benefits in the baseline with planned power station shutdown of Matimba and Medupi (2025 to 2071 timeline).

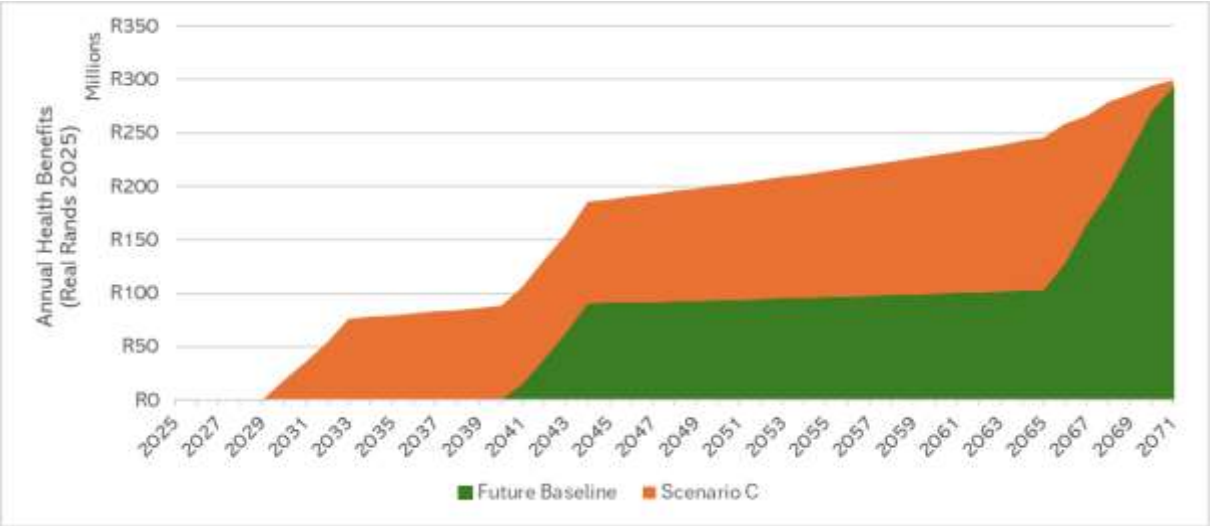

Figure 3-4: Cumulative health benefits of Scenario C (wet FGD) over the baseline (2025 to 2071).

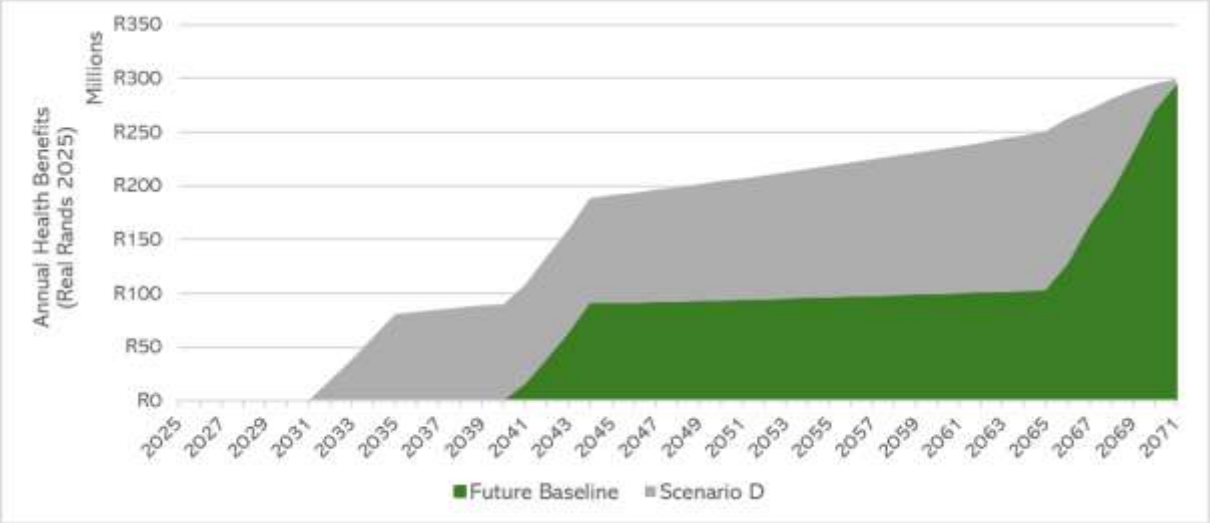

Figure 3-5: Cumulative health benefits of Scenario D (semi-dry FGD) over the baseline (2025 to 2071).

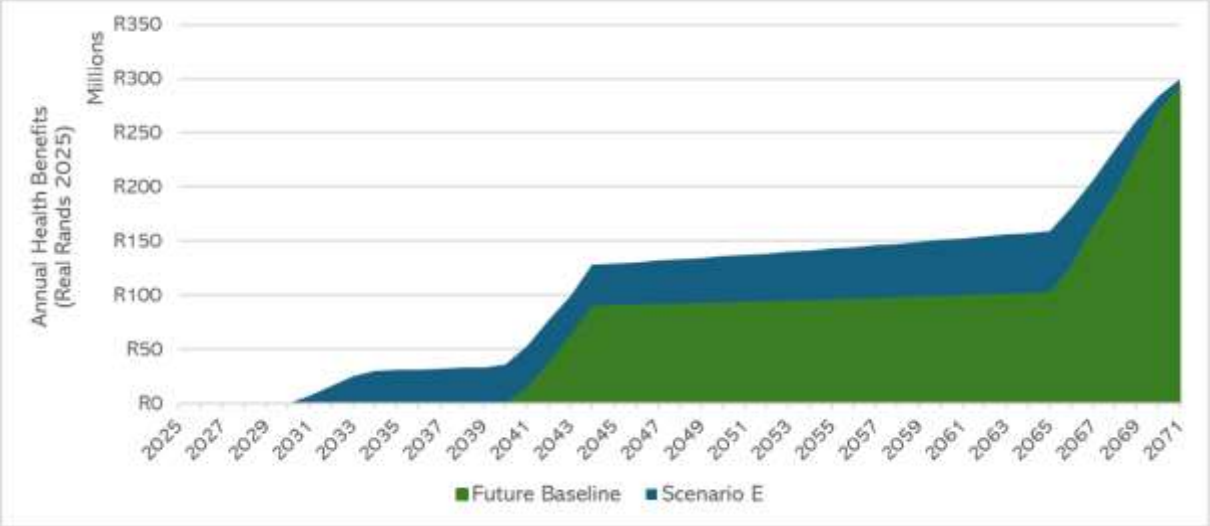

Figure 3-6: Cumulative health benefits of Scenario E (dry FGD) over the baseline (2025 to 2071).

3.1.1.2 BCA Timeline 2025 - 2055

The **health benefits** over the shorter timeline period with Medupi shutdown completed in 2055 are summarised in Figure 3-7:

- Similar to full station lifetime (shutdown by 2071), in this shorter timeline span with early plant shutdown (by 2055), we see the same pattern with the health benefits having an impact from the year that the specific abatement technology starts to be commissioned. As discussed in Section 3.1.1.1, wet FGD (Scenario C) is commissioned first at Medupi from 2030 to 2034, followed by semi-dry FGD (Scenario D) from 2032 to 2035 and lastly the dry FGD (Scenario E) from 2031 to 2034. In the shorter timeline span, we see the same health

benefit patterns as observed in the longer operations timeline, however the magnitude of this impact is reduced due to lower emissions impact with early station shutdown. While there are no abatement technologies being commissioned at Matimba, the station's shutdown schedule results in health benefits without the associated abatement costs. These benefits are seen in all scenarios as Matimba is decommissioned from 2039 to 2043. The health benefits from the wet, semi-dry and dry FGD at Medupi continue until Medupi early shutdown from 2050 to 2055.

- The highest overall associated health benefits are seen for wet FGD in Scenario C, with Scenario D delivering slightly lower associated health benefits.
- The lowest associated health benefits are seen in Scenario E with the dry FGD being installed at Medupi. The benefits are considerably lower than for Wet FGD and semi-dry FGD.

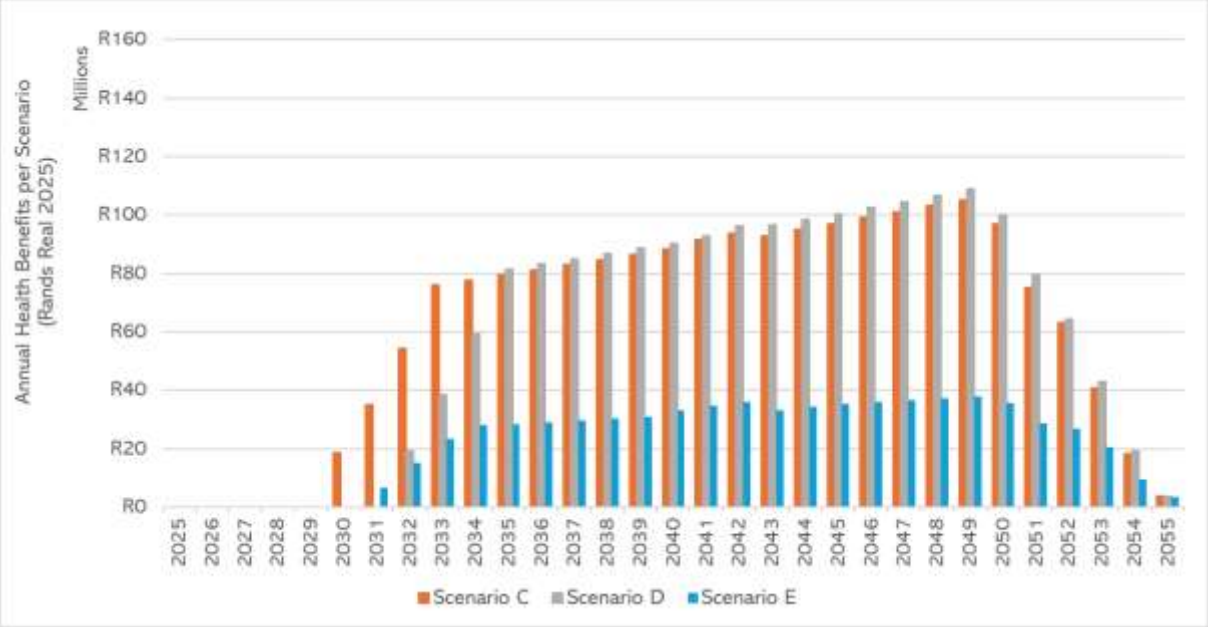

Figure 3-7: Annual health benefits per scenario illustrating the timeline of cumulative health benefits from 2025 to 2055.

The **abatement costs** associated with each scenario are set out in Figure 3-8:

- The capex costs for implementation of wet FGD (Scenario C), semi-dry FGD (Scenario D) and dry FGD (Scenario E) were discussed above in section 3.1.1.1 and remain relevant here.
- Once all retrofits are completed, the difference in the shorter timeline span is seen in the reduced total operational costs because of the earlier shutdown that takes place from 2050 to 2055.
- The operational opportunity costs due to outages (43 outage days per unit for wet FGD, 86 outage days per unit for semi-dry FGD and 129 outage days per unit for dry FGD) remain the same.

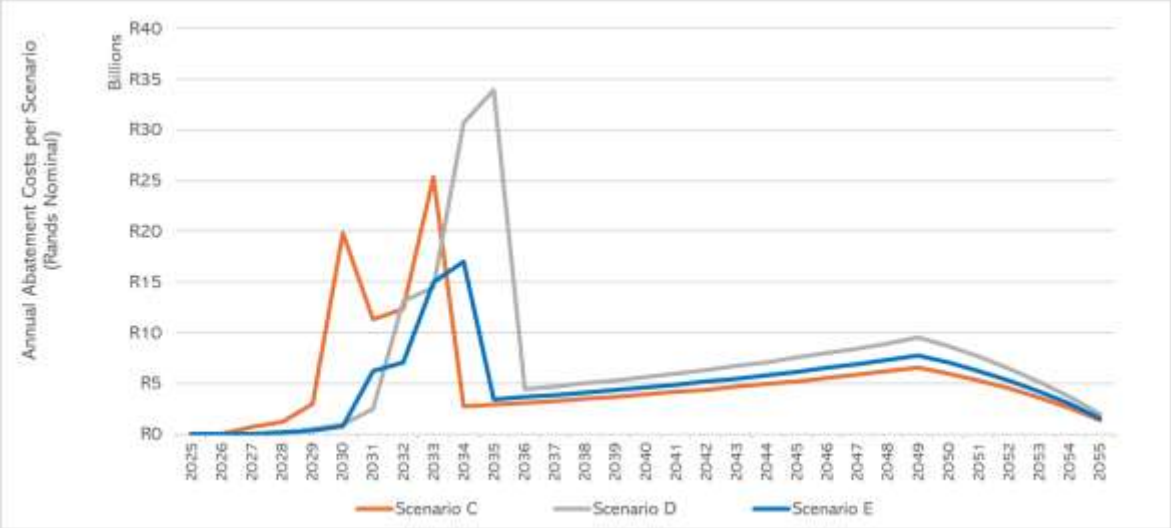

Figure 3-8: Total abatement costs (CAPEX, OPEX, carbon and opportunity costs) associated with each scenario's specific FGD abatement retrofits from 2025 to 2055.

The BCA results for the 2025 to 2055 timeline are provided in Table 3-2:

- The BCA for this shorter timeline yields the same pattern of results as was seen in the longer station life scenario discussed in section 3.1.1.1 and BCA ratios are significantly less than 1.
- Evaluation of the BCA ratios at a social discount rate of 2% in the shorter timeline span also delivers similar results, with all three scenarios ratios remaining less than 1.
- Scenario C (wet FGD) remains the scenario with the largest absolute health benefits and BCA ratio, with gains outweighed by the significantly higher costs to install and operate this technology.
- Scenario D (semi-dry FGD) and E (dry FGD) BCA ratios remain even less favourable than Scenario C in the shorter timeline.

Table 3-2: BCA ratios (lower and upper) for each scenario (discounted at Eskom WACC) in the 2025 - 2055 period

	Scenario C Wet FGD		Scenario D Semi-dry FGD		Scenario E Dry FGD	
Million Rands	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
NPV of Costs	-35,346	-25,037	-32,909	-23,310	-20,987	-14,866
NPV of Benefits	149	825	125	694	52	302
NPV of Benefits minus Costs	-35,197	-24,212	-32,783	-22,616	-20,935	-14,564
Benefit:Cost Ratio (*range*)	0.0042	0.0329	0.0038	0.0298	0.0025	0.0203
Benefit:Cost Ratio (*central*)	0.0186		0.0168		0.0114	

As discussed in section3.1.1.1, in the analyses for the 2025 to 2055 shorter station lifetime above, the health benefits associated with closure of the two power stations form part of the baseline. Thus, the cumulative health benefits over time are not reflected in the BCA ratios presented above.

- The Matimba power station shutdown by 2043 and the Medupi power station shutdown by 2055 (first alternative early shutdown timeline) result in health benefits without associated abatement costs. These benefits, which are dependent on the timing of the shutdown schedule, have been assumed to form part of the BCA baseline and have therefore not been quantified directly in the BCA.
- Figure 3-10, Figure 3-11 and Figure 3-12 provide a visual representation to contextualise the three scenarios that were analysed with respect to the baseline, showing how each of these scenarios contributes to the cumulative health benefits over the analysed timeframe (early station shutdown). The green area illustrates the health benefits realised as a result of station shutdowns relative to the baseline emission impact, showing that as stations shutdown, the population is exposed to less pollution, and the health benefits increase. The orange, grey and blue areas indicate the additional health benefits of the scenarios described above. The figures show the effectiveness of station shutdowns in decreasing health impacts and increasing of health benefits.
- The health benefits from the respective scenarios contribute up to an additional 2.6 times the health benefits of the baseline (estimated on a net present value basis).
- To better demonstrate the relative benefit for scenarios C (wet FGD), D (semi-dry FGD) and E (dry FGD) and the plant closures of Matimba and Medupi, the figures are presented in Real Rand terms.

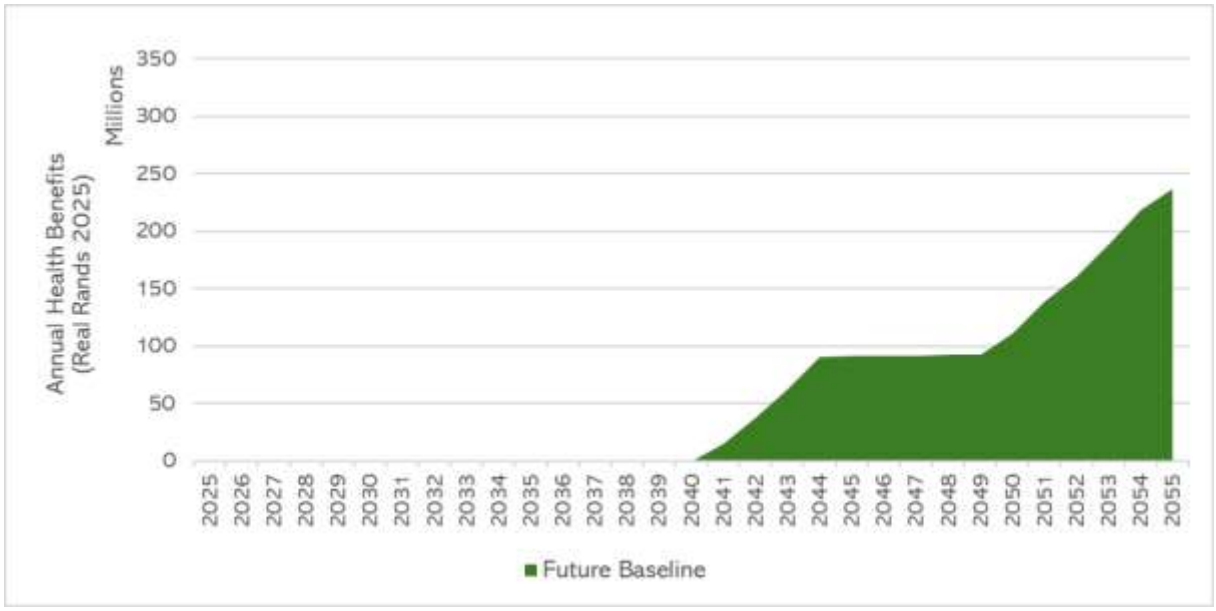

Figure 3-9: Cumulative annual health benefits in the baseline with planned power station shutdown of Matimba and Medupi (2025 to 2055 timeline).

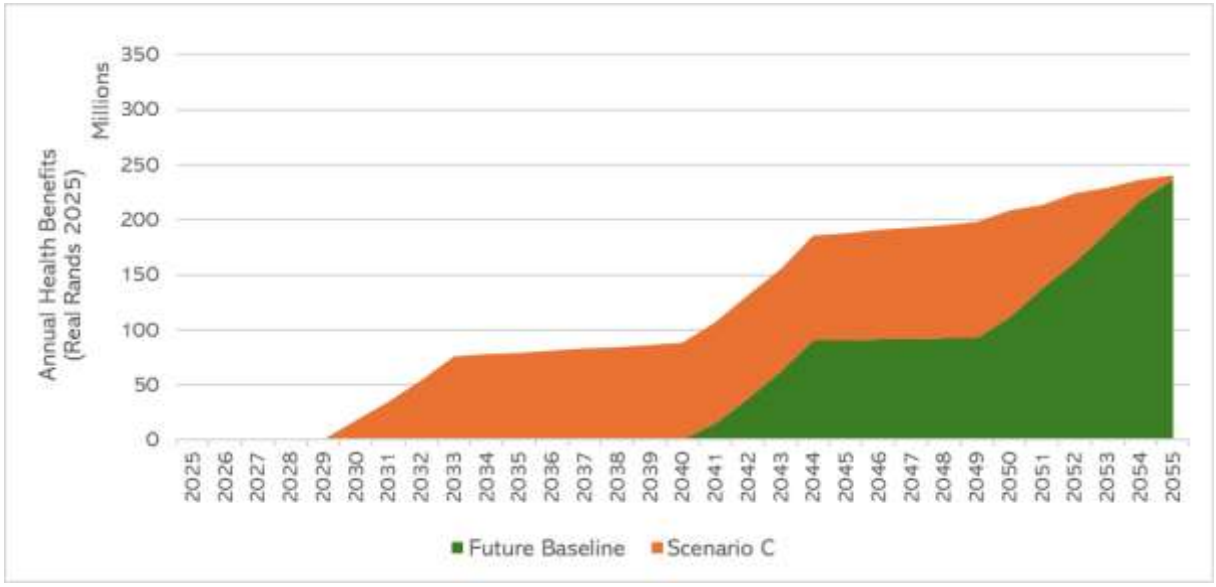

Figure 3-10: Cumulative health benefits of Scenario C (wet FGD) over the baseline (2025 to 2055).

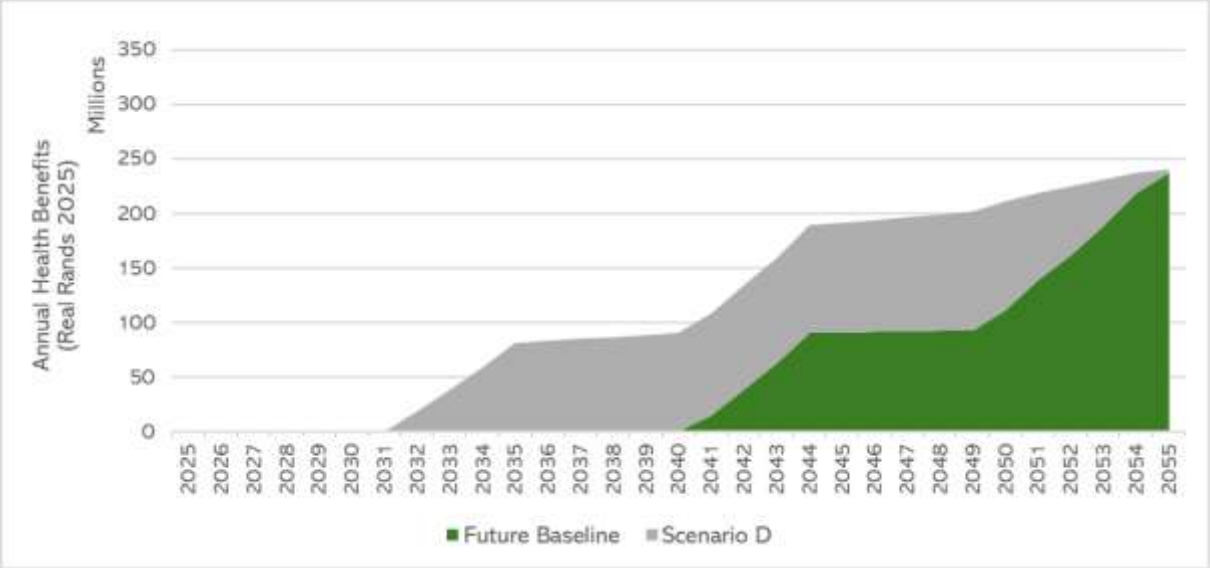

Figure 3-11: Cumulative health benefits of Scenario D (semi-dry FGD) over the baseline (2025 to 2055).

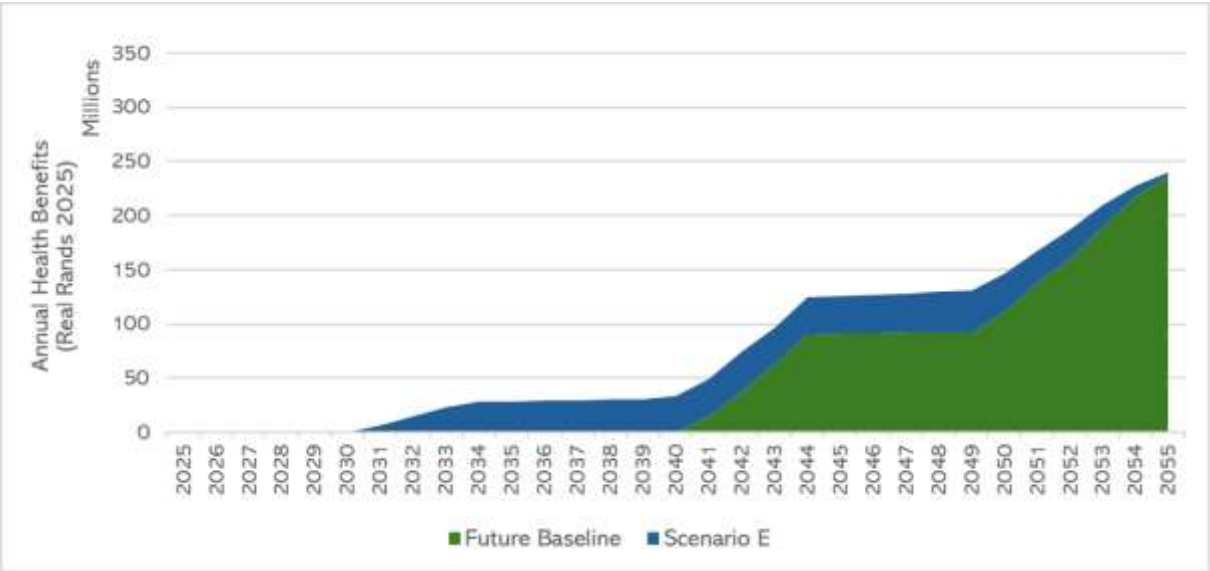

Figure 3-12: Cumulative health benefits of Scenario E (dry FGD) over the baseline (2025 to 2055).

3.1.1.3 BCA Timeline 2025 - 2045

The **health benefits** over the shortest modelled timeline period for Medupi shutdown by 2055 are summarised in Figure 3-13:

- As was seen for other alternative Medupi shutdown dates of 2071 and 2055, in the shortest timeline span, we see the same pattern with the health benefits having an impact from the year that the specific abatement technology starts to be commissioned (see the above sections 3.1.1.1 and 3.1.1.2 for the respective abatement technology retrofit period dates. In this shortest timeline span we see similar patterns as observed in the longer operations

timeline. However, with the shorter timeline, the Medupi power station shutdown schedule coincides with that of the Matimba power station. Matimba is decommissioned from 2039 to 2043 and Medupi from 2040 to 2045. While this does bring health benefits to the region the increased health benefits from the installation of the Wet, semi-dry or dry FGD at Medupi are then only for a brief period until 2045 when the station is shutdown.

- The highest overall associated health benefits are seen in scenario C for wet FGD with slightly lower associated health benefits seen in Scenario D for semi-dry FGD.
- The lowest associated health benefits are seen in Scenario E with the dry FGD being installed at Medupi, however in this shorter timeline the proportional difference in comparison to the wet FGD and semi-dry FGD benefits is much smaller than observed in the longer timelines.

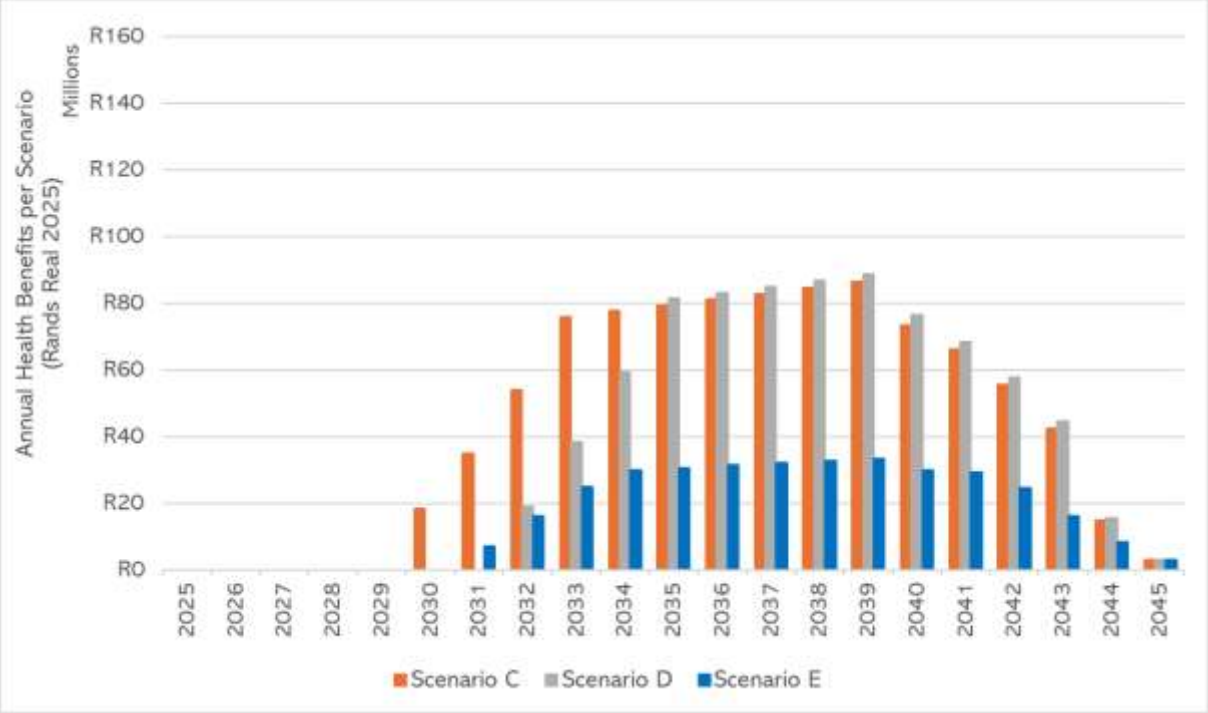

Figure 3-13: Annual health benefits per scenario illustrating the timeline of cumulative health benefits from 2025 to 2045.

The **abatement costs** associated with each scenario are set out in Figure 3-14:

- The capex costs for implementation of wet FGD (Scenario C), semi-dry FGD (Scenario D) and dry FGD (Scenario E) were discussed above in section 3.1.1.1 and remain the same here.
- Once all retrofits are completed, the shortest timeline span has much reduced total operational costs with the much earlier shutdown that takes place from 2040 to 2045.

- The operational opportunity costs due to outages (43 outage days per unit for wet FGD, 86 outage days per unit for semi-dry FGD and 129 outage days per unit for dry FGD) remain the same in this alternative timeline span.

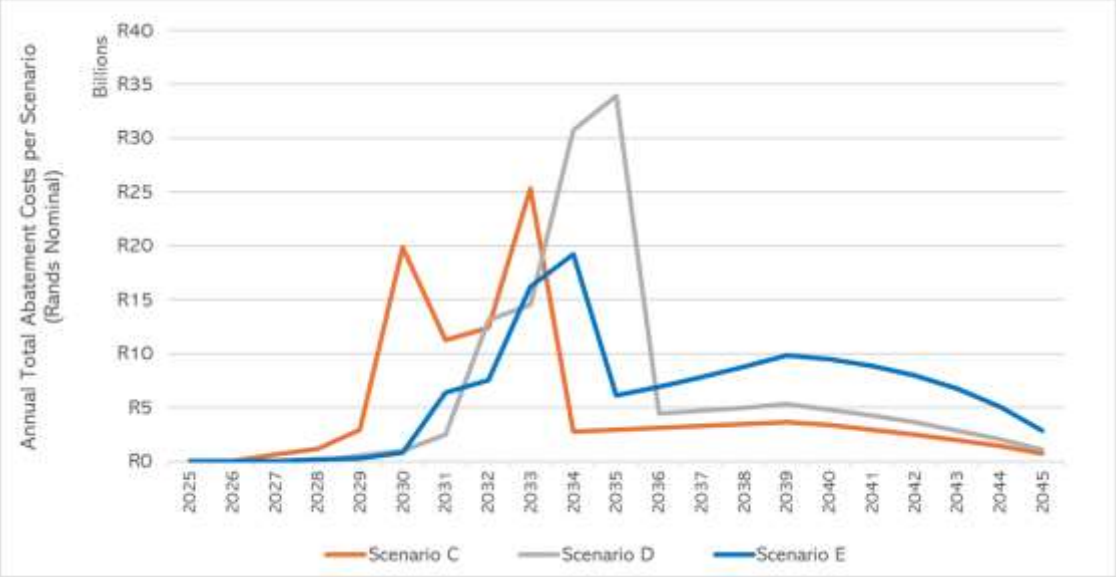

Figure 3-14: Total abatement costs (CAPEX, OPEX, carbon and opportunity costs) associated with each scenario's specific FGD abatement retrofits from 2025 to 2045.

The BCA results for the 2025 to 2045 timeline are provided in Table 3-3:

- The BCA for this shortest timeline yields the same pattern of results as was seen in the other two station life scenarios discussed in section 3.1.1.1 and 3.1.1.2.
- Evaluation of the BCA ratios at a social discount rate of 2% also delivers similar results, with all three scenarios ratios remaining less than 1.
- In this shortest timeline we also see Scenario C (wet FGD) with the largest absolute health benefits outweighed by the significantly higher costs to install and operate this technology.

Table 3-3: BCA ratios (lower and upper) for each scenario (discounted at Eskom WACC) in the 2025 - 2045 period

	Scenario C Wet FGD		**Scenario D Semi-dry FGD**		**Scenario E Dry FGD**	
Million Rands	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
NPV of Costs	-33,474	-23,711	-30,207	-21,397	-24,867	-17,614
NPV of Benefits	109	601	84	465	39	213
NPV of Benefits minus Costs	-33,365	-23,109	-30,123	-20,932	-24,829	-17,401
Benefit:Cost Ratio (*range*)	0.0033	0.0254	0.0028	0.0217	0.0016	0.0121
Benefit:Cost Ratio (*central*)	0.0143		0.0123		0.0068	

In the analyses above for this shortest Medupi station lifetime timeline, as was the case in the previous timelines discussed in section 3.1.1.1 and 3.1.1.2, the health benefits associated with closure of the two power stations form part of the baseline. Thus, the cumulative health benefits over time are not reflected in the BCA ratios presented above.

- The Matimba power station shutdown by 2043 and the Medupi power station shutdown by 2045 (second alternative early shutdown timeline) result in health benefits without associated abatement costs. These benefits, which are dependent on the timing of the shutdown schedule, have been assumed to form part of the BCA baseline and have therefore not been quantified directly in the BCA.
- Figure 3-16, Figure 3-17 and Figure 3-18 provide a visual representation to contextualise the three scenarios that were analysed with respect to the baseline, showing how each of these scenarios contributes to the cumulative health benefits over the analysed timeframe (earliest station shutdown). The green area illustrates the health benefits realised as a result of station shutdowns relative to the baseline emission impact, showing that as stations shutdown the population is exposed to less pollution and the health benefits increase. The orange, grey and blue areas indicate the additional health benefits of the scenarios described above. The figures show the effectiveness of station shutdowns in decreasing health impacts and increasing of health benefits.
- The health benefits from the respective scenarios contribute up to an additional 2.6 times the health benefits of the baseline (estimated on a net present value basis).

- To better demonstrate the relative benefit for scenarios C (wet FGD), D (semi-dry FGD) and E (dry FGD) and the plant closures of Matimba and Medupi, the figures are presented in Real Rand terms.

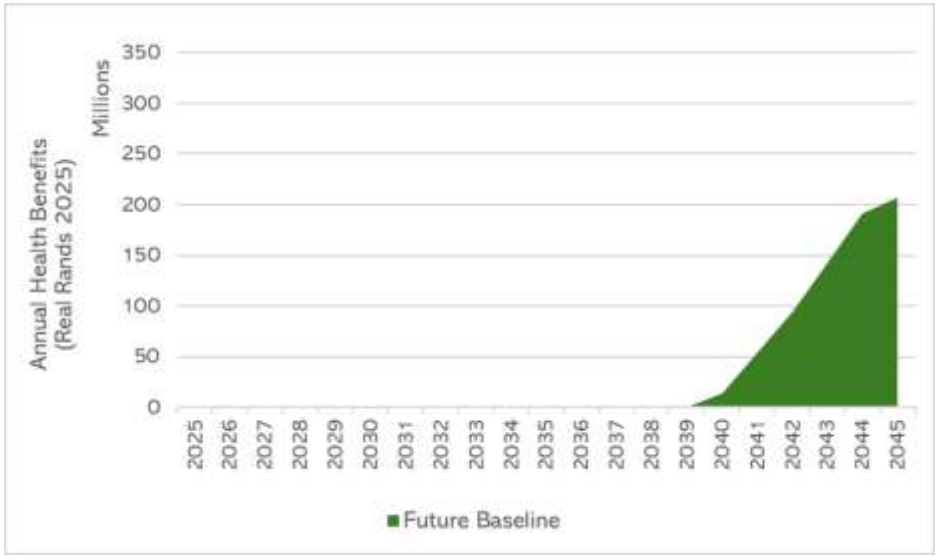

Figure 3-15: Cumulative annual health benefits in the baseline with planned power station shutdown of Matimba and Medupi (2025 to 2045 timeline).

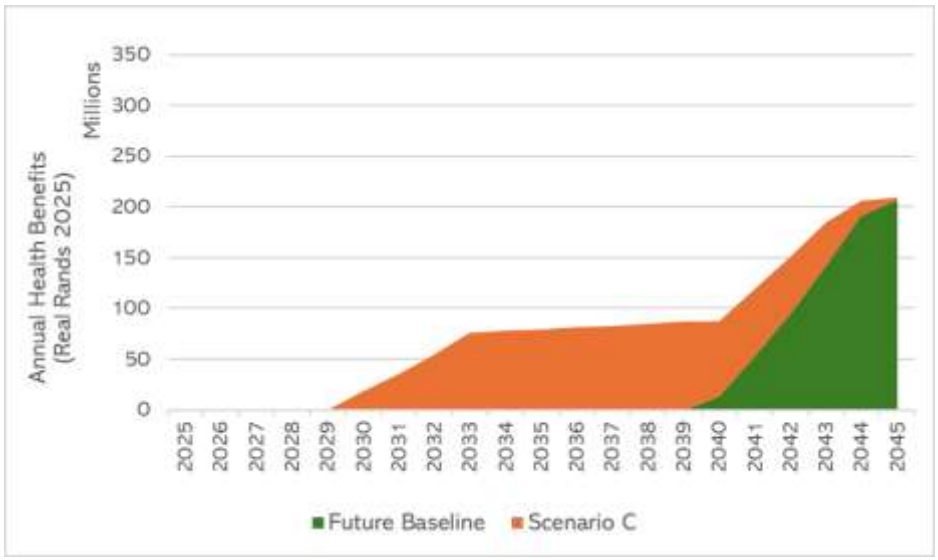

Figure 3-16: Cumulative health benefits of Scenario C (wet FGD) over the baseline (2025 to 2045).

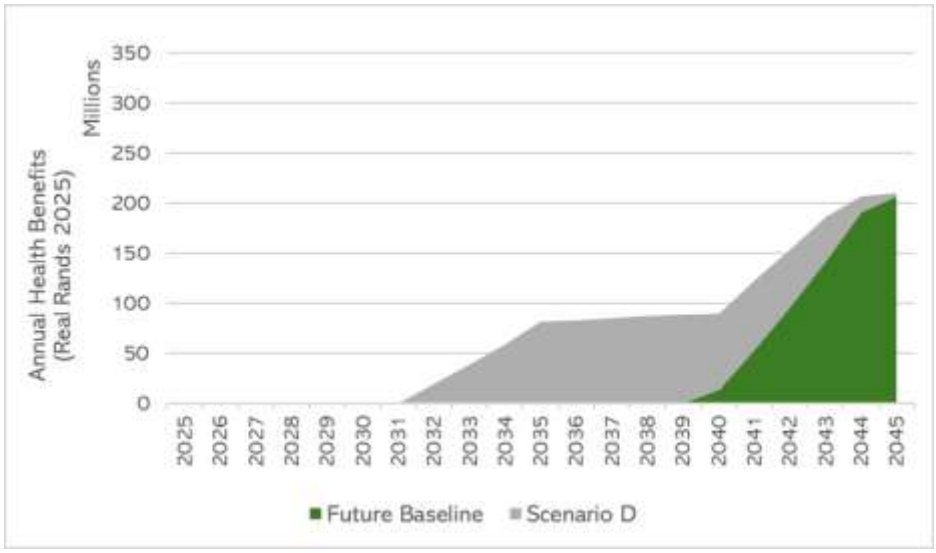

Figure 3-17: Cumulative health benefits of Scenario D (semi-dry FGD) over the baseline (2025 to 2045).

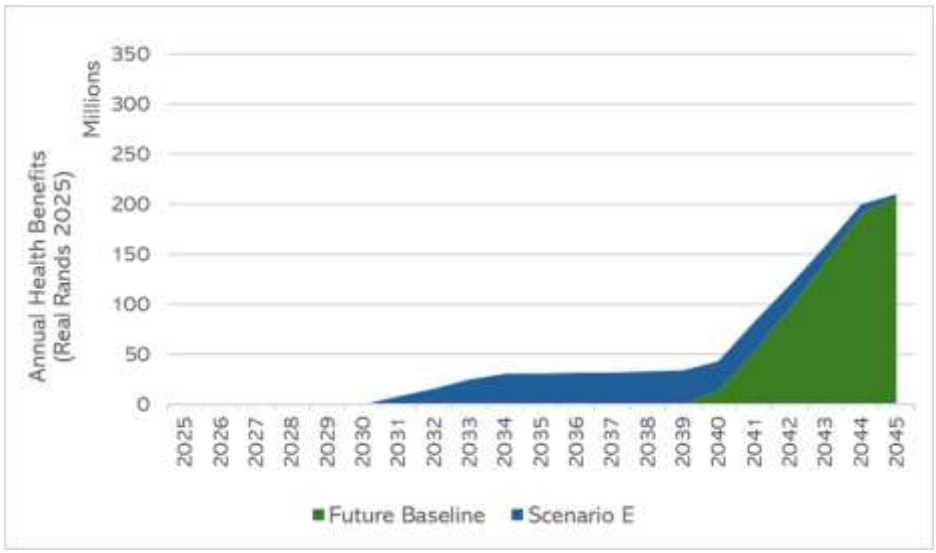

Figure 3-18: Cumulative health benefits of Scenario E (dry FGD) over the baseline (2025 to 2045).

3.1.2 Alternative Scenarios

Health benefits were estimated using all-cause mortality projections available to 2045. To account for decommissioning scenarios that extend to 2055 and 2071, in line with the Minister's request, the health benefits beyond 2045 were projected based on the historic (2024-2045) trend. The reported health benefits should therefore be interpreted as conservative. This limitation applies to all alternative scenarios assessed in the analyses, with the exception of the AQO programme. In addition to SO_2-related health impacts, $PM_{2.5}$-related health benefits were also quantified for the AQO Programme only, as this intervention directly targets household-level exposure pathways. For coal beneficiation, the reported results exclude the WBPA, as coal supplied to this region is already beneficiated and cannot be further beneficiated within the scope of the intervention.

3.1.2.1 Summary of BCA Results

The BCA results for each alternative scenario is summarised in the following three tables (Table 3-4, Table 3-5and Table 3-6), with each table representing the different timelines:

Table 3-4: BCA ratios (lower and upper) for each scenario (discounted at Eskom WACC) in the 2025 - 2071 period

	Eskom AQO Programme ($PM_{2.5}$)		Eskom AQO Programme (SO_2)		Coal beneficiation		HELE		CCUS		LDES		SMR	
Million Rands	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
NPV of Costs	3,426	3,426	3,426	3,426	42,847	128,540	5,634	7,300	196,592	1,489,712	-	-	-	-
NPV of Benefits	53,305	233,281	10,571	25,475	1,746	5,238	1,282	1,453	9,985	11,036	84.1	126.2	261	3,920
NPV of Benefits minus Costs	49,879	229,855	7,145	22,049	-41,100	-123,300	-4,350	-5,845	-186,600	-1,478,669	84.1	126.2	261	3,920
Benefit:Cost Ratio (*range*)	15.6	68.1	3.1	7.4	0.041	0.041	0.228	0.199	0.051	0.007	n/a	n/a	n/a	n/a
Benefit:Cost Ratio (*central*)	35.2		5.1		0.041		0.212		0.012		n/a		n/a	

Table 3-5: BCA ratios (lower and upper) for each scenario (discounted at Eskom WACC) in the 2025 - 2055 period

	Eskom AQO Programme ($PM_{2.5}$)		Eskom AQO Programme (SO_2)		Coal beneficiation		HELE		CCUS		LDES		SMR	
Million Rands	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
NPV of Costs	3,426	3,426	3,426	3,426	42,510	127,530	5,570	7,217	181,979	1,378,062	-	-	-	-
NPV of Benefits	49,498	216,621	9,816	23,655	1,746	5,237	1,282	1,453	9,771	10,799	84.1	126.1	261	3,910
NPV of Benefits minus Costs	46,072	213,195	6,390	20,229	-40,764	-122,291	-4,287	-5,763	-172,204	-1,367,258	84.1	126.1	261	3,910
Benefit:Cost Ratio (*range*)	14.4	63.2	2.9	6.9	0.041	0.041	0.230	0.201	0.054	0.008	n/a	n/a	n/a	n/a
Benefit:Cost Ratio (*central*)	32.7		4.7		0.041		0.214		0.013		n/a		n/a	

Table 3-6: BCA ratios (lower and upper) for each scenario (discounted at Eskom WACC)in the 2025 - 2045 period

	Eskom AQO Programme ($PM_{2.5}$)		Eskom AQO Programme (SO_2)		Coal beneficiation		HELE		CCUS		LDES		SMR	
Million Rands	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
NPV of Costs	3,426	3,426	3,426	3,426	41,319	123,958	5,429	7,032	149,556	1,130,348	-	-	-	-
NPV of Benefits	42,615	186,498	8,451	20,366	1,745	5,234	1,279	1,449	9,290	10,268	83.9	125.8	259	3 887
NPV of Benefits minus Costs	39,189	183,072	5,025	16,940	-39,574	-118,724	-4150	- 5,583	-140,266	-1,120,080	83.9	125.8	259	3 887
Benefit:Cost Ratio (*range*)	12.4	54.4	2.5	5.9	0.042	0.042	0.236	0.206	0.062	0.009	n/a	n/a	n/a	n/a
Benefit:Cost Ratio (*central*)	28.2		4.0		0.042		0.219		0.015		n/a		n/a	

3.1.2.2 Primary health-risk mitigation: AQO Programme

For the purposes of modelling the benefits and costs, it is assumed the AQO programme is implemented from 2026 to 2030 (a 5-year period). Across all timelines, the health benefits from the AQO programme begin immediately following implementation and increase rapidly during the implementation period until 2030. Thereafter, benefits continue to increase, however, at a slower rate until the final decommissioning year (i.e., 2071, 2055 or 2045).

Across all timelines, the costs of implementation are incurred from 2026 to 2030 and remain constant throughout the rollout period as it has been assumed that the same number of households are targeted each year.

The AQO Programme delivers substantial net benefits across both $PM_{2.5}$ and SO_2 reductions. For the 2025 - 2071 timeline, the net present value of health benefits associated with $PM_{2.5}$ reductions ranges from approximately R53 to R233 billion (Table 3-4), while benefits from SO_2 reductions range from R10 to R25 billion, compared to implementation costs of R3.4 billion. The higher magnitude of benefits associated with $PM_{2.5}$ reflects its stronger and more direct relationship with all-cause mortality, as well as its ability to affect a broader exposed population due to its persistence and dispersion. The resulting benefit-cost ratio is considerably higher than 1 for both pollutants, indicating that benefits outweigh costs and highlighting the strong economic case for targeted household-level air quality interventions.

For the 2025 - 2055 timeline the AQO Programme continues to demonstrate strong economic performance across both $PM_{2.5}$ and SO_2 reductions. The net present value of health benefits is slightly less than the 2071 timeline, with the value of the benefits being R49 - 216 billion and R10 - 24 billion for $PM_{2.5}$ and SO_2, respectively (Table 3-5). The costs remain unchanged from the 2071 assessment. The benefit-cost ratios remain well above 1 for both pollutants, reinforcing the robustness of this intervention even across shorter timeframes.

For the 2025 - 2045 timeline, the AQO Programme delivers substantial health benefits across both $PM_{2.5}$ and SO_2 reductions, with SO_2-related benefits in the range of R8 to R20 billion relative to costs of R3.4 billion. Benefit-cost ratios remain above 1, indicating that benefits outweigh costs even over this shorter timeframe.

Table 3-7 summarises the key advantages and limitations of the AQO Programme, focusing on implementation practicality and the nature of the associated health benefits, to complement the BCA results presented above.

Table 3-7: Summary of key advantages and limitations of the AQO programme

Pros:	Cons:
Delivers direct and immediate reductions in household-level exposure to $PM_{2.5}$ and SO_2	Requires large-scale programme coordination and household uptake
Strong and well-established link to improved health outcomes, particularly for vulnerable groups	Implementation success depends on effective targeting and sustained funding
Benefits accrue rapidly and are highly localised in priority areas	Limited impact on emissions from large point sources that affect large areas
Proven intervention with credible technology	Requires ongoing monitoring and verification to ensure sustained benefits

3.1.2.3 Marginal health mitigation: Coal beneficiation, HELE and CCUS

For coal beneficiation, the health impacts show a diminishing trend across all timelines. From a health benefits perspective there is an additional benefit as result of the scheduled power station shutdowns across the timeline. For the 2025 - 2071 timeline the net present value of the benefits from coal beneficiation is in the range of approximately R1.7 to R5.2 billion, but these are outweighed by significantly higher implementation costs resulting in a BCA ratio of approximately 0.05 (Table 3-4). This indicates that costs exceed benefits even over a longer timeline span. Similarly for the 2055 and 2045 decommissioning timelines, the net present value of benefits from coal beneficiation are in the range of approximately R1.7 - 5.2 billion, however the higher implementation costs result in BCA ratios of around 0.041 for both respective timelines (Table 3-5 and Table 3-6).

For the purpose of modelling the BCA for the HELE scenario, it is assumed that the CFBC capital investment will take place from 2030 to 2035 evenly across this period while the operating costs will start from 2030 and be incurred annually until the relevant final decommissioning year. The health benefits from HELE begin immediately following capital investment. The health impacts diminish as a result of scheduled power station shutdown. The net present value for the benefits from HELE is in the range of approximately R1.3 - 1.5 billion with only marginal changes in values across the different timelines. The BCA ratios are well below 1 across the different decommissioning timelines, indicating that implementation costs outweigh the possible associated health benefits (Table 3-4, Table 3-5 and Table 3-6).

In modelling the BCA for the CCUS scenario, it has been assumed that the capital investment will take place from 2027 to 2040 with equal annual amount being incurred every year. The operating costs begin in 2027 and are incurred annually until the relevant final decommissioning year. The health benefits from CCUS begin immediately following implementation in 2027. The health impacts have a marginally decreasing trend until the relevant final decommissioning year. The net present value of the health benefits from CCUS

is in the range of approximately R9 to R11 billion (for 2071 timeline - Table 3-4), R9 to R10 billion (for 2055 timeline - Table 3-5) and R9 to R10 billion (for 2045 timeline -Table 3-6). These benefits are minor compared to the high costs of implementation, resulting in low BCA ratios. Moreover, the cost of CCUS implementation as presently established is an order of magnitude larger than that of any of the other options, likely making it unaffordable to Eskom.

Table 3-8 summarises the key advantages and limitations of the marginal health-mitigation options (coal beneficiation, HELE and CCUS), focusing on implementation feasibility, delivery risks, and the relative scale of health benefits, to complement the BCA results presented above.

Table 3-8: Summary of key advantages and limitations of coal beneficiation, HELE and CCUS

Pros:	**Cons:**
Coal beneficiation	
Can be implemented upstream in the coal supply chain without requiring major retrofits at power stations	SO_2 reductions are marginal and achieved at relatively high cost, resulting in limited overall environmental benefit
May improve certain coal quality parameters (e.g. ash content), potentially reducing total coal burn	Coal is still combusted in the same inefficient power stations, limiting the overall emissions and efficiency gains
	Reduces mining yield and generates significant discard, creating additional environmental risks and increasing coal costs
HELE	
CFBC technology can achieve substantially lower SO_2, NO_x and particulate emissions compared to conventional boilers	CFBC does not necessarily result in high-efficiency energy conversion on its own and should strictly not be equated with HELE
	CFBC plants typically operate at lower temperatures and pressures, resulting in lower thermal efficiency and potentially higher CO_2 emissions per MWh than modern pulverised fuel boilers
	Achieving true HELE performance would require advanced ultra-supercritical (USC) boiler technology, which is not yet widely proven at large scale in combination with CFBC

Pros:	Cons:
CCUS	
Offers potential reductions in SO_2, NO_x and PM through the inclusion of compulsory MES abatement plant prior to CO_2 capture	Demonstration plants are small-scale and capture only a fraction of total flue gas, raising significant scalability concerns
Provides long-term potential for CO_2 emissions reduction	Scaling CCUS to large generating units (>600 MW) would require very large capture plants with high energy, chemical and sorbent consumption
	Generates substantial by-products with limited or no current market, adding to operational and environmental management challenges
	Application to older, low-efficiency coal plants would require even larger capture systems per MW, further reducing overall plant efficiency
	Has high technical complexity and very high costs at utility scale

3.1.2.4 Structural transition measures with incidental health benefits: LDES and SMR

SMR and LDES are both expected to generate health benefits, with SMR health benefits significantly larger due to the scale of SMR implementation possible. In both cases, there are no additional costs required to achieve health benefits and thus BCA ratios are not relevant.

For LDES it is estimated that a total of 100 - 150 MW will be implemented from 2027 - 2035. For the purposes of modelling the benefits for LDES, it has been assumed that these MW will be evenly spread across the implementation period. The benefits associated with LDES begin in 2027, with the annual benefits showing an increasing trend up to 2035, and thereafter show a declining trend until 2045, 2055 and 2071 for each respective timeline.

With respect to SMR, it is estimated that a total of 33 units will be implemented from 2031 - 2041, at around 20 - 300 MW per unit. For modelling purposes, it is assumed that the units will be implemented evenly across the 11-year implementation period. The benefits associated with SMR show an increasing trend from 2031 to 2036, thereafter having a decreasing trend from 2037 until 2045, 2055, and 2071 under each respective decommissioning timeline.

The costs for both the LDES and SMR are to be incurred not purely for health benefits, but rather as a result of national development initiatives as guided by the IRP. As such, both the

LDES and SMR scenarios generate incidental health benefits irrespective of their cost of implementation.

The net present value of the health benefits associated with the LDES scenario is in the range of R84 million to R126 million, with only marginal differences in each decommissioning timeline (see Table 3-4, Table 3-5 and Table 3-6).

The net present value of the health benefits associated with the SMR scenario is in the range of R260 million - R3.9 billion, with only marginal differences in each decommissioning timeline (see Table 3-4, Table 3-5 and Table 3-6).

Table 3-9 summarises the key advantages and limitations of the structural transition measures (LDES and SMR), focusing on implementation readiness and the indirect nature of the associated health benefits, to complement the BCA results presented above.

Table 3-9: Summary of key advantages and limitations for LDES and SMR

Pros:	**Cons:**
LDES	
Can reduce emissions (SO_2, NO_x, PM and CO_2) indirectly by displacing coal-fired generation when charged with renewable energy	Emission and health benefits are conditional on the availability of sufficient renewable generation to charge storage systems
Enables storage of excess wind and solar generation that would otherwise be curtailed, supporting greater utilisation of renewable energy	If renewable generation is limited, LDES may be charged using fossil-based electricity, reducing or negating emissions benefits
Supports reduction in coal plant load factors where sufficient renewable energy and storage capacity are available	Health benefits are indirect and depend on system dispatch decisions rather than guaranteed emissions reductions
Improves system flexibility and supports integration of higher shares of variable renewable energy	Benefits materialise only at sufficient scale of both LDES and renewable energy deployment
SMR	
Provides low-emission baseload electricity, enabling displacement of coal-fired generation over the long term	Deployment timelines are medium to long
Avoids direct air pollutant emissions at the point of generation	Significant regulatory, licensing, financing and institutional requirements remain unresolved
Can contribute to long-term system reliability and decarbonisation objectives	Although the technology exists in South Africa, scaling it up may introduce uncertainty around cost, schedule and implementation

3.1.2.5 Risk and impact rating

Table 3-10 summarises a risk and impact assessment for the alternative scenarios based on IFC risk assessment methodology. Each scenario is rated according to likelihood, consequence, and overall impact, alongside the key beneficiaries and implementation requirements. The assessment is intended to complement the BCA results by providing a practicality and implementation feasibility lens. While all alternative scenarios have the potential to deliver positive air quality and health outcomes, implementation readiness and delivery risk vary considerably. With the exception of the Eskom AQO Programme, most options would require additional development and refinement beyond the current level of assessment to confirm their feasibility at scale. The risk assessment should therefore be interpreted as an indicative screening of relative potential and implementation practicality, rather than as confirmation of near-term implementation readiness.

Table 3-10: Risk Assessment of Alternative Scenarios

Alternative Scenario	**Beneficiaries**	**Likelihood of Successful Implementation**	**Consequence Rating (Air Quality and Health Outcomes)**	**Overall Impact Rating**	**Maturity and Implementation requirements**
1. Eskom AQO Programme	(i) Households in HPA and WBPA (ii) Broader communities through improved ambient air quality	Almost certain (5)	Major (4)	20 (High) High impact, low delivery risk	(i) Feasibility testing completed (ii) Selection of appropriate technologies (iii) Capital requirements
2. Coal beneficiation	(i) Populations downwind of coal-fired power stations (ii) National population through reduced total emissions	Almost certain (5)	Minor (2)	10 (Significant) Limited impact, with low implementation complexity	(i) Research phase (ii) Coal supply chain feasibility and contracting arrangements (iii) Water availability and waste management requirements (iv) Beneficiation plant capacity and operational readiness
3. HELE	(i) Communities near retrofitted stations (ii) Priority area populations	Unlikely (2)	Major (4)	8 (Medium) High potential benefit, limited implementation readiness	(i) Current scenario is at demonstration level (ii) Pre-feasibility and opportunity screening (iii) Selection of appropriate units and technology

Alternative Scenario	Beneficiaries	Likelihood of Successful Implementation	Consequence Rating (Air Quality and Health Outcomes)	Overall Impact Rating	Maturity and Implementation requirements
4. CCUS	(i) Communities near affected stations (ii) National population (air quality benefits) (iii) Global climate benefit	Unlikely (2)	Major (4)	8 (Medium) High potential benefit, but very low practicality	(i) Current scenario is at demonstration level (ii) Pre-feasibility and opportunity screening
5. LDES	(i) National population through reduced coal dispatch (ii) Communities near coal stations	Possible (3)	Major (4)	12 (Significant) System-level benefit with moderate uncertainty	(i) Current scenario is at demonstration level (ii) Pre-compliance risk assessment and opportunity screening
6. SMR	(i) National population through reduced coal generation (ii) Communities near coal stations	Possible (3)	Major (4)	12 (Significant) Long-term option, high uncertainty, not near term	(i) Global - Demonstration proceeding to commercial deployment

Likelihood reflects the likelihood of successful implementation and delivery of intended outcomes, while consequence reflects the expected magnitude of impacts on air quality and community health outcomes. Overall impact is calculated as Likelihood × Consequence. The overall impact ratings provide a qualitative screening based on 1-5 likelihood and consequence scores and are intended to complement the BCA results by highlighting implementation practicality.

While all alternative scenarios have the potential to deliver positive air quality and health outcomes, their levels of implementation readiness and delivery risk vary considerably. With the exception of the Eskom AQO Programme, most alternatives are currently assessed as having limited or uncertain practicality due to early-stage development, technical complexity, or cost-related constraints. As a result, further investigation and development in the medium to longer term would be required to confirm their feasibility and effectiveness at scale. The overall ranking presented in section 3.1.2.6 should therefore be interpreted as indicative and forward-looking, reflecting relative potential and practicality rather than near-term implementation certainty.

3.1.2.6 Overall ranking of alternative scenarios

Following the risk and impact assessment, the alternative scenarios were ranked to support decision-making. The ranking reflects a balanced consideration of potential air quality and health benefits, implementation readiness, and delivery risk, rather than modelled benefits alone. As reflected in the assessment above, the Eskom AQO Programme demonstrates a higher level of implementation certainty, while the remaining alternatives are at earlier stages of development and would require further technical evaluation and planning to confirm their practicality. The ranking should therefore be interpreted as indicative and forward-looking, highlighting relative potential and feasibility rather than near-term implementation decisions.

1. Eskom AQO Programme
   Delivers direct and immediate reductions in household-level exposure, with strong health benefits in priority areas and a high level of implementation readiness.
2. SMR
   Can displace some coal-fired generation in the Highveld priority area with low-emission supply, reducing SO_2 and $PM_{2.5}$ emissions at the point of generation.
3. Long Duration Energy Storage (LDES)
   Can enable greater use of wind and PV and reduce coal dispatch, with air quality benefits where storage is charged from renewable generation and dispatched in place of coal generation.
4. HELE
   Can achieve high SO_2 reductions, but implementation is constrained by retrofit complexity and additional technical requirements to achieve high-efficiency performance.
5. Coal beneficiation
   Provides very marginal SO_2 reductions at relatively high cost (more expensive than HELE), with additional trade-offs including increased water use (if wet beneficiation), discard generation and reduced yield.
6. CCUS
   Has high technical complexity and very high costs at utility scale, with significant challenges to expand beyond demonstration projects

4 CONCLUSION

The Waterberg-Bojanala Priority Area (WBPA) in the analysed period (2022 - 2024) is found to be in general compliance with the National Ambient Air Quality Standards (NAAQS). It is expected that, with the continued operation of the Medupi and Matimba power stations, it will not result in non-compliance with these national standards. In the modelled domain (108,900km^2), in 2025 an estimated 1.5 million people out of the total 1.67 million people are expected to be exposed to more than an additional 1 µg/m^3 of SO_2.

The benefit-cost analysis (BCA) for the three technical scenarios comparing wet, semi-dry and dry FGD to the baseline shows BCA ratios that are considerably less than 1. This implies that there are significant financial costs for a relatively limited health benefit across all three scenarios. The early shutdown of the stations was modelled to comply with the Ministers requirements. This produces similar BCA ratios as operation to the planned end of life (2071), While early shutdown does result in a reduction in total health impact it is associated with negative impacts on funding viability, electricity provision and electricity tariff levels.

Overall, the alternative scenarios assessed indicate that a range of interventions can deliver health benefits; however, for most scenarios these benefits are either low relative to costs or subject to significant uncertainty due to early-stage development, high capital requirements, or implementation risks. In addition, previous assessments have shown that the early shutdown of coal-fired power stations delivers substantial air quality and health benefits. Any alternative scenario that extends the operational life of coal stations beyond planned decommissioning dates would therefore reduce these potential benefits. As a result, the realisation of these benefits remains contingent on further planning, technological maturity, and implementation certainty, and should therefore be regarded as probable rather than confirmed. Eskom is already involved in investigations into these alternatives to better asses these in support of national energy planning. In contrast, the Eskom Air Quality Offset (AQO) clean cooking programme consistently demonstrates substantial net health benefits, very high benefit-cost ratios, and a high likelihood of implementation.

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6 APPENDIX

Please see separate Appendix document containing all appendices.