Health impacts of Eskom's non-compliance with minimum emissions standards

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| 01/2023

CREA
Centre for Research on Energy and Clean Air

CREA is an independent research organisation focused on revealing the trends, causes, and health impacts, as well as the solutions to air pollution.

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Key findings

- Under Eskom’s planned retirement schedule and emission control retrofits, emissions from the company’s power plants would be responsible for a projected 79,500 air pollution-related deaths from 2025 until end-of-life (95% confidence interval 48,200–122,000).
- Full compliance with the MES at all plants that are scheduled to operate beyond 2030 would avoid a projected 2,300 deaths per year from air pollution (95% confidence interval: 1,500 – 3,400) and economic costs of R42 billion (USD2.9 billion) per year (95% confidence interval: R26 – 60bn), starting from 2025[1].
- Eskom’s retrofit plan only realizes one quarter of the health benefits associated with compliance with the MES, due to the almost complete failure to address SO_2 emissions.
- On a cumulative basis until the end-of-life of the power plants, compliance would avoid a projected 34,400 deaths from air pollution (95% confidence interval: 21,600 – 49,300) and economic costs of R620 bn (USD 41.7 bn; 95% confidence interval: R390 – 870). Other avoided health impacts would include 140,000 asthma emergency room visits, 5,900 new cases of asthma in children, 57,000 preterm births, 35.0 million days of work absence, and 50,000 years lived with disability.
- If the compliance deadline was delayed to 2030 instead of 2025, compliance with the emission limits would still avoid a projected 26,400 deaths from air pollution (95% confidence interval: 16,600 – 37,700) and economic costs of R470bn (USD 32.0 bn; 95% confidence interval: R300 – 660bn).
- Requiring the application of best available control technology at all plants, instead of the current MES, by 2030, would avoid 57,000 deaths from air pollution (95%

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[1] 1 USD = 14.79 R; 2021 average exchange rate.

confidence interval: 34,800 – 86,500) and economic costs of R1,000bn (USD 68.0 bn (95% confidence interval: R610 – 1,500bn) compared to the Eskom plan.

Introduction

South Africa's Minimum Emissions Standards (MES) for combustion installations were issued in 2010, with a phased introduction where existing sources had to meet a more lenient set of standards by 2015 and a more stringent set of standards by 2020. Most importantly, these standards would require, for the first time, coal-burning facilities to install sulphur dioxide emissions controls.

After the issuance of the standards, South Africa's largest emitter Eskom failed to initiate the required planning and implementation of the emission control retrofits, and government authorities failed to monitor Eskom's actions, leading to an impossible situation where there was no more enough time to retrofit the fleet.

Because of this, Eskom was granted postponements to the standards until 2025. For plants planned to retire by 2030, compliance with the standards was suspended. While the postponements were time-limited, Eskom made it clear that it did not intend to comply even after the deadlines ran out. In 2020, the emission limit for SO_2 was further weakened from 500 to 1,000 mg/Nm^3, potentially enabling the standards to be met using emission technology with lower investment costs.

Compliance with the MES, even after the weakening, would result in major reductions in air pollutant emissions. However, in comparison to best international practice, the MES are highly lenient. For example, the European Union now requires old coal-fired power plants to limit SO_2 in flue gases to an annual average of 95 mg/Nm^3, less than one tenth of the limit value in South Africa.

As a result of the failure to act on its SO_2 emissions, Eskom has become the largest power sector emitter of SO_2 in the world (Myllyvirta, 2021). Other major emitters, particularly Chinese utilities, have carried out major retrofit programs and successfully reduced their SO_2 emissions.

Results

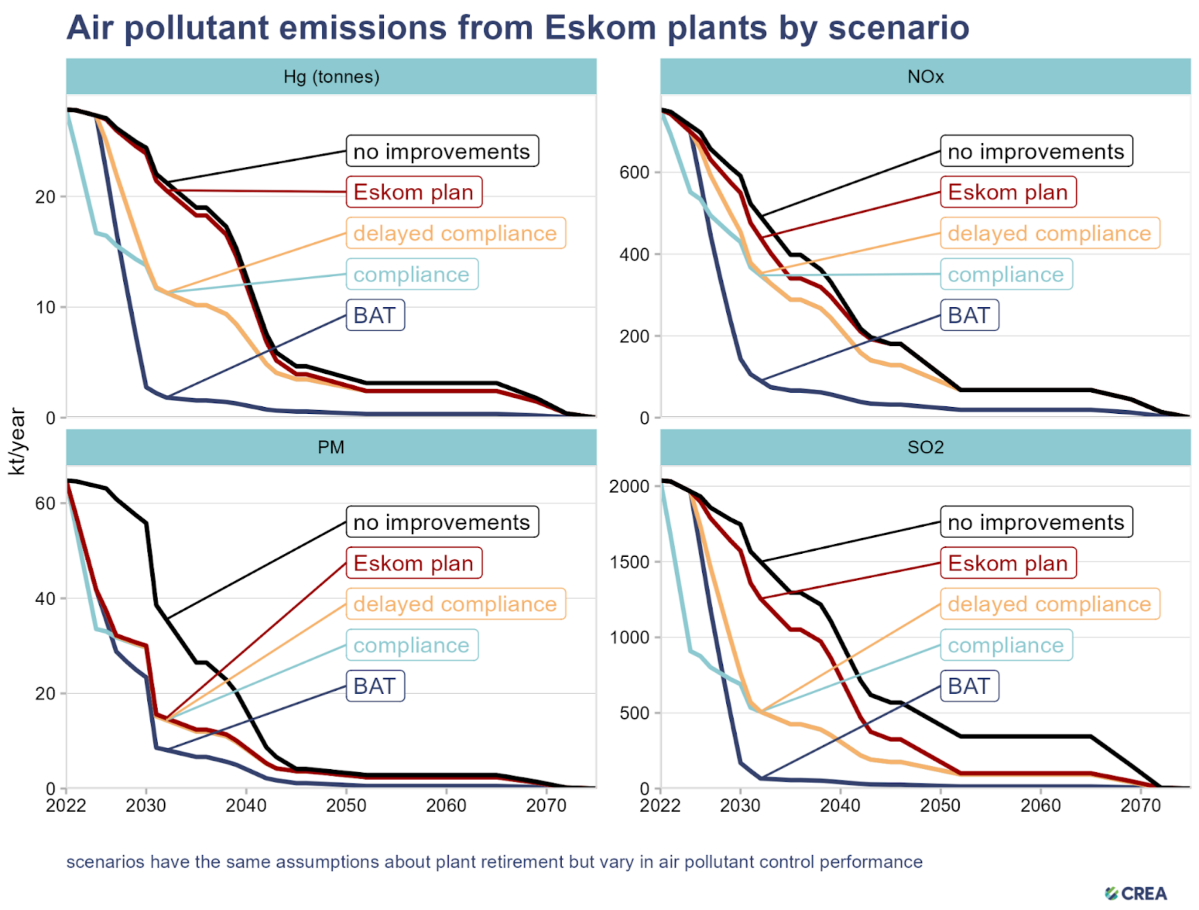
Emissions

We project emissions, air quality impacts and the resulting health and economic impacts of air pollution from Eskom's coal power plant fleet under four different scenarios of compliance with the MES. The first one being the "compliance scenario" which assumes that Eskom meets its legal obligations and complies with the MES by 2025 at all stations that have not received a suspension. The "delayed compliance" scenario assumes that it takes until 2030 to achieve compliance. The "Eskom plan" scenario follows Eskom's proposed plant retrofits which see all plants except Medupi and Kusile operate until end-of-life in breach of the emissions limits, particularly for SO_2. Finally, the "Best Available Technology" (BAT) scenario assumes that compliance with the MES is delayed until 2030, but the emission limits are tightened to align with best international practice.

Full compliance with the MES would reduce Eskom's emissions of SO_2 by 60%, PM by 50%, NO_x by 20% and mercury (Hg) by 40%, compared with a scenario of no improvements in emission control technology (Figure 1). Mercury is not regulated under the MES, but compliance would significantly affect the emissions of this toxic pollutant regardless, as the installation of SO_2 controls captures mercury from the flue gases as a side benefit.

Eskom's proposed retrofit plan would bring the fleet into compliance with the MES for PM and realize the associated emissions reductions by 2030, five years after the deadline. However, the plan would only reduce SO_2 by 13%, NO_x by 11% and Hg by 3%, compared with a scenario of no improvements in emission control technology. The small reductions in SO_2 emissions are the main concern, as SO_2 is the pollutant with by far the largest health impacts from Eskom's power plants, due to the formation of secondary $PM_{2.5}$.

Requiring Best Available Technology at all the power plants would reduce SO_2 by 93%, PM by 78%, NO_x by 80%, and mercury by 90%.

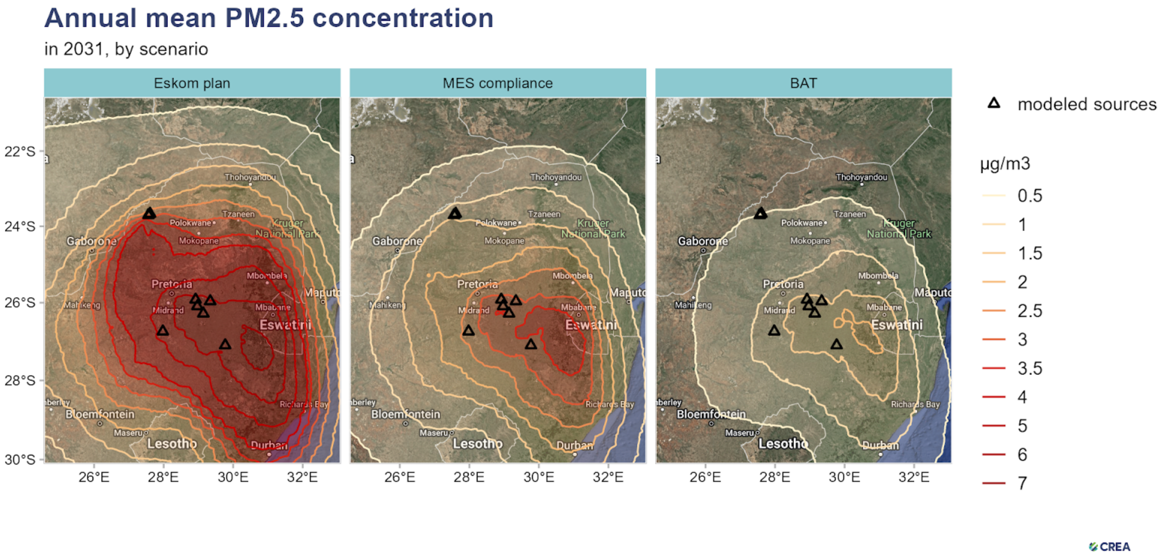

Air pollutant emissions from Eskom plants by scenario

scenarios have the same assumptions about plant retirement but vary in air pollutant control performance

Figure 1. *Projected emissions by scenario.*

Air quality and mercury fallout

The results of our air quality simulations are shown below for the different pollutants and mercury (Figures 2, 3, 4 and 5). The compliance scenario realizes very significant improvements in air quality across Mpumalanga, Limpopo and Gauteng, as well as in neighboring provinces by 2026. The delayed compliance scenario achieves these improvements by 2031. The BAT scenario leads to much larger improvements, with air pollutant concentrations attributed to Eskom emissions falling to a fraction of current emissions.



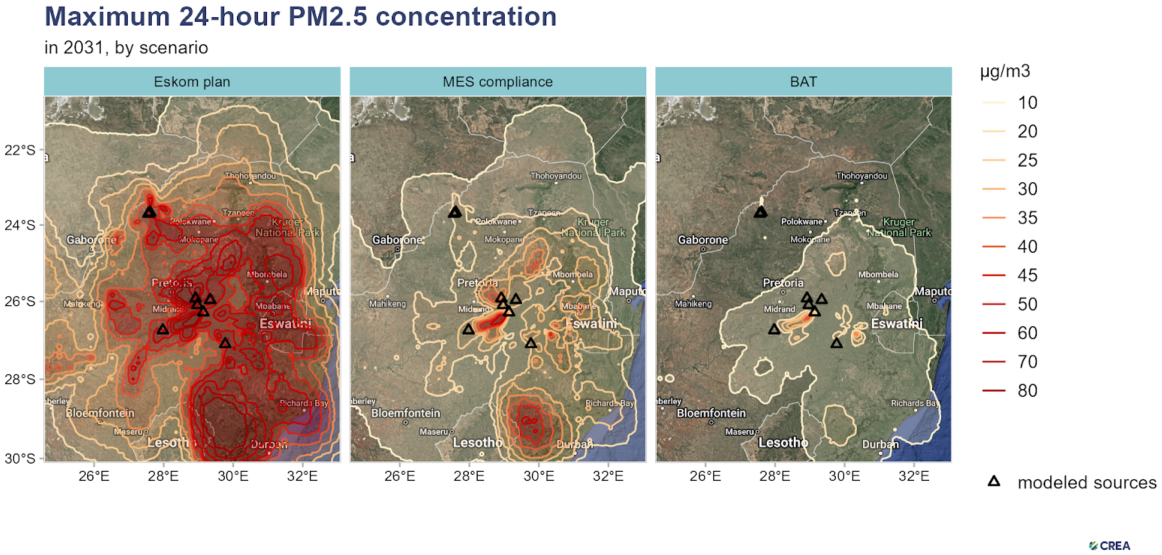


Figure 2. *$PM_{2.5}$ concentrations attributed to Eskom emissions in 2031 in different scenarios.*

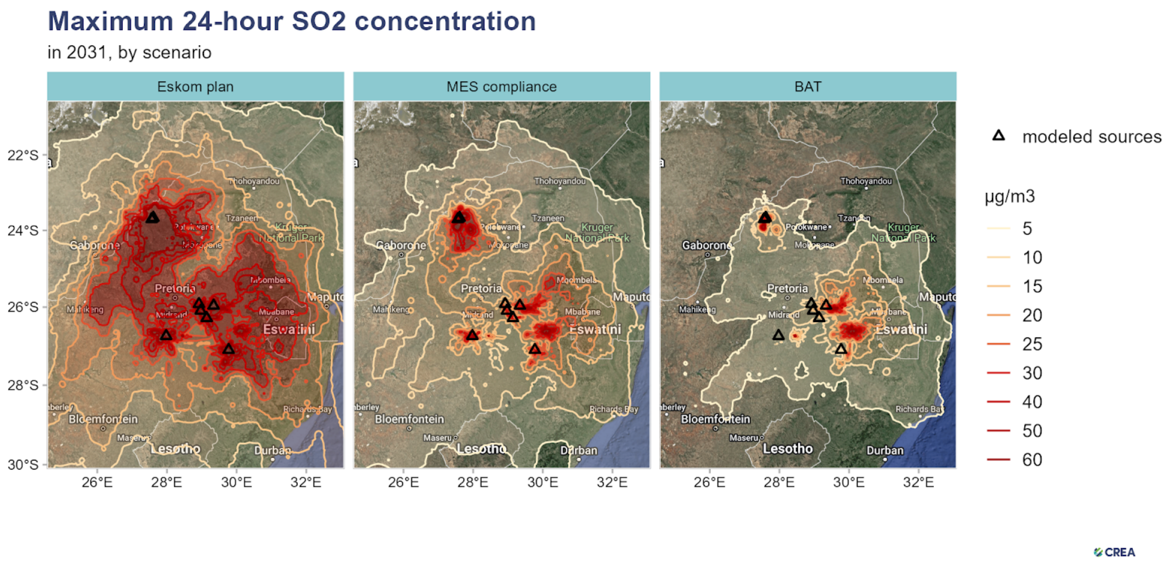
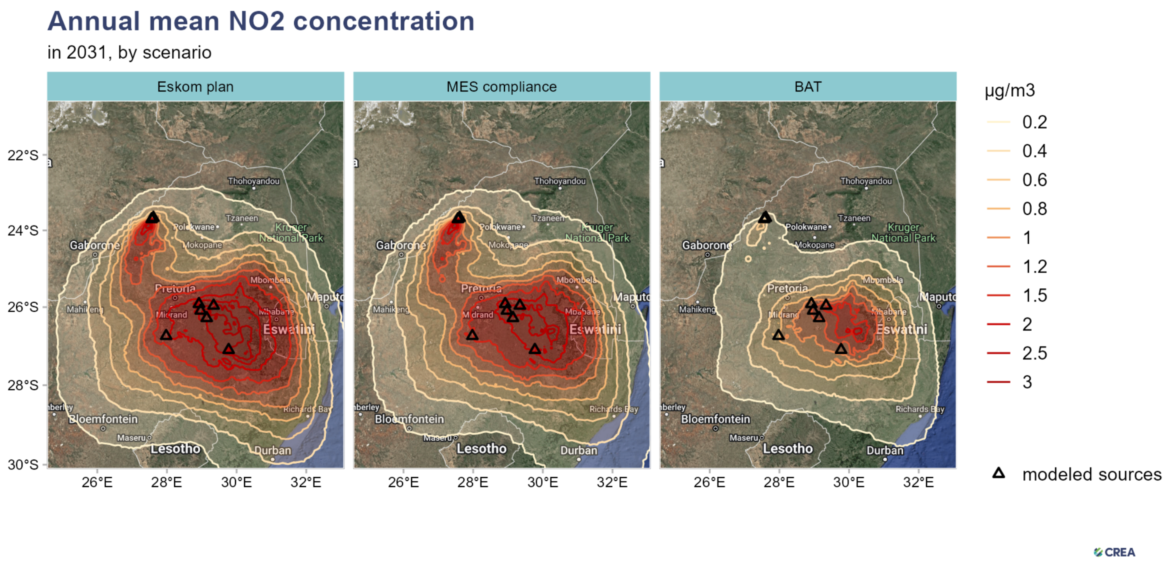


Figure 3. *SO_2 concentrations attributed to Eskom emissions in 2031 in different scenarios.*



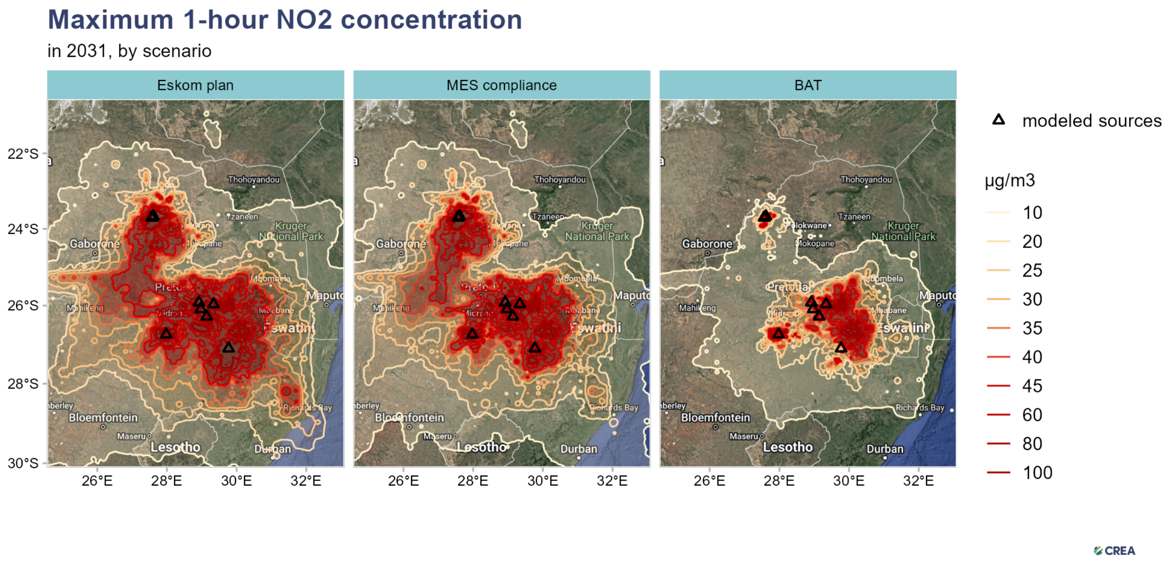
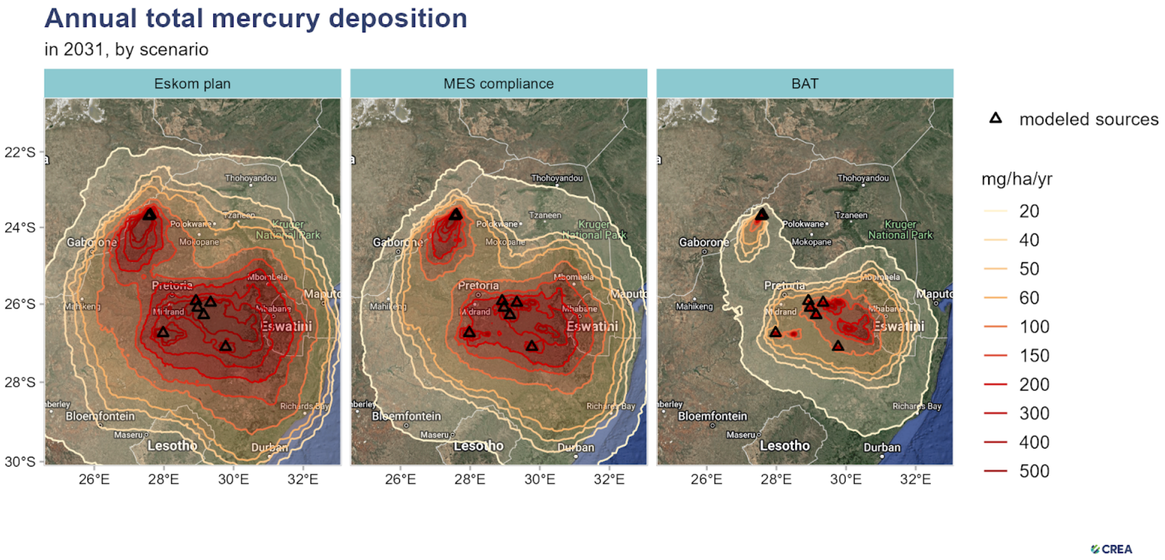


Figure 4. *NO_2 concentrations attributed to Eskom emissions in 2031 in different scenarios.*



Annual total mercury deposition

in 2031, by scenario

Figure 5. *Annual total mercury deposition attributed to Eskom emissions in 2031 under different scenarios.*

Health and economic impacts

Given the very large geographical area and population affected by the emissions, changes in Eskom's emissions have major public health implications. Figure 6 and Tables 1–4 show the projected number of deaths attributed to Eskom's emissions under different scenarios, as well as other health impacts and the associated economic costs.

The reductions in annual health impacts in the "no improvements" scenario reflect solely the effect of emissions reductions due to planned plant retirements, with the assumption that the generation output of the retired plants is replaced with clean energy rather than made up for by increased generation at other coal-fired power stations. Comparison between the "Eskom plan" and "no improvements" scenarios shows that the effect of the planned retrofits is a relatively modest 15% reduction in annual health impacts, with the installation of the FGD at Medupi being by far the most impactful measure.

The compliance scenario sees annual health impacts approximately halve after 2025 with MES compliance, avoiding a projected 1,900 deaths and economic costs of R33.3bn (USD 2.3bn) per year. In the "delayed compliance" scenario this effect is only realised by 2031, at which point the two scenarios converge.

The BAT scenario entails a more than 90% reduction in the health impacts of Eskom emissions by 2031, avoiding an estimated 1,400 deaths and economic costs of R25bn (USD 1.7 bn) per year compared with MES compliance.

The upward slope of the impacts during periods of constant emissions reflects the effect of population growth and epidemiological changes (increased incidence of chronic diseases due to population ageing).

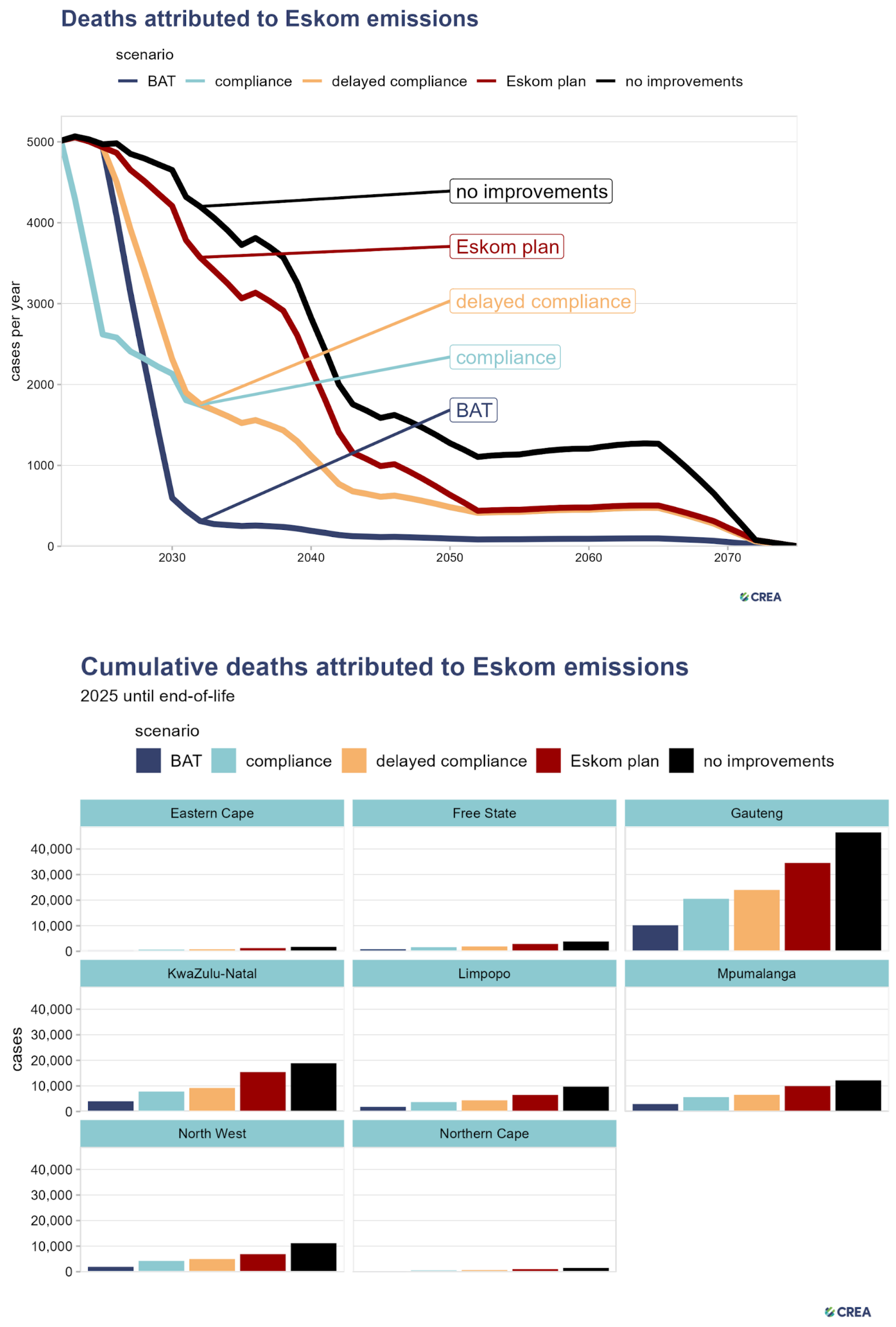


Figure 6. *Annual deaths and cumulative deaths attributed to Eskom emissions by scenario.*

Table 1. *Projected health impacts avoided in 2031 through compliance with the MES, compared with Eskom's plan.*

Outcome and cause		**Pollutant**	**central estimate**	**95% confidence interval**	
				low	**high**
deaths		all	2,010	1,270	2,890
of which due to:	*chronic obstructive pulmonary disease*	$PM_{2.5}$	*125*	*77*	*167*
	diabetes	$PM_{2.5}$	*131*	*42*	*213*
	ischaemic heart disease	$PM_{2.5}$	*140*	*95*	*178*
	lower respiratory infections	$PM_{2.5}$	*345*	*248*	*458*
	lung cancer	$PM_{2.5}$	*85*	*56*	*123*
	stroke	$PM_{2.5}$	*84*	*41*	*113*
	all causes	NO_2	*133*	*64*	*283*
	all causes	SO_2	*935*	*621*	*1,300*
deaths of children under 5 due to lower respiratory infections		$PM_{2.5}$	36	23	54
asthma emergency room visits		$PM_{2.5}$	8,040	4,740	11,300
new cases of asthma in children		NO_2	369	73	887
preterm births		$PM_{2.5}$	3,420	1,660	3,630
work absence (million sick leave days)		$PM_{2.5}$	2.01	1.71	2.3
years lived with disability due to	*chronic obstructive pulmonary disease*	$PM_{2.5}$	*1,300*	*731*	*1,810*
	diabetes	$PM_{2.5}$	*1,210*	*304*	*2,430*
	stroke	$PM_{2.5}$	*291*	*110*	*462*
total economic cost, bln R		all	33.3	20.8	46.7

Table 2. *Projected deaths and total economic costs attributed to air pollution from Eskom power plants by scenario in 2031 (after the commissioning of Medupi FGD).*

Outcome and scenario		central estimate	95% confidence interval	
			low	high
deaths	BAT	317	178	549
	compliance	1,770	1,050	2,850
	delayed compliance	1,790	1,050	2,880
	Eskom plan	3,630	2,220	5,500
	no improvements	4,270	2,610	6,470
total economic cost, bln R	BAT	5.43	3.07	9.21
	compliance	30.9	18.2	48.6
	delayed compliance	31.1	18.3	49.1
	Eskom plan	64.2	39	95.3
	no improvements	75.6	46	112

Table 3. *Projected cumulative health impacts avoided from 2025 until the end-of-life of Eskom's coal fleet through compliance with the MES, compared with Eskom's plan.*

Outcome and cause		Pollutant	central estimate	95% confidence interval	
				low	high
deaths		all	34,400	21,600	49,300
of which due to:	*chronic obstructive pulmonary disease*	$PM_{2.5}$	*2,210*	*1,350*	*2,960*
	diabetes	$PM_{2.5}$	*2,330*	*747*	*3,800*
	ischaemic heart disease	$PM_{2.5}$	*2,470*	*1,680*	*3,150*
	lower respiratory infections	$PM_{2.5}$	*6,070*	*4,370*	*8,050*
	lung cancer	$PM_{2.5}$	*1,490*	*979*	*2,170*
	stroke	$PM_{2.5}$	*1,490*	*719*	*1,990*
	all causes	NO_2	*2,180*	*1,040*	*4,640*
	all causes	SO_2	*15,500*	*10,300*	*21,600*
deaths of children under 5 due to lower respiratory infections		$PM_{2.5}$	*589*	*383*	*891*
asthma emergency room visits		$PM_{2.5}$	137,000	81,100	193,000
new cases of asthma in children		NO_2	5,870	1,150	14,100
preterm births		$PM_{2.5}$	57,400	27,900	60,900
work absence (mln sick leave days)		$PM_{2.5}$	34.9	29.7	40
years lived with disability due to	*chronic obstructive pulmonary disease*	$PM_{2.5}$	*22,900*	*12,900*	*32,000*
	diabetes	$PM_{2.5}$	*21,700*	*5,360*	*43,300*
	stroke	$PM_{2.5}$	*5,140*	*1,940*	*8,170*
total economic cost, bln R		all	617	385	868

Table 4. *Projected cumulative deaths and total economic costs attributed to air pollution from Eskom power plants by scenario from 2022 until the end-of-life of Eskom's coal fleet.*

Outcome and scenario		central estimate	95% confidence interval	
			low	high
deaths	BAT	22,500	13,400	35,600
	compliance	45,100	26,600	72,900
	delayed compliance	53,100	31,600	84,400
	Eskom plan	79,500	48,200	122,000
	no improvements	107,000	65,600	161,000
total economic cost, bln R	BAT	397	236	614
	compliance	785	462	1,240
	delayed compliance	928	551	1,440
	Eskom plan	1,400	847	2,110
	no improvements	1,890	1,150	2,790

Methodology

Emissions projections

Monthly emissions — reported by Eskom for each station — are used as the basis for the current emissions for each major air pollutant for the FY 2021–2022 (Eskom, 2023). Using the monthly emissions values allows us to take into account the seasonal variations in plant operation.

Since Eskom does not report mercury emissions from its power plants, we took mercury emissions per tonne of coal burned for each power plant from Scott (2011), and updated the emissions estimates to coal use in FY 2021–22. For Medupi and Kusile, which were not included in that study, we used coal mercury content for nearby power plants from Scott (2011), and calculated the emissions based on the methodology of the UNEP (2017) Mercury Toolkit. The calculation uses the formula

$$E = CC \times MC \times (1 - CE),$$

where CC is the coal consumption of the power plant in tonnes, MC is the mercury content of the coal, and CE is the mercury control efficiency, based on the type of air pollutant control technology in the power plant as reported in UNEP (2017) Mercury Toolkit.

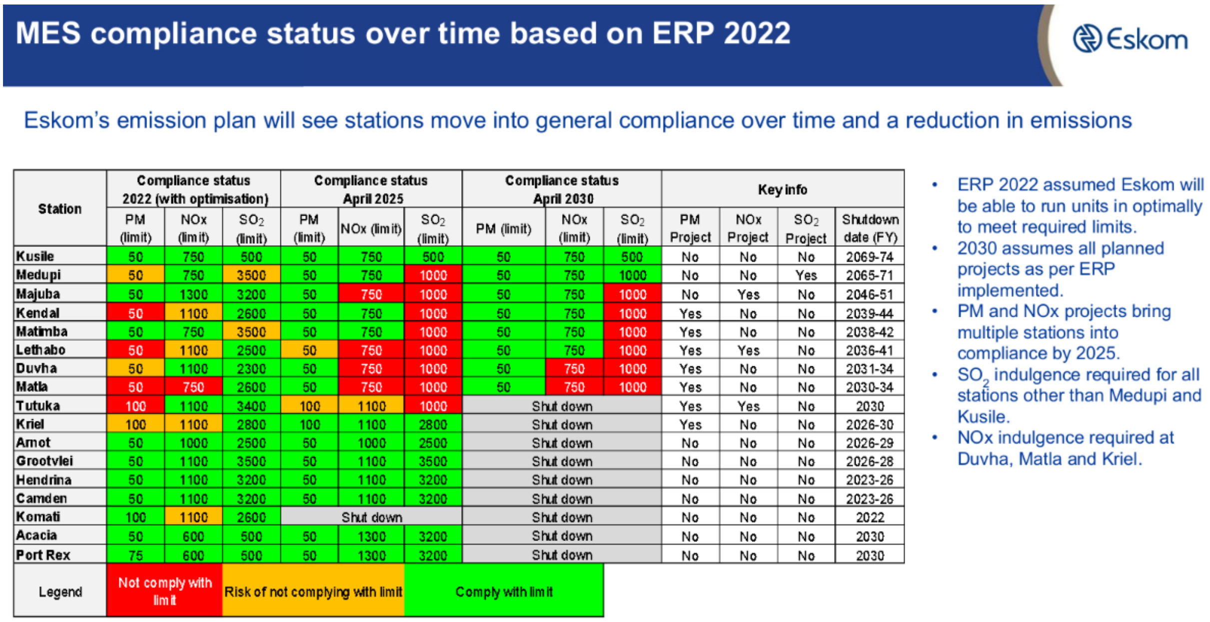
We projected the air pollutant emissions from Eskom's coal-fired power plants under five different scenarios:

- Compliance: The compliance scenario assumes that Eskom meets its legal obligations and complies with the MES by 2025 at all stations that have not received a suspension. The exception is Tutuka, which Eskom now plans to retire by 2030; we assume that Tutuka's compliance would be suspended although current regulation does not provide for this.
- Delayed compliance: all plants which are not scheduled to retire by 2030 reach compliance with the MES by 2030, except for Medupi and Lethabo which complete the retrofits by 2031 and 2032, respectively, per Eskom's schedule.
- Eskom plan: emission control improvements under Eskom's plan (Table 5) are fully implemented. This implies that all plants except Medupi and Kusile operate until end-of-life in breach of the MES emissions limits, particularly for SO_2.

- BAT: compliance with the MES is delayed until 2030, but the emission limits are tightened to align with the use of best available control technology. The definition of best available technology (BAT) was based on the BAT-aligned emission levels in the EU BAT Reference Document. These limits are legally binding and are currently being met in a large number of old coal power plants, making them a valid basis for assigning BAT in South Africa.
- No improvement: emissions from each plant unit remain at 2021-22 levels until end-of-life.

Assumptions on plant retirements follow Eskom's plan under all the scenarios.

Table 5. *Emission limit compliance, planned emission control retrofits and retirement dates indicated by Eskom.*



MES compliance status over time based on ERP 2022

Eskom

Eskom's emission plan will see stations move into general compliance over time and a reduction in emissions

Station	Compliance status 2022 (with optimisation)			Compliance status April 2025			Compliance status April 2030			Key info			
	PM (limit)	NOx (limit)	SO_2 (limit)	PM (limit)	NOx (limit)	SO_2 (limit)	PM (limit)	NOx (limit)	SO_2 (limit)	PM Project	NOx Project	SO_2 Project	Shutdown date (FY)
Kusile	50	750	500	50	750	500	50	750	500	No	No	No	2069-74
Medupi	50	750	3500	50	750	1000	50	750	1000	No	No	Yes	2065-71
Majuba	50	1300	3200	50	750	1000	50	750	1000	No	Yes	No	2046-51
Kendal	50	1100	2600	50	750	1000	50	750	1000	Yes	No	No	2039-44
Matimba	50	750	3500	50	750	1000	50	750	1000	Yes	No	No	2038-42
Lethabo	50	1100	2500	50	750	1000	50	750	1000	Yes	Yes	No	2036-41
Duvha	50	1100	2300	50	750	1000	50	750	1000	Yes	No	No	2031-34
Matla	50	750	2600	50	750	1000	50	750	1000	Yes	No	No	2030-34
Tutuka	100	1100	3400	100	1100	1000	Shut down			Yes	Yes	No	2030
Kriel	100	1100	2800	100	1100	2800	Shut down			Yes	No	No	2026-30
Arnot	50	1000	2500	50	1000	2500	Shut down			No	No	No	2026-29
Grootvlei	50	1100	3500	50	1100	3500	Shut down			No	No	No	2026-28
Hendrina	50	1100	3200	50	1100	3200	Shut down			No	No	No	2023-26
Camden	50	1100	3200	50	1100	3200	Shut down			No	No	No	2023-26
Komati	100	1100	2600	Shut down			Shut down			No	No	No	2022
Acacia	50	600	500	50	1300	3200	Shut down			No	No	No	2030
Port Rex	75	600	500	50	1300	3200	Shut down			No	No	No	2030
Legend	🟥 Not comply with limit		🟧 Risk of not complying with limit			🟩 Comply with limit							

- ERP 2022 assumed Eskom will be able to run units in optimally to meet required limits.
- 2030 assumes all planned projects as per ERP implemented.
- PM and NOx projects bring multiple stations into compliance by 2025.
- SO_2 indulgence required for all stations other than Medupi and Kusile.
- NOx indulgence required at Duvha, Matla and Kriel.

Emissions under the MES compliance were projected based on the following logic:

- For SO_2, we identified the highest monthly average flue gas concentration (FGC) in 2021–2022 for each plant, and assumed that the SO_2 control equipment needed to meet the MES will have to have sufficient control efficiency to bring this highest value into compliance with the MES limit (1,000mg/Nm^3). Annual emissions under compliance with the emission limit value (ELV) where then calculated as:

$E_C = E_{FY22} \times \frac{ELV}{max(FGC)}$, where E_{FY22} denotes actual emissions in FY2021–22.

- For NO$_x$, we calculated the average NO$_x$ flue gas concentrations for those plants that are in compliance with their current Atmospheric Emission License emission limits, per Eskom's own assessment (Table 5). For each plant, we compared this average FGC to the plant's emission limit value, to calculate how much below the limit average FGCs are for compliant plants. We calculated the average of these ratios (R) and applied this ratio to the MES limit (750mg/Nm^3):

$$E_C = E_{FY22} \times \frac{ELV \times R}{mean(FGC)}$$

- For PM, we calculated the average flue gas concentration in those power plants that are currently in compliance with the PM MES, per Eskom's own assessment (FGC_C), and applied this average flue gas concentration to all plants that are currently not in compliance.

$$E_C = E_{FY22} \times \frac{FGC_C}{mean(FGC)}$$

- For mercury, we projected the increase in capture efficiency resulting from adding SO$_2$ controls to the power plants using default capture rates for different emission control systems in the UNEP (2017) Mercury toolkit.

The speciation of mercury in the flue gases of the power plants was based on Zhang et al. (2016).

As the EU BAT-aligned emission levels are given on an annual average basis, we calculated the average flue gas concentrations in FY 2021–22 for each power plant and scaled the emissions down by the ratio of the BAT level to the current flue gas concentration.

The operating rates of each power plant are assumed to stay constant over time. This is a 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.

The power plants were modeled as buoyant point sources, taking into account the stack height and thermal plume rise from the stacks. The stack characteristics were collected from Eskom Atmospheric Impact Reports for the suspension of minimum emission standards at the power plants (DFFE 2019).

Atmospheric modeling

We simulate air pollutant concentrations using the CALPUFF air dispersion model, version 7 (Exponent, 2015). CALPUFF is a widely-used industry standard model for long-range air quality impacts of point sources. The model has been evaluated extensively by the US Environmental Protection Agency, is open-source, and fully documented. CALPUFF calculates the atmospheric transport, dispersion, chemical transformation and deposition of the pollutants, and the resulting incremental ground-level concentrations attributed to the studied emissions sources. Chemical transformations of SO_2 and NO_2 to $PM_{2.5}$ are calculated using the ISORROPIA chemistry module in CALPUFF.

Background concentrations of oxidants (ozone, ammonia, hydrogen peroxide) are taken from a global atmospheric chemistry model. Meteorological input data are generated from the Weather Research Forecasting (WRF) model (Skamarock et al., 2008), version 4.2.2. WRF was set up with 33 vertical levels and 3 nested grids. The mother nest has a grid resolution of 15 km, and spans approximately 1,600 km in both the north-south and east-west directions. The inner nests both have a grid resolution of 5 km, spanning around 300 km in both the north-south and east-west directions, and one is centred over the Lephalale (Limpopo) town and the other is centred over the town of Leandra (Mpumalanga), which is nearly 100 km east of Johannesburg. Mother and inner domains use a two-way nesting technique which ensures dynamical interaction between them. WRF simulations use initial and lateral boundary conditions from NCEP (National Centers for Environmental Prediction) CFRS (Climate Forecast System Reanalysis) dataset of NOAA (National Oceanic and Atmospheric Administration) producing three-dimensional, hourly meteorological data covering the full calendar year 2021.

The power plants were modeled as buoyant point sources, taking into account the stack height and thermal plume rise from the stacks. The stack characteristics were obtained from Eskom Atmospheric Impact Reports for the suspension of minimum emission standards at the power plants (DFFE 2019).

CALPUFF simulations were run separately for each of the 15 power stations. Annual pollutant concentrations were then projected using the POSTUTIL facility in CALPUFF, which allows emissions inputs to be scaled, results from different simulations to be summed up and the nitrogen chemistry to be re-run to account for the interaction between the different plumes. This approach allowed the air pollutant concentrations to be projected for different scenarios and calculation years at a manageable computational cost.

Health and Economic Impact Assessment

CREA has developed a detailed globally implementable health impact assessment framework based on latest science. This framework includes as complete a set of health outcomes as possible without obvious overlaps.

The emphasis is on outcomes for which incidence data are available at the national level from global datasets and outcomes that have a high relevance for health care costs and labour productivity. These health endpoints were selected and quantified in a way that enables economic valuation, adjusted by levels of economic output and income in different jurisdictions.

For each evaluated health outcome, we have selected a concentration-response relationship that has already been used to quantify the health burden of air pollution at the global level in peer-reviewed literature. This indicates the evidence is mature enough to be applied across geographies and exposure levels. The calculation of health impacts follows a standard epidemiological calculation:

$$\Delta cases = Pop \times \sum_{age} \left[Frac_{age} \times Incidence_{age} \times \frac{RR_{conc,age} - 1}{RR_{conc,age}} \right],$$

where *Pop* is the total population in the grid location, *age* is the analyzed age group (in the case of age-dependent concentration-response functions, a 5-year age segment; in other cases, the total age range to which the function is applicable), $Frac_{age}$ is the fraction of the population belonging to the analyzed age group, *Incidence* is the baseline incidence of the analyzed health condition, and *c* is the pollutant concentration, with c_{base} referring to the baseline concentration (current ambient concentration). $RR_{(c,\ age)}$ is the function giving the risk ratio of the analyzed health outcome at the given concentration for the given age group compared with clean air. In the case of a log-linear, non-age specific concentration-response function, the RR function becomes: $RR(c) = RR_0\ c{-}c_0\ \Delta c_0\ when\ c > c_0,\ 1\ otherwise$, where RR_0 is the risk ratio found in epidemiological research, Δc0 is the concentration change that RR_0 refers to, and c_0 is the assumed no-harm concentration (in general, the lowest concentration found in study data).

Data on total population and population age structure were taken from Global Burden of Disease results for 2019 (IHME 2020). The spatial distribution of population within the country, as projected for 2020, was based on the Gridded Population of the World v4 (CIESIN 2018).

Following the update of the WHO Air Quality Guidelines in 2021, which now recognize health harm from NO_2 at low concentrations, we use the mortality risk function for NO_2 based on the findings of Huangfu & Atkinson (2020), and include impacts down to 4.5 $\mu g/m^3$, the lowest concentration level in studies that found increased mortality risk (Table 6).

Adult deaths and disabilities were estimated using the Global Burden of Disease (IHME 2020) risk functions.

Deaths of small children (under 5 years old) from lower respiratory infections linked to $PM_{2.5}$ pollution were assessed using the Global Burden of Disease risk function for lower respiratory diseases (IHME 2020). For all mortality results, cause-specific data were taken from the Global Burden of Disease project results for 2019 (IHME 2020).

Health impact modelling projects the effects of pollutant exposure during the study year. Some health impacts are immediate, such as exacerbation of asthma symptoms and lost working days, whereas other chronic impacts may have a latency of several years. Concentration-response relationships for emergency room visits for asthma and work absences were based on studies that evaluated daily variations in pollutant concentrations and health outcomes; these relationships were applied to changes in annual average concentrations.

The annual average baseline concentrations of $PM_{2.5}$ and NO_2 were taken from van Donkelaar et al. (2016) and Larkin et al. (2017), respectively. Since the no-harm concentration for SO_2 is very low and the risk function is linear with respect to the background concentration, there was no need for data on SO_2 background concentrations.

The development of the health impacts into the future took into account projected changes in population, population age structure and mortality by age group, based on the UNPD (2019) World Population Prospects Medium Variant. This factors in the expected reduction in baseline infant mortality and increase in deaths from chronic diseases in older adults as a part of the population and epidemiological transitions and improvements in health care.

Table 6. *Input parameters and data used in estimating physical health impacts.*

Age group	Effect	Pollutant	Concentration-response function	Concentration change	No-risk threshold	Reference	Incidence data
1-18	New asthma cases	NO_2	1.26 (1.10 - 1.37)	10 ppb	2 ppb	Khreis et al. 2017	Achakulwisut et al. 2019
0-17	Asthma emergency room visits	$PM_{2.5}$	1.025 (1.013, 1.037)	10 µg/m^3	6 µg/m^3	Zheng et al. 2015	Anenberg et al. 2018
18-99	Asthma emergency room visits	$PM_{2.5}$	1.023 (1.015, 1.031)	10 µg/m^3	6 µg/m^3	Zheng et al. 2015	Anenberg et al. 2018
Newborn	Preterm birth	$PM_{2.5}$	1.15 (1.07, 1.16)	10 µg/m^3	8.8 µg/m^3	Sapkota et al. 2012	Chawanpaiboon et al. 2019
20-65	Work absence	$PM_{2.5}$	1.046 (1.039-1.053)	10 µg/m^3	N/A	WHO 2013	EEA 2014
0-4	Deaths from lower respiratory infections	$PM_{2.5}$	IHME 2020		5.8 µg/m^3	IHME 2020	IHME 2020
25-99	Deaths from non-communicable diseases and lower respiratory infections	$PM_{2.5}$	IHME 2020		2.4 µg/m^3	IHME 2020	IHME 2020
25-99	Disability caused by diabetes, stroke and chronic respiratory disease	$PM_{2.5}$	IHME 2020		2.4 µg/m^3	IHME 2020	IHME 2020
25-99	Premature deaths	NO_2	1.02 (1.01-1.04)	10 µg/m^3	4.5 µg/m^3	Huangfu & Atkinson 2020; NRT from Stieb et al. 2021	IHME 2020
25-99	Premature deaths	SO_2	1.02 (1.01–1.03)	5 ppb	0.02 ppb	Krewski et al 2009	IHME 2020

Numeric values in the column "Concentration-response function" refer to odds ratio corresponding to the increase in concentrations given in the column "concentration change." Literature references indicate the use of a non-linear concentration-response function. No-harm threshold refers to a concentration below which the health impact is not quantified, generally because the studies on which the function is based did not include people with lower exposure levels. Data on concentration-response relationships do not exist for all geographies, so a global risk model is applied to all cities. Incidence data are generally unavailable at the city level so national averages have to be applied.

Economic Valuation

Air pollution both increases the risk of developing respiratory and cardiovascular diseases, and increases complications and deaths from them, significantly lowering the quality of life and economic productivity of people affected and increasing healthcare costs. Economic losses as a result of air pollution were calculated using the methods outlined in Myllyvirta (2020). The valuation of deaths was updated to the values derived by Viscusi and Masterman (2017) which are based on labour market data, and pay particular attention to applicability in middle- and low-income countries. The valuation of different health outcomes used in the study is shown in Table 7.

The Global Burden of Disease project has quantified the degree of disability caused by each disease into a “disability weight” that can be used to compare the costs of different illnesses. The economic cost of disability and reduced quality of life caused by these diseases and disabilities are assessed based on disability weights, combined with the economic valuation of disability used by the UK environmental regulator DEFRA (Birchby et al., 2019), and adjusted by GNI PPP for South Africa (Table 7). The deaths of young children are valued at twice the valuation of adult deaths, following the recommendations in OECD (2012).

The valuation of future health impacts is based on the premise that the long-term social discount rate is equal to long-term GDP growth rate, and the economic loss associated with different health impacts is proportional to the GDP, resulting in a constant present value of health impacts over time.

Table 7. *Input parameters and data used to estimate economic costs of health impacts.*

Outcome	Valuation at world average GDP/GNI per capita, 2017 international dollars	Valuation in South Africa, current USD	Valuation in South Africa, current ZAR	Reference
work absence (sick leave days)	85	35	514	EEA 2014
number of children suffering from asthma due to pollution exposure (increased prevalence)	1,077	438	6,486	Brandt et al. 2012
deaths	2,637,000	1,069,000	15,810,000	Viscusi & Masterman 2017
deaths of children under 5	5,273,000	2,138,000	31,630,000	OECD 2012
asthma emergency room visits	232	95	1,399	Brandt et al. 2012
preterm births	107,700	43,850	648,500	Trasande et al. 2016
years lived with disability	28,480	11,550	170,800	Birchby et al. 2019

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