Air quality and health impacts of doubling the South African standards for SO2 emissions from power plants

Lauri Myllyvirta, lead analyst, Greenpeace Global Air Pollution Unit *3 July 2019*

Executive Summary

South Africa's Department of Environment, Forestry and Fisheries is planning to increase the Minimum Emissions Standards (MES) for SO2 from 500mg/Nm3 to 1000mg/Nm3. This change would double the permitted emissions of SO2 from coal-fired power plants and other industrial sources of SO2 emissions, with dire impacts on public health. It would also lead to far higher emissions of mercury as the standard would likely enable plant operators to use emission control methods that, unlike SO2 scrubbers, don't improve mercury capture or can even impair it.

This briefing assesses the implications of this change for the air quality and health impacts of Eskom's coal fired power plants, by far the largest emitter of SO2 in South Africa. If other industrial sectors and private power plants were included as well, the implications would be larger.

Compared against a scenario of full compliance with the current limit of 500mg/Nm3, the weakened emissions standard would allow Eskom to emit an excess 280,000 tonnes of SO2 per year, for a total of 5.5 million tonnes over the lifetime of the plants. The failure to install SO2 scrubbers would increase mercury emissions by an estimated 15,000 kilograms per year or 200,000 kilograms over the remaining operating life. These estimates are based on the assumption that all units retire after 50 years of operation - a longer operating life would mean larger excess emissions.

To assess the health impacts of these increases in permitted emissions, the Greenpeace Global Air Pollution Unit carried out CALPUFF dispersion modeling closely following the methodology of the modeling used in Eskom's Cost-Benefit Analysis, with the modeling domain expanded to cover most of South Africa's population. Separate model runs were carried out for each of the 15 Eskom power stations, and contributions of SO2 to ambient PM2.5 levels, through the formation of sulfate particles from the emitted SO2, were isolated for each station. This allowed us to project the reductions in ambient air pollution levels at each location of the modeling domain over time. The resulting avoided health impacts were projected following the Global Burden of Disease methodology for PM2.5 health impacts (Stanaway et al 2018). The projections take into account expected population growth (UN DESA 2017) and epidemiological transition associated with improved health care and an aging population (WHO 2018).

Based on these atmospheric modeling results, doubling the SO2 emissions limit would increase population exposure to PM2.5 caused by Eskom's coal-fired power plants by 70%, as most of the PM2.5 exposure is due to secondary sulfate formation.

We project that, over time, the higher SO2 MES limit of 1000mg/Nm3 will lead to the following avoidable health impacts, compared with compliance with the current regulation:

- 950 premature deaths due to increased risk of lower respiratory infections, including in young children
- 350 premature deaths due to increased risk of stroke
- 320 premature deaths due to increased risk of death from diabetes
- 560 premature deaths due to increased risk of chronic obstructive pulmonary disease
- 720 premature deaths due to increased risk of ischaemic heart disease, and
- 520 premature deaths due to increased risk of lung cancer associated with chronic PM2.5 exposure

In total, an estimated 3,300 premature deaths (95% confidence interval: 3,000 to 3,500 deaths) would be caused by doubling the SO2 emissions limit. Annual excess health impacts peak at 170 premature deaths in 2025-26.

The location of Eskom's highly polluting coal-fired power plant fleet in the vicinity of the highly populated region of Gauteng, with many plants located within 100km of the region, is a particular public health concern. Eskom's coal power plant emissions are responsible for approximately 420 premature deaths (95% confidence interval 330 to 500) per year in Gauteng. Of the 3,300 excess deaths projected from weakening the MES, approximately 1,000 would take place in Gauteng.

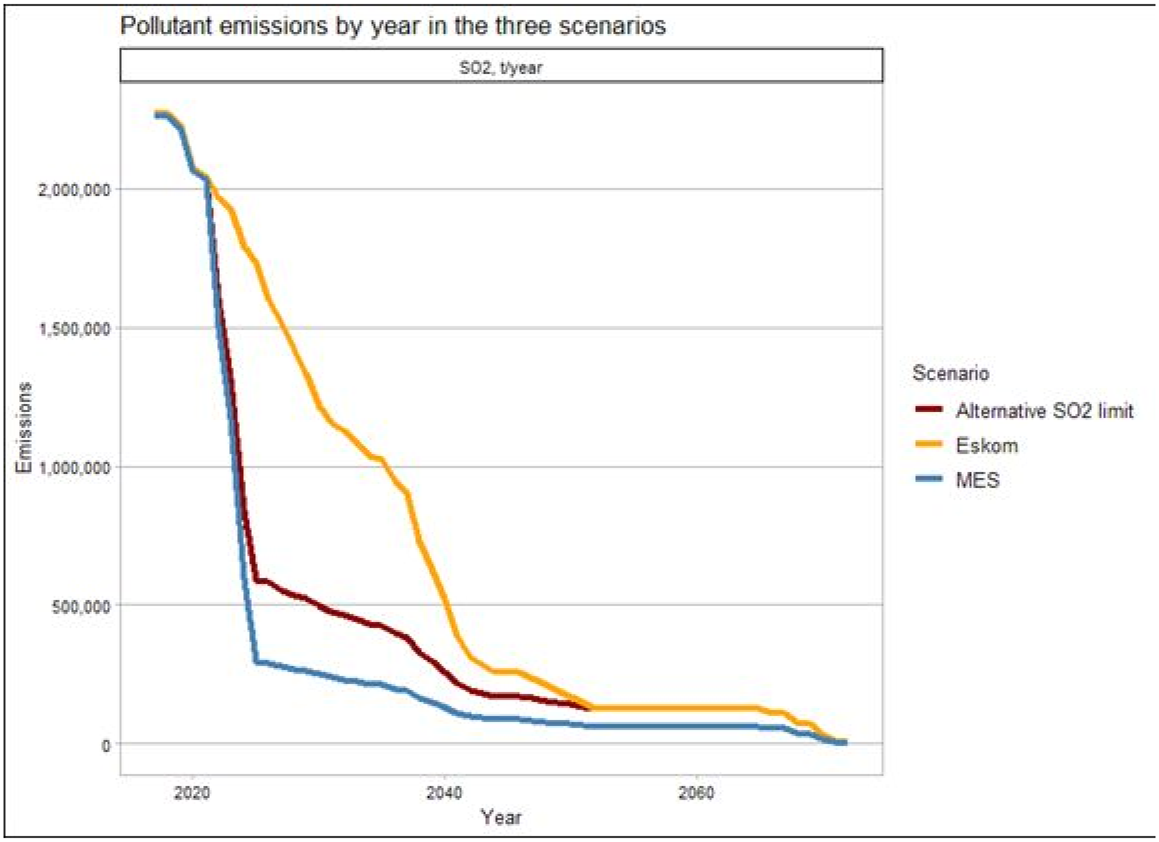
Most of the health impact is due to emissions from Medupi, followed by Matimba, Kendal and Majuba.

Mercury deposition from the existing Eskom coal power plants, and from Kusile and Medupi, once completed, is projected to exceed levels which can cause health risks, over an area of 89,000km^2, with 3.4 million inhabitants. The mercury emissions result in an estimated 2,300kg per year of mercury deposited on land and on freshwater bodies within the modeling domain. Cumulatively, the doubling of the SO2 MES would cause a projected 13,000kg of excess mercury deposition locally in South Africa, compared with the current MES limit of 500 mg/Nm3.

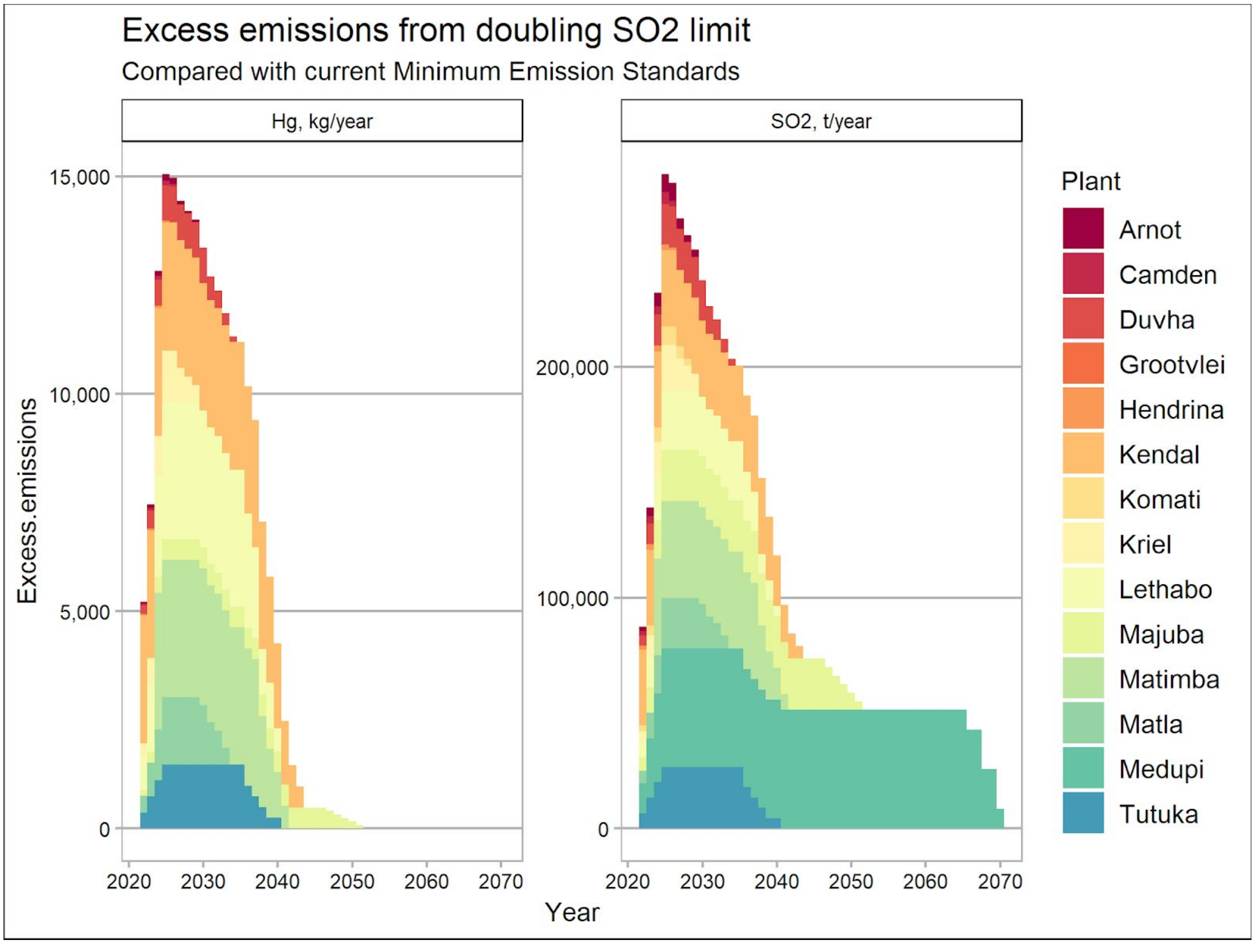
Results

Emissions: Two scenarios are compared, a scenario of full compliance with the current SO2 MES of 500 mg/Nm3 by 2025 for all units operating beyond 2030, and compliance with the proposed weakened SO2 MES of 1,000mg/Nm3. In both scenarios, units scheduled to close by 2030 are allowed to exceed the MES while other units are retrofitted in 2022 to 2025 in a phased manner.

The assumption of completing the retrofits by 2025 is in line with experiences from other emerging economies: China retrofitted approximately 250 gigawatts of existing coal-fired capacity with FGD between 2005 and 2011, bringing the share of capacity with SO2 controls from 14.3% to 89.1% in six years. These installations were in response to the national emission standards introduced in 2004. Similarly, after the emission standards were updated in 2011 to levels that required selective catalytic NOx controls (SCR), these retrofits were carried out on approximately 480GW of capacity by 2015, raising penetration from 18.2% to 84.5% in four years. Now India is targeting to bring its entire coal fleet into compliance with stricter standards than the MES by 2022, requiring retrofits in much of its 220GW of operating capacity.



The difference in emissions between these two scenarios is the “excess emissions” allowed by Eskom’s numerous requests for postponements, alternative emission limits and exemptions.



Excess SO2 peaks at 300,000 tonnes per year, and mercury at 15,000 kilograms.

Air quality: the impacts of these emissions are estimated using the state-of-the-art CALPUFF atmospheric modeling system. This model was also used for Eskom's Cost-Benefit study, but with the major difference that the study excluded the majority of South Africa's population from the assessment of the health impacts, and most of the health impact pathways included in Global Burden of Disease and other authoritative studies, capturing only a tiny fraction of the total health impact.

The largest impact on average SO_2 levels occurs in the area within 10-20km of each power plant. In contrast, the impact on PM2.5 concentrations is much more widespread, as most of the concentrations are due to the formation of PM2.5 particles from SO2 emissions as the flue gases travel downwind. Consequently, the largest contribution to annual PM2.5 levels is seen downwind, to the east and southeast of the power plants, but the impact is considerable in the entire region from Limpopo to Johannesburg and Newcastle.

The modeling results indicate that emissions from Eskom power plants expose 1.6 million people to at least one exceedance of South Africa's air quality standard for 1-hour SO_2 concentration standard per year, showing the urgent need to mitigate SO2 emissions. The contributions of each plant's SO_2, NOx and PM emissions to ambient PM2.5 and NO2 emissions are quantified separately to allow calculation of health impacts under different emissions scenarios.

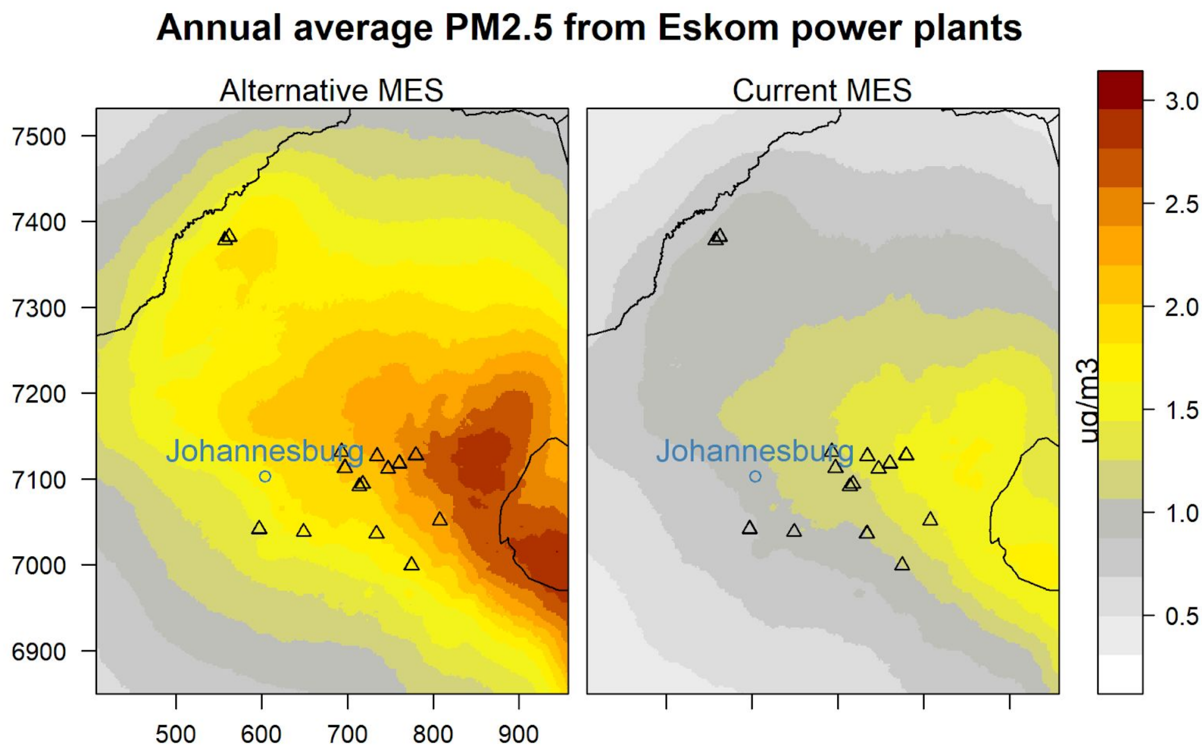
Toxic deposition: The mercury emissions from Eskom's power plants result in an estimated 2,300kg per year of mercury deposited on land and on freshwater bodies within the modeling domain. Cumulatively, the excess emissions from Eskom's proposed non-compliance would cause a projected 13,000kg of excess mercury deposition locally in South Africa, while the rest of the 240,000kg of excess mercury emissions would enter the global cycle.

Mercury deposition rates as low as 125mg/ha/year can lead to accumulation of unsafe levels of mercury in fish (Swain et al 1992). Eskom's emissions are estimated to cause mercury deposition above 125mg/ha/yr over an area of approximately 89,000km2, with a population of 3.4 million people.

Discussion: The results, obtained using a methodology that closely mimics Eskom's own cost-benefit study, but eliminates its obvious and seemingly intentional shortcomings, show that likely health impacts of Eskom's air pollutant emissions are far larger than reported by the study.

Atmospheric modeling and health impact assessment results have considerable uncertainties, both upwards and downwards, as is apparent from the wide uncertainty ranges; however we believe the results reliably demonstrate the magnitude of the health benefits from requiring Eskom to install basic air pollution controls in its power plants.

This health impact assessment is an update of the report "Health impacts and social costs of Eskom's proposed non-compliance with South Africa's air emission standards" published in 2014 (Myllyvirta 2014). That report was reviewed, among other similar studies on health impacts of power plant emissions in South Africa, by authors from University of Johannesburg and The Nova Institute, who concluded that the study "appears to be a reasonable quantification of the health risk in remote areas, but is probably a large over-estimation of the health risk in more polluted areas," because the exposure-response relationships used "may well not be" applicable in industrialized areas due to the high overall pollution levels (Langerman&Pauw 2018). For this update of the results, the recommendations of the authors for exposure-response relationships better suited to these conditions were adopted.


Annual average PM2.5 from Eskom power plants
Alternative MES
Current MES
Johannesbug
Johannesbug
7500
7400
7300
7200
7100
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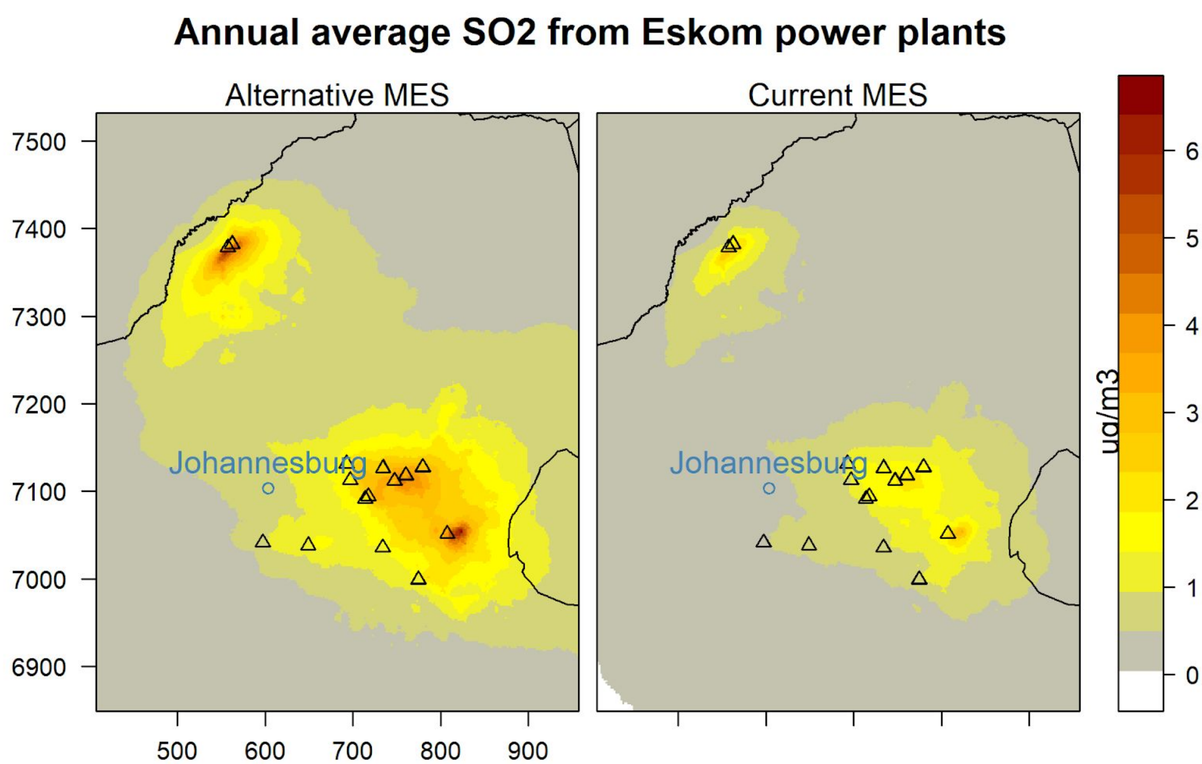
ug/m3


Annual average SO2 from Eskom power plants
Alternative MES
Current MES
Johannesbug
Johannesbug
7500
7400
7300
7200
7100
7000
6900
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600
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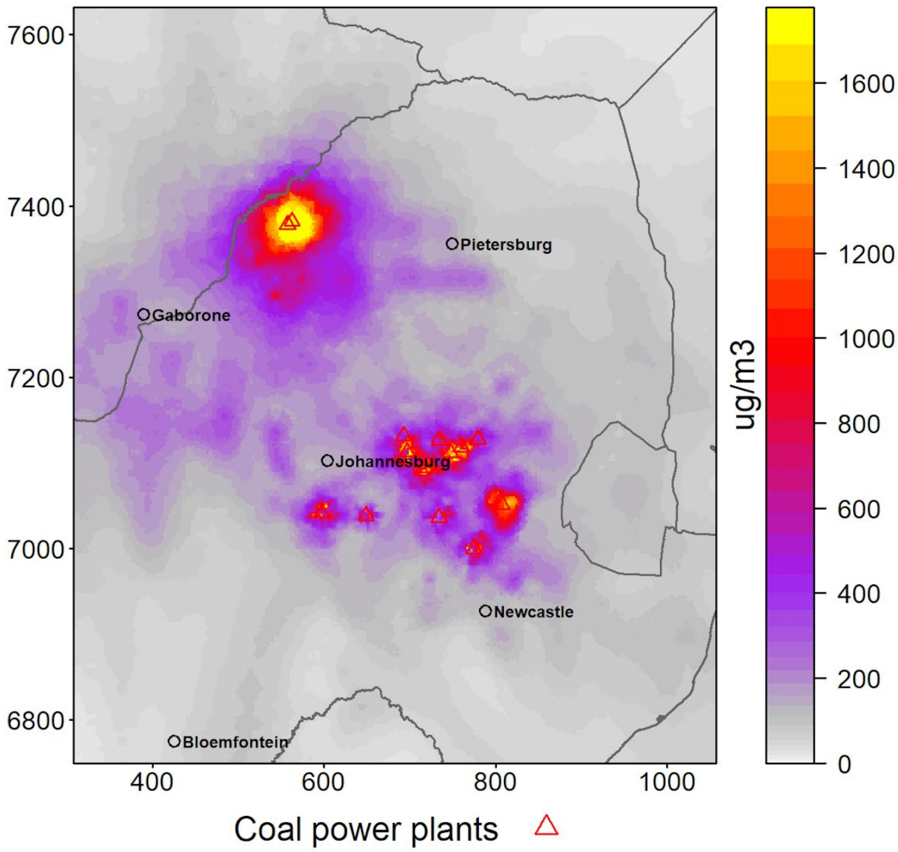
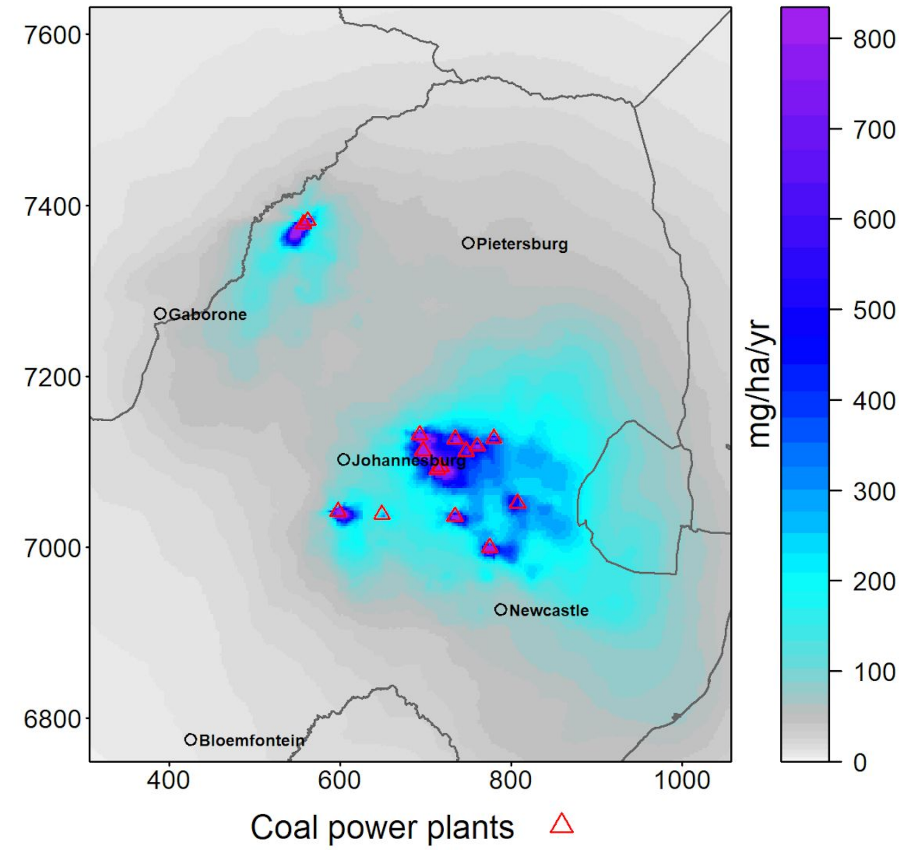
Maximum 1-hour SO_2 concentration from all Eskom coal plants



Annual total mercury deposition from all Eskom coal plants



Health impacts: The health impacts of the changes in air quality are quantified using the Global Burden of Disease methodology for PM2.5.

Cause	***Excess deaths***	***95% confidence interval***
Acute lower respiratory infections	*952*	*(835 - 1006)*
Chronic obstructive respiratory disease	*593*	*(494 - 622)*
Diabetes	*315*	*(116 - 375)*
Ischemic heart disease	*716*	*(609 - 747)*
Lung cancer	*524*	*(434 - 590)*
Stroke	*347*	*(211 - 385)*
Total	*3316*	*(3034 - 3521)*

Projected cumulative premature deaths resulting from doubling the SO2 emissions limit for Eskom power plants, by emitting plant

Plant	***Central***	***95% confidence interval***
Medupi	*1563*	*(1301 - 1651)*
Matimba	*415*	*(346 - 438)*
Kendal	*376*	*(294 - 405)*
Majuba	*334*	*(247 - 366)*
Lethabo	*241*	*(190 - 260)*
Tutuka	*199*	*(152 - 216)*
Matla	*106*	*(83 - 115)*
Duvha	*86*	*(67 - 93)*
Kriel	*57*	*(45 - 62)*

Materials and methods

Emissions projections

To project emissions under different scenarios, current annual air pollutant emissions are compiled from Eskom's Annual Emissions Reports and emissions data reported in Eskom's MES postponement applications. For Medupi and Kusile, annual emissions are taken from their Environmental Impact Statements, except for Kusile where SO2 emissions are calculated based on stated emissions without flue gas desulfurization and the reported 93% SO2 removal efficiency in performance tests.

Emissions of SO_2 in the scenarios are estimated based on reported current annual emissions and current emission limits. In cases where an alternative emission limit is requested until 2020, and this limit is higher than the current limit, the alternative limit is assumed to be representative of current emission control performance. Annual emissions under new, stricter emissions limits are calculated as:

[current annual emissions] * [new emission limit] / [current emission limit]

The rationale for this calculation is that average pollutant flue gas concentrations have to be significantly below the emission limit value in order to ensure emission limits are consistently met. The ratio of average emission values and emission limit is assumed to stay the same when a new emission limit is applied. In reality, given that the MES are extremely weak in international comparison, retrofits are likely to result in significantly lower emissions rates than required by the standards, making the calculation conservative.

As Kusile's Flue Gas Desulphurization devices have already been committed, it is assumed that Kusile's SO2 emissions are not affected by the weakening of the standard.

The operating rates of each power plant are assumed to stay constant over time. This is another potentially conservative assumption, as operating rates would seem likely to increase substantially in the 2030s when a large number of older existing units retire. This would result in higher emissions from the remaining units.

Properties of modeled stacks

Power station	Stack	Stack height, m	Effective stack diameter, m	Lat UTM	Lon UTM	Stack exit temperature (℃)	Stack exit velocity, m/s
Arnot	1	193	11	779.601	7127.669	145	27.5
Arnot	2	193	11	779.631	7127.459	145	27.5
Camden	1	154.5	8.74	807.5673	7051.729	150	10
Camden	2	154.5	8.74	807.6571	7051.745	150	10
Camden	3	154.5	8.74	807.737	7051.76	150	10
Camden	4	154.5	8.74	807.836	7051.78	150	10
Duvha	1	300	12.47	734.213	7126.385	120	23.2
Duvha	2	300	12.47	734.308	7126.612	120	23.2
Grootvlei	1	152	8.99	648.888	7038.364	140	19.57
Grootvlei	2	152	8.99	648.924	7038.251	140	19.57
Hendrina	1	155.5	11.14	760.383	7118.306	128	15.4
Hendrina	2	155.5	11.14	760.304	7118.047	128	15.4
Kendal	1	210	13.51	696.808	7112.86	125	27
Kendal	2	210	13.51	697.053	7112.786	125	27
Kriel	1	213	14.3	717.541	7094.474	130	17
Kriel	2	213	14.3	717.645	7094.275	130	17
Komati	1	220	8	747.225	7112.052	150	24
Komati	2	220	8	747.348	7111.997	145	24
Lethabo	1	275	13.34	597.261	7041.798	145	24.7
Lethabo	2	275	13.34	597.029	7041.693	145	24.7
Majuba	1	250	12.3	774.816	6999.525	125	22
Majuba	2	250	12.3	774.683	6999.307	125	22
Matimba	1	250	12.82	562.317	7382.199	127.5	22.5
Matimba	2	250	12.82	562.259	7382.446	127.5	22.5
Matla	1	213	14.3	713.89	7091.286	138	24
Matla	2	275	12.47	713.785	7091.519	138	24
Medupi	1	220	15.58846	557.231	7378.553	140	18
Medupi	2	220	15.58846	557.271	7378.342	140	18
Tutuka	1	275	12.3	733.759	7036.088	135	35
Tutuka	2	275	12.3	733.999	7036.106	135	35
Kusile	1	250	15.58846	692.3035	7132.023	80	18
Kusile	2	250	15.58846	692.0672	7131.792	80	18

Modeled emissions in the 'current situation', tonnes per year

Power station	Stack	NOX	SO2	PM
Arnot	1	22864	32406	768
Arnot	2	22864	32406	768
Camden	1	9656	17443	290
Camden	2	9656	17443	290
Camden	3	9656	17443	290
Camden	4	9656	17443	290
Duvha	1	31992	62346	2134
Duvha	2	31992	62346	2134
Grootvlei	1	12376	23939	4084
Grootvlei	2	12376	23929	4084
Hendrina	1	18231	42531	469
Hendrina	2	19751	46177	469
Kendal	1	37967	115019	4591
Kendal	2	37967	92015	4591
Kriel	1	44653	60937	4786
Kriel	2	44653	60937	4786
Komati	1	54179	76910	3326
Komati	2	54179	76910	3326
Lethabo	1	47927	89690	4718
Lethabo	2	47927	89690	4718
Majuba	1	62705	78030	1104
Majuba	2	62705	78030	1104
Matimba	1	33796	154631	2452
Matimba	2	33796	154631	2452
Matla	1	54179	76910	4390.32
Matla	2	54179	76910	2195.16
Medupi	1	35336	205333	215
Medupi	2	35336	205333	2150
Tutuka	1	47166	80108	8581
Tutuka	2	47166	80108	8581
Kusile	1	38827	11327	3532
Kusile	2	38827	11327	3532

Installing SO2 scrubbers in coal-fired power plants would have significant ancillary mercury control benefits. If the weakened SO2 MES allowed plants to forego this installation and comply using sorbent injection, these mercury control benefits would be lost, leading to higher mercury emissions than in the case of compliance with the current MES.

As Eskom has neglected to report mercury emissions, these are estimated based on UNEP 2009. Meeting the New Source MES is assumed to require the installation of FGDs but not SCRs at all units. Resulting reductions in mercury emissions are estimated based on UNEP 2017.

Mercury removal rates assumed for different air pollution control technologies.

ESP	30%
Fabric filter	50%
Fabric filter + FGD	70%

Atmospheric modeling

Atmospheric dispersion modeling for the study was carried out using version 7 (June 2015) of the CALPUFF modeling system. CALPUFF is an advanced non-steady-state meteorological and air quality modeling system adopted by the U.S. Environmental Protection Agency (USEPA) in its Guideline on Air Quality Models as the preferred model for assessing long range transport of pollutants and their impacts.

Meteorological data for the simulations was generated by combining two sources: hourly observations from 18 meteorological stations in South Africa and neighboring countries, and prognostic 3-dimensional weather fields generated using the TAPM modeling system, developed by Australia's national science agency CSIRO, and also used for Eskom's own cost-benefit study. TAPM uses as its inputs global weather data from the GASP model of the Australian Bureau of Meteorology, combined with higher-resolution terrain data. TAPM outputs were converted into formats accepted by CALPUFF's meteorological preprocessor, CALMET, using the CALTAPM utility, and the meteorological data were then prepared for CALPUFF execution using CALMET. CALMET generates a set of time-varying micrometeorological parameters (hourly 3-dimensional temperature fields, and hourly gridded stability class, surface friction velocity, mixing height, Monin-Obukhov length, convective velocity scale, air density, short-wave solar radiation, surface relative humidity and temperature, precipitation code, and precipitation rate) for input to CALPUFF.

Terrain height and land-use data were also prepared using the TAPM system and global datasets made available by CSIRO. Two sets of nested grids with a 50x50 grid size and 30km, 10km and 5km horizontal resolutions and 12 vertical levels was used, centered on the Highveld and Limpopo.

30% of emitted fly ash was assumed to be PM2.5, and 67.5% PM10, in line with the U.S. EPA (1998) default value for electrostatic precipitators. Particulate matter larger than 10 microns were modeled with a mean aerodynamic diameter of 15 microns. Reported annual emissions were converted into hourly emission rates using monthly and diurnal emissions profiles reported by Eskom.

For modeling mercury, the recommended parameter values from EPA (1997) were adopted. Mercury speciation was based on Lee et al. (2006).

Chemical transformation of sulphur and nitrogen species was modeled using the ISORROPIA/RIVAD chemistry module within CALPUFF. The chemical reaction set requires background pollutant concentration parameters (ozone, ammonia and H_2O_2 levels). For ozone, monitoring data for 2017 was available for 11 stations within the modeling domain. Monthly average background ammonia levels were obtained from a study by North-West university (Martins et al 2007).

As H_2O_2 data was not available, the U.S. EPA default (1ppb) was used, and a sensitivity test was carried out to ensure the results are not sensitive to this assumption by repeating one of the simulations with an 80% lower value; resulting average PM2.5 concentrations were 5% lower due to less secondary particle formation, showing that this parameter was not a significant source of uncertainty.

The CALPUFF results were reprocessed using the POSTUTIL utility to repartition different nitrogen species (NO, NO_2, NO_3 and HNO_3) based on background ammonia concentrations.

Health impact assessment

The health impacts of the changes in ambient air pollution concentrations were assessed following the Global Burden of Disease methodology. The basic foundation for the health impact estimates are numeric scientific studies that show that the risk of chronic diseases such as stroke and lung cancer is increased for people who live in areas with higher PM2.5 levels. The Global Burden of Disease project has developed “integrated risk functions” that combine studies covering a very wide range of PM2.5 exposure levels and thereby avoid extrapolating epidemiological results beyond the concentration range in which they were obtained.

The implementation of the GBD methodology followed two steps: first, reproduction of the GBD results for total mortality related to PM2.5 for each grid cell, and second, modifying the PM2.5 concentration to remove the contribution from Eskom power plants, and calculating the change in health impacts.

Health impact assessment was implemented in a 1x1km grid, with atmospheric modeling results interpolated linearly and population data aggregated to the grid. Premature deaths in a given grid cell are calculated as

Pd = PAF * DR * pop * AF, and

PAF(conc) = 1 - 1 / RR(conc),

in which RR(conc) is the cause-specific risk ratio for the average PM2.5 concentration conc in the grid cell, based on the non-linear concentration-response function RR integrated for the GBD project from dozens of epidemiological studies in Stanaway et al (2018). PAF is the population attributable fraction, share of deaths from cause c in the relevant age group that are attributable to PM2.5 exposure, DR is the baseline death rate from cause c in the relevant age group, pop is the total population in the grid cell, and age fraction AF is the fraction of population that belongs to the relevant age group (25 years and above for chronic diseases and under 5 years for Acute Respiratory Infections).

Given baseline mean PM2.5 concentration $conc_{base}$, and concentration attributed to the modeled coal-fired power plants $conc_{coal}$, the PAF for the coal plants specifically is obtained as:

$$PAF_{coal} = PAF(conc_{base}) - PAF(conc_{base} - conc_{coal})$$

Put another way, PAF_{coal} is the projected reduction in mortality from a specific cause if the modeled power plant emissions are completely eliminated.

For stroke and ischaemic heart disease, the GBD concentration-response functions are age-specific. Appropriate functions for the entire South African adult population are derived as averages of the age-specific functions weighted by the population share of each age group in South Africa.

To get baseline PM2.5 concentrations we used global gridded PM2.5 data for 2016 derived by combining available ground-level measurements with satellite-based aerosol retrievals and atmospheric model outputs (van Donkelaar et al 2016). Using 2016 baseline concentrations as the basis for future impacts can be seen as conservative, if overall air quality is likely to improve in the future, which would increase the health impacts attributed to the power plants due to the concave shape of the risk functions.

To further apportion the health impacts to individual power plants, the share of total mortality in a given grid cell attributed to emissions of species s from power plant i was calculated as:

$$PAF_{i,s} = PAF_{coal} \times conc_{i,s} / conc_{coal}$$

where $conc_{i,s}$ is the modeled PM2.5 concentration at the given grid cell that is attributable to emissions of s from the power plant i. Apportionment was done linearly rather than using the non-linear function as otherwise results would depend on the order in which impacts are apportioned to different power plants. Obtaining the $PAF_{i,s}$ values for each power plant, pollutant and grid cell enabled us to project the impacts of changes in emissions by scaling each value in proportion to changes in emissions.

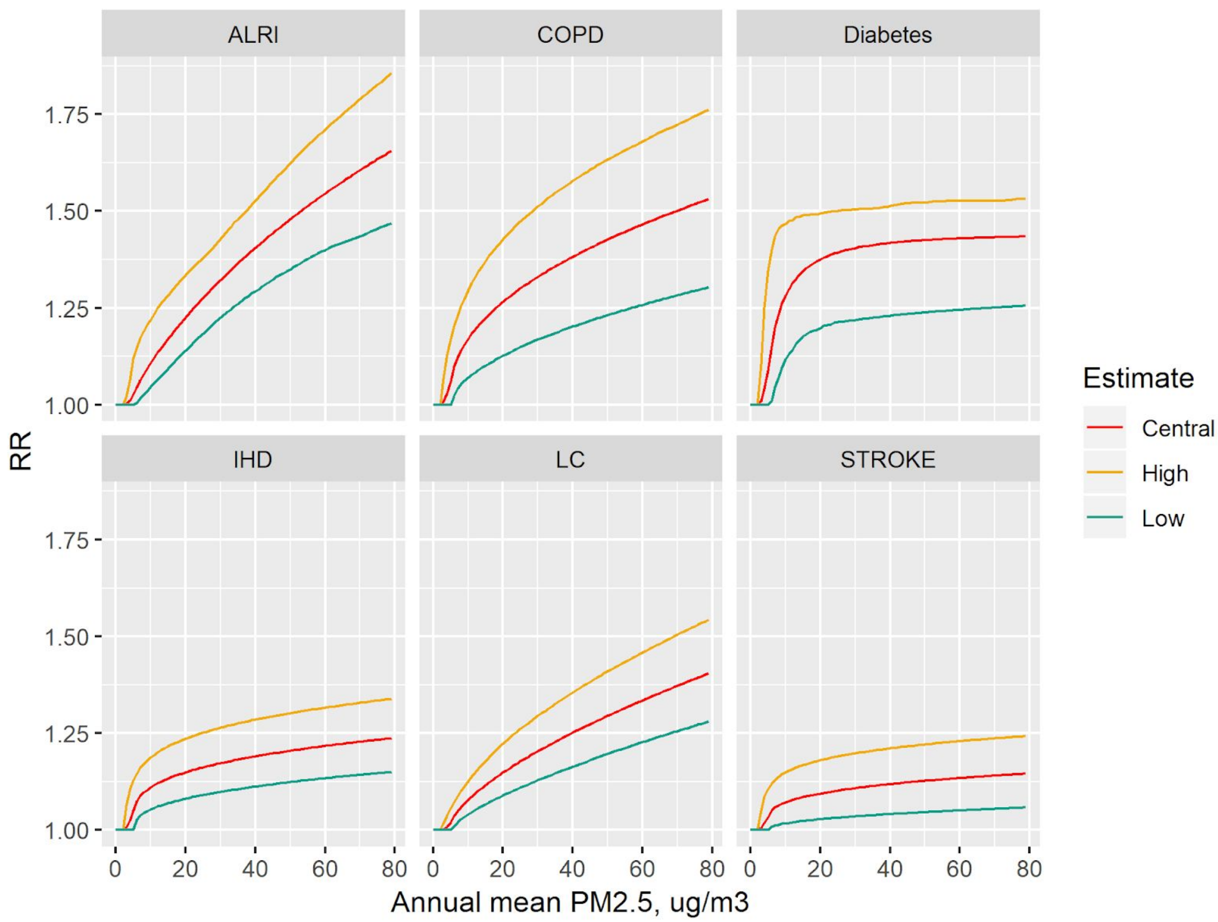
For stroke and IHD, the RR function is derived separately for different age groups, at 5-year intervals. The appropriate aggregate RR functions were derived as the mean of age-specific RR function values at each concentration level, weighted by the share of the age group in total cause-specific mortality.

In addition to PM2.5 health impacts, premature deaths from NO2 exposure were assessed using the risk ratio for daily mortality based on WHO (2013) recommendations, from Mills et al (2016). This choice of risk ratio is conservative as it only includes the short-term effects of PM2.5 exposure; including chronic effects could result in almost 10 times as high current health impact. However, the effect on projected health impacts of “excess emissions” would be small as these are dominated by the health impacts of excess SO2 emissions.

We obtained current death rates by cause and by country from Global Burden of Disease data (IHME 2018). The projections take into account expected population growth and epidemiological transition associated with improved health care and an ageing population. High-resolution spatial distribution of population from NASA SEDAC (CIESIN 2018) was used. Birth rates and incidence of low birth weight were obtained from the World Bank (undated).

For future projections of health impacts, population growth is assumed to follow the UNPD 'Medium variant'. Incidence of different causes of death in 2015 is based on WHO Global Health Estimates (2018). For future incidence, the change projected GHE for sub-Saharan Africa is used to adjust the incidences, entailing reductions in baseline child mortality from Lower Respiratory Infections and increases in chronic cardiovascular diseases and cancers for adults.

Concentration-response functions developed for the Global Burden of Disease study and applied to assessing the health impacts.



Deposition results were differentiated by land use type using the European Space Agency global land use map for the year 2015 at 300m resolution (ESA 2018; see Figure 12). Land use codes 10-30 were mapped as cropland; codes 50-100 and 160-170 were mapped as forest.

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