# INVESTIGATING the AIR QUALITY CO-BENEFITS of TRANSITIONING to NET ZERO in the SOUTH AFRICAN ENERGY SECTOR

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From previous research and subsequent policy globally, it is clear there are significant co-benefits to a country transitioning towards a Net Zero greenhouse gas (GHG) emissions profile. A significant co-benefit is improved air quality. Reducing GHG emissions often (though not always) leads to a decrease in air pollutants as well. The energy sector encompasses electricity generation, industrial processes and transportation and is a key contributor to GHG emissions, especially in South Africa. This paper presents research done for the Presidential Climate Commission that estimated the air quality co-benefits of two potential pathways for transitioning the South African energy sector to Net Zero GHG emissions. First, realistic pathways were derived, and an energy systems model developed to quantify the GHG and air pollutant emissions impacts. This was achieved through the Energy Systems Research Group national energy model, built on their SATIMGE framework. The energy model provided the necessary scaling factors which were subsequently applied to a gridded air pollutant emissions inventory that fed into an air quality model run by the CSIR Climate and Air Quality Modelling group. Air quality model output provided the anticipated changes in ambient concentrations over the model domain between the two scenarios and a reference case. These changes in concentrations were further translated into health impacts, namely a reduction in premature mortality due to air quality. This research quantifies potential air quality benefits while demonstrating an approach and the methodology for developing robust emission scenarios that are applicable to relevant policies and sectors.

Keywords: Net Zero, energy, modelling, health impacts.

## 1. Background and introduction

South Africa's latest national greenhouse gas (GHG) inventory estimates that the energy sector contributes as much as 86% to the total $CO_2$eq emissions in 2020, and that a majority of this is due to usage of coal, gas and crude oil (DFFE 2022). In terms of sub-sectors, the highest contribution is from electricity and heat production with road transport in second place (albeit by a large margin). The determination of pathways to make deep reductions into GHG emissions is therefore a key priority for the country, as it moves towards updating its Nationally Determined Contributions. South Africa's Low Emissions Development Strategy further aims moving towards a goal of Net Zero carbon emissions by 2050.

The concept of net-zero GHG emissions is aimed at mitigating rising atmospheric temperature due to climate change by ensuring the total anthropogenic emissions for a specific region are effectively zero. However, how this is achieved is complex, with questions around which GHG should be included, the regional extent, whether it should target direct process emissions or lifecycle, if offsetting emissions should be allowed, the practical and useful timelines in achieving net-zero and if transitioning fuels should be used (Rogelj et al. 2021).

As GHGs such as $CO_2$ and $CH_4$ are often co-emitted at the source with air pollutants such as NOx and PM since the processes involve combustion of carbon rich fossil fuels, there is opportunity to synergistically decrease both emissions through mitigation strategies, provided the linkages between the two are investigated as comprehensively as possible. This is particularly relevant for South Africa, given air pollutant emissions from these key GHG emitting sectors occur in South Africa's most polluted regions (DEA 2012; DEA 2014 and DEFF 2020). However, reducing emissions of GHG could also result in unintended increases in air pollutants at the process level (e.g. carbon capture at power plants; EEA 2011) or due to dynamics within the economic and resource systems that allow socio-economic growth (e.g. intermediate fossil fuels required to maintain generation capacity until higher renewable uptake). As the country further develops its mitigation strategy towards Net Zero any co-benefits to be derived from this transition to net-zero needs to be unpacked and analysed such that a full understanding of the target sectors (and processes) and the resultant dynamical impact on a regional scale be attained.

However, the benefits of improved air quality may not be convincing enough for countries to allocate additional funding as often only the environmental (including human health) aspects are covered or perceived. Addressing the potential health impacts and further translating these to monetary terms provide a more comprehensive means to communicate the benefits. In fact, it may be argued that the benefits to improving air quality should be more readily pursued as they are more directly accrued in a shorter period and localized. Once translated to monetary terms they may also provide more benefit than reductions in GHG (Aldy et al. 2021).

This paper describes an air quality co-benefit assessment of net-zero GHG mitigation scenarios for the energy sector in South Africa. This assessment formed part of a larger study funded by the UKPACT for the Presidential Climate Commission. The assessment was achieved through the linking of a GHG emissions optimized energy model (SATIMGE), a gridded air pollutant emissions inventory and a photochemical air quality model (CAMx). Output of ambient concentrations were translated into impacts on human health.

This research presents the first time that an air quality co-benefits assessment of different decarbonisation pathways for South Africa has been conducted. Including air quality in any South African GHG mitigation assessment also assists in allowing air pollution issues to gain traction within spheres of government that do not traditionally consider it (e.g., energy and transport). This would hopefully lead to alignment of policy. The key to ensuring well guided policy development is an assessment of net-zero aimed mitigation strategies that includes as much as possible the complexities and dynamic nature of sources of emissions (GHG and air pollutant), their interactions with each other, the subsequent transport and transformation within the atmosphere and eventual health impacts. While this is still only a portion of the considerations, it includes the key factors that play a role in determining effectiveness in terms of air quality co-benefits.

## 2. Approach to assessment

A common approach in both global (e.g. Shindell et al. 2018) and local (e.g. Wang et al. 2020) studies is to use energy models designed for GHG reduction scenarios to predict air pollutant emissions, which subsequently feed into air quality modelling. Figure 1 provides an overview of the approach and flow of data and processing used for this study.

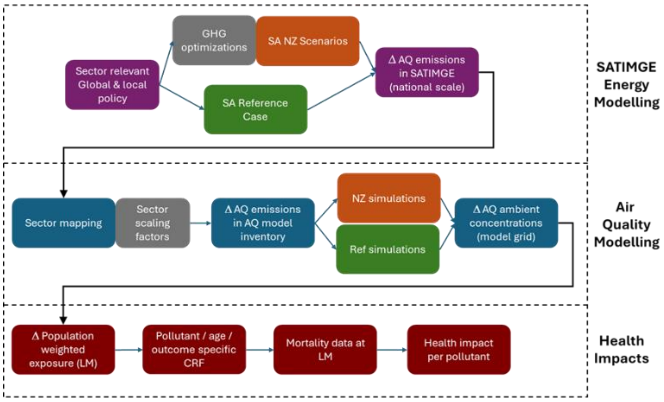

Figure 1: Overview of approach and flow of processes

### 2.1 Energy-economic model

To assess the dynamic consequences of each scenario, various forms of modelling were used. Firstly, a national scale energy-economic single region multi-sectoral model called SATIMGE was developed by the Energy Systems Research Group at University of Cape Town. It can show how shifts in the annual energy balance, solved on a system least-cost basis within various GHG, technological and other constraints and assumptions, cause shifts in the annual economic balance, which in turn causes the cost-optimal annual energy balance to shift, and so the iterative cycle repeats. One of the outputs is emissions of GHG and air pollutants NOx, SO$_2$, CO, PM$_{10}$, NMVOC and NH$_3$. It included current day (year 2023) anthropogenic GHG source sectors as a baseline and provided retrospective estimates down to 2019 and projections up to 2050. Once developed and populated, SATIMGE was then used to translate policy context and conditions into reference cases projections up to 2050, and scenario projections up to the same time horizon. The scenarios incorporate global economic and political pressures to decarbonize, as well as local constraints such as finance and socio-economic development. The global context is separated into what was termed “World A” (Ambitious with strong multilateral rules-based regime, with stricter policies on carbon-intensive trade, a more rapid transition to EVs, reduced demand for fossil fuels and a greater market for ‘green’ export trade, and greater climate support for developing countries) and “World B” (Divergent with slower transition to clean fuels, products and technologies, and more limited or no support to developing countries. This world comes with high risks that SA and other developing countries will be subject to greater pressure to mitigate than in World A). The broad scenario elements and their variations of the scenarios are summarized in Table 1.

Table 1: Scenario parameters and variations

| Parameter | Values |
|---|---|
| World | A, B |
| Net zero $CO_2$ year | 2050, 2055 and not reached |
| GHG limit (2021-50) [GtCO2eq] | 8, 9, 10, 11 and unlimited (reference) |
| Building Energy Efficiency | Variations on adjusted 2015 National Energy Efficiency Strategy, or not achieved at all |
| Sasol CTL | Crude oil refining to cease in 2034; Sasol CTL Plan 2023, Early retirement from 2035 or late retirement linearly from 2045 to 2050. |
| Green exports | Yes or No |
| SA carbon tax* | Current (R120/ton $CO_2$e) or High (ramped up to ~$120/ton until 2050). |
| Localisation | Current levels or reaching draft South African Renewable Energy Masterplan 2022 targets |

* This projection represents the latest data as of the energy modelling completion and is based on World Bank (2023) and IMF (2023) as seen in SARB (2024).

Table 2 lists the scenarios selected for air quality model simulation and the purpose of each.

Table 2: Selected scenarios and description

| Scenario name | Purpose |
|---|---|
| 9Gt | Low GHG reduction (9Gt $CO_2$e limit) |
| 8Gt | High GHG reduction (8Gt $CO_2$e limit) |
| REF | BAU; Unconstrained (No NetZero achieved) |

Note that even though SATIMGE provides projections for all years between 2019 and 2050, three years had to be selected for air quality modelling due to time constraints. The early and late year limits are selected due to 2023 being the base year (thus utilizing current real-world data), while 2050 was selected as it was the horizon year for achievement of full net zero. The year 2033 reflected a point of major changes for the Eskom fleet of coal fired power stations.

## 2.2 Air pollutant emissions inventory

Output of the SATIMGE model, namely estimated changes in associated air pollutant emissions per individual process in each sector, was then mapped to the sub-sector categories of a gridded emissions inventory developed to feed into a regional air quality model. This emissions inventory was developed during a World Bank funded project (through their Pollution Management and Environmental Health Program; World Bank Group, 2020)). Figure 2 shows the inventory extent, with the domain grid resolution being 0.06° (~6km).

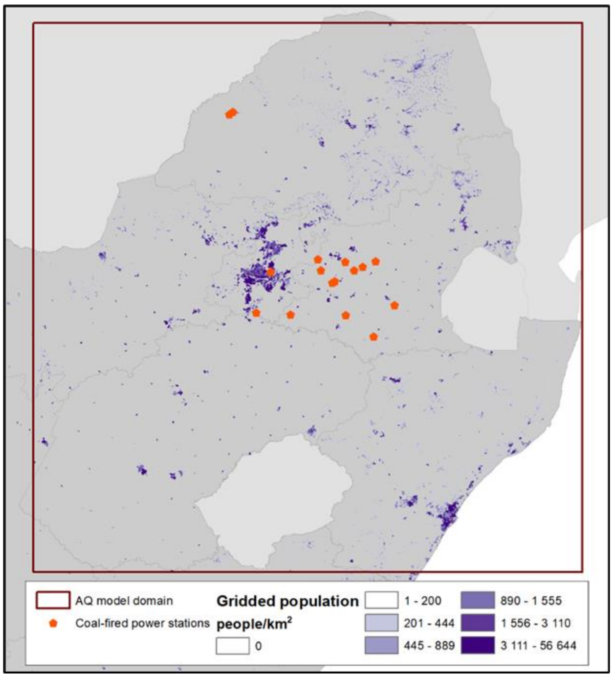

Figure 2: Air quality modelling domain and gridded population (from Gridded Population of the World version 4; Center for International Earth Science Information Network, 2018)

Considering that the focus of the scenarios were energy sector related (thus covering a wide variety of sources), and the air quality model simulated ambient concentrations for use in health impact estimation, the emission inventory included multiple sectors which are briefly summarized as follows:

- **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 and NOx from soil due to microbial activity.
- **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 croplands.

The base emissions inventory is representative of year 2019. These emissions were gridded at 0.06° (~6km) resolution and each sector given a temporal profile such that seasonal, weekly and hourly variation is represented. Figure 3 illustrates how SATIMGE sectors were mapped to the air quality model emissions inventory (AQM EI). This includes the number of sub-sectors and individual emission processes.

Figure 3: Illustration of emissions sector mapping between SATIMGE and AQM EI. MOTOV: Private passenger vehicles; P: Petrol; D: Diesel; LCV: Light commercial vehicles; HCV: Heavy commercial vehicles; LTO: Landing and Take-off; Dom: Domestic; Int: International; Reg: Regional

Scaling factors (i.e. ratio of emissions in 2023 to other years) are derived from changes in emissions within SATIMGE processes. These are applied to an associated air quality modelling emissions process. Note that for industry, each SATIMGE process was mapped to individual stacks, with some facilities encompassing multiple processes and thus mapping. The scaling factors are also unique to each pollutant, as some mitigation technologies have non-linear impacts. SATIMGE did not include natural sectors such as biomass burning or wind-blown dust, nor the anthropogenic sector of informal waste burning.

## 2.3 Air quality modelling platform

The air quality model platform consists of a comprehensive gridded, hourly emissions inventory (as noted above), a mesoscale numerical weather prediction model (Weather Research and Forecast model version 4.2; Skamarock et al. 2019) and at its core the photochemical model CAMx (Comprehensive Air Quality Model with Extensions version 7.2; Ramboll 2022). Figure 2 shows the model domain. Output from the air quality model consisted of gridded hourly near surface ambient concentrations of air pollutants for each scenario (8Gt and 9Gt) and reference case (REF). The changes in concentrations were used together with exposure-response functions (ERF) from literature to derive associated changes in selected health outcomes. The impacts on health were limited to pollutants $SO_2$, $NO_2$ and $PM_{2.5}$ (including inorganic and organic secondary aerosol).

Both the emissions inventory and air quality modelling platform were developed and assessed previously during a World Bank funded project. Model skill at representing measured concentrations was iteratively improved through numerous successive simulations, and emissions and meteorological input were refined. The model was focused on PM over Gauteng, and Figure 4 shows an overview of output compared to measurements at eight AQI monitoring sites. The comparison shows good performance on average for $PM_{2.5}$ and $NO_2$, however there is some over-estimate of $SO_2$.

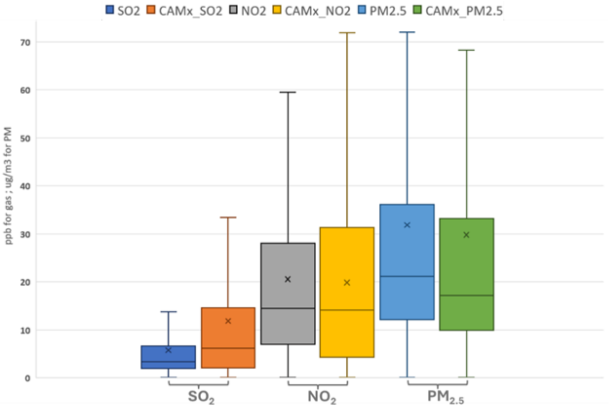

Figure 4: Modelled and measured concentrations (2019) averaged across sites. Boxes show 1st, 2nd and 3rd quartiles with “X” denoting the average.

Whiskers indicate the largest/smallest value <= 1.5 times the interquartile range. Outliers are not shown.

## 2.4 Approach to estimating health impacts

The ‘impact pathway’ approach was 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 (Table 2).

Exposure to pollution is based on the simulated annual average ambient concentrations (more specifically changes thereof) of $SO_2$, $NO_2$ and $PM_{2.5}$. To account for the spatial distribution of people, the population weighted exposure was used, which uses the Gridded Population of the World product (Figure 2; Center for International Earth Science Information Network 2018). Next, to translate the changes in annual average exposure to changes on the selected health outcome, exposure response functions (ERFs) are used. The outcome considered here is premature all-cause mortality for all ages. These are sourced from literature and are listed in Table 3.

Table 3: List of ERFs used for estimating impact on all-cause premature mortality for all ages

| **Pollutant** | **ERF as Relative Risk** | **Source** |
|---|---|---|
| $NO_2$ | RR=1.01 (0.99-1.03) for a change in 5.32 ppb | Beelen 2014 |
| $SO_2$ | RR = 1.02 for a change in 5.34 ppb | Krewski et al., 2009 |
| $PM_{2.5}$ | RR = 1.0123 for a change in 10 µg/m$^3$ | Heroux et al., 2015 in Lehtomaki et al, 2020 |

The prevalence of the target health outcome, in this case mortality rate, is required within the domain. The 2016 Statistics SA Community Survey is the most recent source of total mortality data and is available at local municipal level. This spatial granularity is useful as the population-weighted exposure is effectively at a 0.06° resolution. The reduction in premature mortality associated with a reduction in air pollution represented by the different emission reduction scenarios is thus used as an indicator of health co-benefits. The limitations on pollutants and annual averaging period were determined purely by the available concentration response functions and mortality data (only annual is available).

# 3. Results

## 3.1 Trends in emissions

The scaling factors derived from SATIMGE output were applied accordingly to the air quality emissions inventory sectors (at the associated sub-sector/process level as possible). Figure 5 shows the sector wide trends for NOx for the three most relevant (to that pollutant) sectors.

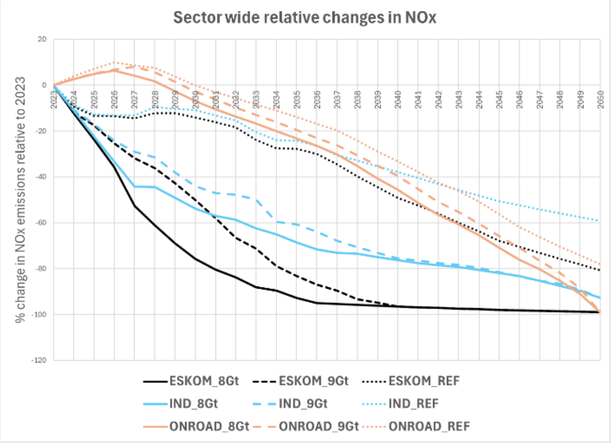

Figure 5: SATIMGE projected sector aggregated percentage change (relative to 2023) in NOx emissions

Note that these percentage changes are not weighted by relevance, and for example a 10% change in Eskom NOx emissions are far greater in tonnage than a 10% change in on-road vehicle emissions. Another often overlooked factor when looking only at sectoral totals, is spatial distribution. This is a very important aspect in air quality as the impacts are more localized and immediate than GHG. Complexities such as the stationary point location of Eskom power stations vs the more distributed nature of vehicles; and the fact that Eskom emit through tall stacks while vehicles emit at the ground; are all important when considering the ultimate impact on concentrations within the region. To further illustrate this, Figure 5 shows the sectoral wide decreasing trend of NOx for non-Eskom industry no matter the scenario. However, if one looks at the individual processes that make up a sector (non-Eskom industry in this case), there are some increasing trends (Figure 6), even for the high GHG mitigation 8Gt scenario. This would have a role in increasing concentrations in specific locations, even though the sector as a whole is decreasing. Air quality modelling can capture these factors and is a useful tool in investigating the finer details of sub-sector/process level decarbonization as projected by SATIMGE.

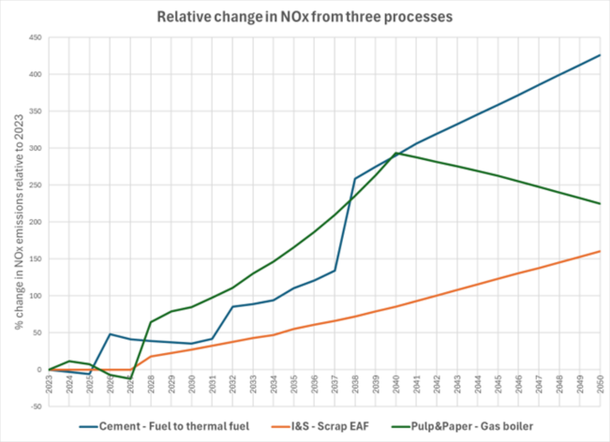

Figure 6: Projected percentage changes (relative to 2023) in NOx for three selected processes for the 8Gt scenario.

## 3.2 Changes in ambient concentrations

Nine full year CAMx simulations were carried out according to Table 2. Changes in concentrations were determined by subtracting the reference (REF) simulation from each of the scenarios (8Gt and 9Gt) per year of simulation (2023, 2033 and 2050). The maps below show the changes in surface concentrations due to the 8Gt scenario (compared to REF) for 2050 for each pollutant. Decreases in $NO_2$ are the highest within urban regions and along major routes, indicating a larger contribution from the decreasing on-road vehicle emissions. There is a small (up to 2.2 ppbv) increase within the North-West province due to increasing NOx emissions from the cement industry sector. For $PM_{2.5}$ only decreases are seen for this scenario and year, and these are relatively localized around industrial sources. For $SO_2$, there are also only decreases, with some around industry and Matimba and Medupi power stations. Note that there are numerous (albeit small) increases seen within other scenarios/years that are not shown here, and all are due to increases in non-Eskom industrial emissions. Some may be ascribed to ramping up of existing gas boilers/process heating or introduction of new ones.

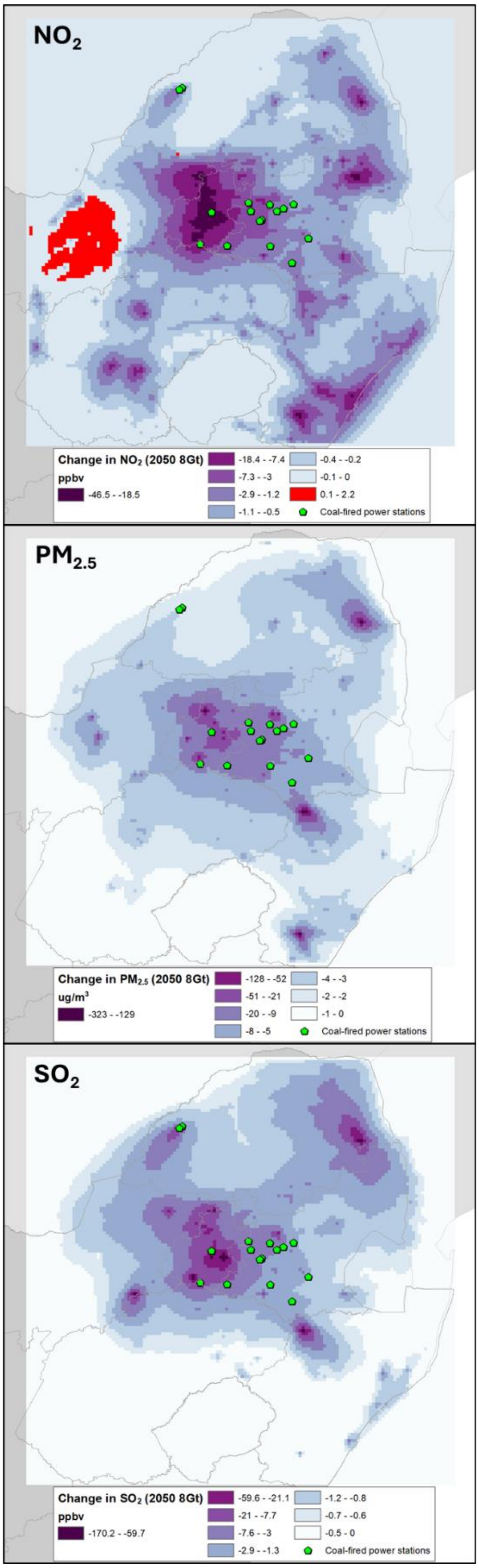

Figure 7: Simulated changes in annual average concentrations for 8Gt 2050

### 3.3 Health impacts

Health impacts are expressed in terms of reductions of all-cause mortality across all ages for each pollutant. Reductions are estimated per local municipality (the spatial resolution of the mortality data) but are reported here as domain-wide aggregates. Note that these impacts are derived from mainly reductions in emissions and an associated response in ambient concentrations which includes atmospheric chemistry (e.g. transformation of $SO_2$ to $PM_{2.5}$ via sulfate). Table 4 provides the estimated reduction in premature mortality. Reductions are higher, but not significantly, for the high GHG mitigation scenario (8Gt) for all pollutants. The highest reductions are estimated for 2050 (not shown), which is when the difference in concentrations between Reference and scenarios are the largest, particularly for areas that are highly populated. The largest differences between scenarios can be seen for 2033, when the emission reductions for the 9Gt scenario are not as high as the 8Gt scenario (particularly for the non-Eskom industry sector; Figure 5).

Table 4: Estimated reduction in premature mortality (all ages) aggregated over three years

| | **Reduction (number of persons)** | | |
|---|---|---|---|
| **Scenario** | **$NO_2$** | **$PM_{2.5}$** | **$SO_2$** |
| 8Gt (High mitigation) | 5 821 | 6 031 | 12 987 |
| 9Gt (Low mitigation) | 5 521 | 5 500 | 11 162 |

It is useful to compare these results with similar studies, as far possible. Table 5 shows results from four studies focusing on the portions of the energy sector within South Africa. All of them include some form of air quality modelling, although each result covers only a single year. A further complication in comparing the estimates is that the health outcomes are not exactly the same as premature mortality across all ages (as is in this study). The higher estimates within Marais et al (2019) are due to the national coverage of the model domain and the fact that the emissions inventory used assumes higher rates for vehicles. The lower estimate by Van der Walt (2023) is due to the limited sectoral coverage (only Eskom power stations) and health outcomes restricted to those over 25 years of age. Nevertheless, the range of estimates are well within each other.

Table 5: Estimated reductions in selected health outcomes due to changes in simulated $PM_{2.5}$ from other similar studies in South Africa

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

## 4. Conclusions

This study represents a comprehensive approach to assessing air quality health co-benefits to projections in pursuing net-zero through decarbonisation pathways. Suitable models encompassing the energy, economic and physical atmosphere were employed in order to include the dynamic considerations vital to understanding the potential impact. This study represents the first time that air quality co-benefits have been quantified for South Africa's potential GHG mitigation pathways.

Key findings indicate that there are clear and significant air quality related health co-benefits to implementing GHG mitigation policies that target the energy sector. The spatial aspect is important as there are isolated regions where air quality will not improve, primarily due to the necessary use of transition fuels.

Comparisons with other studies show the need to select standard health outcomes for use in such assessments as this could allow comparison and continuous updates and trends. Furthermore, the health endpoints should ideally include forms of morbidity to enable a more comprehensive view of the potential impact. Integration of impacts/benefits through the years of implementation is also key to adequate quantification. Related to this are the following assumptions and limitations notable for this assessment.

- The SATIMGE domain is national, while the air quality model domain is regional, centred around the Highveld. This was due to inaccessibility of the vital nationwide industrial emissions through the National Atmospheric Emission Inventory System

(NAEIS) hosted by the DFFE. Therefor nationally relevant changes in emissions were applied to regionally located sources. This limitation is somewhat alleviated by the fact that a majority of energy sector related emissions occur within the air quality model domain. Furthermore, the extent of the domain still includes the potential large-scale circulation of pollutants from the Highveld. If pollution does leave the domain, it is unlikely that in the real world they would recirculate back to populated areas at significant concentrations.

- Only three years from the total SATIMGE output period (2023-2050) where simulated within the air quality model, and therefore health impacts are for these years only. While impacts within intervening years could be interpolated, the sectoral emission trends display significant non-linearity (Figure 5) as power stations close within single years and the transport sector changes exponentially. The result of this for the assessment is that the aggregated health impacts are conservative.
- The mortality rates (2016) are assumed to remain the same for all years, with some marginal variation in population sizes. If regular (annual) retrospective and projected data was available, the result would be more robust as mortality rates are impacted by local and global factors such as influenza and other regularly occurring phenomena. In addition, the improving air quality itself will influence mortality rates.
- Other emission scenarios (particularly the 10Gt; Table 1) may be more relevant to the current situation in South Africa. Indeed, it would have provided more variability in the result.
- All other air quality model inputs were held static representing year 2019. This included boundary conditions, meteorology and emissions sources (majority natural) not driven by changes projected by SATIMGE. There is scope to further investigate the impact of climate change on air pollution within the 2050 horizon.

Finally, as this assessment includes utilizing output of a complex energy-economy model, driven with global and national considerations, there is some uncertainty around the future pressure (economically and politically) to decarbonise, which is bound in the interactions of different countries and markets and decisions being made at every economic forum or meeting. This influences the national pace and the global finance available to support a South African transition to a lower carbon energy sector.

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