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Technical Report

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ENERGY SECTOR DECARBONISATION PATHWAYS TO MEET A NATIONAL NET ZERO EMISSIONS TARGET BY 2050:

CO-BENEFITS OF NET ZERO PATHWAYS

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Executive Summary

ES1. Introduction

Energy supply systems, the transportation sector and industrial processes are known to have wide ranging environmental impacts for air pollution, water quality and water use. Measures that are thus taken to decarbonise these sectors have the potential to reduce these environmental impacts. Reduced combustion of fossil fuels for example, not only decreases greenhouse gas (GHG) emissions but simultaneously reduces air pollution emissions, with potential for health benefits. When these benefits occur because of an intervention implemented for the primary purpose of reducing GHG emissions, these are referred to as 'co-benefits'.

The purpose of this report is to present the approach and key findings from the assessment of the potential co-benefits of the different decarbonisation pathways developed in the project. These co-benefits include improvements in local air quality and benefits for human health and have potential improvements in water quality and use.

ES2. Air Quality and Human Health Co-benefits

Objective

The sources of air pollutants and greenhouse gases are often the same. As such decarbonisation is often associated with improvements in ambient air quality, but this is not always a given. The goal of the analysis was therefore important to consider the air quality implications of different energy pathways.

Approach

To estimate these co-benefits an emission inventory of priority air pollutants were compiled for each of the decarbonisation pathways developed in the project. This was used as an input into an air dispersion model, namely, the Comprehensive Air Quality Model with Extensions (CAMx) to determine the changes in ambient air quality associated with different decarbonisation pathways. The air quality co-benefits were assessed through the estimated reductions in SO_2, PM and NO_2 emissions, the resulting improvements in air quality and the subsequent associated health benefits via reduced premature mortality associated with SO_2, $PM_{2.5}$ and NO_2.

The air quality model has been run for the Reference NZ10_2050A_08E (high GHG reduction) and NZ10_2050A_09E (low GHG reduction) pathways for selected years of the SATIMGE projection, i.e., 2023, 2033 and 2050. Only the emissions are altered, while all other model input remain the same. The SATIMGE projections offer changes in emissions for a majority of the anthropogenic sectors (power generation, other manufacturing industry, on-road vehicles, domestic fuel combustion and airports).

Key findings

The projected SATIMGE reductions in emissions result in significant reductions in ambient pollutant concentrations. There are however some localized increases seen due to specific industrial sub-sectors. There are large differences between scenarios for year 2033, but less for 2023 and 2050.

Health benefits estimated include the reductions in premature mortality due to reductions in concentrations of SO_2, $PM_{2.5}$ and NO_2.

Table ES1: Estimated reduction in premature mortality (all ages) for the three years simulated.

	Reduction (number of persons)		
Scenario	NO_2	$PM_{2.5}$	SO_2
High reduction (NZ10_2050A_08E)	5821	6031	12987
Low reduction (NZ10_2050A_09E)	5521	5500	11162

The reductions were translated into monetary terms via Value of Statistical Life metrics. Results show that in monetary terms there is only a ~11% difference between scenarios; however, the total amount includes only the three years simulated. The total monetary savings due to reduction in all-cause premature mortality across all ages brought about by the emission reductions is $30bn for the Low scenario and $33bn for the High scenario. In order to understand the potential cumulative impacts throughout the SATIMGE projection (i.e., 2023-2050), the health costing was also projected across this period. Results show a larger difference between the High ($111bn) and Low scenarios ($73bn). It was noted however that these estimates are conservative, and there is a high likelihood that monetary savings due to reduction in premature all-cause mortality from the pathways would be more in reality.

ES3: Water Co-benefits

Objective

A transition to net zero emissions can yield a diverse range of positive impacts on water resources and related systems. These benefits relate to both the quantity and quality of water resources. In terms of water quantity impacts, fossil-fuel based power production generally requires significant amounts of water for cooling and other purposes, while other forms of power production require significantly less (Pocock and Joubert, 2021). In addition, fuels such as coal require water to be mined, processed and in some cases transported (UoCS, 2010). In terms of water quality, a reduced reliance on coal for electricity and oil production will potentially reduce eutrophication (Singh et al., 2012), toxicity (Bergesen et al., 2014) and acidification (Luderer et al., 2019) of water resources.

It is important to note that the adoption of renewable energy technologies can also result in negative impacts on water resources (Luderer et al., 2019). For example, the development of biofuels from crops can require significant amounts of water and land and result in eutrophication of water resources if agrochemicals are not carefully managed. The building of dams for hydropower generation alters aquatic environments and results in losses of water to evaporation.

Approach

South Africa's power sector heavily relies on fossil fuels, **known for their water-intensive nature**. This study investigates the water consumption during electricity generation under different decarbonization pathways modelled in the larger project. We project how water use might evolve, focusing on **direct (on-site) water needs** like cooling in power plants. While "upstream" water use - like is used in mining coal or manufacturing renewables - **is outside the scope of this high-level analysis, the significant impact of coal mining on South Africa's water resources warrants a brief discussion.**

The assessment of the water co-benefits of decarbonization therefore includes sections on:

- different electricity generation technologies and how they use water,
- the impact of coal mining on water quantity and quality,
- historical water use in the electricity sector,
- projections of future water use in the electricity sector (based on decarbonization pathways modelled in this project),
- comparison of results with other projections of water use.

Key findings

The projections of future water use for electricity generation indicate substantial reductions in water use across all decarbonization scenarios assessed (Figure ES3.1).

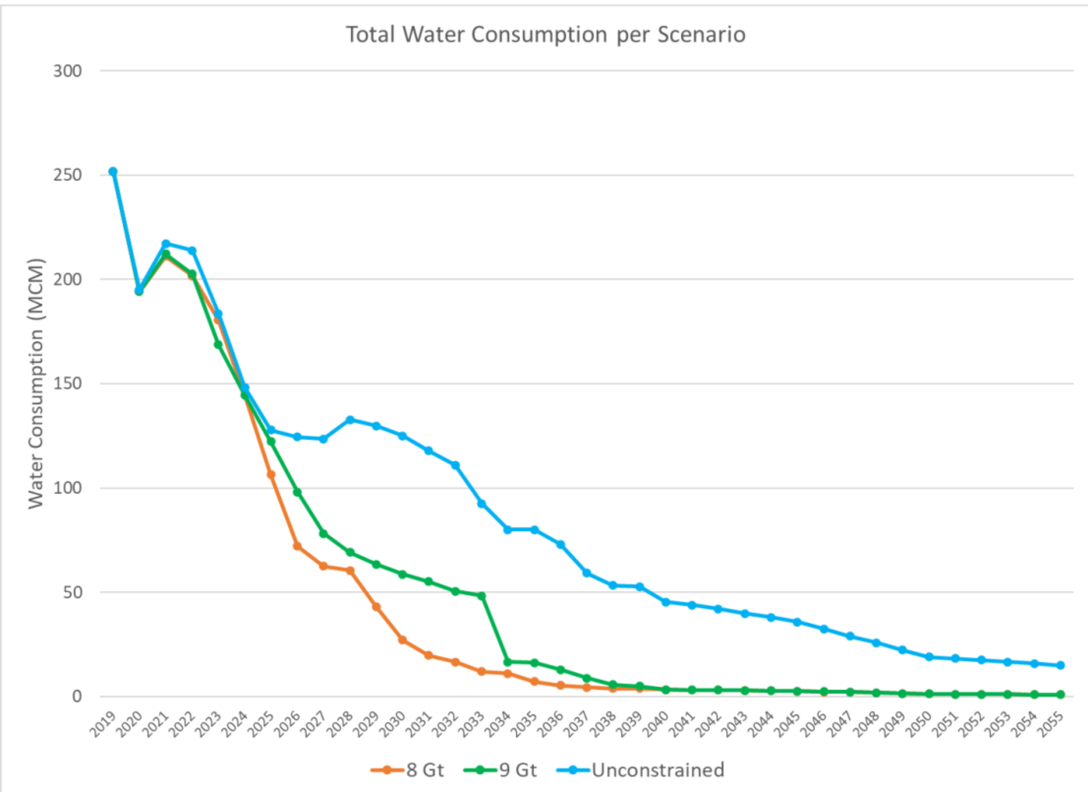

Figure ES3.1: Total water consumption for the Unconstrained, 9 Gt and 8 Gt scenarios

While the Unconstrained scenario exhibits a slower reduction, by 2050 the water use is similar (slightly higher) to the other scenarios. The large reduction in water use is consistent with previous projections developed (IRP2019), although the rate of initial reduction is more rapid in most scenarios.

While transitioning away from coal could improve water quality, the long-term effects of past mining remain a concern. Decommissioning coal plants offers potential water quality benefits, but ongoing monitoring and mitigation efforts are crucial.

The projected savings in water derived from transitioning away from coal imply that additional water will become available for other uses e.g., agriculture, urban, industry and meeting environmental flow requirements (especially in over-allocated water catchments). This bodes well for the constrained Integrated Vaal River System which is a critical resource that supports the economic hub of Gauteng and surrounding provinces. Water requirements for agriculture are likely to increase in future due to warmer temperatures, while urban water use will increase due to urbanization and population and economic growth. The freeing up of water for other uses has the potential to benefit the economy and create jobs.

It is important to take note of other assumptions (not related to upstream water use) made in the water use projections, notably the lack of account of climate change impacts on water use. As more intense rainfall is projected in future, water quality may also be impacted, which may then have knock-on effects for water consumption at power stations. Another important assumption made in the water use projections was that any future nuclear power stations would be built at the coast and would use seawater for cooling (as the existing Koeberg nuclear power station does).

In conclusion, the water-related co-benefits of decarbonisation of the electricity sector will be significant in terms of water quantity, and eventually in terms of water quality.

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Glossary of terms

Counterfactual concentration	Concentration above which the impacts are estimated
Cessation lag	Used to denote the likely time lag between reductions in long-term average pollutant concentrations and a consequent reduction in mortality risk.
95 % confidence interval.	This implies that there is 95 % probability that the true value lies in the range defined by the interval
Exposure/Concentration-response functions (ERF/CRF)	Allow concentration changes to be translated into impacts. These functions express changes in outcomes per unit in concentrations (measured in micrograms per cubic metre, $\mu g/m^3$).
Exposure–lag–response association.	Type of dependency that enables health outcomes of air pollution exposure at a given day to be sustained in the future and to vary according to the intensity and the lag period (Xia et al., 2019).
Life table/mortality table	Represents a hypothetical cohort of 100,000 persons born at the same instant who experience the rate of mortality represented by qx, the probability that a person age x will die within one year, for each age x throughout their lives. We assume a uniform distribution of deaths for ages greater than 0
Photolysis rates	Supplemental alterations to chemical reaction rates that are dependant on solar radiation.
Premature death	Deaths that occur before a person reaches an expected age. This expected age is typically the life expectancy for a country, stratified by sex. Premature deaths are considered preventable if their cause can be eliminated (EEA, 2018).
Relative risks	Capture the increase in mortality that can be attributed to a given increase in the air pollutant concentration. are defined at the population level (as statistical averages) and cannot be assigned to specific individuals. In the case of mortality it is therefore not possible to identify which individual cases are caused by air pollution (EEA, 2018)
Speciated emissions	Emissions are generally estimated for either discrete or aggregated gases/aerosols. For air quality modelling, particularly atmospheric chemistry, the aggregated gases/aerosols need to be split into their functional species. E.g., emissions are estimated for $PM_{2.5}$, however the model requires these to be split into nitrates, sulfates, elemental carbon etc for input.
Years of life lost (YLL)	Defined as the years of potential life lost due to premature death. YLL is an estimate of the number of years that people in a population would have lived had there been no premature deaths. The YLL measure takes into account the age at which deaths occur and therefore the contribution to the total is greater for a death occurring at a younger age and lower for a death occurring at an older age (EEA, 2018).

Acronyms

AEL	Atmospheric Emissions License
AMD	Acid Mine Drainage
AQMP	Air Quality Management Plan
CAMx	Comprehensive Air Quality Model with Extensions
CSP	Concentrated Solar Power
ERF	Exposure Response Function
ESRG	Energy Systems Research Group
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GHG	Greenhouse Gas
IIASA	Applied Systems Analysis
NMVOC	Non-methane volatile organic compounds
VRESS	Vaal River Eastern Sub-System
IVRS	Integrated Vaal River System
VRESAP	Vaal River Eastern Sub-System Augmentation Project
VSL	Value of Statistical Life

Introduction

Energy supply systems, the transportation sector and industrial processes are known to have wide ranging environmental impacts for air pollution, water quality and water use. Measures that are thus taken to decarbonise these sectors have the potential to reduce these environmental impacts. Reduced combustion of fossil fuels for examples, not only reduces greenhouse gas (GHG) emissions but simultaneously reduces air pollution emissions, with the potential for health benefits. When these benefits occur as a result of an intervention implemented for the primary purpose of reducing GHG emissions, these are referred to as 'co-benefits'.

This report represents the results of the co-benefits determined by an assessment of air quality, health and water co-benefits arising from Energy sector decarbonisation pathways as simulated by the UCT ESRG SATIMGE model.

Air quality co-benefits

The sources of air pollutants and greenhouse gases are often the same. As such decarbonisation may be associated with improvements in ambient air quality, but this is not always a given. It is therefore important to consider the air quality implications of climate change strategies to mitigate costs and to optimise gains.

To investigate the impacts of transitioning to a GHG Net Zero on air quality, changes in pollutant emissions are derived and used as input into an air quality model, namely, the Comprehensive Air Quality Model with Extensions (CAMx) to determine the changes in ambient air quality (that which we breathe) associated with different decarbonisation pathways. The changes in simulated ambient air quality associated with different decarbonisation pathways are then used to derive health benefits (via reduction in premature mortality) and thereafter to assess the monetized health co-benefits of these pathways. Note that due to the high computational requirements and thus runtime for the air quality model, it was decided that only selected time periods from the SATIMGE projections be utilized in the air quality co-benefits analysis. The periods selected were 2023 (this is the beginning of projection), 2050 (end of projection; and when GHG Net Zero should be achieved) and 2033 (a period of large differences between scenarios). Two scenarios NZ10_2050A_08E (high GHG reduction; 8Gt carbon budget) and NZ10_2050A_09E (low GHG reduction; 9Gt carbon budget) were simulated and compared to the reference scenario (NZ10_2099B_99N; "Unconstrained").

Air quality modelling platform

Air quality modelling is required to simulate ambient air pollutant concentrations by accounting for the atmospheric transport and chemistry that emissions experience from the point of release to their fate in the atmosphere and deposition into land and water. This approach thus includes the spatial, temporal and chemical variability of air pollution. The model is applied to a three-dimensional grid covering the domain of interest (Figure 1).

The modelling platform itself is comprised of several sub-models and data processing elements (Figure 2). It was developed during 2020-2021 through funding from the World Bank's "Pollution

Management and Environmental Health Pilot" for a project which focused on the development of a quantitative rapid assessment tool to inform air quality management within the Gauteng region (specifically for the City of Johannesburg, City of Tshwane and City of Ekurhuleni). This involved collaboration with the International Institute for Applied Systems Analysis (IIASA) to populate a version of their Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model with locally specific data (including deriving the necessary emission/concentration sensitivities needed for GAINS through numerous full CAMx simulations). The model platform as applied here utilized the parent domain (0.06° x 0.06° cell sizes; 0.06° ≈ 6km) which has a higher coverage over the region and captures the Eskom power stations.

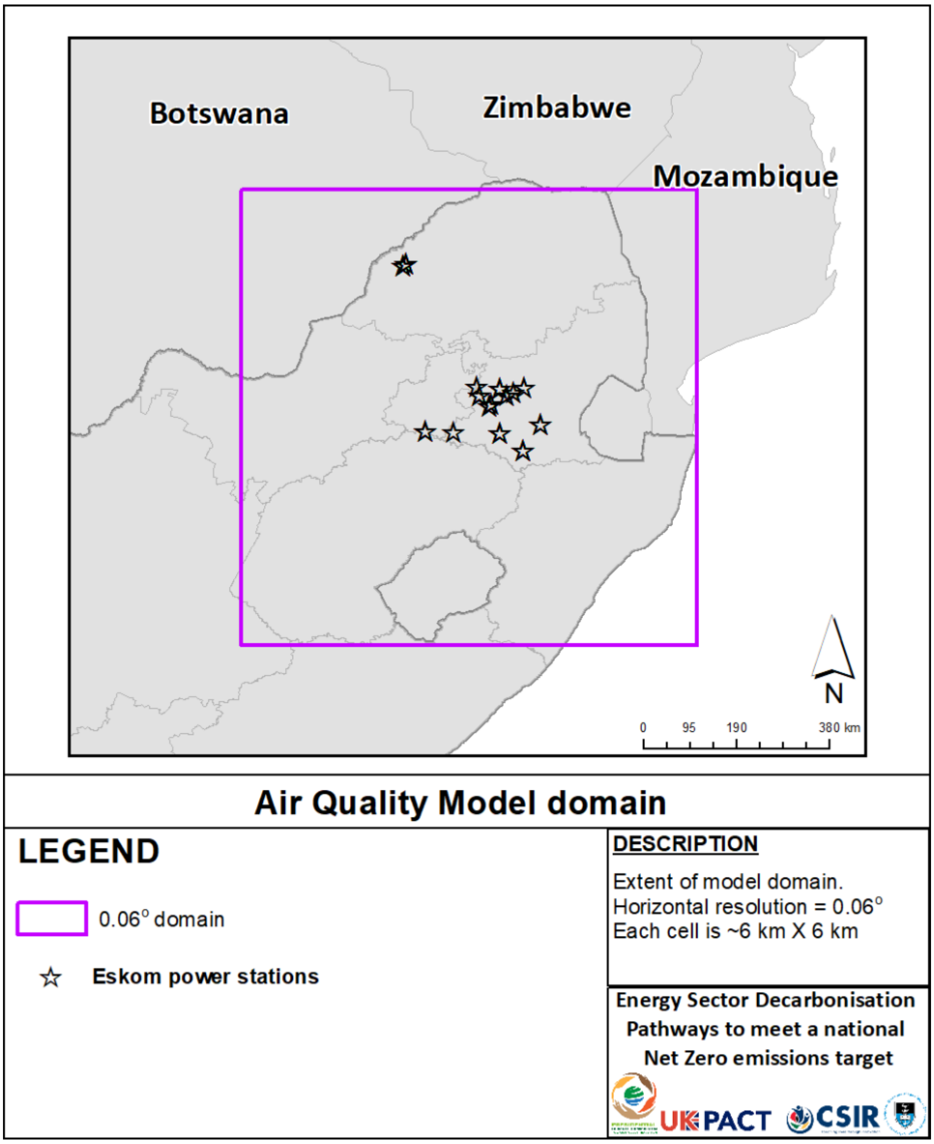

Figure 1: Map showing air quality model domain extent.

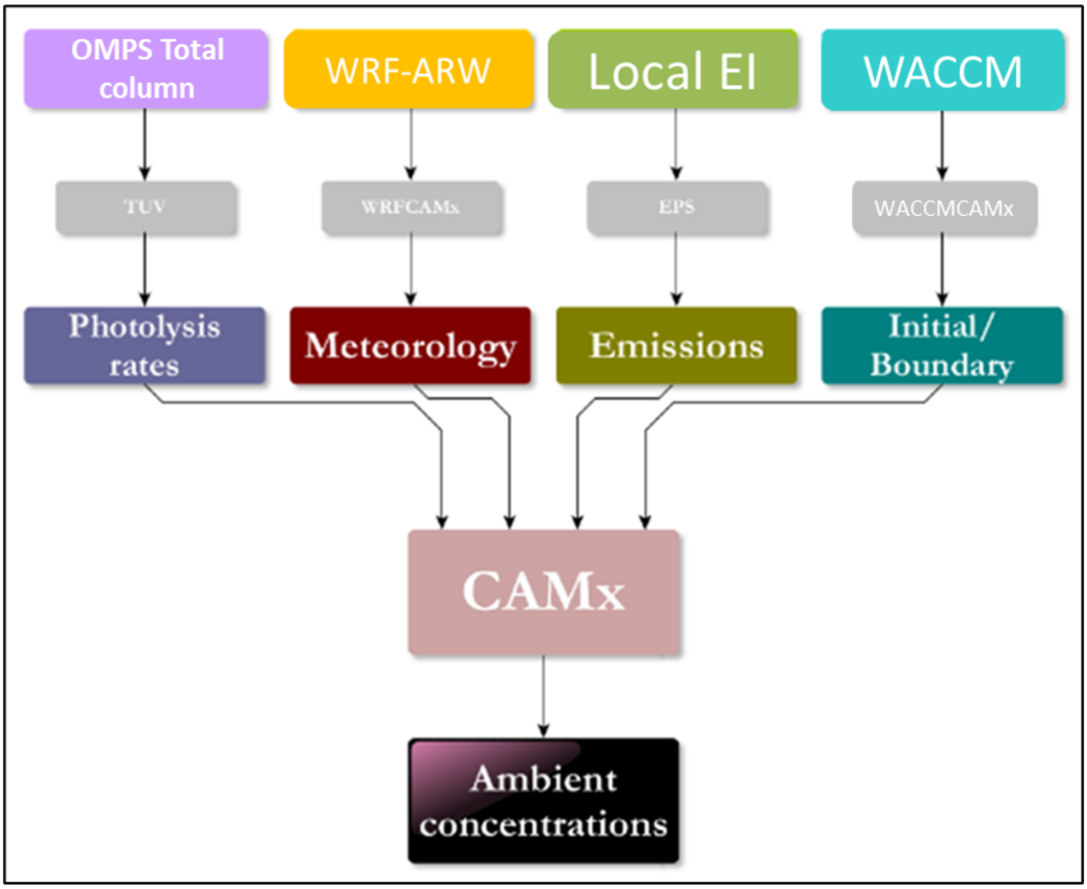

Figure 2: Overview of components of air quality modelling platform.

Central to the model platform is the Comprehensive Air Quality Model with Extensions (CAMx; Rambol, 2019). CAMx is a Eulerian (grid-based) chemical transport model that is suitable for the integrated assessment of gaseous and particulate air pollution. The model allows for integrated "one-atmosphere" (signifying that all sources and pollutants are to be modelled simultaneously) assessments of gaseous and particulate air pollution over many spatial scales, ranging from sub-urban to continental. This is achieved by solving Eulerian pollutant mass continuity equations forward in time on three-dimensional grids. It is designed to unify all of the technical features required of "state-of-the-science" air quality models into a single system. CAMx is thus able to simulate ambient air quality due to both primary and secondary air pollutants at varying spatial and temporal scales. It is therefore, for example, able to account for conversion of SO_2 gas to sulfate aerosol.

The CSIR uses CAMx to conduct air quality research and contract work. CAMx can provide a Level 3 assessment in terms of the South African Code of Practice for Air Dispersion Modelling in Air Quality Management in South Africa (Gazette No. 37804, 11 July 2014). The model has been applied previously in South Africa for numerous regional studies such as the Sasol/Eskom Photochemical Ozone Study, Western Cape Health Study, City of Johannesburg Air Quality Management Plan (AQMP), Highveld Health Study, Vaal Triangle Airshed Priority Area AQMP, and Eskom Waterberg Study.

Air quality model input

The CAMx model requires input of photolysis rates (for those photochemical reactions included by the selected gas phase chemistry scheme), meteorological data, initial and boundary conditions and a comprehensive gridded, speciated (both non-methane volatile organic compounds (NMVOC) and particulate matter (PM)) and hourly emissions inventory. Most of these inputs are based on the already established modelling platform. For application in this co-benefits study, emission sectors captured by the SATIMGE were further altered accordingly to account for the decarbonization pathways.

The base emissions inventory is representative of year 2019, and included the following source sectors:

- **Industrial facilities** – Primarily those listed sources requiring Atmospheric Emissions Licenses
- **Domestic fuel combustion** – Household scale combustion of LPG, paraffin, wood and coal for energy provision
- **On-road vehicles** – All classes of vehicles (including freight) operating on all road types within the domain. Includes emissions from exhaust, evaporative and brake and tyre wear. Additionally, emissions of resuspended dust ($PM_{2.5}$ and PM_{10}) due to vehicles operating on unpaved roads are included for the Gauteng province only.
- **Informal waste burning** – Burning of uncollected household waste.
- **Airports** – Aircraft emissions due to landing, taxiing and take-off from all major airports.
- **Biomass burning** – Emissions due to large fires (both natural and anthropogenic) as detected by satellite instruments.
- **Biogenic NMVOC and NOx** – Natural emissions of NMVOC from vegetation due to metabolism and NOx from soil due to microbe respiration.
- **Wind-blown dust** – Emission of dust ($PM_{2.5}$ and PM_{10}) due to wind action on bare/erodible surfaces. This includes separately estimated dust emissions from abandoned mine tailings facilities within City of Johannesburg.
- **Ammonia from agriculture** – Emissions of ammonia due to animal husbandry and application of fertilizer on crops.

These emissions were gridded at 0.06° resolution and each sector given a temporal profile such that seasonal, weekly and hourly variation is represented. As an example of spatial scale and detail, Figure 3 shows estimated gridded annual total NOx emissions from on-road vehicles.

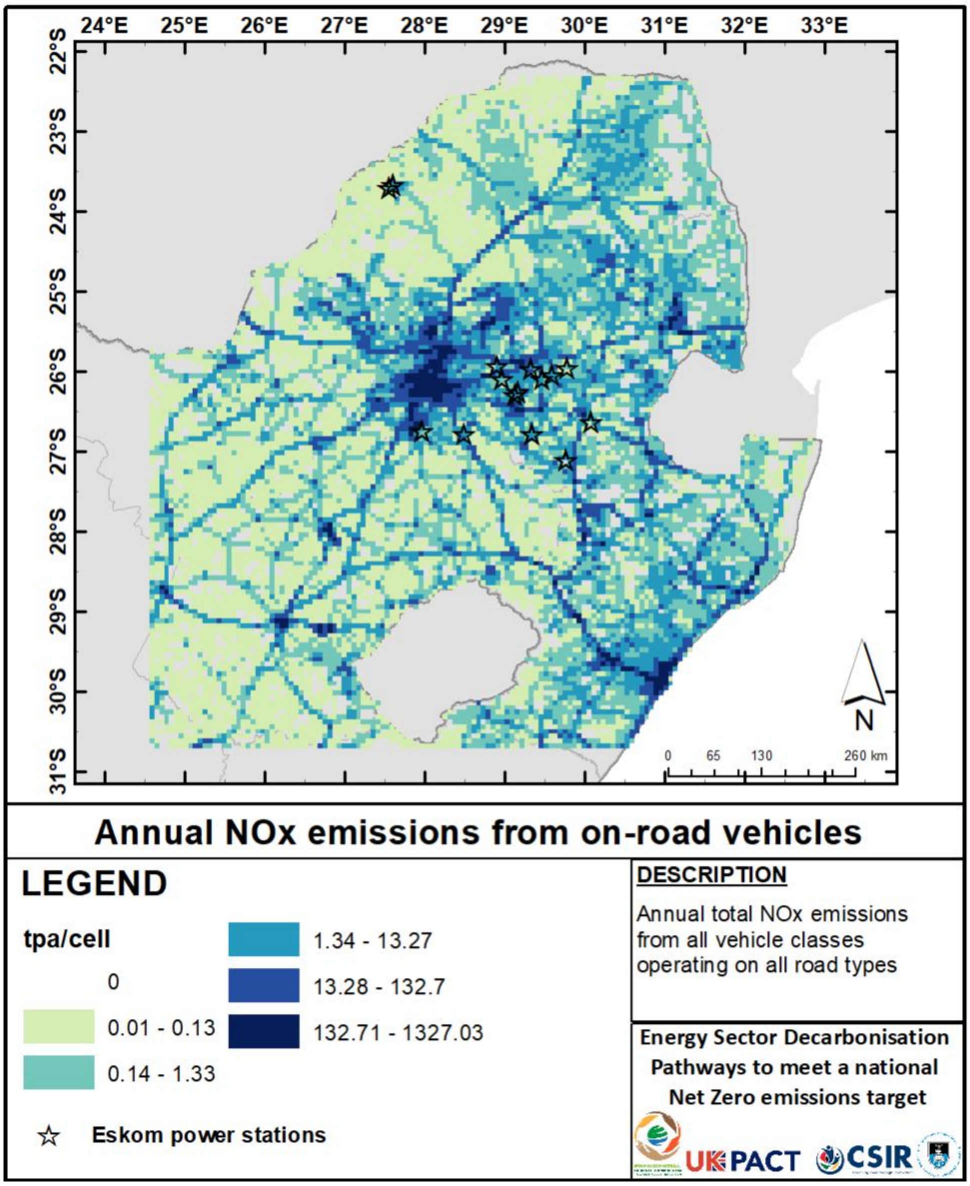

Figure 3: Gridded (0.06° resolution) total annual NOx emissions (tpa/cell) from on-road vehicles (all classes).

Pollutants covered by the air quality model emissions inventory are CO, SO_2, NOx (split into NO_2 and NO per process), PM_{10}, $PM_{2.5}$ (split into model specific aerosol species), NH_3 and NMVOC (split into model specific volatile gas species).

Meteorological data is required to drive pollutant transport and provides important parameters for chemistry. This data must be provided on the CAMx model grid at an hourly rate. The Weather Research and Forecasting model (WRF-ARW version 4.2; Skamarock et al., 2019) was used to generate a year (2019) of meteorological data for CAMx, as well as to drive the emissions models for wind-blown dust, unpaved roads, and biogenic NMVOC and NOx. Temperature data from the WRF model was also used to parameterize emission factors for evaporative emissions from on-road vehicles (petrol only).

CAMx is a limited-area model and requires boundary (and initial) input of key gases and aerosols. This input provides context for the model by specifying (at each model hour) the concentration of gases and aerosols entering the model domain from either side and from above. These concentrations were derived from the Whole Atmosphere Community Climate Model (WACCM; Gettleman et al., 2019) run by the US NCAR Atmospheric Chemistry, Observations and Modelling (ACOM) group. WACCM is a global chemistry transport model and provided information around continental scale air quality impacts on this study's model domain.

CAMx also requires initial photolysis rates. These are photochemical reaction rates and depend heavily on the amount of solar radiation (at specified wavelengths) available at each level in the atmosphere across the domain. The initial step involves feeding NASA OMPS (Jaross, 2017) total column ozone data into the NCAR TUV radiative transfer model[1]. Additionally, the TUV model incorporates various look-up tables developed by the CAMx model developer to facilitate its calculations. This forms an initial input as CAMx further modifies these rates based on the concurrent simulation of aerosol, and WRF input cloud cover.

Emissions changes due to SATIMGE pathways

The previous section describes the modelling platform developed during an earlier project and which serves as a starting point for this study. To assess the impact on air quality due to the emission changes projected through SATIMGE, changes to the 2019 emissions inventory are made. This requires mapping the SATIMGE defined sectors to those contained in the air quality model emissions inventory. All non-emissions input to the air quality model remains the same (i.e., meteorology, photolysis rates and initial and boundary conditions); thus, the response to the decarbonisation pathways is isolated. While SATIMGE provides air pollutant emissions per year in its projections, these aren't used as is here, but rather a scaling factor is derived (simply the ratio of 2019 vs year of concern). Scaling factors for each SATIMGE pollutant are covered, namely SO_2, CO, NOx, NMVOC and PM_{10} (note that discrete factors are needed as scaling for each pollutant even within a process may differ as they are dependent on technology mix as well). For the pollutants included in the air quality modelling emissions inventory but not within SATIMGE, the closest (process wise) SATIMGE pollutant scaling factor was used (e.g., for air quality $PM_{2.5}$ emissions changes, a scaling factor derived from SATIMGE PM_{10} is used).

The air quality model has been applied to two SATIMGE scenarios (NZ10_2050A_09E and NZ10_2050A_08E) and for three key years: 2023, 2033 and 2050. However, as impacts are assessed through changes, a baseline projection was required to represent the business-as-usual (BAU; NZ10_2099B_99N) case.

[1] See http://cprm.acd.ucar.edu/Models/TUV and http://www.camx.com/download/support-software.aspx

Table 1: Summary of air quality model scenarios

SATIMGE scenario name	Years simulated	Purpose
NZ10_2050A_09E	2023, 2033 and 2050	Low GHG reduction (9Gt CO_2e limit)
NZ10_2050A_08E	2023, 2033 and 2050	High GHG reduction (8Gt CO_2e limit)
NZ10_2099B_99N	2023, 2033 and 2050	BAU; Unconstrained (No NetZero achieved)

A key aspect of translating SATIMGE projected changes in air pollutant emissions to the air quality modelling emissions inventory is mapping sectors at the level of individual processes.

While sectors like domestic fuel combustion are relatively straightforward (processes of combustion of wood, LPG, coal or paraffin) the industrial sector is much more involved due to the numerous processes for each individual facility in the air quality emissions inventory. Figure 4 illustrates a summary of the mapping of each air quality relevant SATIMGE sector to the air quality emissions inventory.

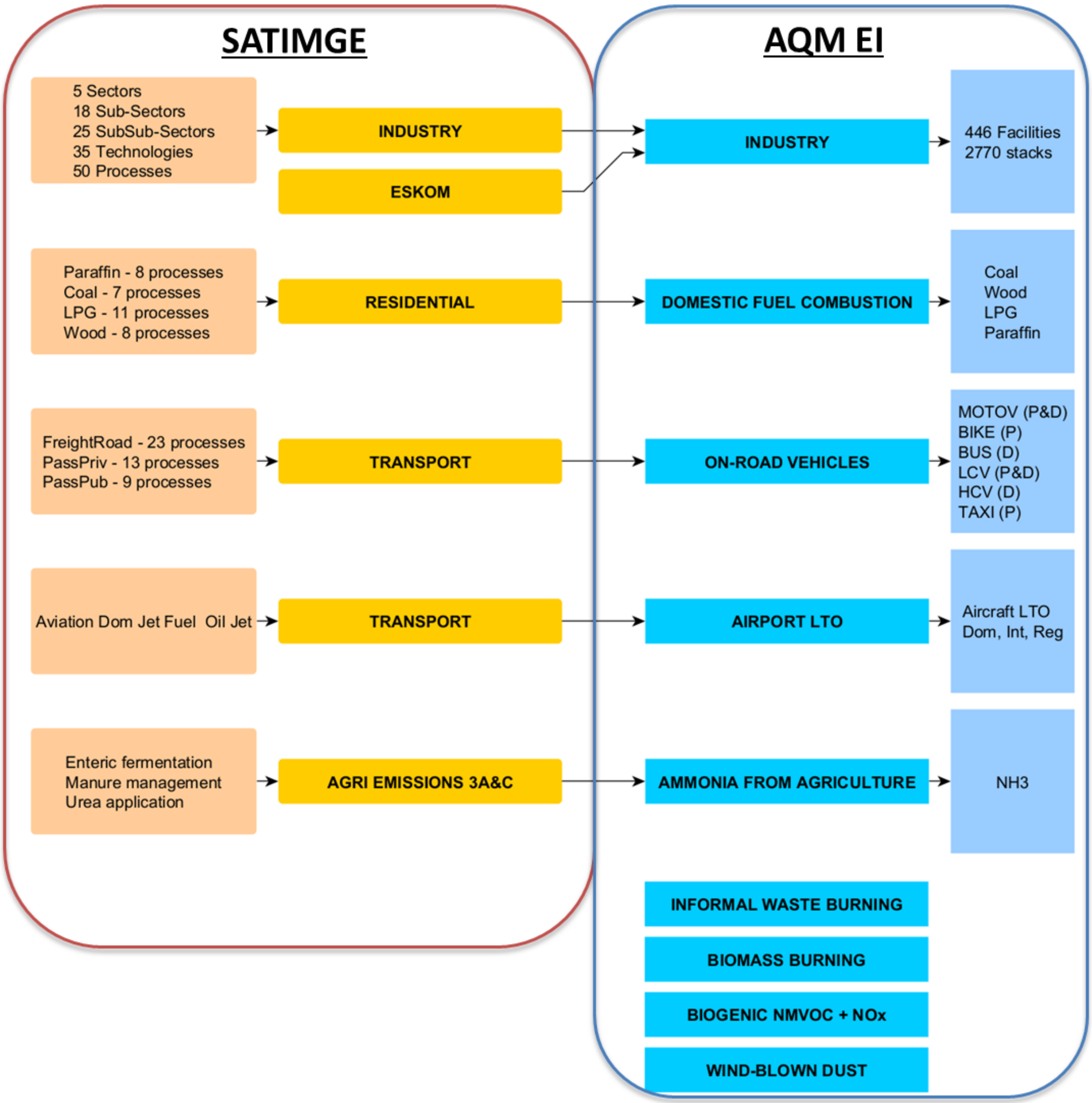

Figure 4: Summary of mapping SATIMGE sectors to air quality model emissions inventory

A majority of sectors are able to be mapped to SATIMGE, and mainly natural emissions are not modified (and are thus kept static through scenarios). Figure 4 also shows individual sub-sectors that were used to drive the changes applied to the emissions inventory. Note that Eskom emissions are specified per plant within SATIMGE, allowing a more detailed spatial scaling. This is something that is vital considering the energy focus and Eskom reliance on coal-fired power stations.

Emission changes to power generation industry

This sector includes Eskom coal-fired power stations as well as the privately owned Kelvin Power station in Gauteng (coal) and Avon IPP in KwaZulu-Natal (diesel fuelled OCGT). Figure 5 shows the projected power station specific percentage change in SO_2 emissions relative to 2023 for each year for the high GHG reduction scenario (NZ10_2050A_08E). This serves to illustrate the different responses simulated for each station. Komati is defined as closed before 2023. Post 2033 all power stations are either closed or significantly reduced. Figure 6 shows the aggregated changes in SO_2 for each scenario while Figure 7 to Figure 9 show the absolute emission tonnages (in kilotons) as input into the air quality model.

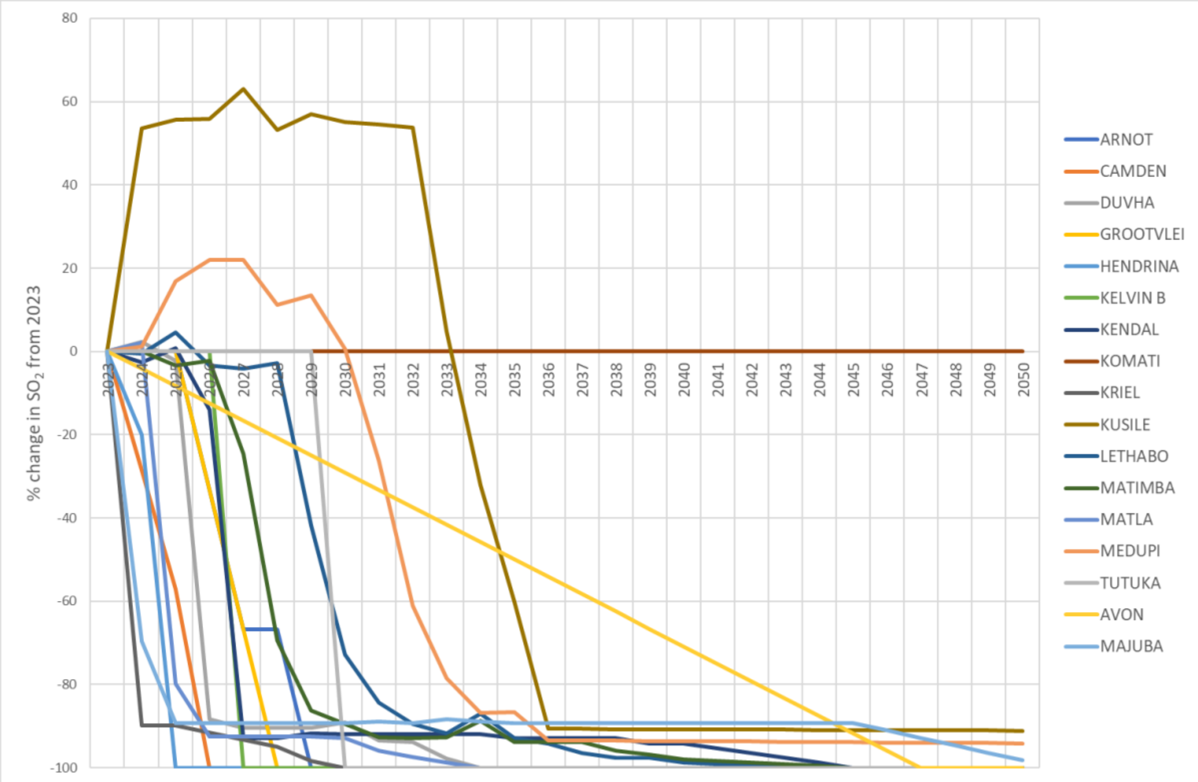

Figure 5: SATIMGE Power generation wide projected % changes in SO_2 emissions from individual power stations for the high GHG reduction scenario (NZ10_2050A_08E)

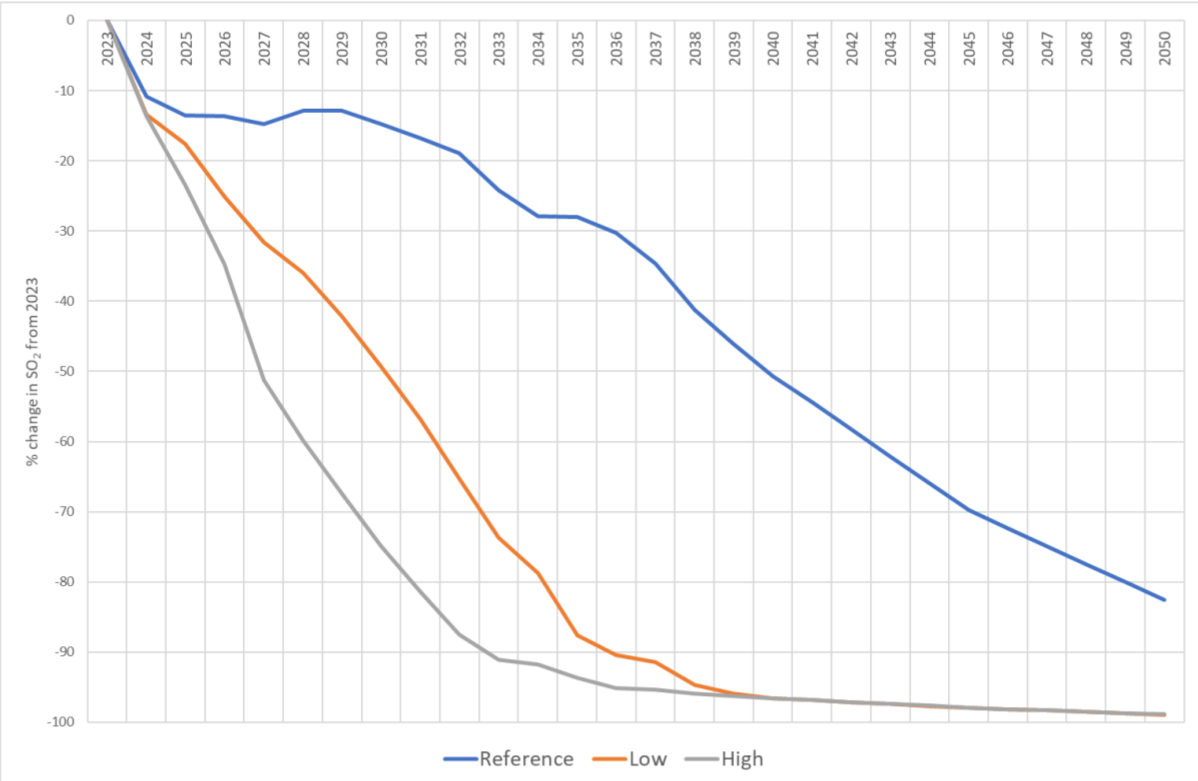

Figure 6: SATIMGE Power generation wide aggregated projected changes in SO_2 for the Reference, Low and High GHG reduction scenarios.

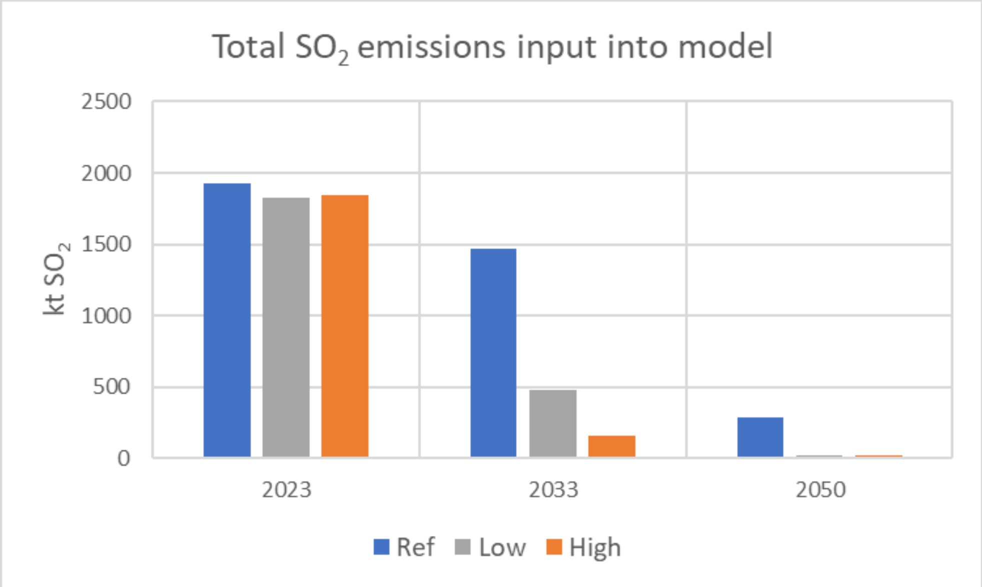

Figure 7: Power generation wide emissions (kt/year) of SO_2 for the selected years of modelling.

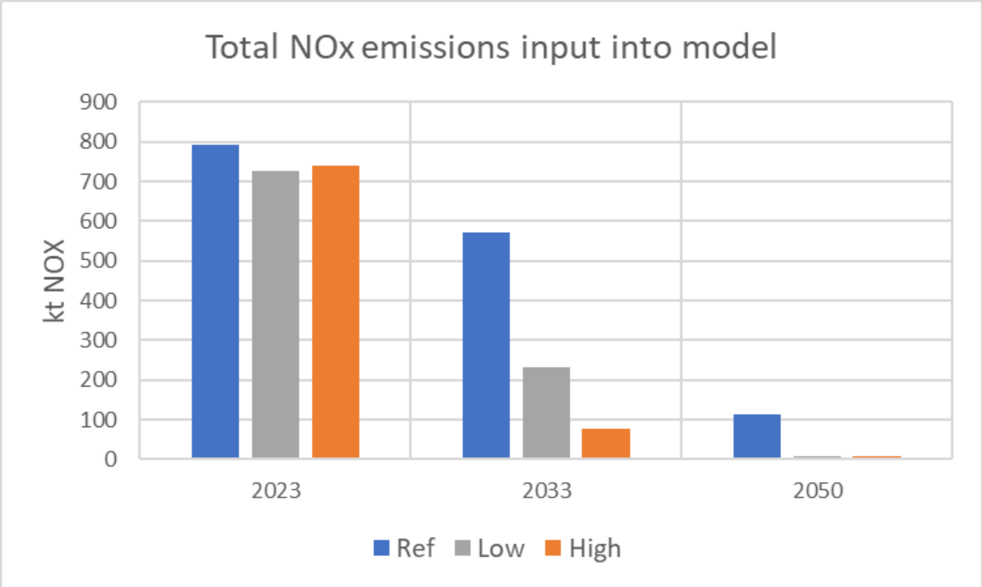

Figure 8: Power generation wide emissions (kt/year) of NOx for the selected years of modelling.

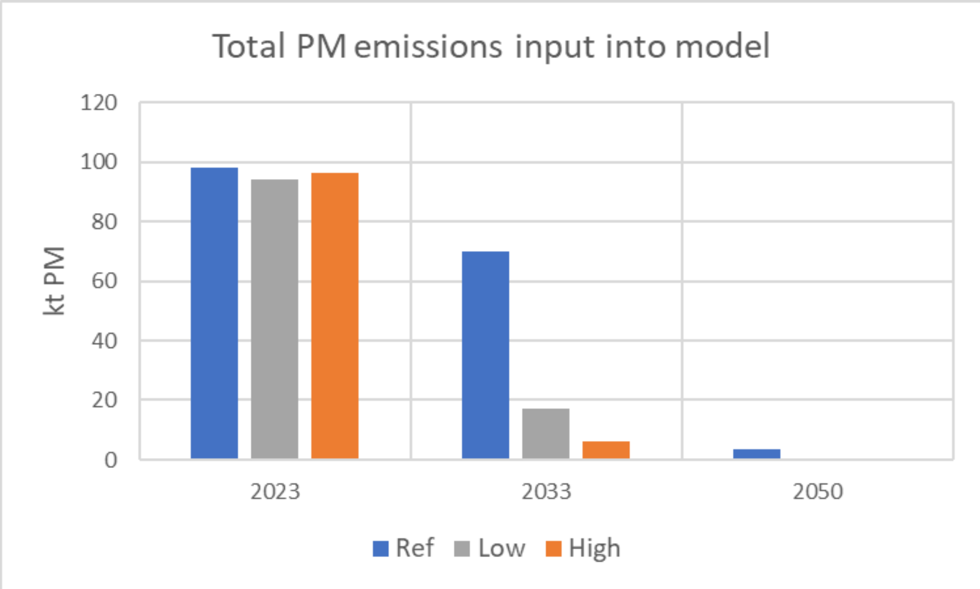

Figure 9: Power generation wide emissions (kt/year) of PM for the selected years of modelling.

Emission changes to the on-road vehicles sector

These changes are based on the SATIMGE projections for the Transport sector. What is defined as the Transport sector within SATIMGE corresponds to more than on-road vehicles, and also includes rail, aircraft and off-road vehicles. The changes to air quality emissions for on-road vehicles were derived from SATIMGE sub-sectors for freight (heavy and light), private passenger and public passenger (heavy and light) transport. Electric vehicles were included in the technology mix. Figure 4 shows the vehicle classes considered (incl. petrol and diesel). Figure 10 and Figure 11 show the on-road vehicle sub-sector relative (to 2023) changes in SO_2 and NOx emissions. Figure 12 and Figure 13 show the absolute emission totals for SO_2 and NOx input into the air quality model for each period and scenario.

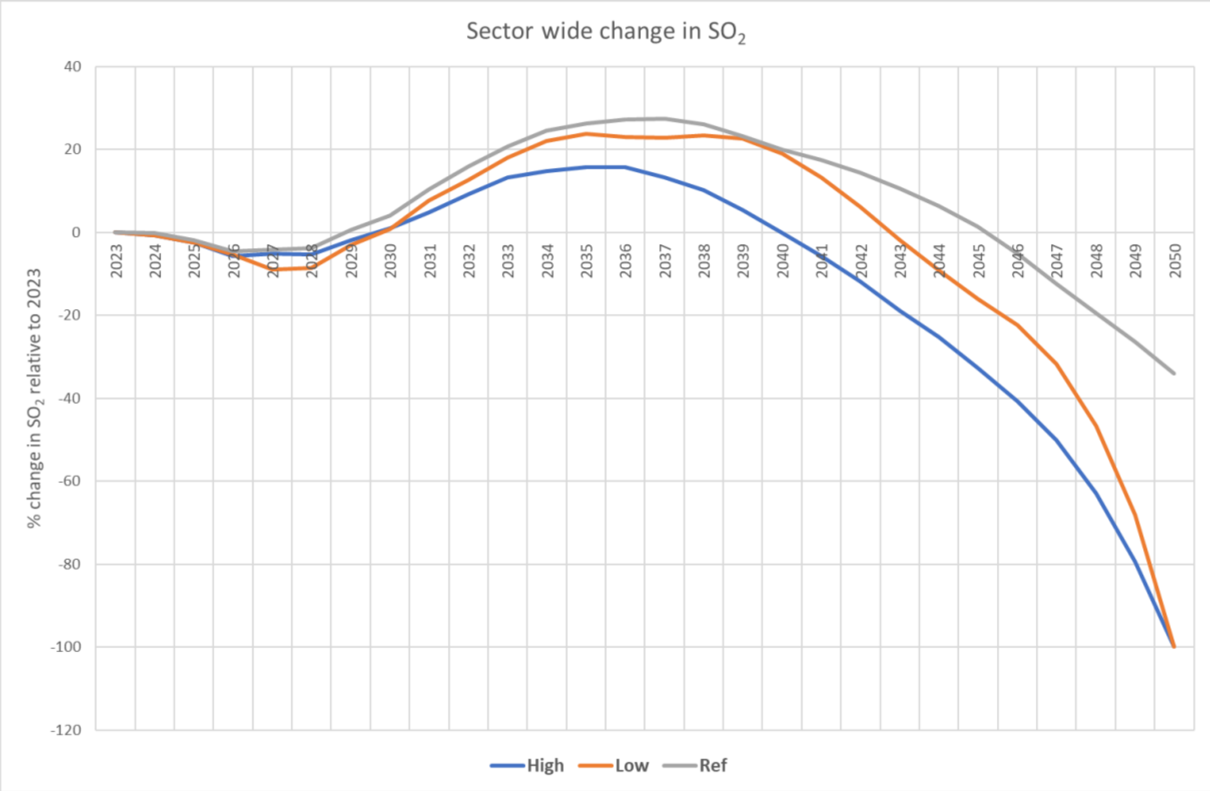

Figure 10: SATIMGE projected % changes (relative to 2023) in on-road vehicle SO_2 emissions (incl. freight, passenger private and passenger public).

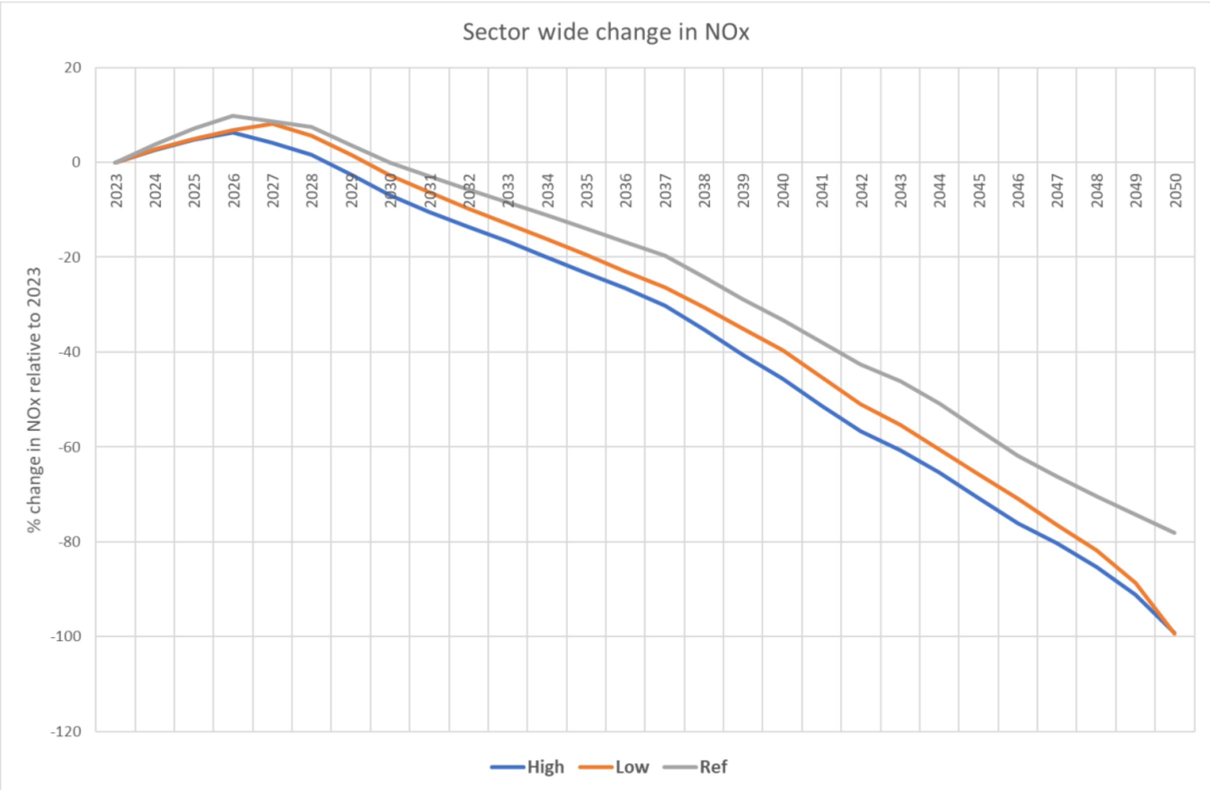

Figure 11: SATIMGE projected % changes (relative to 2023) in on-road vehicle NOx emissions (incl. freight, passenger private and passenger public).

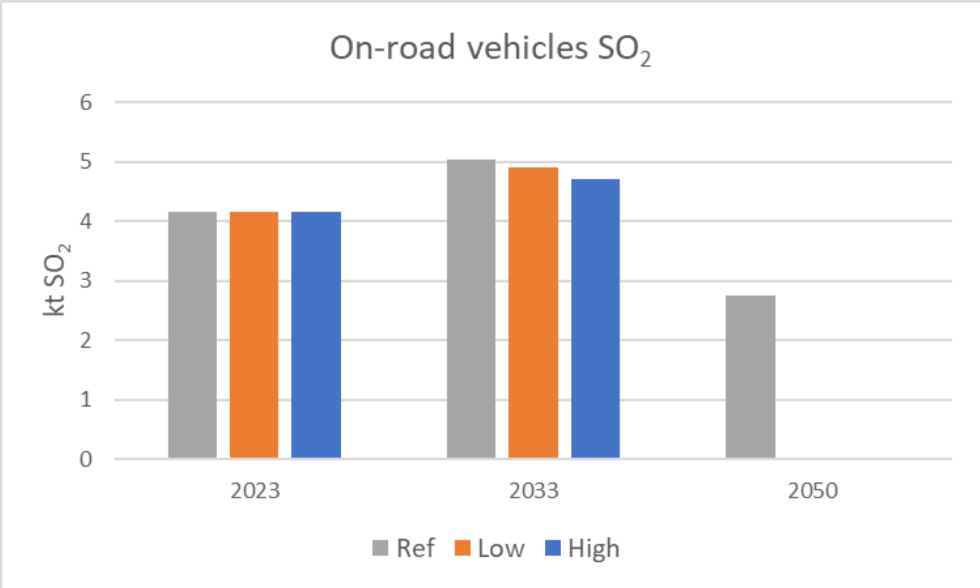

Figure 12: On-road vehicle emissions (kt/year) of SO_2 for the selected years of modelling as input into air quality model.

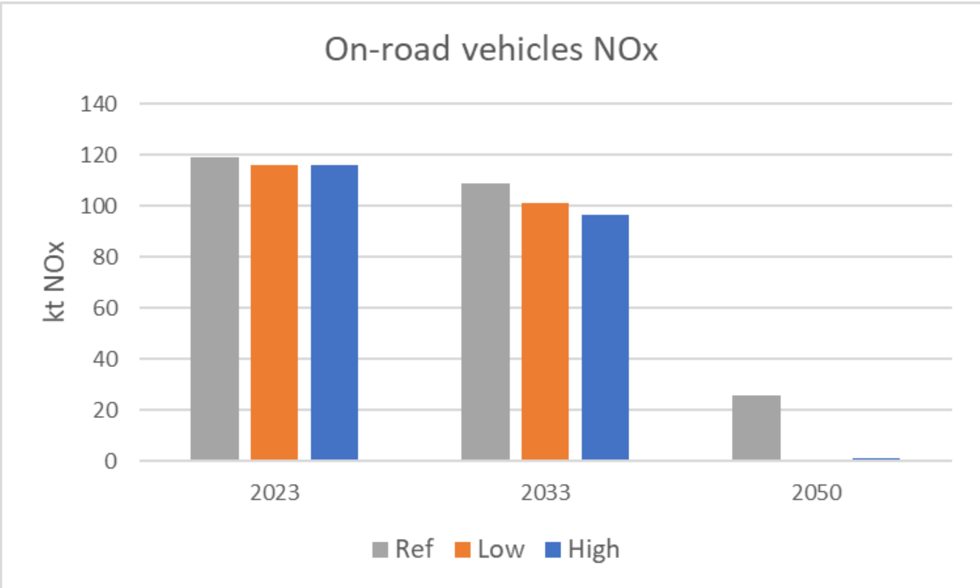

Figure 13: On-road vehicle emissions (kt/year) of NOx for the selected years of modelling as input into air quality model.

Emission changes to the domestic fuel combustion sector

This sector includes household combustion of coal, LPG, paraffin and wood for cooking and heating purposes. The sector and sub-sectors within SATIMGE align well with those in the air quality emissions inventory as both make use of standardised energy consumption modelling data and Census statistics. Figure 14 and Figure 15 show the sector aggregated relative changes in NOx and PM emissions as projected by SATIMGE. Figure 16 and Figure 17 show the absolute emission as input into the air quality model for the selected years.

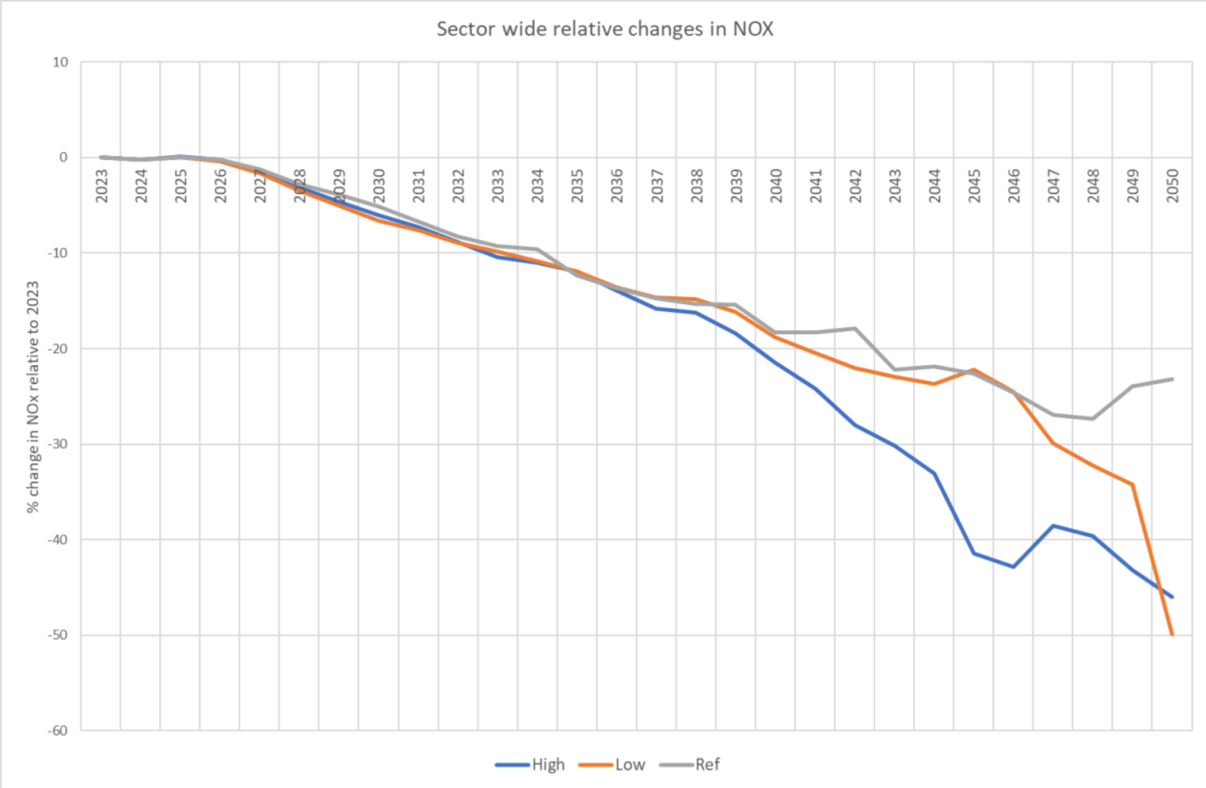

Figure 14: SATIMGE projected % changes (relative to 2023) in domestic fuel combustion (all fuels and technologies) NOx emissions.

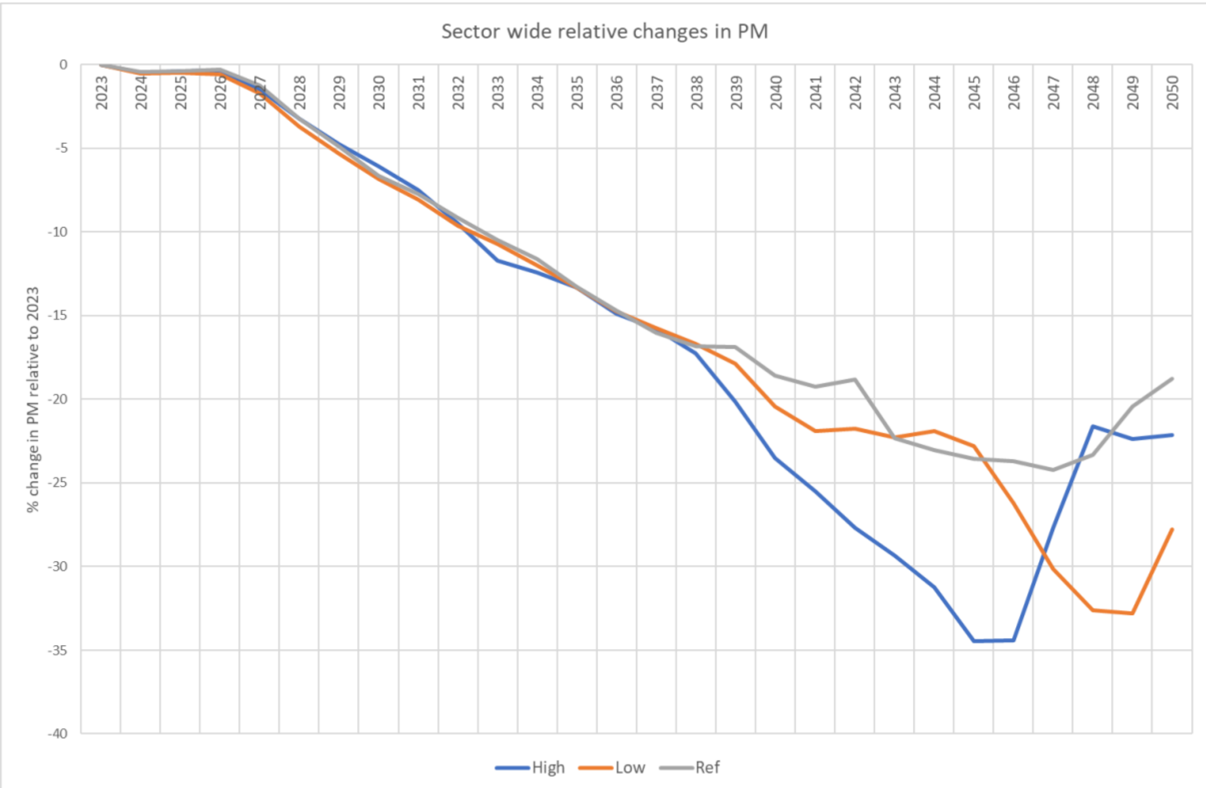

Figure 15: SATIMGE projected % changes (relative to 2023) in domestic fuel combustion (all fuels and technologies) PM emissions.

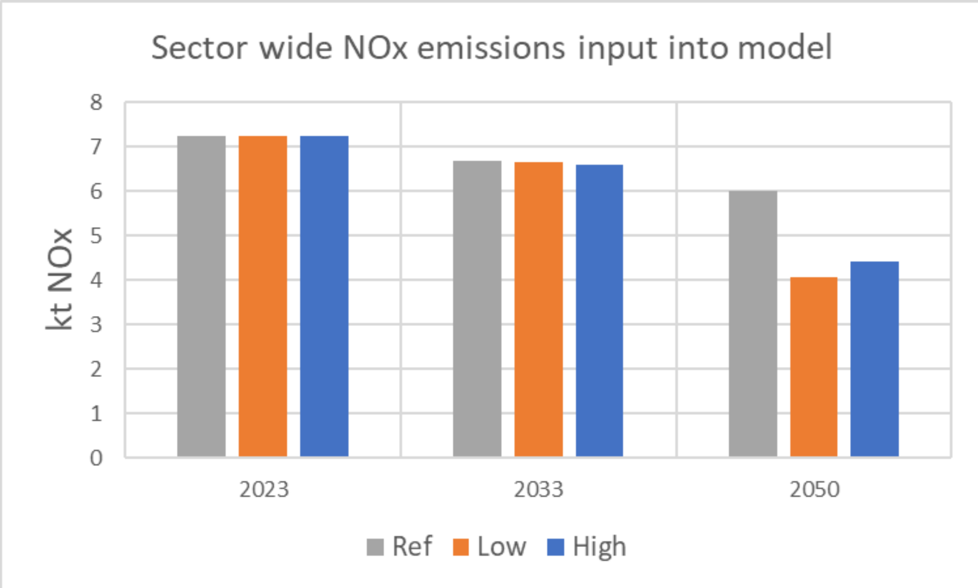

Figure 16: Domestic fuel combustion emissions (kt/year) of NOx for the selected years of modelling as input into air quality model.

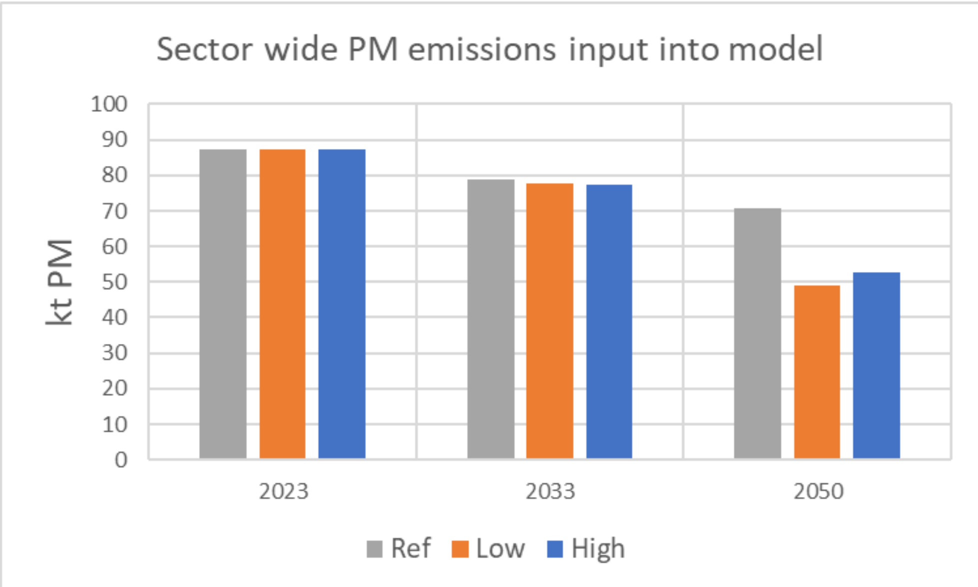

Figure 17: Domestic fuel combustion emissions (kt/year) of PM for the selected years of modelling as input into air quality model.

Emission changes to non-Eskom industry

This sector is comprised of all industries within the model domain that require submission of an Atmospheric Emissions License (AEL) to operate. These are typically the large industries and emit the most pollutants. In the emissions inventory, each industrial facility contains both stack (elevated or low stacks) and fugitive emissions, as each industry reports for submission in their respective AELs. For the stacks, information on height, exit temperature and exit velocity is used to estimate plume rise as the model runs. Each stack is associated with a process at that facility, and industries like Sasol for example have over 50 stacks. In total, the dataset used to drive the non-Eskom industrial emissions was made up of 2770 stacks. Each of these was mapped to the one of the 41 closest matching SATIMGE processes. Like other sectors, scaling factors were derived from the ration between SATIMGE 2019 and 2023, 2033 or 2050 emission estimates for the various pollutants included. Figure 18 to Figure 20 show the sector aggregated relative changes in NOx SO_2 and PM emissions as projected by SATIMGE.

The relative increase in SO_2 for the High GHG mitigation scenario (Figure 19) between 2037 and 2046 is driven by SATIMGE "Industry-Chemicals-boiler/process heating" and "Industry-Precious & Non-Ferrous metals-boiler/process heating" processes. However, note that there looking at aggregated trends from SATIMGE and relating to changes in the air quality modelling emissions inventory can be misleading. This is seen if one compares the relative change aggregated directly from SATIMGE (Figure 18 to Figure 20) and the air quality emissions as input into the model (Figure 21 to Figure 23). For example, in the reference scenario, both NOx and SO_2 are on a downward trend according to the SATIMGE projections, however this is aggregated and there are some processes that are individually increasing, but because their magnitude of contribution to total emissions within SATIMGE sector is low, they do not influence the trend as much. The upward trajectory for the reference scenario for 2050 (Figure 21) is due to the SATIMGE increases in the "NMM-Cement" sector, very large SATIMGE increases in "Precious Non-Ferrous metals coal boilers/process heating" (in combination with already high emissions for 2019 in the air quality emissions inventory) and "Pulp and Paper coal boilers". Figure 24 Shows the projected trends from SATIMGE for these specific processes (as opposed to the aggregated trends in Figure 18 to Figure 20). This in conjunction with high combined NOx emissions tonnage in the air quality modelling emissions inventory from those three process groups results in the higher 2050 emissions compared to 2033 (Figure 21).

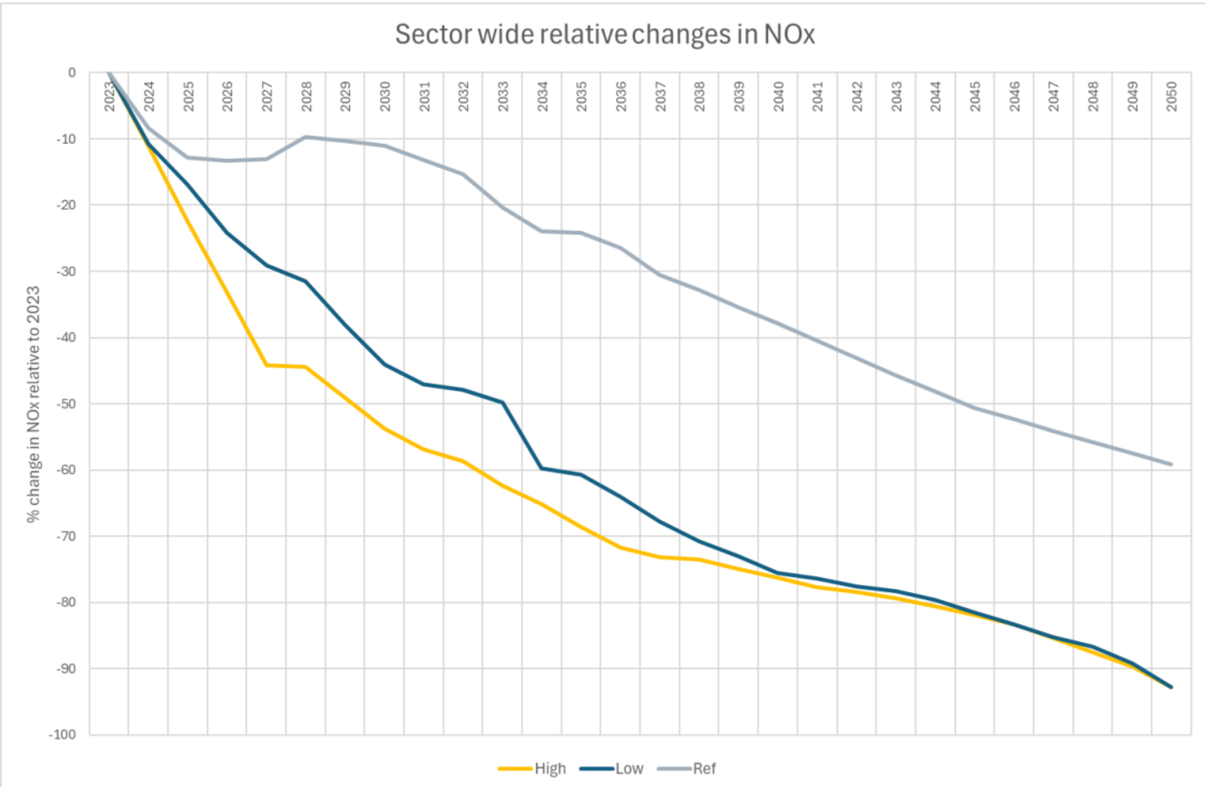

Figure 18: SATIMGE projected % changes (relative to 2023) in non-Eskom industry sector NOx emissions (High = high mitigation scenario)

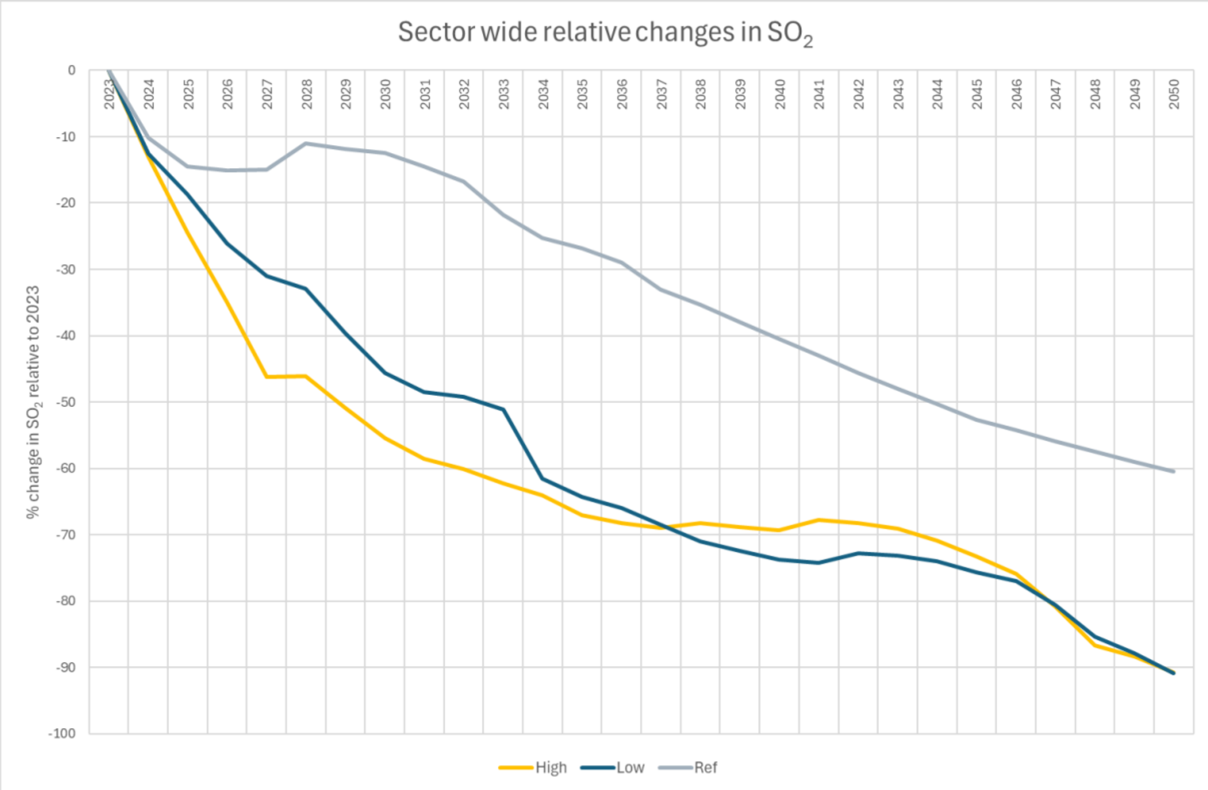

Figure 19: SATIMGE projected % changes (relative to 2023) in non-Eskom industry sector SO_2 emissions (High = high mitigation scenario)

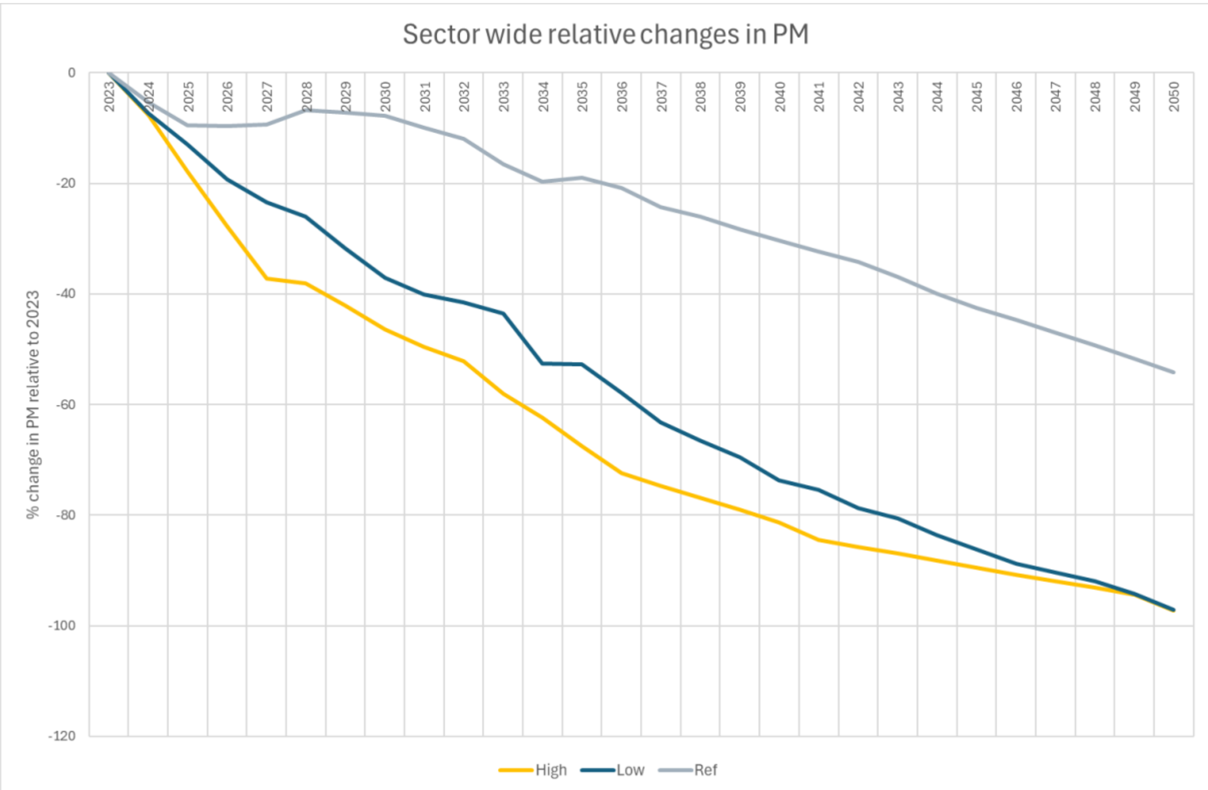

Figure 20: SATIMGE projected % changes (relative to 2023) in non-Eskom industry sector PM emissions (High = high mitigation scenario)

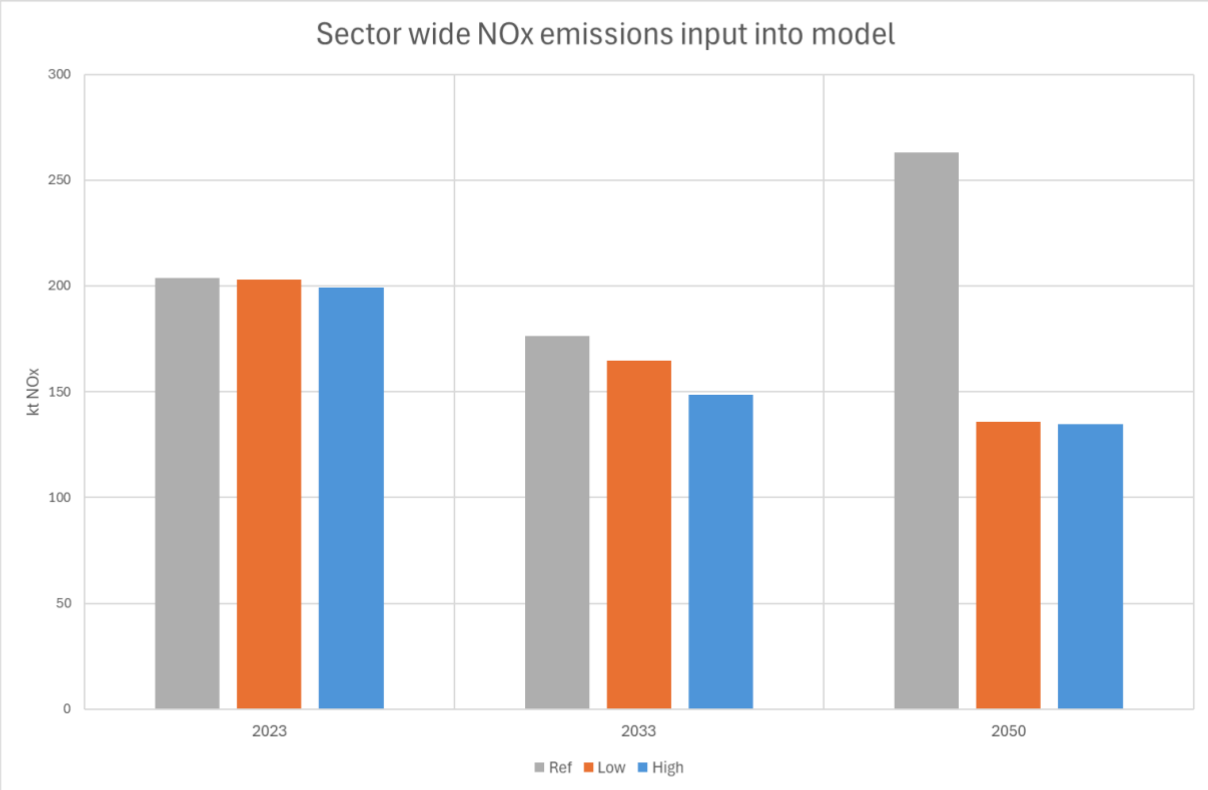

Figure 21: Non-Eskom Industry emissions (kt/year) of NOx for the selected years of modelling as input into air quality model (High = High GHG mitigation scenario)

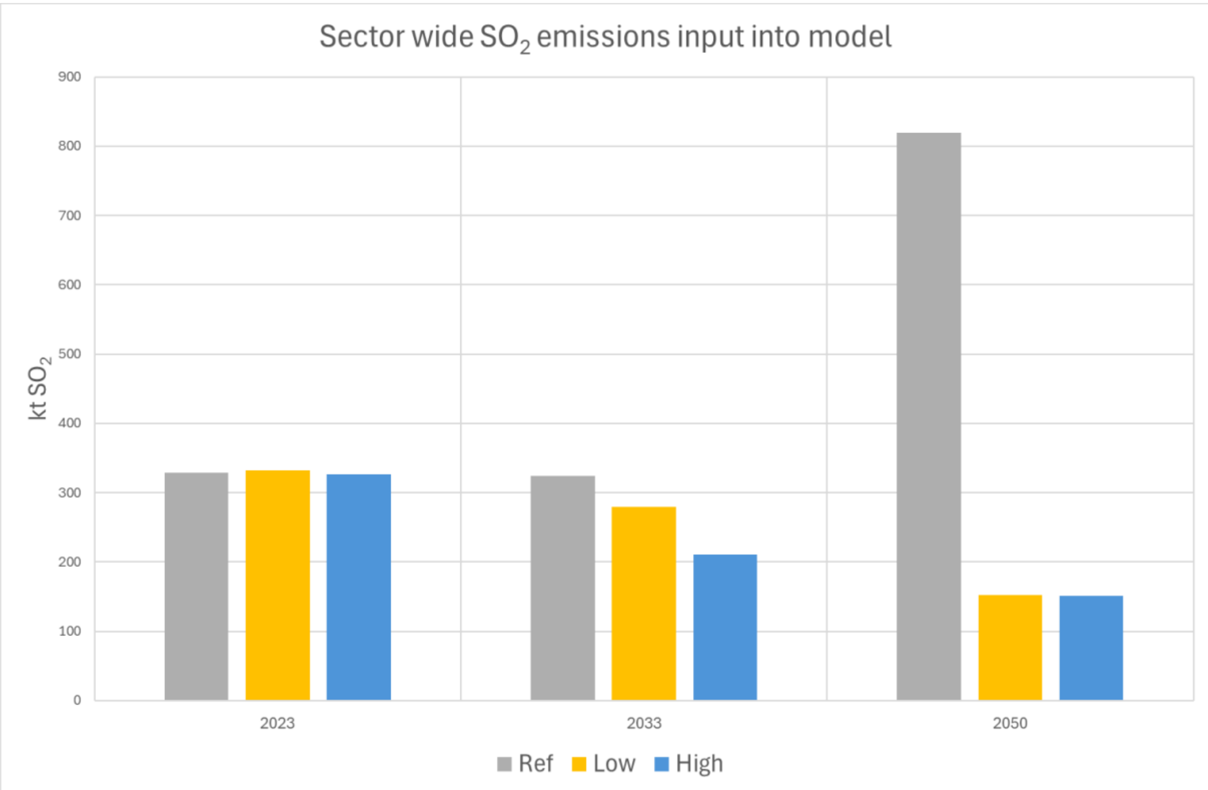

Figure 22: Non-Eskom Industry emissions (kt/year) of SO_2 for the selected years of modelling as input into air quality model (High = High GHG mitigation scenario)

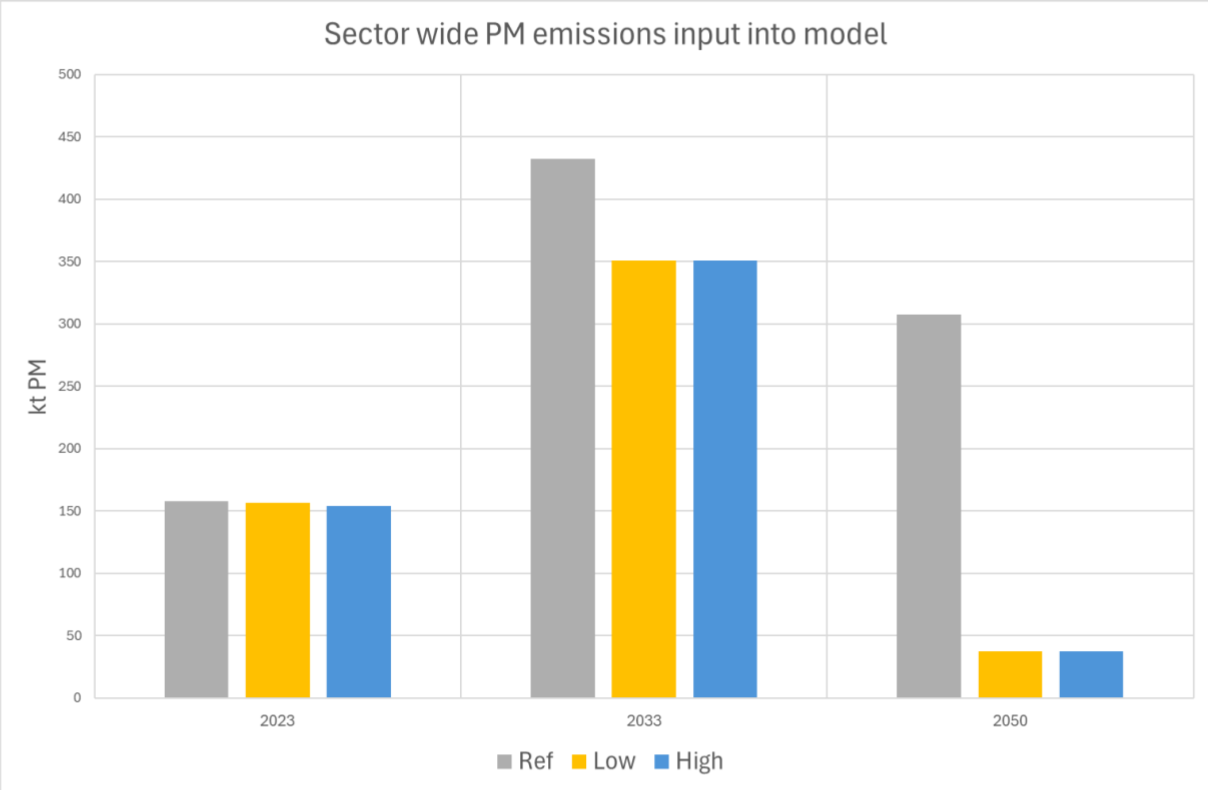

Figure 23: Non-Eskom Industry emissions (kt/year) of PM for the selected years of modelling as input into air quality model (High = High GHG mitigation scenario)

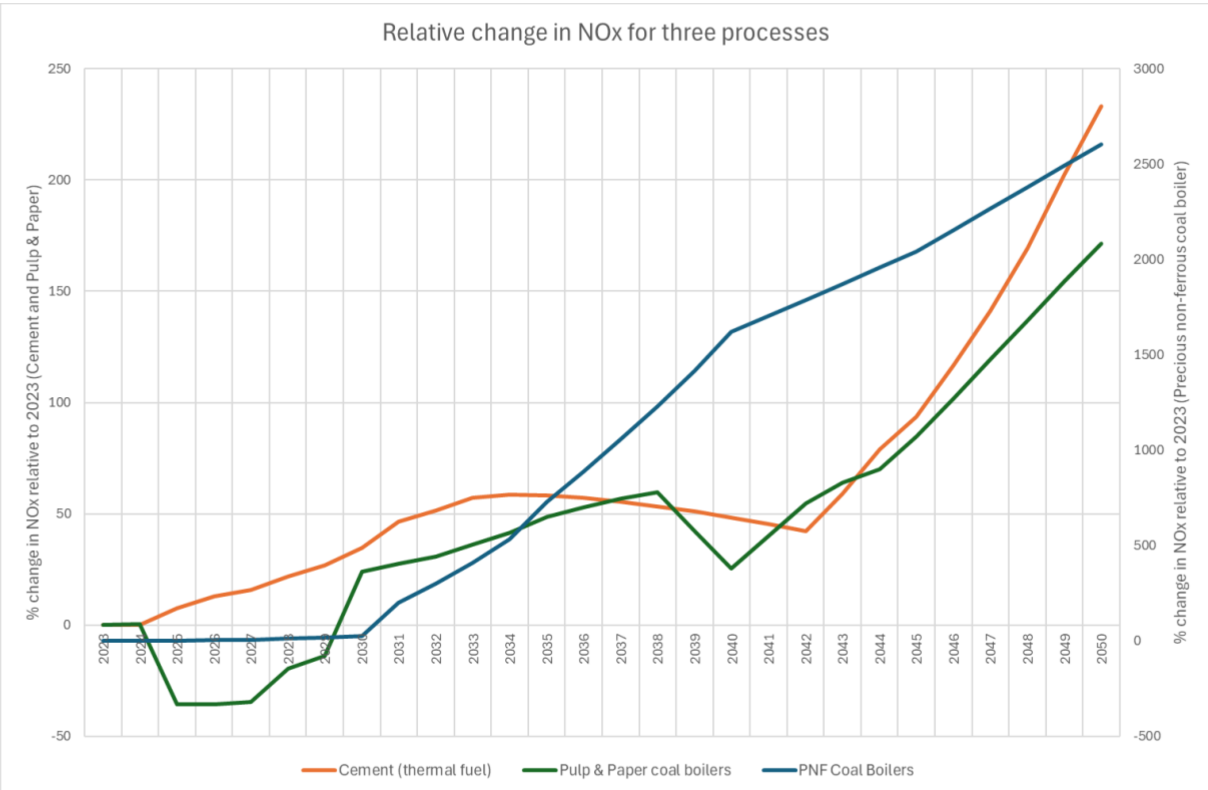

Figure 24: SATIMGE projected % changes (relative to 2023) in NOx for three selected processes for the reference scenario (unconstrained).

Air quality model runs

The CAMx model is run at the Centre for High Performance Computing located in Rosebank, Cape Town. The model was run for the three selected years for each scenario (i.e., Reference, High and Low), see Table 1. Thus, the number of runs performed are 9 in total. Each full year run takes approximately 22 hours to complete (excluding post-processing). Model output is comprised of pollutant (gas and aerosol) concentrations at each grid point for each hour of the year of simulation. Post-processing included format conversions and time averaging. Annual averages of SO_2, NO_2 and $PM_{2.5}$ were derived, considering these relate to the health impacts to be estimated.

Air quality and health impact assessment

Estimating the changes in health impacts (co-benefits) due to air quality improvements

The 'impact pathway' approach has been used to guide the assessment of the change in health impacts (health co-benefits) associated with a change in air pollutant concentrations because of the different emission change scenarios (Figure 25).

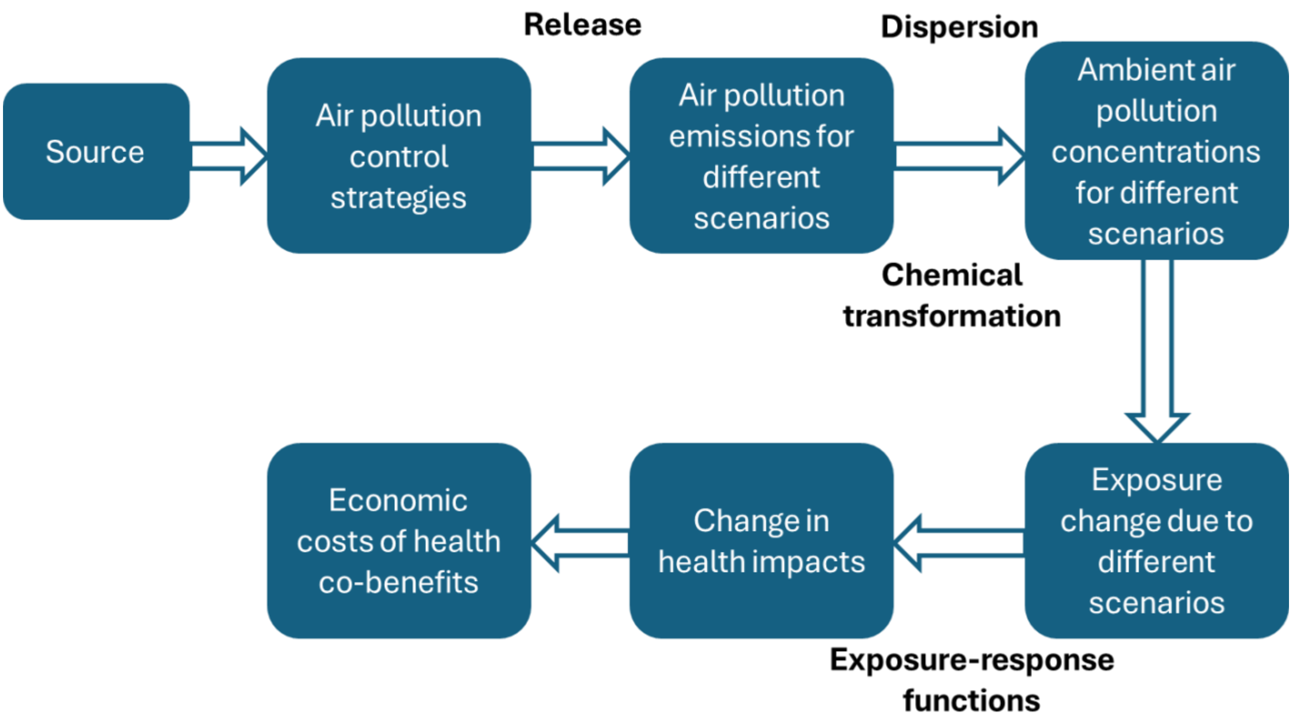

Figure 25. Impact pathway approach applied to assess health co-benefits associated with an improvement in air quality.

Availability of morbidity and mortality effects data

The following are indicators of health impacts related to air pollution exposure:

- **mortality effects of long-term (or chronic) exposure (all-cause mortality)**
- mortality effects of short-term (or acute) exposure

- morbidity effects of short-term exposure: respiratory hospital admissions
- morbidity effects associated with long-term (chronic) exposure. These are ischaemic heart disease, stroke, lung cancer, asthma (in adults and children) and chronic bronchitis, diabetes.

Although specific morbidity effects that may be associated with short-term and long-term exposure are recorded, data are not available at local municipal level. However, mortality effects represent the most serious impact of air pollution and the one for which the evidence is most robust (EEA, 2018). Mortality data is being recorded by StatsSA. The most recent cause-of-death (for which place of death is recorded) processed by Stats SA is up to 2018. Data is however only released at provincial level. Post-2018, data from the National Population Register is commonly used (pers. comm., Rob Dorrington). However, these data do not record place of death. Data from Home Affairs office on the place where a death was registered may be used and allows (with suitable adjustment) estimates of deaths at the level of the province of the province. However, this data is much less useful even at the level of metro, and even less so at municipal level).

In addition, while, with some effort, the adjustment to correct for under/overreporting of deaths may be possible at the level of the province, it becomes much more difficult to do for the metros and district councils given that we have limited understanding of the 'place-of-death catchment areas' of each Home Affairs office.

The 2016 StatsSA Community Survey is the most recent source of total mortality data at local municipal level. All-cause mortality, thus selected as an indicator of mortality effects of long-term (chronic) exposure to air pollution is usually assessed in terms of premature deaths and years of life lost (EEA, 2018). The reduction in premature mortality associated with a reduction in air pollution represented by the different emission reduction scenarios was thus used as in indicator of health co-benefits.

Exposure to changes in air pollution concentrations associated with different scenarios

The resulting changes in pollutant concentrations due to changes in $PM_{2.5}$, SO_2 and NO_2 emissions (exposure) are subsequently translated to human health impacts (as measured by a reduction in all-cause mortality). The literature was assessed to identify the most recent exposure/concentration-response functions and source the most recent health (all-cause mortality) data.

Exposure/concentration-response functions

These functions are referred to as either concentration-response functions or exposure-response function. For simplicity's sake, we will use the term exposure-response function (ERF) here. These functions quantify the health impact per concentration unit of air pollutant (EEA, 2018). The ERF relationship for each selected health outcome is based on whether it had already been used to quantify the health burden of air pollution, according to peer reviewed literature.

According to Khomenko et al. (2021), the choice of ERF is very important because it has the greatest effect on the final assessment outcome.

The following criteria are considered when selecting ERFs for different pollutants:

- Minimum concentration for which impacts can be determined (called a counterfactual)
- Adjusted vs non-adjusted functions
- Linearity vs non-linearity (Concentration-response functions are in general linear, but this may not be true for very low or very high concentrations (EEA, 2018))
- Lags between exposure and response
- The true ERF might vary between sub-populations, which may result in bias during risk estimate extrapolation.

Particulate matter ($PM_{2.5}$)

The updated Exposure-Response Functions (ERF) recommended for use by COMEAP is a summary effects estimate, derived by Chen and Hoek, 2020 (*in* COMEAP, 2022, p 1).

$$1.08 \text{ (95\% CI: 1.06, 1.09) per 10 } \mu g/m^3 \text{ annual average } PM_{2.5}. \quad (1)$$

The recommended ERF for $PM_{2.5}$ (see (1) above) is not adjusted for effects of other pollutants. This implies that:

i. effects caused by other correlated pollutants (such as other fractions of PM and NO_2) will likely be included to some extent (COMEAP, 2018);

ii. addition of mortality effects estimated using this coefficient to estimates of mortality effects associated with other pollutants, will likely overestimate the effects of the pollution mixture and of the benefits of reducing concentrations.

Counterfactual concentrations for $PM_{2.5}$ have been determined as 0 $\mu g/m^3$, which means the full range of concentrations is considered (EEA, 2018).

In making the decision to incorporate nonlinearity into the ERF, it should be noted that the output could result in large discrepancies in estimates of excess deaths if the true association is nonlinear (Yan et al., 2019). One study found that the shape for respiratory mortality was positive and linear at lower concentrations of $PM_{2.5}$, but then levelled off at the higher concentrations (Yan et al., 2019). Thus, when quantifying the mortality burden of $PM_{2.5}$ attributable to particulate air pollution (which may result in very low or even zero concentrations), continuing linearity is recommended (COMEAP, 2022, p 23).

When $PM_{2.5}$ is reduced due to an intervention, associated health benefits (e.g. reduction in mortality) are unlikely to manifest immediately due to some of the health effects of previous exposure persisting for some time. This delay, called a cessation lag, may assume that 30% of the risk reduction occurs in the first year after reducing pollution, 50% (years 2 to 5) with the remaining 20% being distributed across years 6 to 20 (COMEAP, 2022).

Sulphur dioxide (SO2)

There is a lack of a unified analysis of mechanistic, toxicological, and human clinical data on the health impact of SO_2 (WHO, 2021).

A 2021 review found a small but statistically significant association between short-term SO2 exposure and increased asthma hospital admissions/emergency room visits (RR = 1.010 per 10 μg/m^3 increase) (WHO, 2021). However, the review highlighted low certainty in the evidence due to limitations in data analysis.

Another 2021 review found a small but statistically significant association between short-term SO_2 exposure and increased non-accidental mortality (RR = 1.0059 per 10 μg/m^3 increase).

The association with respiratory mortality was also significant (RR = 1.0067 per 10 μg/m^3 increase), with higher certainty in the evidence compared to all-cause mortality.

Both reviews suggest a potential link between SO_2 and health risks, but further research is needed to clarify the specific effects and underlying mechanisms.

The Relative Risk for long-term mortality outcomes related to SO_2 has been determined to be 1.02 (1.02-1.03) (Krewski et al. 2009).

Nitrogen dioxide (NO2)

To estimate the effect on mortality of reductions of the whole pollution mixture, the COMEAP (2018) report recommended that the unadjusted annual average NO_2 is used (i.e., not adjusted for $PM_{2.5}$ or PM_{10} or other pollutants), following random-effects summary coefficient (hazard ratio) for NO_2:

1.023 (95% CI: 1.008, 1.037) per 10 μg/m^3 increment in NO_2 (2)

This function was derived from coefficients from single pollutant models from 11 studies (excluding studies on specific age groups) (COMEAP, 2018). Since these measures will also reduce PM concentrations, an alternative calculation of benefits associated with this reduction, using the unadjusted $PM_{2.5}$ coefficient was also recommended:

1.06 (95%CI: 1.04-1.08) per 10 μg/m^3 annual average $PM_{2.5}$ (3)

COMEAP (2018) indicated that either of these calculations is likely to underestimate the likely benefits of interventions and thus recommended the use of the higher of the two values calculated from these two approaches to enable a better prediction of the benefits.

The COMEAP-recommended hazard ratio for NO_2, adjusted for $PM_{2.5}$/PM_{10}, is:

1.026 (95% CI: 1.015, 1.037) (4)

Data presented on linearity for the relationship of NO_2 with all-cause mortality suggest it is unlikely that significant non-linearity would have been found in the older age group that dominates the mortality data (COMEAP, 2018). WHO recommended a counterfactual concentration of 20 μg/m^3

for NO_2, because the evidence of the concentration-response function for lower concentrations was not deemed sufficiently robust (WHO, 2013 in EEA, 2018). However, COMEAP (2018) does not recommend a lower threshold for effects at the population level because associations were observed in studies with NO_2 concentrations as low as 5 µg/m^3 NO_2 (COMEAP, 2018).

Two approaches have therefore been proposed:

- Using a cut-off or counterfactual of 5 µg/m3 (which, in practice, results in subtracting a value of 5 from grid concentrations (COMEAP, 2018)
- Not using a cut off (i.e., at 0 µg/m3) and assuming a linear dose-response relationship continues below the range of studied concentrations. This approach estimates the additional benefit (or effect) that is likely under the assumption that the same concentration-response relationship holds below concentrations that have currently been studied (COMEAP, 2018). Without such extrapolation any benefit (or effect) below 5 µg/m3 annual average NO2 remains unquantified.

Unadjusted coefficient for NO_2 reflects any causal effect of NO_2 and also, to some extent, the effects of other pollutants with which NO_2 is correlated. These include PM2.5, other fractions of PM, and other components of the air pollution mixture (e.g. ultrafine particles, Black Carbon, Volatile Organic Compounds etc.) (COMEAP, 2018).

Uncertainty

Sources of uncertainty throughout the impact pathways process, include (DEFRA, 2023):

- ERF based on assumptions made in epidemiological studies used to derive these benchmarks (reported as a confidence interval around a mean or central estimate, usually a 95% CI)
- dispersion modelling used to calculate impacts
- potential impacts caused by exposure to air pollutants that have not yet been identified and quantified by the research community
- complex mixture of several air pollutants, some of which are correlated which may result in double counting
- distribution of exposure data – everyone in a particular grid is assumed to be exposed to the same concentration and population movement is not considered.
- Availability and reliability of baseline health data
- Counterfactual concentration, when absolute numbers of premature deaths are considered (EEA, 2018)
- valuation of emissions not been adjusted to account for potential confounding effects of other pollutants

No specific meta-analysed ERFs exist for distinct age, sex, or socioeconomic status categories for South Africa. However, previous research has suggested that socioeconomic group and age (people older than 65 years old) results in differential exposure to air pollution and thus a greater risk of adverse health effects. Vulnerability and Health Impact Assessments that can account for the differential health effects that are based on region, age, sex, and socioeconomic status can therefore provide a deeper understanding of the variation of sensitivity and the capacity to cope within the population. Stratifying on the socioeconomic level also enables consideration of the modifier effect of socioeconomic status on the air pollution-mortality relationship (Kihal-Talantikite et al., 2018). These factors contribute to explaining how and why adverse health effects vary and will inform more targeted policy actions where they are needed the most.

Population-weighted mean concentrations

Since lives are lost at all ages, we have taken a population-weighted average. The average relationship between emissions and exposure to concentrations is calculated as a population-weighted mean for a pollutant divided by the total annual emissions of that pollutant. This provides the basis for 'national' damage cost estimates (DEFRA, 2023).

Population-weighted mean annual mean air pollutant concentration can be calculated by multiplying each grid annual mean concentration values from the model by the population statistics for all ages that applies to the same grid. The values for all the grid squares are then summed and divided by the total population summed across each area.

Placing population density maps over the concentration maps at the same resolution produces a picture of population exposure (EEA, 2018). This enables the estimation of the percentage of the population exposed to the whole range of concentrations, in increments of 1 $\mu g/m^3$. Information on the age and sex distribution of the population, if available, may also be used in the calculation of the attributable mortality as appropriate.

Baseline health

Country-specific data on life expectancy and mortality, categorized by age and sex, provide valuable insights into population health. However, these metrics represent the average experience and mask individual variations in exposure and susceptibility to air pollution's adverse effects. Consequently, estimated premature deaths based on such data provide a general understanding of air pollution's impact on the population but lack the granularity needed to assess individual risk. (EEA, 2018). The baseline mortality incidence is determined by the total number of deaths per year.

Years of life lost (YoLL)

This indicator considers the age at which premature deaths occurred. City (EEA, 2018). To complement the premature mortality estimates preventable upon the reduction of air pollution levels, the Years of Life Lost (YoLL) due to the premature deaths can be determined (Khomenko et al., 2021):

*YLL = Air pollution deaths (in age group) * life expectancy at age of death*

The average age of death can be estimated as the mean age for each age group. The standard life expectancy at the age of death can be obtained from country-level life tables (WHO, 2021).

Determining a change in health effects

A standard epidemiological equation is used to calculate changes in health effects (in this case mortality cases, resulting in lives saved) (adapted from: CREA/SFOC).

$$\Delta \text{Cases} = \text{POP x} \sum age \left[Frac_{age}\ x\ Incidence_{age}\ \text{x} \left(1 - \frac{RR(C_{base} +\ \Delta C_{source} age)}{RR(C_{base,}\ age)} \right) \right]$$

Where:

POP = total population in the grid location

Age = analysed age group

$Frac_{age}$ = fraction of the population belonging to the analysed age group

Incidence = baseline incidence of analysed health condition

C= pollutant concentration

C_{base} = baseline/current ambient concentration

ΔC = concentration attributed to specific source. The current contribution to pollutant concentrations from the source will have a negative sign (subtracted from the baseline concentration) and projected future incremental concentration a positive sign (added on top of the baseline concentration)

RR(c, age) = function giving the risk ratio of the analysed health outcome at the given concentration, for the given age group, compared with clean air.

Premature mortality

The number of deaths attributed to exposure to pollutant P in each grid:

RR= exp (β x conc) .... (β is determined by the increment of the ERF, e.g. if the increment is 6% in all-cause mortality per 10 ug/m^3, β is 0.006); concentration can be the exposure concentration in a particular grid, or the change/reduction in concentration due to an intervention.

AF = (RR-1)/RR

Premature deaths (PD) = AF * mortality *population

Total number of deaths attributed to pollutant P (or deaths prevented through reduction of pollutant P) in the whole area in year Y = Sum(deaths in each grid)

All-cause mortality is expressed as x premature deaths with a 95% CI between a and b.

The data inputs used to determine the health impacts are shown in Table 2.

Table 2: Data inputs for determining health impacts related to air pollution exposure

Health outcome	Ages	Pollutant	Averaging period	Baseline health data	ERF as Relative Risk (RR) *	Source of ERF
All-cause Mortality	all	NO_2	Annual	LM level from StatsSA	RR=1.01 (0.99-1.03) for a change in 10 μg/m^3	Beelen 2014
All-cause Mortality	all	SO_2	Annual	LM level from StatsSA	RR = 1.02 for a change in 5.03 ppb SO_2	Krewski et al., 2009
All-cause Mortality	all	$PM_{2.5}$	Annual	LM level from StatsSA	RR = 1.0123 for a change in 10 μg/m^3 $PM_{2.5}$	Heroux et al., 2015 in Lehtomaki et al, 2020

Monetizing mortality risk reductions

The Value of a Statistical Life (VSL) is commonly used in such studies to estimate cost from premature mortality. The VSL is the monetary value that a group of people are willing to pay to slightly reduce the risk of premature death in the population" (US EPA, 2018).

"The value of a statistical life (VSL) is the marginal rate of substitution between income (or wealth) and mortality risk. The VSL indicates how much individuals are willing to pay (WTP) to reduce the risk of death. It can vary among individuals, communities, and countries due to differences in income levels and associated priorities. People with lower incomes may have smaller WTP for risk reductions due to more urgent needs for basic necessities The VSL can be estimated via revealed preference data by observing individuals' choices that influence both income and risk levels. For example, the wage-risk literature examines the premium paid to workers in more risky occupations after controlling for other factors. The VSL is also sometimes estimated via stated preference data by querying individuals about hypothetical choices over income and risk. Applied properly, the VSL can be used in benefit-cost analysis to evaluate the efficiency of government policies designed to reduce risk." (Bosworth et al., 2017. US EPA, 2023).

Costs from international literature were translated to South African situation.

VSL adults – $ 1 046 000 (USD 2015; RSA value from Viscusi and Masterman, 2017).

Air quality model results

The modelling platform utilized here was previously (during the World Bank study) validated against surface measurements around the Gauteng region. Numerous iterations of model and emissions configurations were tested and reviewed. The finalized platform was seen to perform well, even against detailed measurements of aerosol species. Figure 26 provides a snapshot of performance looking at comparing annual average $PM_{2.5}$ against measurements. Note that data at the Xanadu station (XANA) was of poor quality.

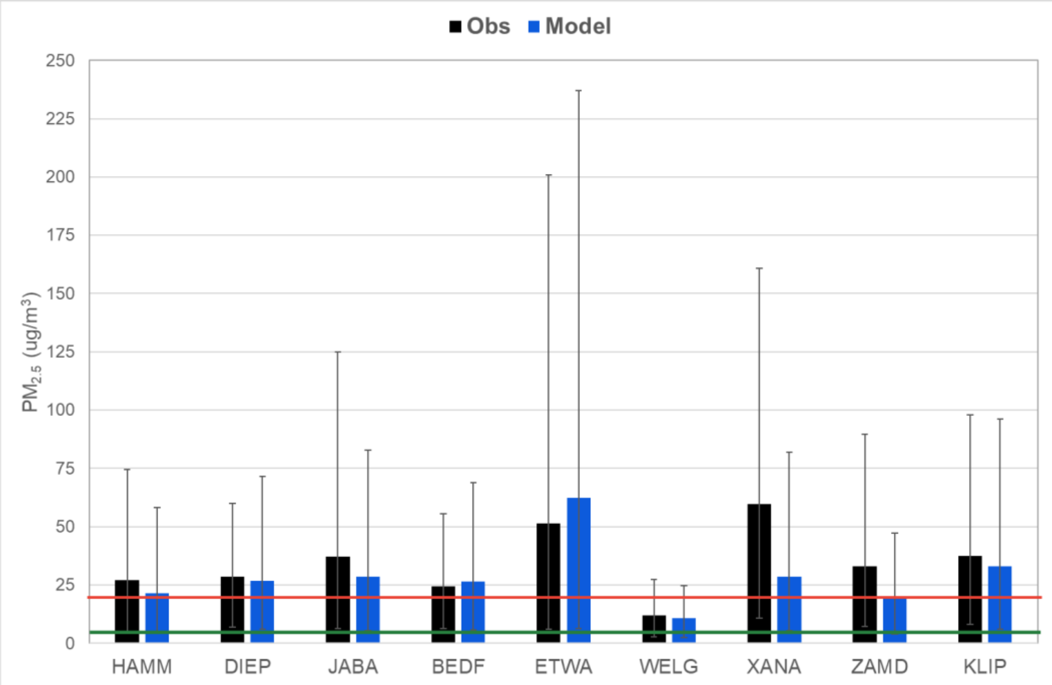

Figure 26: Comparison of simulated annual (2019) average $PM_{2.5}$ with measurements at sites across Gauteng.

The results shown here are comprised of annual average concentrations for SO_2, NO_2 and $PM_{2.5}$. These pollutants are included in the health impact assessment as they are criteria pollutants considered by the National Ambient Air Quality Standards (NAAQS) and are those for which we have health exposure response functions for. As the health impacts are assessed through changes in exposure due to the changes in air pollutant concentrations brought about by the SATIMGE driven reductions in emissions, spatial maps of changes (Reference vs scenario) are also vital in providing the necessary exposure fields.

Simulated reference concentrations

First it is necessary to look at the simulation of the Reference case (NZ10_2099B_99N; Unconstrained) as baseline hotspots of pollution may be identified and linked to the respective emission source. Figure 27 shows the simulated annual mean NO_2 for the Reference case. A majority of exceedances are simulated within the Gauteng region and for the most part associated with low level sources like on-road vehicles. However, as the projection progresses there is an increase in the extent of the exceedance in 2033, with a slight decrease in 2050. The changes across years are mainly driven by increases in SATIMGE precious non-ferrous metals (PNF) and "Industry-Other-boiler/process heating" with some Iron and Steel contributions. Similarly changes in SO_2 (Figure 28) are also driven by increases in precious non-ferrous metals industrial (using coal boilers) seen in the eastern part of Limpopo province. A relevant decrease is seen in 2050 as Matimba power station (western Limpopo) is projected to close. There are significant changes in $PM_{2.5}$ across the years simulated (Figure 29; note scales not same). The increase in concentrations for the 2033 simulation around North-West province are due to the SATIMGE projected increase in Non-Metallic Minerals Products (NMM) Cement (fuel to thermal fuel).

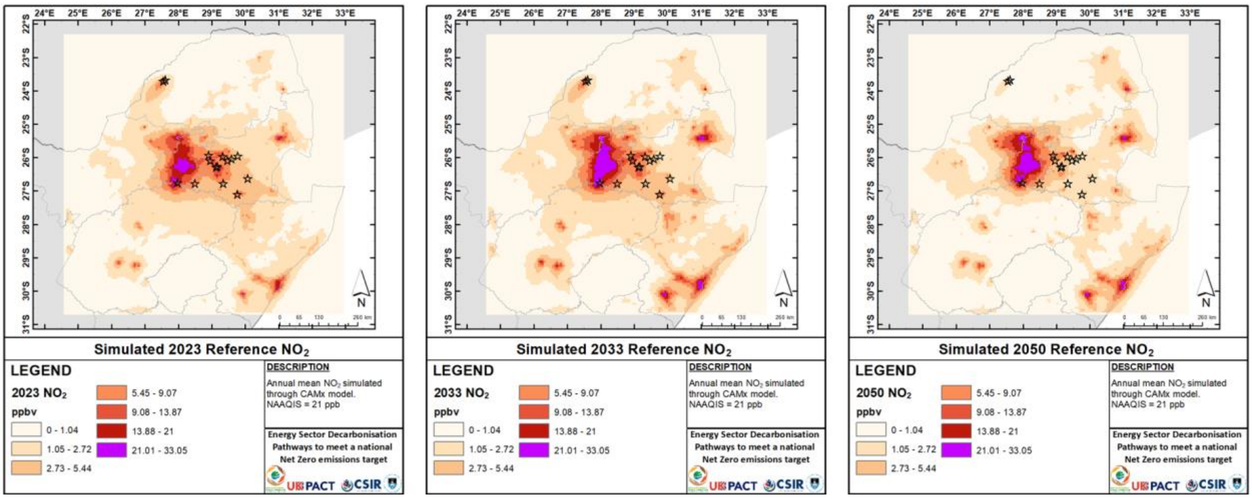

Figure 27: Simulated annual mean NO_2 for Reference scenario (2023, 2033 and 2050); purple indicates exceedance of the NAAQS

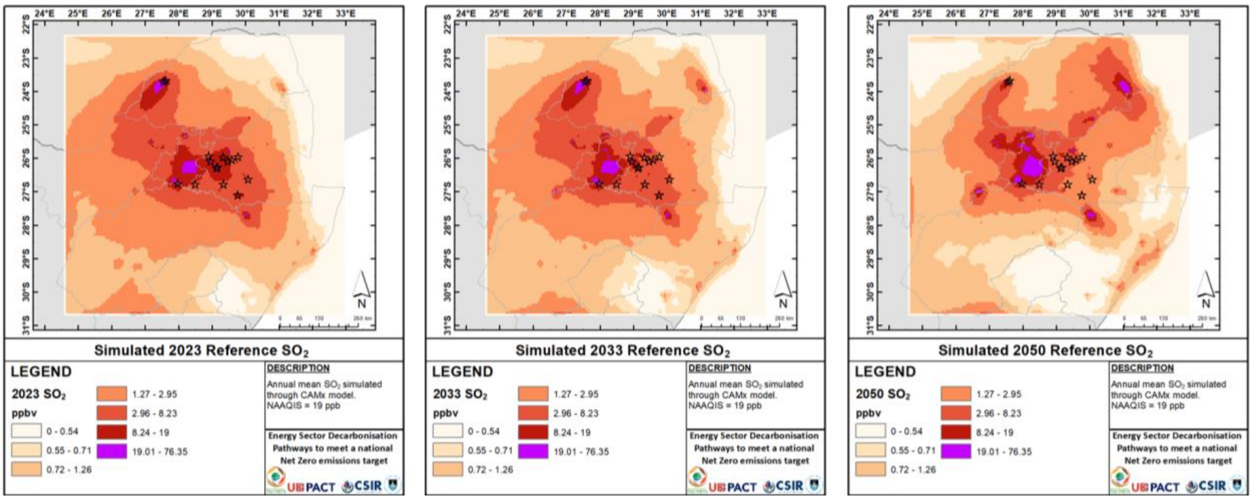

Figure 28: Simulated annual mean SO_2 for Reference scenario (2023, 2033 and 2050); purple indicates exceedance of the NAAQS

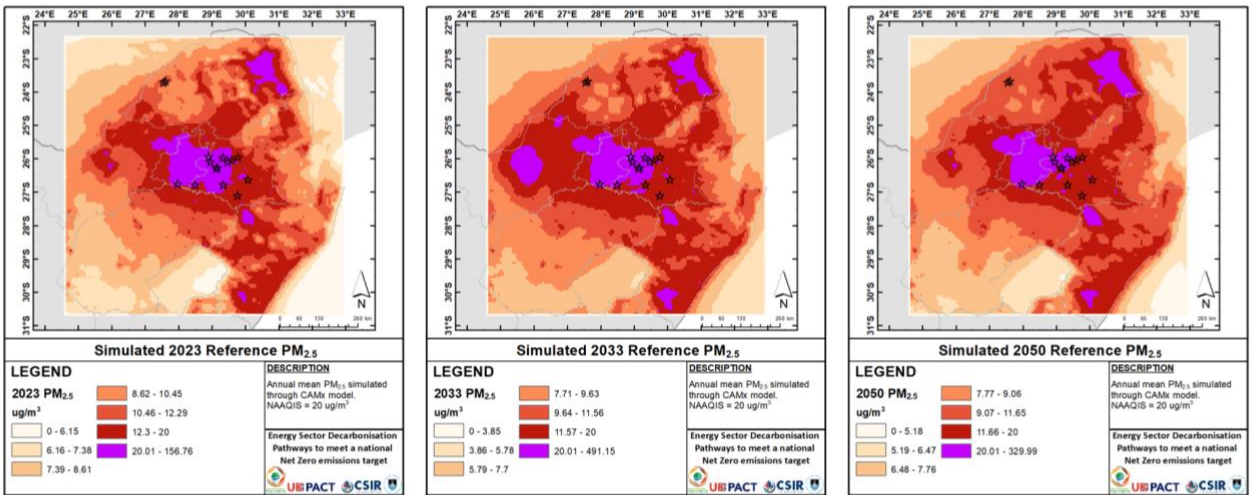

Figure 29: Simulated annual mean $PM_{2.5}$ for Reference scenario (2023, 2033 and 2050); purple indicates exceedance of the NAAQS. Note different scales.

Simulated changes due to High and Low GHG reduction scenarios

Changes in concentration may be assessed by simply subtracting the simulated scenario from the Reference. Figure 30 shows the changes due to the High Reduction (NZ10_2050A_08E) scenario compared to the Reference for each year in simulated. While there are large spread decreases (driven by reductions in vehicle and power generation emissions), some increases are seen. These are due to increases in fuel refining (2023 only) in the Vaal area, PNF industry (specifically heavy fuel oil boiler; 2033) in the North-West province and cement industry (2050) in the North-West province. The Low Reduction (NZ10_2050A_09E) scenario sees a similar increase in cement industry in 2050 however none of the PNF increases in 2033. For 2023 the increases along the coast are due to coal fired boilers in the pulp and paper industry. Note that scales for the High and Low scenarios are different, and that there are larger reductions seen for the High scenario.

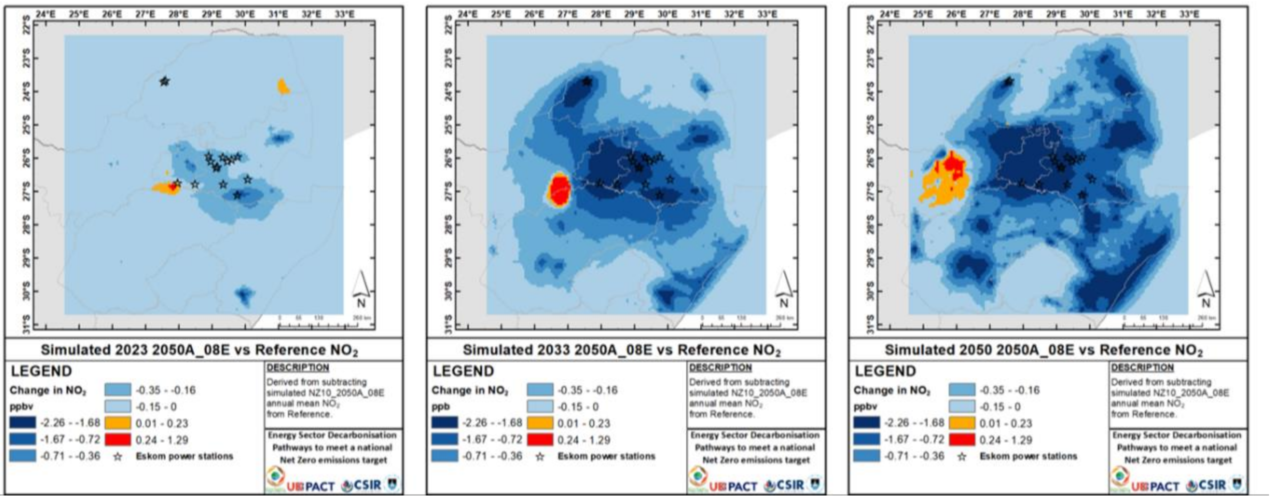

Figure 30: Simulated changes in annual mean NO2 between Reference and High scenarios

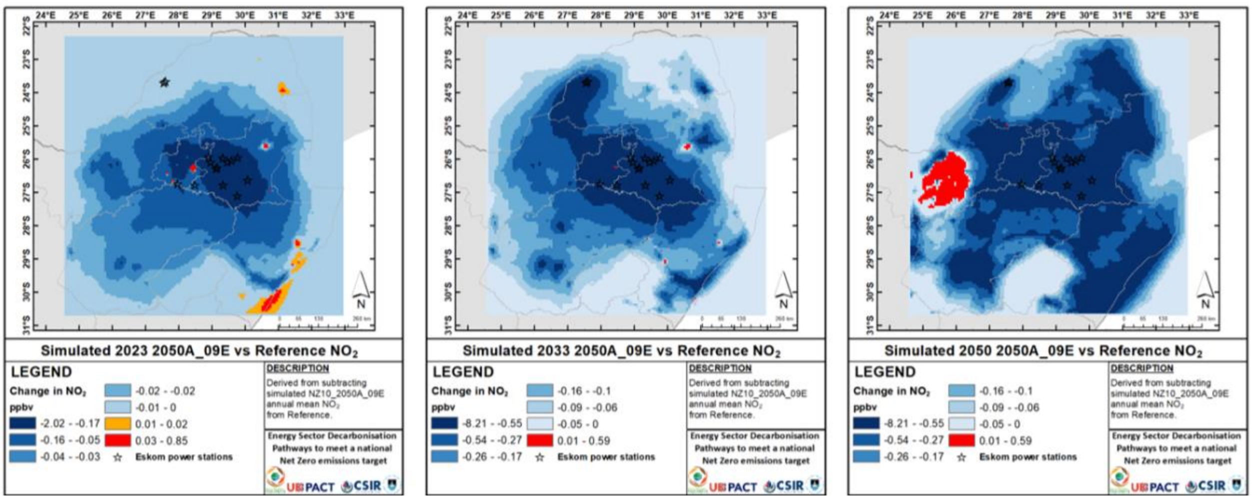

Figure 31: Simulated changes in annual mean NO_2 between Reference and Low scenarios

Simulated changes in SO_2 for the High scenario (Figure 32) show primarily reductions throughout the years. These reductions are high, reaching up to 81 ppb for both 2033 and 2050. For the Low scenario (Figure 33; NZ10_2050A_09E) there are some increases seen in 2023 due to a coal fired boiler used at a pulp and paper industry in Gauteng. The decreases seen for 2033 are much lower than for the High scenario. For 2050 the Low scenario shows some higher but more localized decreases.

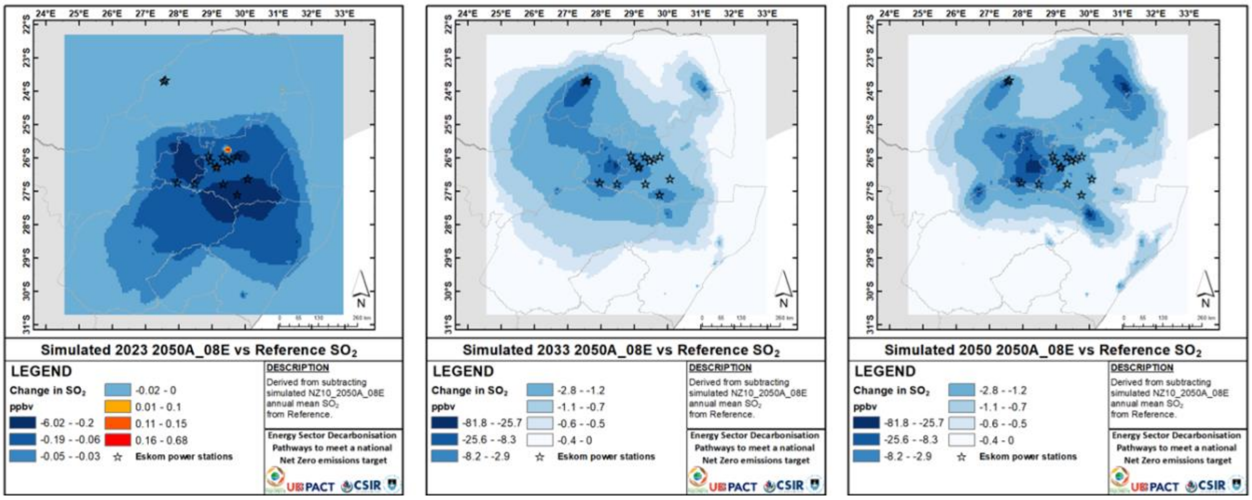

Figure 32: Simulated changes in annual mean SO_2 between Reference and High scenarios

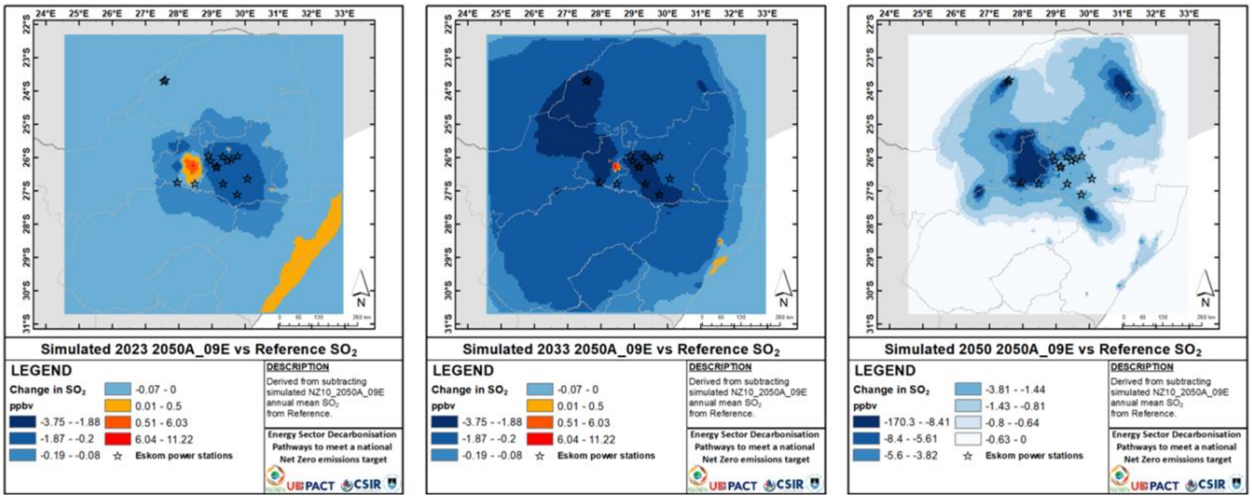

Figure 33: Simulated changes in annual mean SO_2 between Reference and Low scenarios

Some localized small increases (2023) in $PM_{2.5}$ are seen for the High scenario (Figure 34) which are due to mining and a chemical coal boiler in the eastern Limpopo region. This is also seen for the Low scenario with the addition of pulp and paper boilers along the KwaZulu-Natal coast. It must be noted that the simulated ambient $PM_{2.5}$ includes both primary (i.e., emitted from a source) and secondary sources (i.e., formed in the atmosphere from inorganic and organic chemistry). Thus, changes in for example Eskom SO_2 emissions impact simulated $PM_{2.5}$ as well.

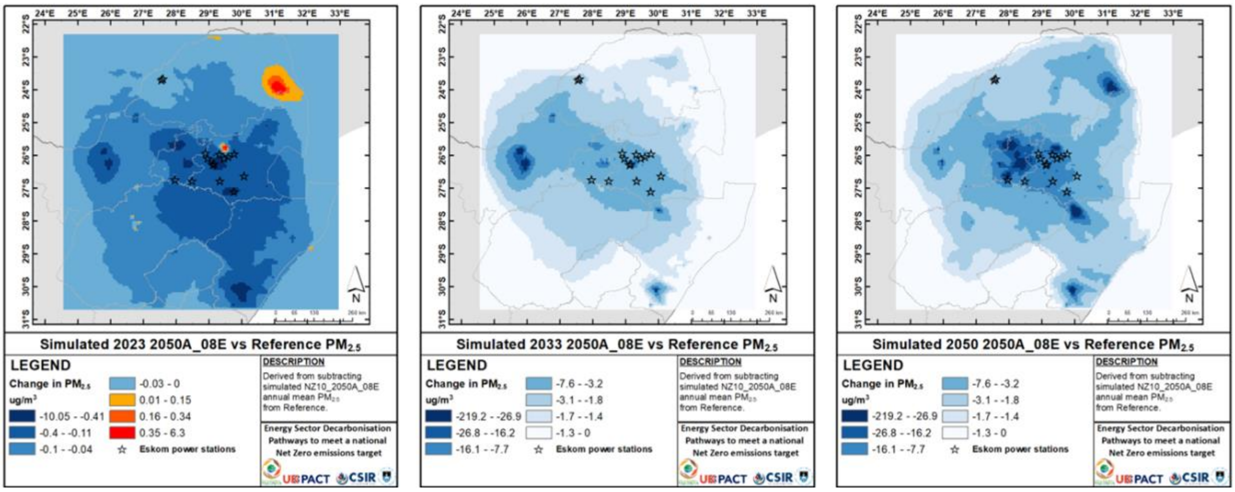

Figure 34: Simulated changes in annual mean $PM_{2.5}$ between Reference and High scenarios

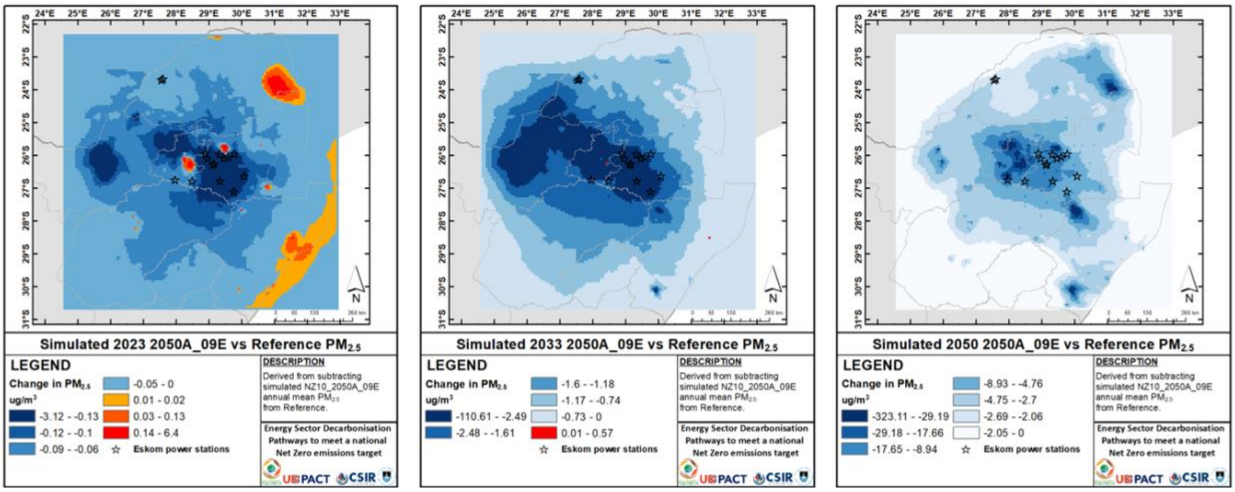

Figure 35: Simulated changes in annual mean $PM_{2.5}$ between Reference and Low scenarios

The changes in pollutant concentrations due to emission reductions can be applied to exposure-response functions. These functions, derived from extensive international studies, link changes in average exposure to specific pollutants over specific periods with associated health impacts such as changes in mortality. Since health data on mortality is only available annually, we focused on changes in annual average concentrations. In addition, the highest available spatial resolution for health data is the local municipality level (LM).

Furthermore, the annual average concentrations (or changes in these) represent only the risk to human health, while human health impacts actually occur only where people are present. It was therefore necessary to derive population-weighted exposure (PWE) for each LM. This is achieved by firstly multiplying pollutant concentrations by population at a gridded scale. A gridded population product such as the Gridded Population of the World (version 4; Center for International Earth Science Information Network, 2018) was used for this purpose, as shown in Figure 36.

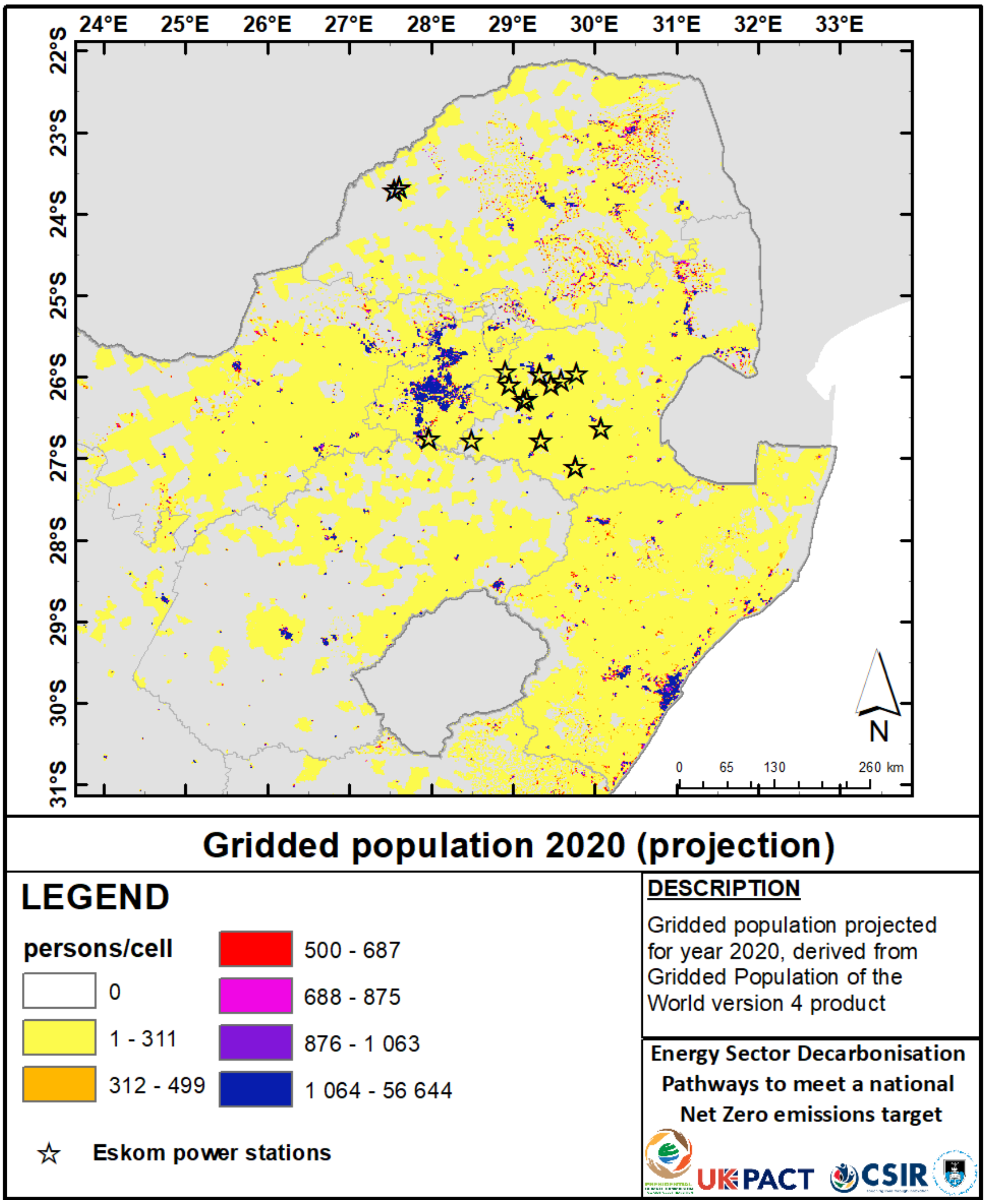

Figure 36: Gridded population used to derive population weighted exposure

Thereafter, this is summed per LM and divided by the total population per LM (based on the GPWv4). An example of the result is shown in Figure 37, which is PWE estimated for the 2050 Low scenario NO_2 concentration reductions (Figure 31). Changes in pollutant concentrations are multiplied by gridded population and aggregated to LM. These PWE are used directly within the health impact calculations (methodology in Section 0).

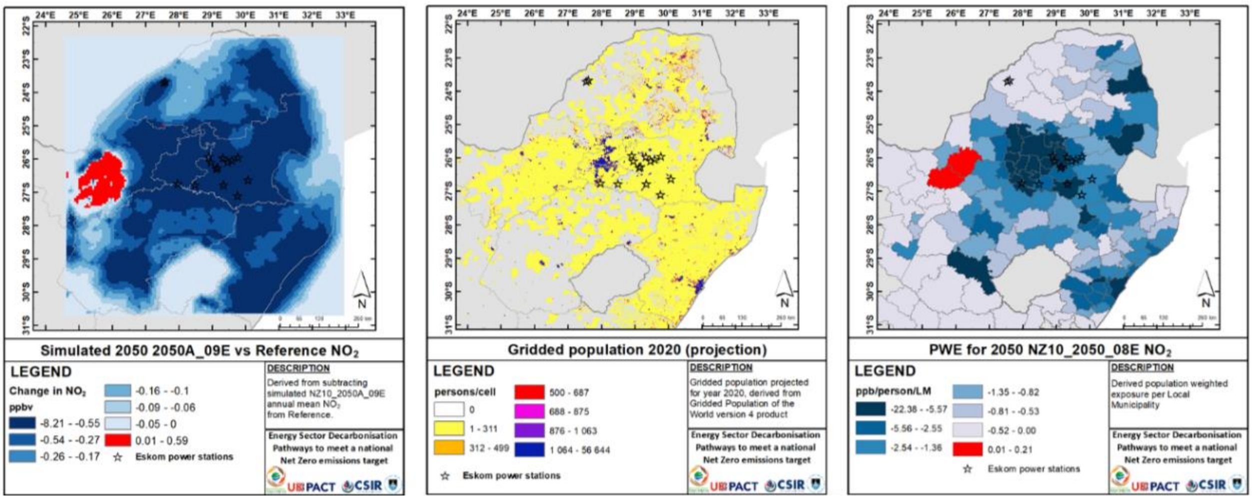

Figure 37: Population weighted exposure as estimated for NO_2 for 2050 Low scenario.

Health impact (benefits) results

Health impacts are estimated for NO_2, SO_2 and $PM_{2.5}$ and are expressed in terms of reductions of all-cause mortality across all ages. Reductions are estimated per LM and are reported here as domain-wide aggregates. Note that these impacts are derived from mainly reductions in emissions and associated response in ambient concentrations and may thus be seen as benefits to the scenarios. Table 3 provides the estimated reduction in premature mortality. Reductions are higher, but not significantly, for the High GHG Reduction scenario (NZ10_2050A_08E) for all pollutants. Highest reductions are seen in 2050, which is when the difference in concentrations between Reference and scenarios are the largest, particularly for areas that are highly populated.

Table 3: Estimated reduction in premature mortality (all ages) for the three years simulated.

	Reduction (number of persons)		
Scenario	**NO_2**	**$PM_{2.5}$**	**SO_2**
High reduction (NZ10_2050A_08E)	5821	6031	12987
Low reduction (NZ10_2050A_09E)	5521	5500	11162

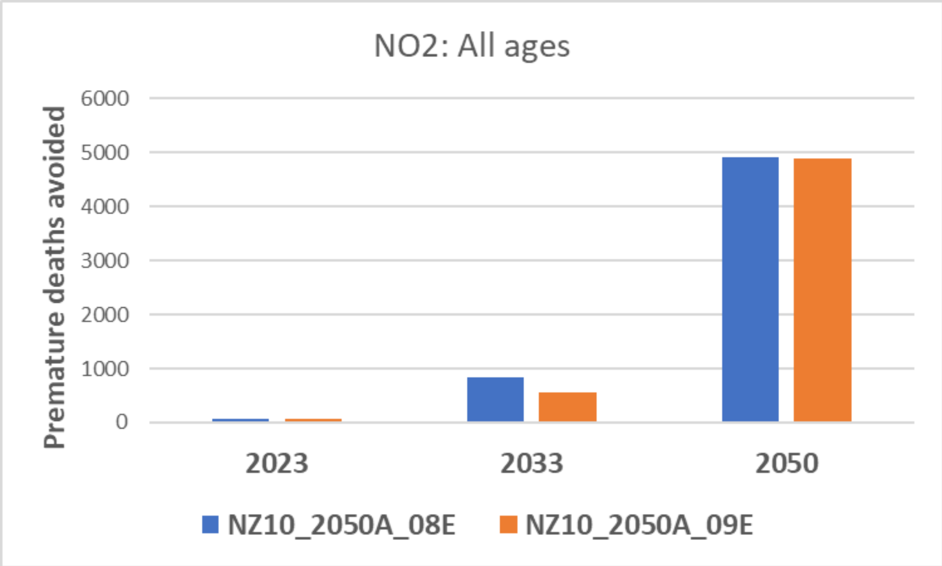

Figure 38: Estimated reduction in all-cause mortality associated with NO_2

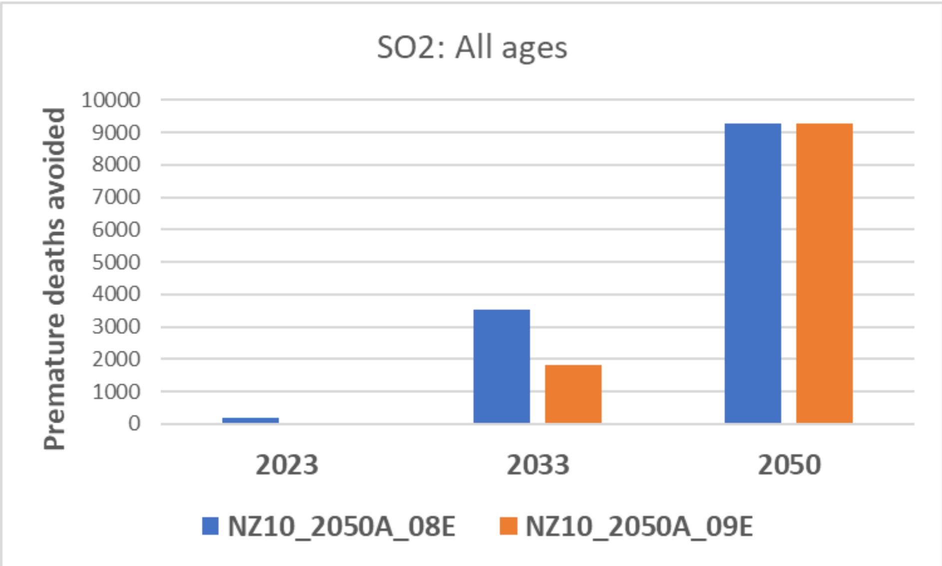

Figure 39: Estimated reduction in all-cause mortality associated with SO_2

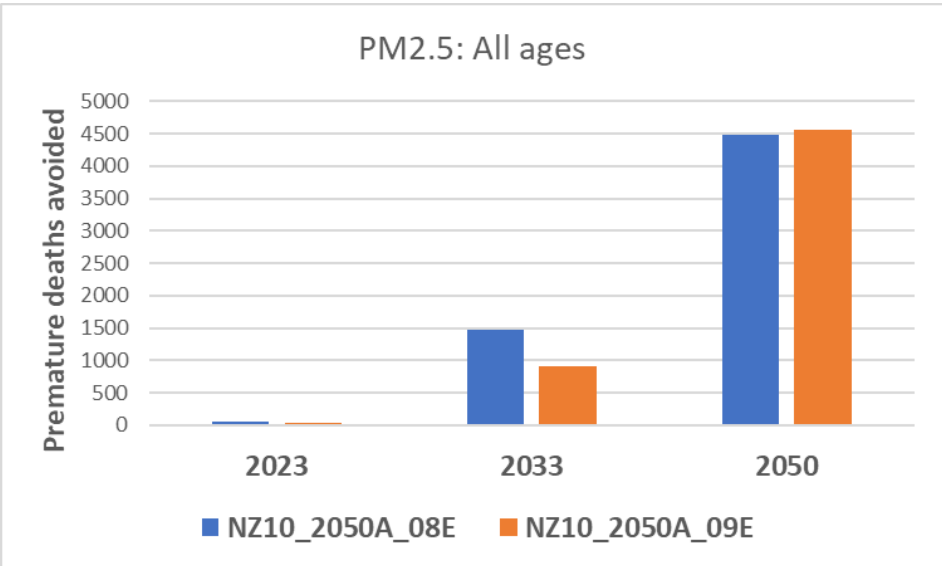

Figure 40: Estimated reduction in all-cause mortality associated with $PM_{2.5}$.

In order to provide some context, Table 4 shows estimates of reduction in premature mortality, due to changes in $PM_{2.5}$ concentrations, from other studies in South Africa. All used some form of air quality modelling that included chemistry, and thus accounted for nitrate and sulfate aerosol that may originate from SO_2 and NOx. The emission reduction scenarios may differ, but all had a focus on the power generation sector, which is primarily comprised of Eskom coal-fired power stations. One potential significant difference is that while the studies use all-cause premature mortality as a health outcome, they look at different age groups. Furthermore, the fraction of population exposed would be different due to different model domains, particularly for the Marais et al. (2019) study that looked at a national scale (and included a higher population; and thus more potential for health benefits). In terms of this study, and considering the others include a single year, the two Highveld estimates fall between the 2033- and 2050-time horizons.

Table 4: Estimated reductions in premature mortality due to changes in simulated $PM_{2.5}$ from other similar studies in South Africa

Domain	Period	Emission reductions	Health outcomes	Estimate (persons)	Ref
Highveld Priority Area	Single year	Closure of all Eskom power stations	All-cause mortality > 25 yo	2 409	Van der Walt, 2023
Highveld Priority Area	Single year	Eskom complying with MES	Sum of lung cancer, IHD, COPD, stroke and LRI for < 5 yo	2 731 (890 – 5 171)	Myllyvirta, 2014
National	Single year	2030 policy scenario for power generation and vehicles	All-cause mortality > 14 yo	10 400 (2 000- 18 300)	Marais et al., 2019

Interpretation of health impact results

The reduction in premature mortality due to the reduction of different pollutants can potentially be added, but with some caveats:

- Different age groups: If the pollutants affect different age groups, it might be more meaningful to weight the reductions for each pollutant based on the number of lives saved in each age group.
- Double counting: If pollutants often co-occur and contribute to the same health problems, simply adding the reductions could overestimate the total benefit.
- Synergistic effects: Pollutants can sometimes have synergistic effects, meaning their combined impact on health is greater than the sum of their individual effects. This can make it difficult to accurately predict the total mortality reduction from reducing multiple pollutants.

- Indirect effects: Reducing pollution can have other indirect effects on health, such as improving mental health and well-being. These benefits are not easily captured in a simple mortality reduction calculation.

Health costing

It is possible to express the health benefits (reductions in premature mortality) through the use of Value of Statistical Life (Section 0). The value of $1 046 000 (2015 USD) was selected to be representative of South African conditions (Viscusi and Masterman, 2017). This was further translated to 2023 USD by adjusting for inflation (increased by factor of 1.29; https://www.usinflationcalculator.com/) resulting in $1 349 340. The total estimated monetary benefits for the three years simulated are provided in Table 5. While it is unsurprising that the High GHG reduction scenario yields higher benefits in ambient concentrations, then reduction in mortality and thus monetary savings, it should be noted that ultimately there is a difference between scenarios of only ~11%. This may be related to the large differences seen only in the mid-period of 2033, with 2023 and 2050 having very little difference (Figure 5 to Figure 17). However, if cumulative benefits are accounted for, it is likely the difference in scenarios would be larger. The estimation of cumulative benefits will however introduce further uncertainty, in addition to those in the emissions, projections, air quality modelling, health impacts and single year costing.

Table 5: Estimated monetary benefits for each scenario based on reductions in all-cause mortality across all ages.

			Low (NZ10_2050A_09E)		High (NZ10_2050A_08E)	
Pollutant	VSL Cost ($)	Year of currency (USD)	Reduction in mortality	Total cost ($)	Reduction in mortality	Total cost ($)
SO_2	$1 349 340	2023	11161	$15 060 924 701	12987	$17 523 966 423
$PM_{2.5}$	$1 349 340	2023	5500	$7 421 451 021	6031	$8 138 255 062
NO_2	$1 349 340	2023	5521	$7 450 100 128	5821	$7 854 911 455
			Total	$29 932 475 850		$33 517 132 940

Projections of health benefits to estimate cumulative cost

It is often necessary to estimate the monetary benefits cumulatively across the time period, i.e., in this case 2023 to 2050 for all years between. This attempts to place value (savings) across the period of the mitigation. There are numerous approaches to accomplishing this, but ideally should be seen within the context of comparing against cumulative mitigation costs to achieve net zero. Thus, the many uncertainties and parameters are at least consistent between two estimates and the value is drawn from a comparison.

Nevertheless, an approach is outlined here, and the result provided for future consideration. Reduction in premature mortality for the three years are updated for years between by using projections in total population. The equation noted in Section 0, for estimating changes in a health outcome, requires population of those exposed. By increasing this factor, more people would be exposed to better air quality, and thus the health benefit would be more. On the monetary benefit side, the concept of Net Present Value (NPV) is utilized. Discount rates are used to modify the value of money through time and assumes that money used currently is worth more than money used in the future. Using these two parameters a projected monetary benefit of improving health, due to improved air quality, across years is estimated.

The population projections are sourced from the U.N. World Population Projections, which were released in 2022. These provide a low, medium and high projection of national scale populations up to 2100. The medium projection for all ages was used here. The projections are used to derive scaling factors for years between 2023, 2033 and 2050; and are used to directly modify the estimated reduced mortality for those years simulated. This assumes the national scale population projected trends will uniformly apply to the model domain region, and that the spatial distribution of people will remain the same. There is also the assumption that the all-cause (all ages) mortality rate used (derived from the Local Municipality cause of death data released by StatsSA in 2018) remains the same. Thus, it is only the total population that is changing.

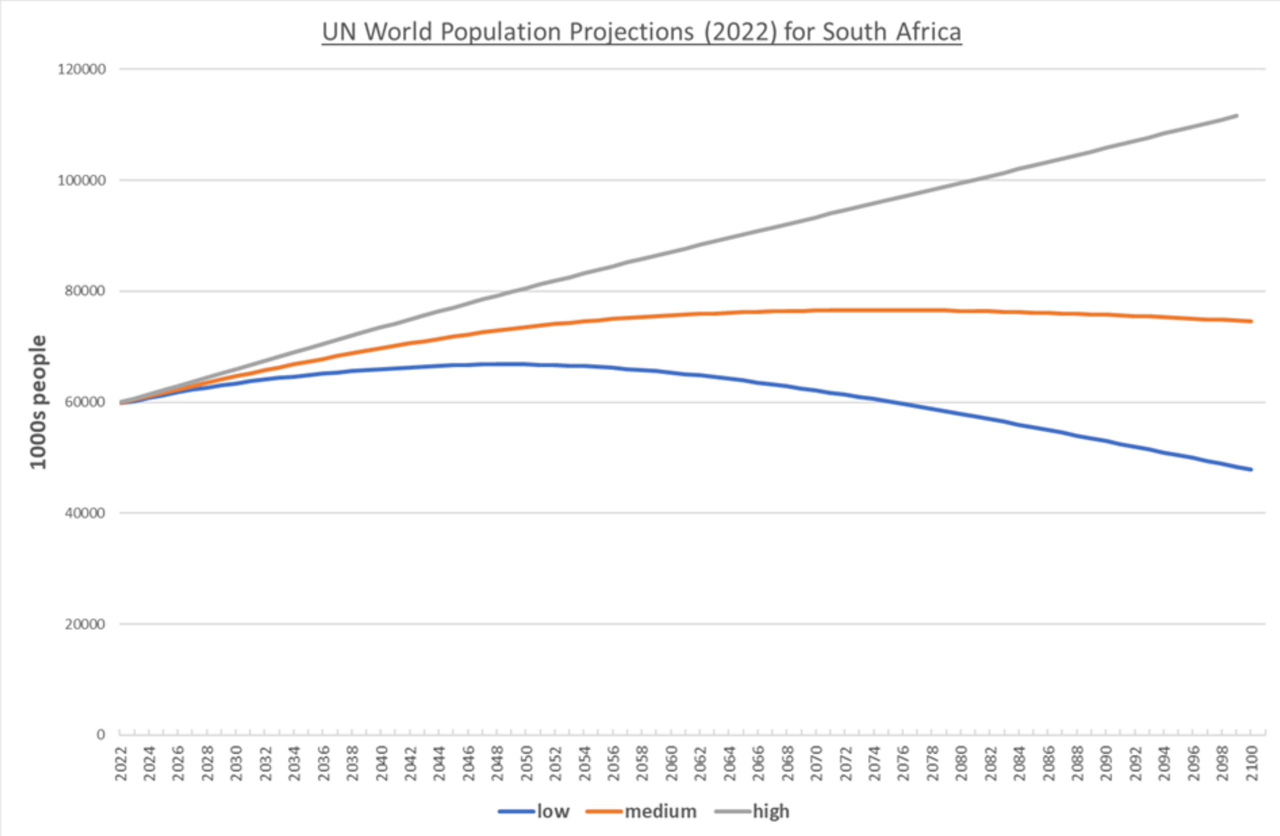

Figure 41: UN World Population Projections for South Africa

Table 6 shows the discount rates used to apply the NPV approach. A range is used as some of the choice may be arbitrary and is often best aligned with the costing side. The source of each rate is also provided in the table. These are kept constant throughout the period, as is inflation. The VSL is also kept constant throughout.

Table 6: Discount rates used in NPV calculations.

Discount rates		
Low	**6**	2023 average inflation
Medium	**8.484**	Annual average for 2023 of SA 3-Month Bond Yield
High	**9.45**	Annual max for 2023 of SA 3-Month Bond Yield

Table 7 shows the estimated cumulative monetary benefit over the period 2023 to 2050. The High GHG Reduction scenario results, on average, in avoided cost (through all-cause premature mortality) of $111 billion (in 2023 USD), while the Low GHG Reduction scenario results in $73 billion. The difference is more significant than if one were to consider the three years simulated. There are some assumptions made that make this estimate conservative, namely that:

- There was no projection in inflation or VSL. Particularly VSL, which is based on willingness-to-pay (see Section 0), is expected to increase as the general costs of living and earning go up.
- The rate of increase in population is lower than the discount rate. This results in a stronger decrease in annual cost avoided as the discount rate decreases the value of the monetary savings faster than the increase in population results in increased mortality avoided (Figure 42). The population projection is complex, and there's no basis for selecting the "high" projection vs the "medium". Furthermore, the choice of discount rate depends on time periods of investment and what you are comparing the benefits with. In either case, it is expected that the increase in VSL and inflation may outweigh the impact if discount rates were higher or population growth was lower.
- There was no interpolation of concentration reductions between the three years simulated. This means the change in ambient air quality was kept consistent between those years, resulting in step changes rather than the expected sloped trend. Considering the pathways and trend toward emission reductions, the intermittent years are expected to yield more savings (mortality and thus cost) than is assumed here.

For these reasons, the cumulative estimate provided here is likely on the low end of the range.

Table 7: Estimated cumulative monetary benefits from reducing all-cause mortality by improving air quality through decarbonization pathways.

<table>
<tr><th colspan="2"></th><th colspan="5">$Bn (2023 USD) cost avoided</th></tr>
<tr><th>Scenario</th><th>Discount Rate</th><th>SO_2</th><th>$PM_{2.5}$</th><th>NO_2</th><th>Total</th><th>Scenario average</th></tr>
<tr><td rowspan="3">NZ10_2050A_08E</td><td>Low DR</td><td>70</td><td>30</td><td>21</td><td>121</td><td rowspan="3">111</td></tr>
<tr><td>Mid DR</td><td>62</td><td>27</td><td>19</td><td>108</td></tr>
<tr><td>High DR</td><td>59</td><td>26</td><td>18</td><td>103</td></tr>
<tr><td rowspan="3">NZ10_2050A_09E</td><td>Low DR</td><td>42</td><td>21</td><td>16</td><td>79</td><td rowspan="3">73</td></tr>
<tr><td>Mid DR</td><td>38</td><td>19</td><td>15</td><td>72</td></tr>
<tr><td>High DR</td><td>36</td><td>18</td><td>14</td><td>68</td></tr>
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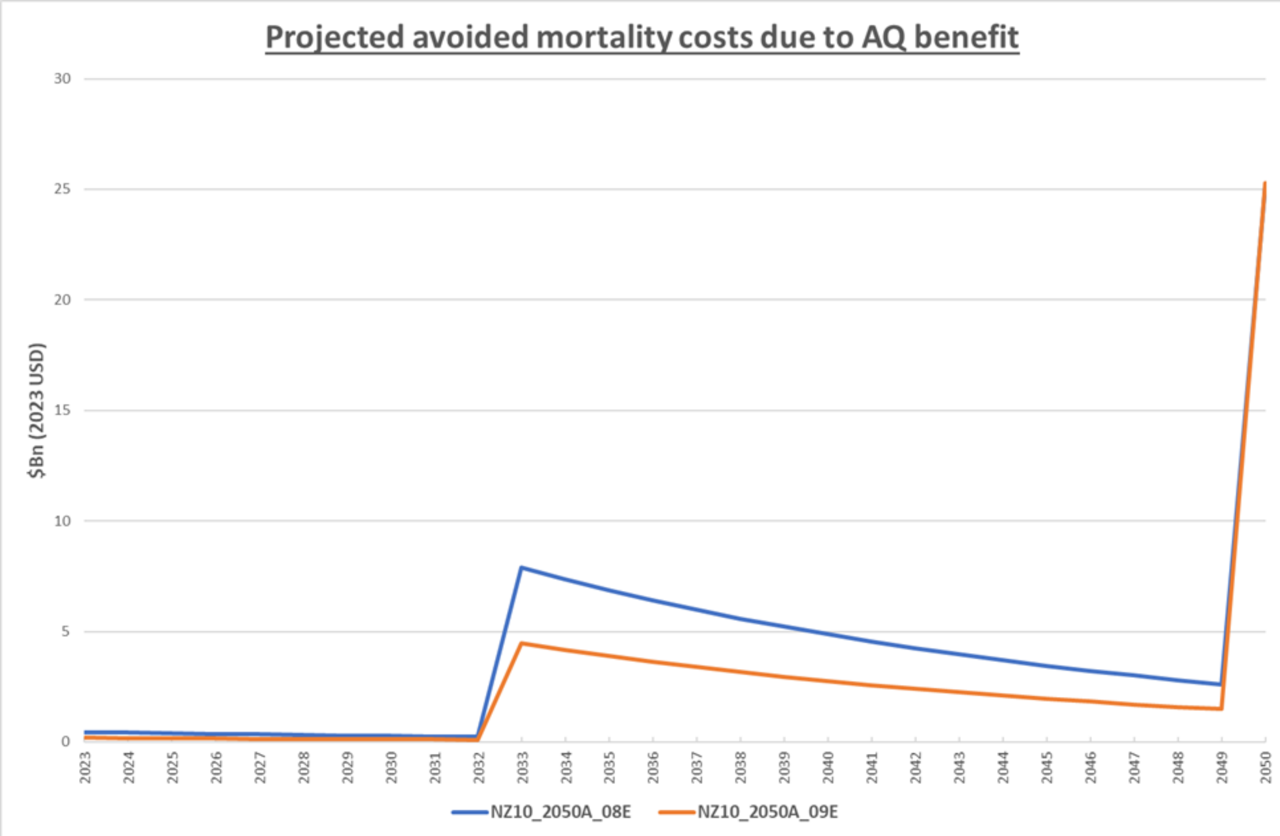

Figure 42: Projected annual avoided costs (average of discount rates) due to improved health from emission reductions in scenarios.

Water co-benefits

A variety of water-related benefits can potentially be realized from a transition to net zero emissions. These benefits relate to both the quantity and quality of water resources. In terms of water quantity impacts, fossil-fuel based power production generally requires significant amounts of water for cooling and other purposes, while other forms of power production require significantly less (Pocock and Joubert, 2021). In addition, fuels such as coal require water to be mined, processed and in some cases transported (UoCS, 2010). In terms of water quality, a reduced reliance on coal for electricity and oil production will potentially reduce eutrophication (Singh et al., 2012), toxicity (Bergesen et al., 2014) and acidification (Luderer et al., 2019) of water resources.

It is important to note that the adoption of renewable energy technologies can also result in negative impacts on water resources (Luderer et al., 2019). For example, the development of biofuels from crops can require significant amounts of water and land, and result in eutrophication of water resources if agrochemicals are not carefully managed. The building of dams for hydropower generation alters aquatic environments and results in losses of water to evaporation.

This study of the water co-benefits of decarbonization focuses on water consumption in electricity production, given South Africa's current heavy reliance on fossil fuels in this sector. This is done by quantifying how water use evolves under selected decarbonization pathways modelled in the larger project. The water use considered in this analysis is that consumed directly (on-site) in electricity generation. Upstream water uses, such as that consumed in mining coal or in the manufacture of solar photovoltaics and wind turbines are not considered in the projections, as they are beyond the scope of this high-level study. However, given the significant impact of coal mining on the country's water resources, a brief review of these impacts is presented.

This chapter on water co-benefits of decarbonization includes sections on:

- different electricity generation technologies and how they use water,
- the impact of coal mining on water quantity and quality,
- historical water-use in the electricity sector,
- projections of future water-use in the electricity sector (based on decarbonization pathways modelled in this project),
- comparison of results with other projections of water use,
- Considerations towards costing water co-benefits, and
- overall conclusions.

Electricity generation technologies and how they use water

South Africa has approximately 16 coal-fired power stations. In coal-fired power stations, freshwater is used for steam generation, cooling, sluicing of ash, ash handling, waste disposal, air pollution control, sewage treatment and mine water recovery processes (CoM, 2017). Most of the water used is for cooling. Thermoelectric power stations (coal and nuclear) boil water, making steam which then turns turbines and generates electricity. Condensers, cooling water, and cooling towers are used to convert the steam back into water. South Africa has a single nuclear power station (Koeberg). This plant mostly uses seawater and a small amount of fresh water.

Hydroelectric power plants utilize the flow of water in a river to drive a turbine which generates electricity. Typically, these plants are located at dams which control the rate of flow of water through the turbines. The only water that is consumed and lost to the system at these plants is the water that is lost from the dams in the form of evaporation and seepage. South Africa has two large-scale hydroelectric plants at the Gariep and Vanderkloof Dams on the Orange River.

Similar to hydroelectric plants, pumped storage schemes generate electricity through the flow of water released from a dam that drives one or more turbines. However, in these plants water is captured in a lower dam and is then pumped back up to the upper dam during periods of low electricity demand. When electricity demand is high, water is released from the upper dam to generate electricity. Similar to hydroelectric plants, the only water that is consumed is water that is lost to dam evaporation and seepage. South Africa has three large-scale pumped storage schemes, these being the Drakensberg, Palmiet and Ingula schemes.

Gas turbines (open cycle or combined cycle) are powered by liquid fuels (diesel or kerosene) or gas. South Africa has approximately six of these plants which are located in coastal locations. Freshwater is used for cooling purposes, and for steam generation in the case of combined cycle gas turbines. Similar to the hydroelectric and pumped storage plants, the gas turbine plants are used to meet peak demand rather than to meet baseload requirements.

Solar photovoltaic (PV) and wind turbine power generation use minimal amounts of water for their operation. This water is used for cleaning purposes to maximize the efficiency of power generation. Concentrating Solar Power (CSP) stations generate power by focusing the suns energy on to a small area. This type of solar power generation comes in different forms and generally requires water for steam production and cooling. The amount of water required depends on whether it is a dry or wet cooling process.

The power generation technologies outlined above are the ones used in South Africa that require water in some form, and which are included in the decarbonization scenarios considered in this study.

Review of the impact of coal mining on water quantity and quality

Introduction

South Africa is one of the world's leading coal-producing countries in the world (Polisi et al., 2021), has the fifth largest coal reserves globally and is a significant user and exporter of coal (CER, 2018). In 2014, South Africa produced 260 mega tonnes of coal, of which 182.7 mega tonnes were sold within the country and 69.6 mega tonnes were exported (CeR, 2018). Therefore, the bulk of the coal that is produced is used domestically (CoM, 2017). South Africa relies primarily on coal fuel for the generation of electricity, steel manufacturing and the production of petrochemicals. In 2014 the country's leading power producer, Eskom, consumed 110 million tons of coal for the generation of electricity (CoM, 2017). Forty million tons was used for the production of synthetic fuels and chemicals by Sasol and 21 million tons was consumed mainly in boilers and furnaces for industrial and domestic heat-production (CER, 2018). As a result, South Africa's economy is extremely dependant on coal mining (CoM, 2017). However, the large economic impact of coal mining comes at a cost, with mining activities having a detrimental impact on the quantity and quality of water resources in the country (Polisi et al., 2021).

Mining operations consume significantly large volumes of water (Askham and Van de Poll, 2017), with the water being used in the processes of extraction, washing and pollution reduction, and also in the disposal of contaminated by-products (Greenpeace, 2012). Furthermore, large volumes of water are required for the generation of coal power. Mining and power generation consume 3% and 2% of South Africa's water resources, respectively (DWA, 2013). In South Africa - one of the world's most water-stressed countries and one of the biggest producers and consumers of coal - the relationship between coal mining, coal reliant energy and water use is an issue of great concern (Greenpeace, 2012).

Impact on water quantity

Coal mining has significant impacts on local water resources, both in terms of water consumption and pollution (World Bank, 2017). Water is used and water resources are impacted across the full life cycle of coal mining and power generation. Every stage in the coal mining chain requires direct use of water including the preparation and extraction of coal from mines, and the measures taken to control dust and pollution at both mines and power stations, its incineration at a coal-fired power station, and the disposal of the coal combustion by-products (Greenpeace Africa, 2012).

For all of these stages, evaporation of water also occurs. The total water-use per ton of coal mined is estimated at 0.46 m^3. Table 8 below gives a breakdown of the water used in coal mining.

Table 8: Estimated water-use in coal mining (Martin and Fischer, 2012)

Process	Water Use (m^3 water / ton coal)
Extraction	0.160
Dust control	0.042
Evaporation	0.220
Coal washing	0.038
Total	**0.460**

This implies that approximately 47 million cubic metres of water would have been required to mine and process the 102.4 million tons of coal used by Eskom (Eskom Holdings SOC) in 2022/23. The total amount of raw water consumed by Eskom at its power stations (for operating the plants) for this period was 256.43 million cubic metres. This demonstrates that the upstream water use (associated with coal mining) required for coal-fired power generation is significant.

In total, South Africa's coal mining industry uses about 102 million cubic metres of water per year (Martin and Fischer, 2012). This water is used to extract and process approximately 255 Mt of coal for power generation, petrochemicals, steel manufacturing and the export market.

Further explanation of how water is used in the various phases of extracting and processing coal is given in the following paragraphs.

Extraction

Coal can be extracted in one of three ways; from surface pits, underground caverns or from mountain tops (UoCS, 2010). For both underground and surface mining, groundwater is pumped out to remove water from the area that will be mined. This results in significant impacts on the quality and quantity of water which include a lower water table, decreased groundwater and surface flow and damage to ecosystems (UoCS, 2010). Mountaintop removal involves the removal of the top layers of rock above a coal seam (World Bank, 2017). The resultant debris can make its way into adjacent streams, resulting in the contamination of water resources and increased risk of localised flooding (World Bank, 2017).

Coal washing

In order to produce coal for the domestic and export markets, it needs to be cleaned and processed. Prior to the coal being burnt at a coal-fired power station, a significant amount of the mined coal requires beneficiation (World Bank, 2017). This process involves washing of coal, usually at the mine itself. In this process, water is used to separate sulphur and impurities from the coal through a flotation process. Due to their greater density, the impurities sink to the bottom while the coal floats freely. This process can produce 45 million tons of discards that are dumped and pumped to slimes dams (CER, 2018). The use of groundwater during the coal washing process results in the accelerated depletion of this resource. Washing coal creates considerable amounts of contaminated sludge which must be disposed of in slurry dams and can pollute freshwater reserves if stored incorrectly (CER, 2018).

Dust Suppression

Large amounts of dust are created as coal is hauled along roads and also results from stockpiles of coal and soil. Dust from surface mining is a much more significant problem than in the underground mining process (Greenpeace, 2012). This means that considerably large amounts of water must be used for both dust suppression and road wetting at the mines.

Impact on water quality

Coal mining and coal-fired power generation are one of the biggest concerns in the management of water quality (Ochieng et al., 2010). Mine water impacts negatively on water resources by increasing the levels of suspended solids, resulting in the mobilization of elements such as iron, cadmium, aluminium, manganese, cobalt and zinc, and also decreasing pH of the receiving water (Ochieng et al., 2010). Mine water results in deterioration of the quality of surface water resources that may lead to impacts on agricultural, domestic and industrial users (Ochieng et al., 2010). Further details of the water quality impacts are elaborated in the following paragraphs.

Acid mine drainage and runoff

The contamination of South Africa's water through acid mine drainage (AMD) is possibly one of the most complex and pressing water quality/mining related problems (CER, 2018). AMD poses a serious threat to both groundwater and surface water resources located near coal mining areas. Acid mine drainage is metal-rich water formed from the chemical reaction between water and rocks containing sulphur bearing minerals such as pyrite (Ochieng et al., 2010). Water draining from coal mines often contains sulphuric acid and heavy metals at high concentrations, which could result in the contamination of streams and agricultural lands, if the water is used for irrigation purposes (Ochieng et al., 2010).

Mine contaminated water can seep into agricultural soils and streams during heavy rainfall events that result in over-bank flooding. Higher concentrations of heavy metals in the soils and streams, accompanied with acidic pH, are likely to increase the ingestion of heavy metals by plants and man, which poses a high health risk to the people who consume the contaminated agricultural products (Ochieng et al., 2010). If AMD is not properly managed, it is estimated that per day, approximately 200 million litres of AMD may pollute the area's water resources, placing the security of the water supply from the Vaal River System under severe risk.

Coal ash sedimentation and leachate

Coal ash is a naturally occurring and non-combustible residue produced during the burning of coal. Coal ash contains high, and possibly toxic, concentrations of many substances that can pollute any water that comes into contact with the ash, as it contains the same elemental constituents as the parent coal, but at much higher concentrations (Groenewald, 2012). Water polluted with coal is referred to as leachate, and it tends to be alkaline and enriched in various substances such as sulphate, iron, boron, aluminium, zinc as well as toxic heavy metals, such as antimony, arsenic, chromium, barium, cadmium, manganese, lead and mercury (Groenewald, 2012). The majority of toxic metals found in coal are retained in the solid waste after combustion. Coal ash leachate commonly seeps out from the ash and enters and contaminates natural groundwater and surface water systems (Groenewald, 2012).

The major environmental impacts from coal ash include leaching of potentially toxic substances into soils, groundwater and surface waters; impeding effects on plant communities; and the accumulation of toxic elements in the food chain (Rowe et al., 2002).

Research findings from various studies have documented the negative effects of coal ash on the physiology, morphology and behaviour of aquatic organisms as well as the health of aquatic ecosystems (CER, 2018). These studies cited damage to fish populations from selenium leaching from coal ash landfills and surface impoundments as the most widespread impact (CER, 2018). Research has also recorded the potential harm from coal ash contamination in drinking water to human health. Some of these health impacts include cancer and damage to the nervous systems and other organs, particularly in children (Physicians for Social Responsibility, 2010).

Sediment runoff from mining sites

Runoff after rain can give rise to detrimental pollution threats. The disturbed lands or active overburdened dumps piled up near mines are typically very susceptible to erosion and can often lead to silting (Tiwary, 2001). At times, overburdened dumps, piled up at the bank of a river, runs off into water resources thus increasing the suspended particulate load in the surface water (Tiwary, 2001).

Dirty water' and leaching of pollutants

Mine quarries typically have water inflow, either due to rainfall or to interception of ground water flows. This water is usually an unwanted feature of mining and may have to be discharged into the adjacent land or water resources. Furthermore, in overburdened dumps, rainfall can permeate into them and may result in the dissolving of toxic metals from the heap, leading to the contamination the water course (Tiwary, 2001).

Historical Water Use in the Electricity Sector

Eskom is the largest producer of electricity in South Africa. Currently, most of its electricity is generated by coal-fired power stations. Most of these stations are located in Mpumalanga, with exceptions to this including one station in the Free State and two in Limpopo. Approximately ten of the coal-fired stations are supplied with water from the Vaal River Eastern Sub-System (VRESS), which is a part of the larger Integrated Vaal River System (IVRS). The VRESS draws water from the upper Vaal, Slang, Usuthu and Komati River catchments. The VRESS is also supplemented with water from the Vaal Dam through the Vaal River Eastern Sub-System Augmentation Project, or VRESAP (Eskom, 2018a). Two power stations receive water directly from the Vaal Dam, while the two stations in Limpopo receive water from the Mokolo River catchment. There are future plans to transfer water from the Crocodile West catchment to the Moloko catchment, which will effectively link the Limpopo power stations to the IVRS (Eskom, 2018a).

Eskom's water use license in the VRESS entitles it to use 360.3 million cubic metres (MCM) of water per year (Eskom, 2018a). As a strategic water user, the utility is supplied with water at a very high level of assurance of 99.5% (Eskom, 2023). Eskom employs a variety of water reuse and recycling methods to use water as efficiently as possible (Eskom, 2018b). Water use is monitored as a key environmental performance indicator. Total freshwater use over the past ten years (net raw water consumption across all power stations) is shown in Figure 43 (data taken from Eskom, 2014, 2017, 2020, 2023), with the average annual use over this period amounting to 291.8 MCM. Figure 43 shows a gradual decline in water use over time.

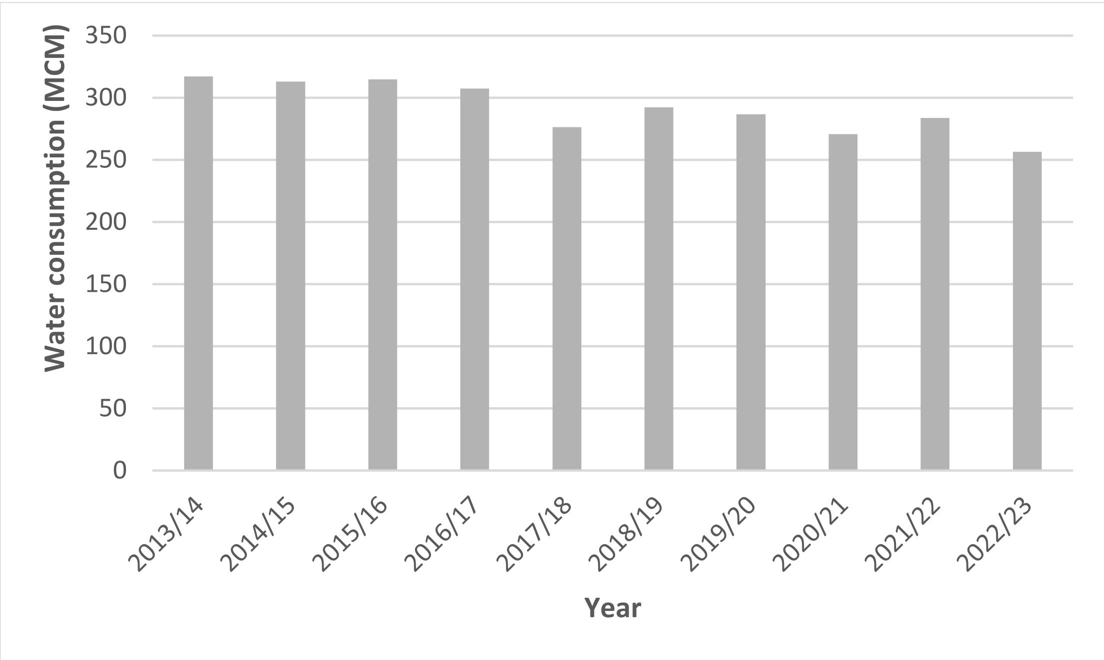

Figure 43: Net annual raw water consumption of Eskom power stations for 2013/14 – 2022/23

This trend is expected to continue into the future as older, less water-efficient power plants are de-commissioned, the dispatch of dry-cooled stations increases and the transition away from fossil fuels progresses. This will be offset to some extent by the retrofitting of emissions abatement technology which will tend to increase water use (Eskom, 2023).

Projections of future water use in the electricity sector

This section quantifies the benefits of transitioning away from fossil fuels in terms of the water savings that can potentially be realized in the electricity sector. This is done by quantifying how water use evolves under selected decarbonization pathways modelled in the larger project.

Methodology

The decarbonization pathways for which water use was estimated are outlined in

Table 9: Description of decarbonization scenarios for which water use was estimated.

. In the context of the water use analysis the three scenarios are referred to according to the GHG budget assumed (“Unconstrained”, “10 Gt”, “9 Gt”), this being the most distinguishing feature of the scenarios.

Table 9: Description of decarbonization scenarios for which water use was estimated.

Scenario Attribute	Scenario		
	“Unconstrained”	“9 Gt”	“8 Gt”
Net zero CO_2 reached in...	Never	2050	2050
Assumed land sink [-MtCO2]	10	10	10
GHG budget [GtCO2eq, 2021-55]	Unconstrained	9 Gt	8 Gt
Energy efficiency (NEES) included?	No	Yes	Yes
Sasol phase down from 2030	Yes	Yes	Yes
Carbon Tax	Current levels (pre-2022 budget)	Current levels (pre-2022 budget)	Current levels (pre-2022 budget)
Green exports?	No	No	No

Several key assumptions were made regarding the water use analysis:

- Only water use in the electricity sector was considered (i.e., not transport, industry etc.)
- Only onsite water use for operating power stations was considered (i.e., not upstream use such as water used in coal mining or manufacturing of solar PV etc.)
- Only water used to generate electricity within South Africa was considered (i.e., imported electricity was not considered)
- As freshwater is scarce and seawater is abundant, only the use of freshwater was considered.
- The influence of changes in climate (e.g., warmer temperatures, possible deterioration in water quality) on water use were not accounted for.

It is common in the electricity sector to express water use for power generation in terms of the water required per unit of electricity generated (e.g., EPRI, 2010; Pocock and Joubert, 2021; Eskom, 2023). This is known as specific water consumption and is often quantified in units of litres per kilowatt hour (L/kWh). If specific water consumption of a power plant (or group of similar plants) is known, it can be combined with the electricity generated for a certain period to estimate the total volume of water consumed in that period. The evolution of future water use in the electricity sector (for the selected decarbonization pathways) was estimated in this way in this project.

Water use was estimated for the current and proposed coal-fired power stations by the team conducting the energy modelling in the project. The specific water consumption assumed for each of the coal-fired power stations is given in Table 10. While fixed values were assumed, it is recognized that in practice the rate of water use varies over time due to operational reasons. For example, if recovered water is of very poor quality then more raw water is required for dilution (Eskom, 2018b). If electricity production is constrained, there is often no opportunity to take generating units out of service to correct any inefficiencies in the water management systems (Eskom, 2023).

The coal-fired power stations reflected in Table 10 appear in all three of the decarbonization scenarios with the exception of the proposed Waterberg station which only appears in the Unconstrained scenario.

Table 10: Values of specific water consumption assumed in projections of future water use for existing and proposed coal-fired power stations.

Power Station	Specific Water Consumption (L/kWh)
Arnot	2.12
Camden	2.57
Duvha	2.06
Grootvlei	2.25
Hendrina	2.40
Kelvin B	2.57
Kendal	0.14
Komati	3.03
Kriel	2.21
Kusile	0.23
Lethabo	1.82
Majuba Dry	0.13
Majuba Wet	1.80
Matimba	0.11
Matla	1.96
Medupi	0.03
Tutuka	1.97
Generic Waterberg plant (proposed)	0.23

The specific water consumption assumed for other (non-coal-fired) power stations and technology types (to be adopted) are shown in Table 11. Explanation is given for cases where water use was not considered. The scenarios in which the stations and technology types feature are also reflected in Table 11.

Table 11:Values of specific water consumption assumed in projections of future water use for other (non-coal-fired) existing power stations and proposed technology types.

Power Station or Technology	Specific Water Consumption (L/kWh)	Source	Comment	Relevant Scenarios
Biomass municipal waste	N/A	Pather-Elias et al. (undated)	Assume that energy is derived from capturing biogas (methane) rather than by burning the waste. A review of energy from municipal solid waste in South Africa (Mbazima et al., 2022) only refers to this type of waste to energy project. A technical description of the first pioneering municipal waste biogas project in South Africa (in eThekwini) does not mention any use of water (Pather-Elias et al., undated).	All
Combined Cycle Gas Turbine - LNG	0.01	Energy modelling component		Unconstrained
Combined Cycle Gas Turbine - LNG with CCS	0.02	Energy modelling component	Carbon capture and storage (CCS) increases water requirements relative to no CCS	9 Gt 8 Gt
DOE Peakers	0.02	Pocock and Joubert (2021) EPRI (2010)	These are two open cycle gas turbine stations powered by diesel. There are future plans to convert them to combined cycle gas turbines which could run on liquid fuel or LNG gas.	All
Grand Inga	N/A		Ignored as this will be electricity that is imported from outside South Africa	All
Hydro Existing Region	N/A		Ignored as this is electricity that is imported from outside South Africa	All
Hydro Existing South Africa	N/A	Elcock (2010)	The consumptive use of water in hydropower generation relates to water that is lost to evaporation from the dams (Gariep and Vanderkloof) that control the flow of water	All

Power Station or Technology	Specific Water Consumption (L/kWh)	Source	Comment	Relevant Scenarios
		Macknick et al. (2012) Spang et al. (2014)	through the turbines. These dams serve a variety of other uses (irrigation, urban and industrial, recreation, flood control) that provide benefits to a large area. It is likely that dams would have been built in the area to serve these needs even if hydropower was not included in their design and operation. Given that it is difficult to attribute evaporation losses specifically to hydropower, and that these are existing plants whose generation capacity is fixed during the period concerned, their water use is not considered here. This approach is in line with similar studies (Elcock, 2010; Macknick et al., 2012; Spang et al. 2014)	
Nuclear Existing	N/A	Pocock and Joubert (2021)	As the Koeberg power station predominantly uses seawater and negligible amounts of freshwater, its water use is not considered.	All
Nuclear Mid	N/A	Van Zyl and Premlall (2005) Van Wyk (2013)	Given that seawater use at Koeberg is comparable to coal-fired power stations (van Zyl and Premlall, 2005), and that future possible sites identified for nuclear plants are at the coast (van Wyk, 2013), it is assumed that they will be cooled using seawater. Therefore, their water use is not considered.	9 Gt 8 Gt
Open Cycle Gas Turbine - liquid fuels, existing	0.02	Pocock and Joubert (2021) EPRI (2010)	There are two plants that run on diesel and two that run on kerosene and are all located at the coast (Eskom, 2023). The two plants that run on diesel use municipal water (Eskom, 2021a). In the absence of information on the other two stations, it is assumed that they also run on freshwater.	All

Power Station or Technology	Specific Water Consumption (L/kWh)	Source	Comment	Relevant Scenarios
Open Cycle Gas Turbine - LNG	0.02	EPRI (2010)	Assume that freshwater is used.	Unconstrained 9 Gt
Pump Storage All Existing - Single Storage Tech	N/A		Similar to the hydroelectric stations, the water usage in the form of dam evaporation is not accounted for. The existing pumped storage refers to stations (Drakensberg and Palmiet) that have the additional purpose (apart from electricity generation) of transferring water for consumption by other users. The dams concerned also have small surface area as they are not designed for large-scale storage.	All
Pumped Storage New Ingula - Single Storage Tech	N/A		While the dams in the Ingula pumped storage scheme do not have a dual purpose, the evaporative losses from the dams are not accounted for to be consistent with the other pumped storage and hydroelectric stations. The dams concerned also have small surface area as they are not designed for large-scale storage.	All
Solar Central Receiver 09 hrs storage	0.30	Pocock and Joubert (2021) EPRI (2010)	Assume dry cooling since these solar plants are often located in hot, dry locations	All
Solar PV Fixed	N/A	Pocock and Joubert (2021)	Water to clean solar panels is considered negligible. In some cases, it is considered more cost effective not to clean panels despite lower output. Upstream water use in manufacture is not considered	All

Power Station or Technology	Specific Water Consumption (L/kWh)	Source	Comment	Relevant Scenarios
Solar PV tracking	N/A	Pocock and Joubert (2021)	Water to clean solar panels is considered negligible. In some cases, it is considered more cost effective not to clean panels despite lower output. Upstream water use in manufacture is not considered	All
Utility Scale Storage - 4hrs	N/A		Any water-use in the source of energy that is used to charge the batteries will have been accounted for elsewhere. Upstream water use in manufacture of batteries is not considered.	All
Wind	N/A	Pocock and Joubert (2021)	Water to clean wind turbines is considered negligible. Upstream water use in manufacture is not considered.	All

The assumed specific water consumption figures were combined with the annual electricity generated per station / technology to calculate the water used per annum. This was done for period from 2019 to 2055. The annual water use was then plotted per station / technology for each of the decarbonization scenarios (i.e., three plots were created). The total water use across all stations and technologies was then plotted per scenario on a single plot.

Results

The annual water consumption per station or technology is plotted in Figure 44, Figure 45 and Figure 46 for the Unconstrained, 9 Gt and 8 Gt scenarios, respectively.

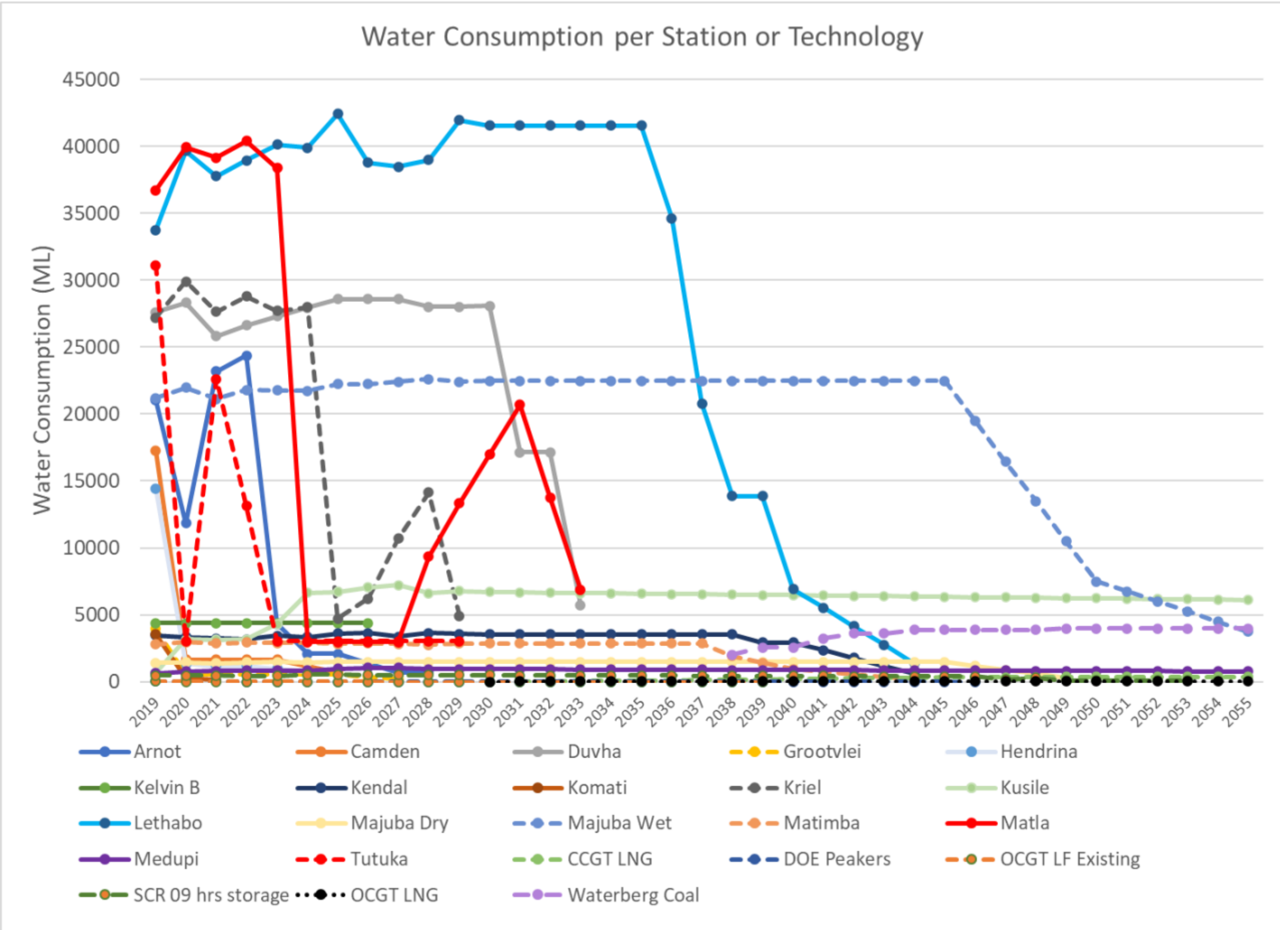

Figure 44:Water consumption per station or technology for the Unconstrained scenario

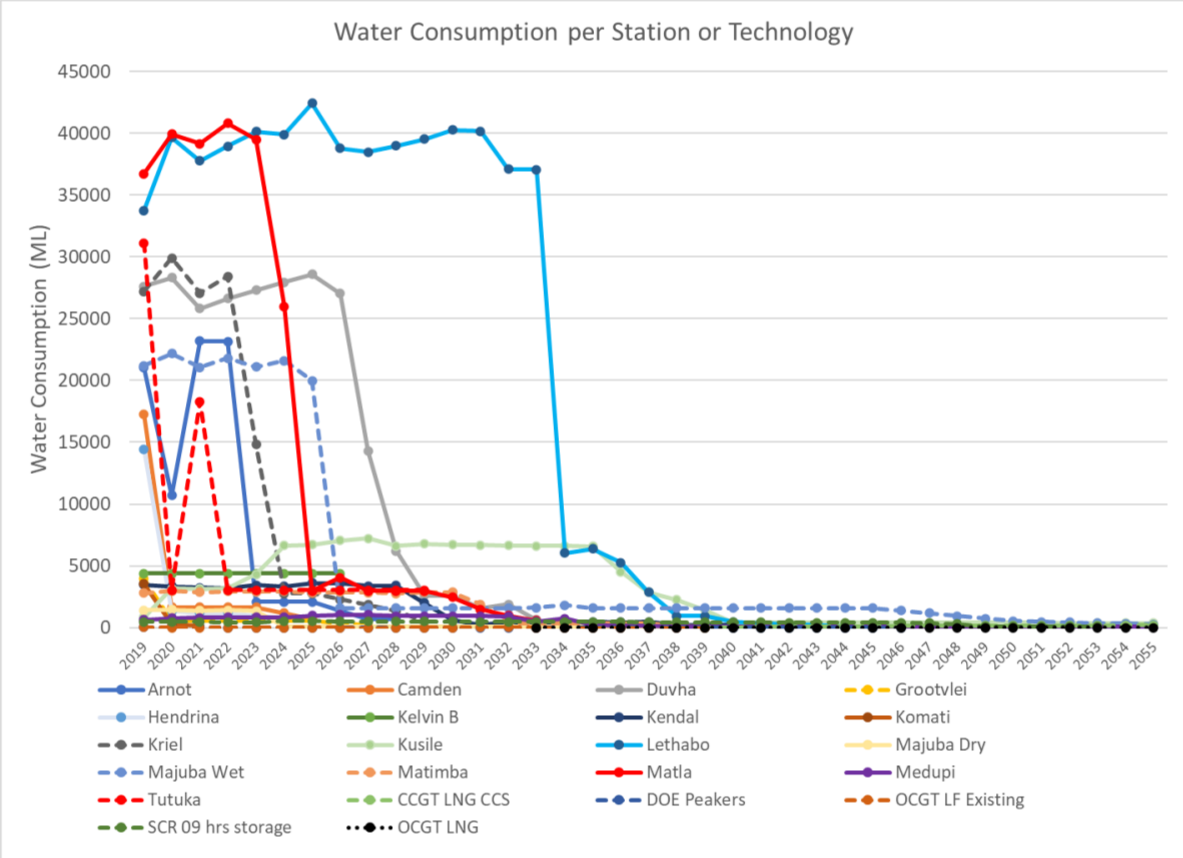

Figure 45: Water consumption per station or technology for the 9 Gt scenario

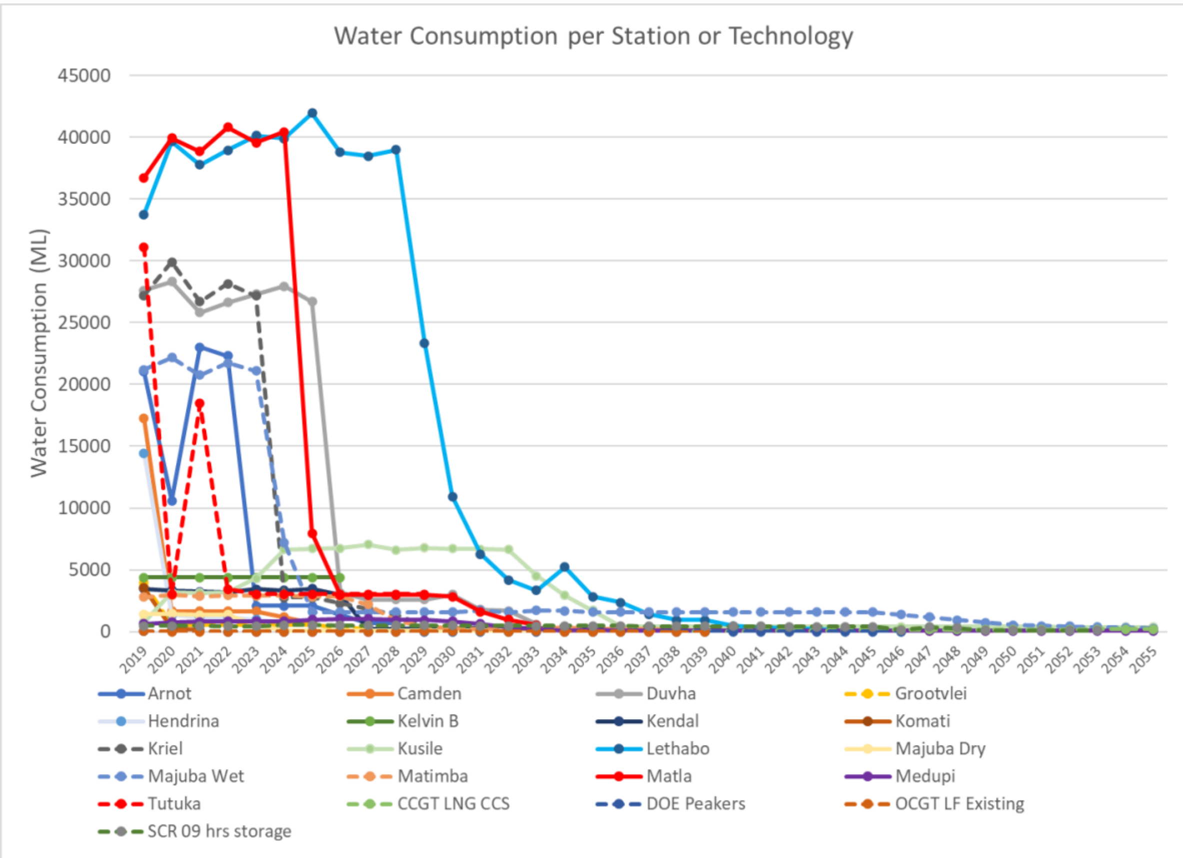

Figure 46:Water consumption per station or technology for the 8 Gt scenario

The water consumption of wet-cooled coal-fired power stations is significantly higher than for dry cooled stations and other technologies. As these wet-cooled stations are phased out, the overall water use decreases markedly. This phasing out happens earlier in the 8 Gt scenario and is followed by the 9 Gt scenario and then the Unconstrained scenario. This reflects in the water use projections with the earliest and sharpest reductions occurring in the 8 Gt scenario. In the present decade the highest annual water use of any individual station or technology (across all scenarios) is about 43 000 ML. However, by 2050 the highest annual water use of any individual station or technology is less than 7500 ML for the Unconstrained scenario, and less than 530 ML for the 9 Gt and 8 Gt scenarios.

The total annual water consumption (sum of all stations and technologies) per scenario is presented in Figure 47. Water consumption is plotted in millions of cubic metres. The reduction in water consumption is similar for the three scenarios until 2025, whereafter they diverge with the 8 Gt scenario showing the steepest reduction in water use. By 2040, the water use of the 8 and 9 Gt scenarios is the same (± 3.4 MCM), while for the Unconstrained scenario it is about 45 MCM. By 2050, the water use of the 8 and 9 Gt scenarios is about 1 MCM, while for the Unconstrained scenario it is about 19 MCM.

The reductions in water use over the period considered are substantial regardless of the scenario considered. The differences in the rate of the reduction in water use between the scenarios is dependent on the speed of the transition away from fossil fuels. However, even for the Unconstrained scenario the water use reductions are significant and by 2050 water use is similar to the 8 and 9 Gt scenarios.

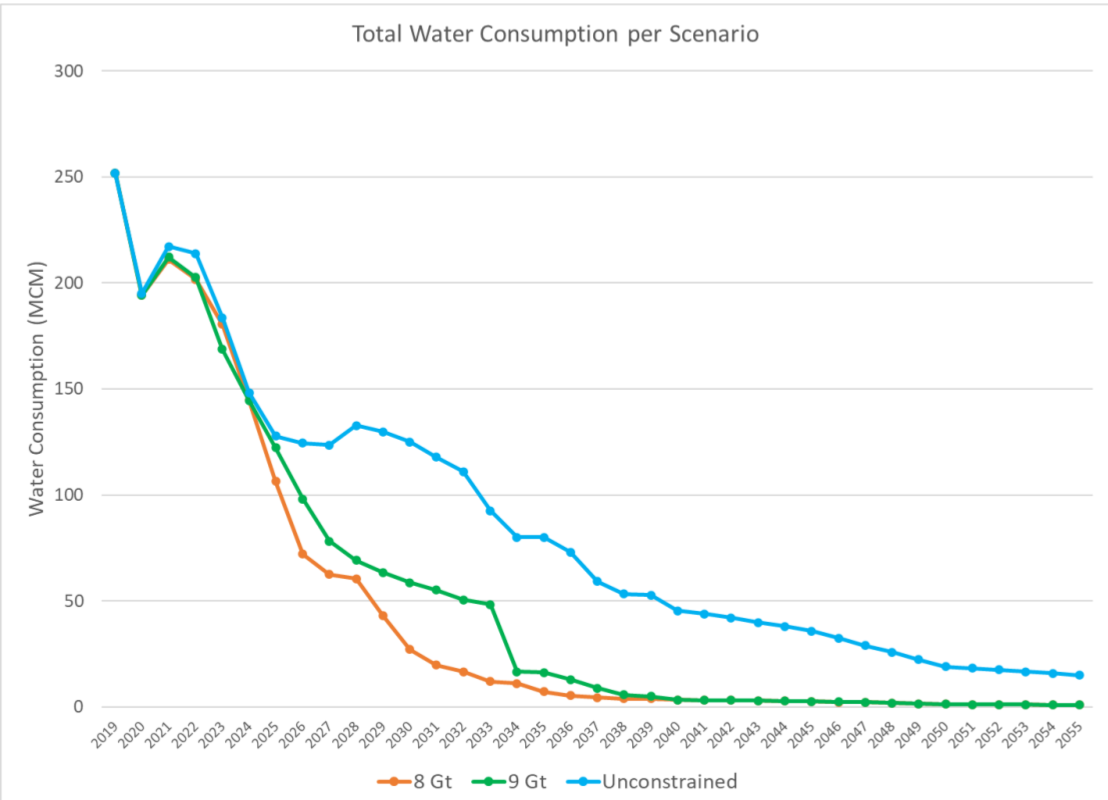

Figure 47:Total water consumption for the Unconstrained, 9 Gt and 8 Gt scenarios

Other projections of future water use in the electricity sector

The projections of water use produced in this study were compared to those in the Integrated Resource Plan (IRP) of 2019 (DMRE, 2019). The IRP has the objectives of balancing cost, water usage, emission reduction and security of supply in relation to planning future electricity production. The IRP2019 developed projections of electricity production and accompanying water use under different scenarios. These scenarios are associated with varying mixes of generation technologies and included:

- no renewable energy annual build rate (IRP1)
- median growth (IRP3)
- market-linked gas price (IRP5)
- carbon budget (IRP6)
- carbon budget plus market-linked gas price (IRP7)

Projections of water use were not published for every year in the time period considered but were made available for the years of 2020, 2030 and 2050. These values of water use are shown in Table 12, along with the equivalent values for the scenarios considered in this project. As the water use estimates for the baseline year of 2020 are different for the two studies, the reductions in water use from 2020 to 2030, 2030 to 2050 and 2020 to 2050 were also calculated and presented in the table, for ease of comparison.

Table 12: Comparison of total water consumption under different decarbonization scenarios (Unconstrained, 9 Gt, 8 Gt) with the water consumption under scenarios from the Integrated Resource Plan 2019

Year	This Project			IRP2019				
	Uncons.	9 Gt	8 Gt	IRP1	IRP3	IRP5	IRP6	IRP7
2020	195	194	194	260	260	260	260	260
2030	125	59	27	199	199	198	199	191
2050	19	1	1	36	54	51	36	38
Reduction 2020 to 2030	70	135	167	61	61	62	61	69
Reduction 2030 to 2050	106	57	26	163	145	147	163	153
Reduction 2020 to 2050	176	193	193	224	206	209	224	222

The water-use projections across the scenarios considered in the IRP2019 are very similar. They differ from the projections developed in this study in that the decline in water use is more linear and does not exhibit the sharp initial decline found in the 9 Gt and 8 Gt scenarios. The water use of the unconstrained scenario in this project behaves more like the IRP scenarios than the 9 and 8 Gt scenarios. The overall reduction in water use of the IRP scenarios (from 2020 to 2050) is greater than the reduction associated with the scenarios in this project, although the final absolute values of water use of the IRP2019 scenarios are higher (at between 36 to 54 MCM).

Considerations towards costing water co-benefits in a net zero transition in the electricity sector

The costing of water related co-benefits of a net zero transition in the electricity sector, could consider factors such as the price that is paid for raw water, the cost of treating water, environmental considerations and the value that can be unlocked by reallocating saved water to other sectors.

The price paid for water depends largely on the costs of the infrastructure that supplies it. These costs are variable over time and are likely to increase in future as supply interventions become more costly due to technical reasons. The price of water also varies with location depending on the scheme supplying water. Eskom has water supply contracts with the Department of Water and Sanitation which are reviewed periodically, including the pricing of water. It was noted in a recent annual report of Eskom that while water usage is expected to decrease in future, the unit cost of water may increase due to the existing infrastructure costs being fixed (Eskom, 2023).

Water quality delivered to power stations varies, and thus also the costs to treat this water. Total treatment costs would tend to decrease due to less water being used in future. However, this may be offset by potential deterioration in water quality due to climate change and failing municipal wastewater treatment infrastructure which is affecting water quality in the Vaal River system. In the global context, Singh et al. (2012) showed that scenarios with carbon capture and storage (CCS) in power production are associated with less increase in eutrophication of water resources than in a base scenario without CCS. This would tend to reduce water treatment costs.

To indicate the cost associated with using water in power generation, Eskom spent about R2.14 billion on water in 2018/19, corresponding to a net raw water consumption of 292.344 MCM (Pocock and Joubert, 2018).

In terms of environmental considerations, the water savings derived from the retirement of wet cooled coal-fired stations could come at the cost of higher air pollution loads as the energy efficiency of dry cooled stations is lower. Emissions abatement technology could offset these higher pollutant loads but also requires more water to operate. Increased reliance on technologies that do not require water for cooling, for example, wind and solar PV, could benefit aquatic ecosystems as these technologies do not raise the temperature of water in the environment or entrap fish and other organisms. In the long term, the aquatic environment will benefit from reduced coal mining which will improve water quality and also lower water treatment costs.

The water savings that are made though the transition to lower carbon power production can potentially unlock value in other sectors as water is reallocated to them. Quantifying this value would require understanding which sectors (e.g. agriculture, industry) the water is likely to be allocated to, and the value of the products produced in those sectors, employment created etc. This will be location dependent. If the water resources of river catchments are over-allocated, water savings may be assigned to meeting environmental streamflow requirements, rather than to producing value in other sectors (although other sectors will ultimately benefit from improved ecosystem functioning).

Discussion and conclusions

The projections of future water use for electricity generation indicate substantial reductions in water use across all decarbonization scenarios assessed. While the Unconstrained scenario exhibits a slower reduction, by 2050 the water use is similar (slightly higher) to the other scenarios. The large reduction in water use is consistent with previous projections developed (IRP2019), although the rate of initial reduction is more rapid in most scenarios.

Although not accounted for in the water use projections, there will also be changes in upstream water usage. Of significance here, would be the reductions in water required for coal mining and processing for electricity generation. This water use is currently estimated to be about 20% of the water used for operating coal-fired power stations. The lowering demand for coal may also yield improvements in environmental water quality, although the negative impacts of mining on water quality can linger long after an existing mine is closed.

It is important to take note of other assumptions (not related to upstream water use) made in the water use projections, notably the lack of account of climate change impacts on water use. Evaporation of water can occur at various stages in the management / use of water at coal-fired power stations. Climate change projections suggest that evaporation from an A Pan evaporimeter will increase by 5 - 10% during the period considered (Schütte et al., 2023). As more intense rainfall and warmer temperatures are projected in future, water quality may also be impacted, which may then have knock-on effects for water consumption at power stations.

Another important assumption made in the water use projections was that any future nuclear power stations would be built at the coast and would use seawater for cooling (as the existing Koeberg nuclear power station does). Koeberg uses a similar amount of water to coal-fired power stations.

It was assumed in the study that specific water consumption is constant for a particular power station or technology (averages were utilized in calculations). However, it is recognized that consumption varies over time due to operational reasons. Another reason why consumption will change in future relates to the retrofitting of emissions abatement technology to the remaining coal-fired stations, which will increase water usage to an extent. For example, in a feasibility study for Medupi power station, the implementation of dry cooling reduces the specific water consumption from approximately 2 l/kWh to 0.14 l/kWh, while the later introduction of abatement technology (wet flue gas desulphurisation) increases consumption to 0.35 l/kWh (Chang, 2018).

The risks for contamination of water resources around coal-fired power stations (due to spills etc.) would decrease as these stations are de-commissioned.

The projected savings in water derived from transitioning away from coal imply that additional water will become available for other uses e.g., agriculture, urban, industry and meeting environmental flow requirements (especially in over-allocated water catchments). This bodes well for the constrained Integrated Vaal River System which is a critical resource that supports the economic hub of Gauteng and surrounding provinces. Water requirements for agriculture are likely to increase in future due to warmer temperatures, while urban water use will increase due to urbanization and population and economic growth. The freeing up of water for other uses has the potential to benefit the economy and create jobs.

In conclusion, the water-related co-benefits of decarbonization of the electricity sector will be significant in terms of water quantity, and eventually in terms of water quality, and adds additional incentive to transition to non-fossil fuel-based generation technologies.

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