Review of a Report Providing Health Impact Assessment and Cost-Benefit Analysis (CBA) of Eskom activities

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14th February 2019

1 Key Findings of the Review

An independent review of the health impact assessment and CBA carried out for Eskom has been undertaken by Dr Michael Holland and Dr Joseph Spadaro. Both have worked extensively on the development of methods for health impact assessment and cost-benefit analysis in relation to air pollution since the early 1990s. Their conclusions are as follows. A full explanation of each conclusion is provided in the main text.

Emissions data: No conclusion can be drawn on the quality of estimates of pollutant emissions and abatement made for the four control scenarios because the necessary data are not presented in the report. There is potential bias towards underestimation of impacts as no account appears to have been taken of additional capacity that would be needed in the future to replace plants that are retired early and to meet additional demand.

Pollutant modelling: It is necessary to extend analysis over a substantial distance in order to capture a major part of the impacts of pollutants released from high stack sources like coal fired power plants. The Eskom study bases most of its analysis on short range modelling (up to 66 km). This is inadequate, especially for secondary pollutants, and will bias to significant underestimation of impacts.

Range of impacts considered: The focus of analysis on mortality only will inevitably lead to some underestimation of impacts on health. Overall, the monetised value of additional impacts seems likely to be in the order of 10% of mortality effects (though there is emerging evidence that the contribution could be greater, perhaps 20%). Relative to other issues identified here, the inclusion of morbidity effects may not affect the outcome of the CBA significantly, though there will be a bias towards underestimation of damage.

Selection of response functions: The process for selecting the response functions is flawed, and again biases the analysis towards underestimation of impacts. To avoid double counting it is appropriate to quantify against the pollutant that has the strongest association with the effect under examination. When this is done, the estimate of impact more than doubles. There are also some computational errors in the limited results identified in the report.

Mortality rates: Population and disease incidence will not be static over time, as implied by the Eskom analysis. It is anticipated that there will be increases in mortality in the future, reflecting, amongst other things, population growth. Failure to account for this will, again, lead to underestimation of impacts.

Linkage of pollutant concentration data to response functions: The approach taken for linking pollutant concentrations with response functions is claimed by the authors to be conservative, leading in their view to higher estimates of the number of deaths from various causes than might otherwise be calculated. It is concluded here, however, that this is not the case. The interval-based approach used in the Eskom report has the effect of removing some part of exposure from the calculations, and hence is inherently non-conservative leading to underestimation of impacts. The degree of underestimation is unknown but could be in the order of 50%. This is additional to other biases towards underestimation identified above.

Valuation: The discount rate used, 8.5%, is significantly higher than that used in socio-economic assessment in other regions and will bias to underestimation of economic damage, undermining the rights of future citizens. This is likely to be offset to some degree by the adoption of an estimate for the value of statistical life (VSL) that we consider too high (the only part of the Eskom analysis that provides any possible bias to overestimation).

Presentation of results and data: Key results and data are not presented. Ideally, the following would be provided:

- Change in emissions for each power plant over time
- Population weighted change in exposure for each scenario
- Attributable deaths by scenario
- Associated monetary values with and without discounting, over time.

Uncertainty analysis: The uncertainty analysis does not provide a structured and full account of the uncertainties present in the CBA. The ranges provided have no firm basis, without which they lack meaning.

Effects on overall results: Accounting for the biases towards underestimation of benefits identified in the Eskom report, we calculate that benefits would exceed costs by a significant margin, a factor of 5 or more, which is sufficient to reverse the conclusions drawn from the Eskom CBA. The difference is not a result of the use of alternative but equally valid methods the choice of which could be said to be a matter of expert opinion. The difference is instead a consequence of errors in the development of the methods used for the Eskom analysis.

It is recommended that the analysis be repeated with stakeholder involvement in the characterisation of the methods used for analysis.

2 Introduction

2.1 Background and objectives

The objectives of this review are to assess the methods used in a report undertaken to inform a cost-benefit analysis of additional pollution controls carried out for the South African power utility, Eskom, and to consider the reliability of the conclusions reached.

Large differences have been noted in quantified estimates of the health impacts associated with air pollution emissions from Eskom's fleet of coal fired power stations in South Africa: a critical question is thus whether these differences are associated with justifiable differences in opinion regarding available science or not.

2.2 Key documents reviewed

The main document reviewed is entitled:

The provision of professional, independent consulting services to assist Eskom in compiling applications for renewed postponement of the Minimum Emission Standards: Component 4: Health impact focused cost benefit analyses, Deliverable 2: Final Report (Version 7.4) 26 November 2018

The report is available at:
http://www.naledzi.co.za/assets/documents/20d9525bfb5bc884ea2d36fdba4c39a1.pdf.

Henceforth in this review, this is referred to as 'the Eskom report'.

Reference is also made to an earlier report for Greenpeace International by Lauri Myllyvirta (2014)[1], which quantified the mortality impacts of Eskom's fleet of coal fired power stations. Myllyvirta gave an estimate of 2,200 deaths per year. Myllyvirta's analysis quantified health impact using dispersion modelling for all of Eskom's coal fired power stations over a domain that extended to the whole of South Africa. The response functions used were consistent with the Global Burden of Disease study's assessment of the year 2010, which used the response functions published by Burnett et al in 2014.

2.3 The review team

The review has been led by Dr Mike Holland, who is based in the UK. Holland received a PhD in Environmental Science from the University of Edinburgh. He undertook post-doctoral research at Imperial College London, funded by the UK's Central Electricity Research Laboratories between 1985 and 1991. He has worked on health impact assessment of air pollution, hazardous chemicals and other burdens since 1991 when he started to work for the UK government's Energy Technology Support Unit, in a major European Commission funded research project called ExternE (Externalities of Energy)[2]. Holland has since refined and applied the methods developed in ExternE in assessment for national and international bodies. These include several national governments, the European Commission and its Agencies, OECD and the World Health Organization.

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[1] https://cer.org.za/wp-content/uploads/2014/02/Annexure-5_Health-impacts-of-Eskom-applications-2014-_final.pdf

[2] Refer to the references section for a list of the most relevant ExternE outputs.

Holland has been assisted by Dr Joseph Spadaro. Spadaro is an Environmental Research Scientist, with a PhD from the École Nationale Supérieure des Mines de Paris, France. He has worked in the United States (Princeton Univ, NJ, Argonne National Labs, Chicago, IL) and in Europe (École des Mines de Paris, International Atomic Energy Agency (IAEA), Austria, and Basque Center for Climate Change, Spain) and he was a principal investigator on the ExternE Project series of the European Commission (EC). Throughout his career, he has been an Expert Consultant on various projects funded by international organizations. These include the World Bank, the Joint Research Centre of the European Commission, the World Health Organization, Climate and Development Knowledge Network, and the OECD.

More complete biographies for the reviewers are available at the end of this document.

2.4 The review process

The review process was funded by Greenpeace. Whilst Greenpeace staff were informed of progress on the report they did not seek to influence the conclusions drawn. Queries for clarification have been addressed in this final version of the review.

Initial reviews of the Eskom report identified the following issues for further consideration:

- Derivation of emissions data
- Approach taken to pollutant modelling
- Range of health impacts considered
- The selection of response functions
- Linkage of pollutant concentration data to response functions
- Valuation
- Presentation of results and data
- Uncertainty assessment

Each is considered below, and conclusions are identified for each point.

The reviewers considered the Eskom report independently. Comments were then combined into this review. There is full agreement between the reviewers on the conclusions reached.

3 Key issue assessment

3.1 Emissions data

Emissions data are not presented in the Eskom health report. Data on total emissions are provided in other material at http://www.naledzi.co.za/public-documents-naledzi.php. No estimates of the change in emissions in the four abatement scenarios considered in the Eskom report have been identified. Without direct access to these data it is not possible to comment whether the assumptions made on abatement are reasonable.

It is noted that data on emissions from Eskom for 2017 are broadly consistent with the data used by Myllyvirta (2014).

The Eskom report considers four scenarios for pollutant reduction:

1. Full compliance with new plant standards (FC) (Scenario 1, S1)
2. Eskom Emission Reduction Plan (ERP) (Scenario 2, S2)
3. ERP + FGD at Kendal and Matimba (Scenario 3, S3)
4. ERP + Early decommissioning (ED) of Komati, Hendrina and Grootvlei (Scenario 4, S4)

Emission reductions for each scenario are not specified in the materials examined from Eskom.

On page 6 of the report, it is stated that "*The scenario with the highest health benefits was ERP+ED (S4), highlighting the immediate results achievable if early decommissioning of power plants can be achieved*." This statement is both obvious and correct. However, it overlooks the question of how the electricity supply is maintained: what is brought in to replace retired capacity?

On page 19, the report states that: "*For the health benefits analysis, it was assumed that all power plants will emit "Current" emissions until abatement technologies are installed, from which time they will emit "Compliance" emissions*."

This begs the question of how demand for energy will change in South Africa in the future. Population and economic growth will increase demand for energy services. The question is then how Eskom believes that this additional demand should be met, whether by building more coal fired plants, through energy efficiency, the development of renewable power or nuclear. If added demand is to be met using coal (which seems the default assumption), associated emissions should be factored into the analysis. Accordingly, Figures 7 through 14 in the Eskom report would need to be revised.

Conclusion: No conclusion can be drawn on the quality of estimates of pollutant emissions and abatement made for the four control scenarios because the necessary data are not presented in the report. There is some possible bias towards underestimation of impacts as no account has been taken of additional capacity that would be needed in the future to replace plant that are retired early, and to meet additional demand.

3.2 Pollutant modelling

The modelling undertaken for the Eskom analysis considers a restricted zone around each power station of 66 by 66 km^2, and a larger zone of 360 km by 270 km to describe the overall contribution of the 13 power stations to pollution in the modelled domain without further controls being introduced. The Eskom report acknowledges that impacts will be experienced outside of the modelled domain, though makes no attempt to quantify the extent to which effects could be underestimated. It has been recognised since the early 1990s that it is necessary to extend the range of analysis substantially to capture a substantial part of the damage associated with emissions from facilities like power stations (ExternE, 1995).

Figure 1 below, from Rabl et al (2014), illustrates this point. Extending to a distance of 300 km for the case shown (a tall stack located in central Europe), brings in only 50% of total impact for primary pollutants and about 35% of total impact for secondary pollutants. The critical distance from source to capture at least 95% of the total impact is in the order of 1000 km.

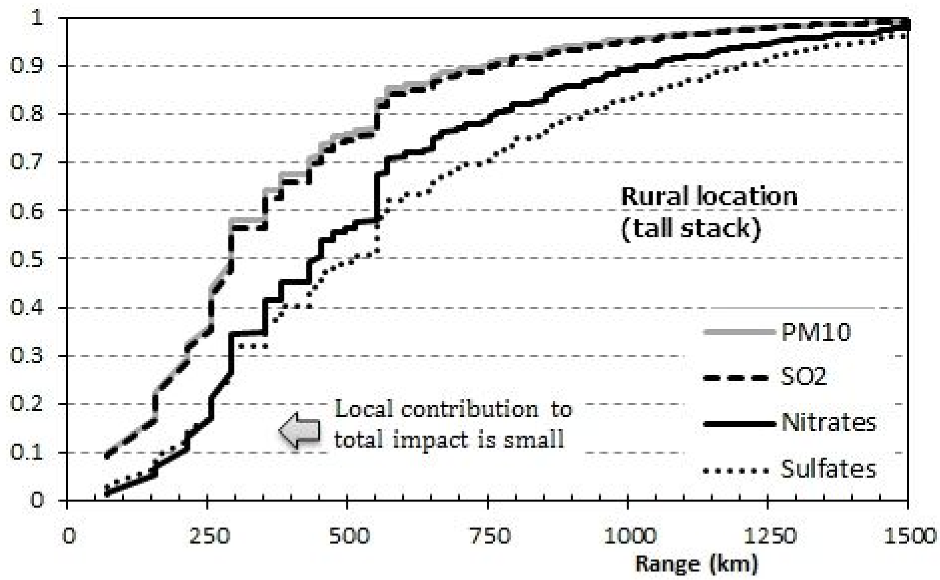

Figure 1. Cumulative impact distribution (fraction of total impact) for primary and secondary pollutants versus radius of analysis area, for a tall stack located in Europe. From Rabl et al (2014).

Whilst Figure 1 is not based on analysis centred on the South African coalfields, it serves to illustrate that restrictions on the analysis can lead to a substantial underestimation of impact. An obvious question is the extent to which the modelling undertaken for Eskom accounts for impacts in the major centres of population including Johannesburg and Pretoria. Are effects on these cities included for all power stations or only for some?

It appears that impacts on neighbouring countries are excluded because of the limits on the modelled domain. This is a further bias against the operation of the Polluter Pays Principle that underpins much global legislation on pollution, from climate change to transboundary shipments of waste. Impacts should be accounted for wherever they occur.

The spatial resolution of the model (municipality and municipal wards) is appropriate. Some would argue in favour of much higher resolution modelling, at the extreme accounting for individual exposures. However, the response functions of most use are based on modelling at the population level and should thus be applied to concentrations assessed at a similar scale.

The Eskom report describes the process for assessing the effect of changes in emissions from each power station on the overall contribution of power stations as follows:

> *The individual dispersion results are less useful for calculating health effects because of their smaller modelling domains (covering smaller populations), however individual models are useful for assessing the impacts of changes in scenarios, as pollution from individual plants can be evaluated. As such, integrated Health CBA Model used the individual models to estimate relative changes between scenarios and years, applied to the health costs derived from the cumulative models.*

It is also unclear precisely how the localised maps have been applied. Following from the preceding discussion, it is not appropriate to base the assessment of secondary particles on short range modelling given that the formation of ammonium nitrate and ammonium sulphate in the atmosphere occurs over time and distance. A better approach would have been to ignore the individual plant modelling altogether, and to run the large domain model separately for each scenario, and ideally over a greater distance, for example out to 600 km or more (a precise distance could be calculated considering the spread of population in the region, relative to the location of the power plants). It is unclear why this was not done, especially when Myllyvirta's work for Greenpeace demonstrated that such analysis is possible.

Conclusion: It is necessary to extend the geographical range of the analysis over a substantial distance around the power stations in order to capture a major part of the impacts of pollutants released from high stack sources like coal fired power plants. The Eskom study bases most of its analysis on short range modelling (up to 66 km). This is inadequate, especially for secondary pollutants arising from SO_2 and NOx emissions, and will bias to underestimation of impacts.

3.3 Range of impacts considered

The Eskom analysis is confined to assessment of mortality in adults, linked to disease of the cardiovascular, cerebrovascular and respiratory systems and diabetes mellitus.

A variety of other impacts have been identified as a result of exposure to ambient air pollution including mortality in childhood, and illness through the life-course. Effects extend to the loss of working days and underperformance at work, leading to direct impacts on business, and time spent at school. A review is provided by the UK's Royal Colleges of Physicians and of Paediatrics and Child Health (RCP/RCPCH 2016).

Past analyses have suggested that additional effects on morbidity add around 10% to the total quantified economic impact of air pollution on health (OECD, 2014), indicating some level of underestimation of total impact in the estimates made in the Eskom report. It is likely that the share of total impact attributable to effects other than mortality will grow over time given the expanding list of effects that have been associated with exposure to one or more combustion-related air pollutants in recent years, perhaps rising to about 20% of the monetised total.

Analysis in Europe has additionally considered impacts of pollutants on ecosystems and buildings. Neither provide substantial additions to the health impact assessment in Europe at the present time. However, it is noted here that SO_2 is a particularly aggressive pollutant for materials such as steel, galvanised steel and stone, and was a cause of much concern in Europe in the 1980s.

Conclusion: The focus of analysis on mortality only will inevitably lead to some underestimation of impacts to health. Overall, additional health costs seem likely to be in the order of 10 - 20% of mortality effects, so their inclusion may not affect the outcome of the CBA significantly, though there will be a bias towards underestimation of damage.

3.4 Selection of response functions

The Eskom report starts selection of response functions from a list developed by Caradee and Oosterhuis (2018) for the South African Medical Research Council. The list is shown in table 3 of the Eskom report, reproduced below. Other sets of response functions have been published, but it seems pragmatic, at least, to accept the views of the South African Medical Research Council.

Table 1. Reproduction of Table 3 from the Eskom report.

Table 3 Indicator pollutants, baseline incidence, relative risks, and costs of each health outcome (Source: SAMRC)

Indicator Pollutant	Health Outcome	Baseline data	Relative Risk or Hazard Ratio per 10μg/m^3	Reference
$PM_{2.5}$	Diabetes Mellitus Mortality	5.5% of total deaths	Hazard ratio 1.13	Pope III et al., 2015
	Cerebrovascular Mortality	5.10% of total deaths	Hazard ratio 1.11	Pope III et al., 2015
	Respiratory Mortality	9.40% of total deaths	RR 1.10	WHO, 2014
	Ischaemic Heart Disease Mortality	2.80% of total deaths	RR 1.05	Burnett et al., 2014
	Cardiovascular Mortality	18.5% of total deaths	Hazard ratio 1.12	Pope III et al., 2015
SO_2	Cardiovascular mortality	18.5% of total deaths In 2012	RR: 1.0103	Maji et al., 2017
	Respiratory Mortality	9.40% of total deaths	RR:1.0106	Maji et al., 2017
NO_2	Respiratory Mortality	9.40% of total deaths	Hazard Ratio 1.02	Fischer et al., 2015
	Cardiovascular mortality	18.5% of total deaths In 2012	RR: 1.0206	Maji et al., 2017

The presentation of response relationships in this way is flawed as it does not fully characterise the functions. The Burnett et al. (2014) relationship is curvilinear with exposure, whereas the remaining $PM_{2.5}$ functions are linear (without threshold). The derivation of functions is also different, with the integrated function of Burnett derived by combining effects from different combustion sources, not only outdoor air pollution, and adopting a non-zero threshold.

The list of nine functions shown in the table above is reduced to four, with the authors citing concerns over the potential for double counting of impacts. These four functions relate to:

- SO_2 and respiratory mortality
- NO_2 and cardiovascular mortality
- $PM_{2.5}$ and cerebrovascular mortality
- $PM_{2.5}$ and diabetes mellitus mortality

The process for selecting the subset of response functions from the longer list shown in the table is described on page 30 of the report as follows:

> *In the AP-HRA, each health outcome must be attributed to an individual indicator pollutant. While health outcomes can be attributed to many different indicator pollutants, using all would result in double accounting of health impacts as these pollutants are associated with each other. For instance, there are three ERFs for respiratory mortality health outcome, respectively for $PM_{2.5}$ (WHO, 2014), for SO_2 (based on a study from India (Maji et al., 2017)), and for NO_2 (based on a study from Holland (Fischer et al., 2015)). These three ERFs give widely varying results. For the purpose of this study, the Indian example, which gave mid-range incidence was selected. Ischaemic heart disease mortality was excluded from the analysis as it is a component of cardiovascular mortality. Variation in health outcome incidences between the various ERFs provided in some cases exceed 80%. This variation was dealt with through performing sensitivity analysis in the CBA (refer to section 2.4).*

It is correct to consider the potential for double counting. However, the approach taken, selecting the pollutant/function combination that generates the middle estimate across the three indicator pollutants, is flawed. Taking an averaged estimate would be appropriate for defining a function for a single impact of a single indicator pollutant. However, the question addressed here is different, concerning which function will give the best estimate of overall impact.

For this question, it is instead logical to accept the pollutant/function combination that generates the highest result for each type of impact. This links the quantification to the pollutant that has the strongest association with the effect under examination. It is quite possible that this position underestimates total damage, as it assumes that there is no separate or additive effect of the other two pollutants.

There is an alternative approach used for quantification in North America (USEPA, 2011) and Europe (WHO, 2013) in favour of quantifying against all-cause mortality (excluding violent or accidental deaths). It is felt that applying an inevitably limited set of cause-specific functions (cause being cardiovascular, respiratory, etc.) leads to underestimation of the overall mortality burden. Comparing the results of previous European and US applications of all-cause- and cause specific mortality functions indicates that the latter, as used by both Myllyvirta and Eskom, leads to some underestimation of impact, by about 33%. More recent analysis by the Global Burden of Disease team (Burnett et al, 2018) indicates that the underestimation could extend to 55%, and hence the underestimation associated with the adoption of cause-specific functions looks likely to be about a factor of two. This is in addition to other biases to underestimation in the selection of response functions identified here.

From consideration of the data shown in Table 3 of the report (reproduced above) it seems likely that the functions that would generate the highest estimates are those expressed against $PM_{2.5}$.

How much difference this may make to the results can be considered by reference to results provided in the Eskom report in Figure 21 (reproduced below). This supplementary analysis proceeds as follows:

- The Eskom report estimates 200 deaths linked to diabetes mellitus annually as a result of operation of the 13 power stations using a function derived against $PM_{2.5}$ exposure, out of a total 534 deaths (334 from respiratory, cardiovascular and cerebrovascular impacts, 200 from diabetes).
- Scaling the result for $PM_{2.5}$ and diabetes by the response functions and incidence data for $PM_{2.5}$ and respiratory, cardiovascular and cerebrovascular mortality, but removing the Eskom results calculated against SO_2 and NO_2 exposure, more than doubles the total estimate of 534 deaths per year to 1,250 (noting that this figure is further increased below in discussion of the linkage of pollutant concentrations to response functions).
- If it is accepted that there are additional direct impacts of SO_2 and NOx (noting that 'indirect' effects via formation of secondary aerosols have been included), the estimate of 1,250 deaths per year is to be regarded as a lower bound of the likely impact. Indeed, for reasons given in other sections of this review, we consider that the likely result is significantly greater than 1,250 deaths per year.

The application of the response functions in the Eskom report does not follow established practice. Burdens at current exposures should be evaluated using the attributable fraction (AF = 1 - 1/[relative risk, RR]), not based on an incremental change in the RR. Although the error shouldn't be big, the approach is methodologically incorrect.

Consider the passage from Page 30 of the Eskom report:

> *Figure 21[3] can also be used to demonstrate an example of how an ERF is applied. In 2018, 4.17 million people were exposed to an additional 2 μg/m^3 from the 13 power stations modelled. Cerebrovascular mortality has a baseline incidence rate of 0.0413%, meaning that we would expect 2,792 mortalities out of the 4.17 million people in that year. However, the incidence of cerebrovascular mortality increases by 11% (from baseline incidence) for every 10 μg/m^3 increase in $PM_{2.5}$ exposure, so a 2 μg/m^3 increase results in a new incidence rate of 0.0422% (0.0413%×1.11^$^{(2/10)}$). This extra 0.00087% incidence or 36.4 cases of cerebrovascular mortality is then attributable to $PM_{2.5}$ from the 13 power plants modelled. Similarly, this method was applied to all pollutants and exposed population ranges and the increased exposure is estimated to result in an additional 334 cases of premature respiratory, cardiovascular and cerebrovascular mortality attributed to air pollution from the 13 power stations in 2018.*"

[3] Figure 21 from the Eskom report is reproduced below, and discussed further in Section 3.6.

We note that some elements of the calculations presented are wrong: 4.17 million multiplied by 0.0413% = 1,722 deaths, not 2,792 as stated.

The use of the 80% variation seen in outcomes from using response functions for different pollutants is not a sound basis for sensitivity analysis. It simply indicates that some pollutants are more strongly associated with health than others. It does not provide a basis for defining ranges of possible impacts.

Conclusion: The process for selecting the response functions is flawed, and again biases the analysis to underestimation of impacts. To avoid double counting it is appropriate to quantify against the pollutant that has the strongest association with the effect under examination. When this is done, the estimate of impact more than doubles. There are some computational errors in the limited results identified in the report.

3.5 Mortality rates

Future mortality rates should be adjusted for changes in air pollution, population and changes in disease incidence rates, which are not constant. The following figure, based on our own research, shows future incidence rates of non-communicable deaths (separated for countries in different income bands) increasing over time.

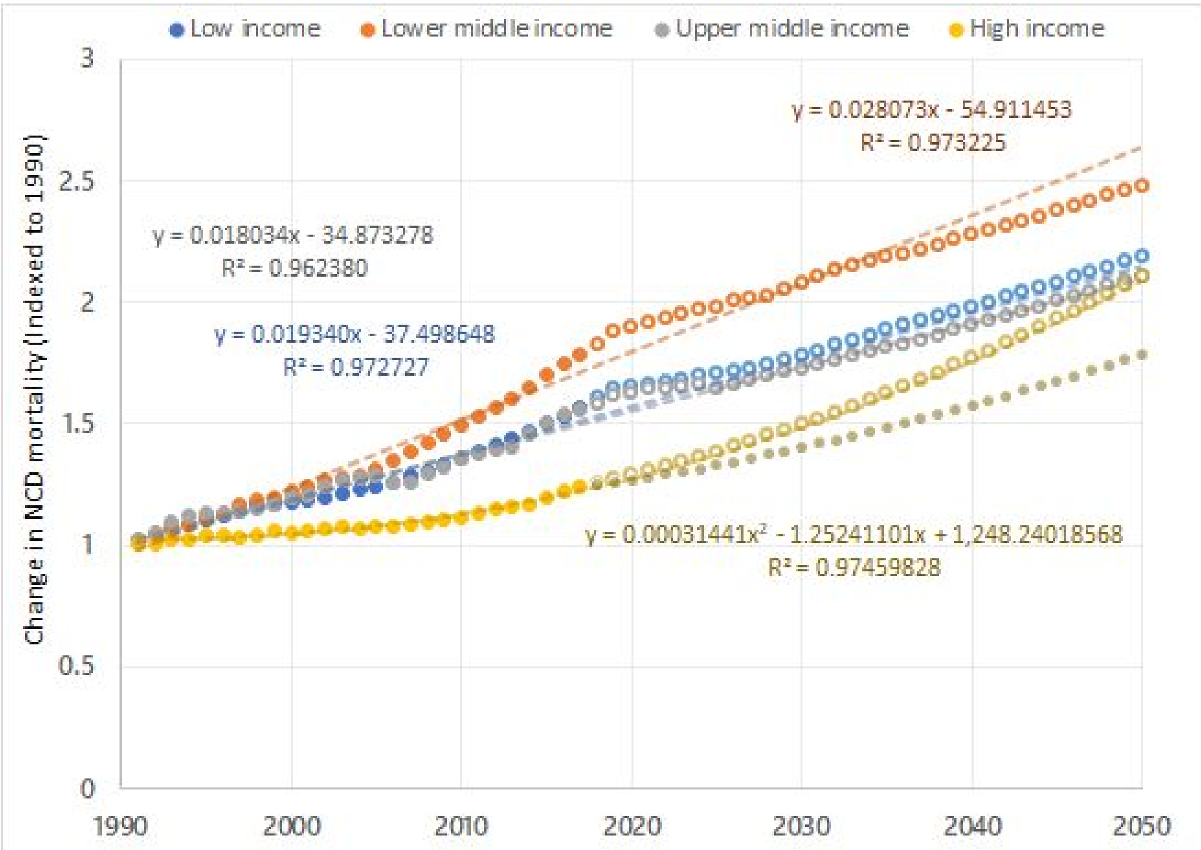

Figure 2. Change in incidence for mortality from non-communicable disease (NCD) by country income, 1990 to 2050. Solid symbols represent historic data, open symbols and dashed lines represent projections, with sensitivity to the approach taken to projection accounted for.

Conclusion: Population and disease incidence will not be static over time, as implied by the Eskom analysis. It is anticipated that there will be increases in mortality over time, reflecting amongst other things, population growth. Failure to account for this will lead to underestimation of impacts.

3.6 Linkage of pollutant concentration data to response functions

Page 30 of the Eskom report provides the following details on the methods for linking pollutant concentrations to the response functions:

> *It is important to understand at what level interval the ERFs would result in significant differences in health outcome incidences. It is also to be noted that the ERFs proposed by the SAMRC were all specified for relatively coarse intervals in ambient concentrations of 10 μg/m^3. These are relative coarse bands and have to be applied to the changes in annual average ambient concentration estimated by the dispersion modelling, which are in the order of 1-3 μg/m^3. Figure 21* [reproduced below] *provides a sensitivity analysis that demonstrates how the choice of finer pollution concentration interval affects the health incidence estimates. At 10 μg/m^3 intervals, at which the ERFs are specified, no health effects are visible. This is because the changes in ambient concentrations modelled are smaller than 10 μg/m^3. At a finer interval of 0.75 μg/m^3, much larger health effects are visible. This study adopted a conservative approach favouring higher health costs per incidence by assuming ERFs are significant at 0.2 μg/m^3 intervals*

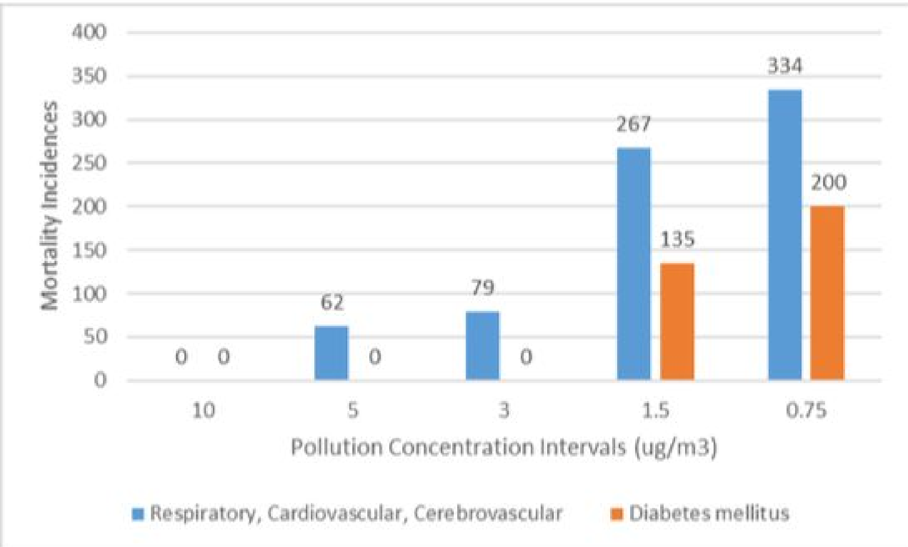

Figure 21 Sensitivity analysis of the effect of pollution concentration intervals on predicted mortality incidence.

The method shows a fundamental misunderstanding of the derivation and application of the response functions derived from epidemiological data. The specification of functions requires information on three parameters:

1. The change in risk
2. The change in pollutant concentration to which [1] applies
3. Any threshold. For particles especially, there is widespread agreement that there is no threshold for effect at the level of the general population (WHO, 2013)

There is an informal convention of citing response functions per 10 $\mu g.m^{-3}$ for the pollutants of interest here. Alternatives used in the literature include per 1 $\mu g.m^{-3}$ or interquartile ranges. There is no significance to the figure selected: it is simply part of the definition of a **continuous response function**.

The effect of using an interval is simply to remove some part of the exposure from analysis. By doing so, the estimate of damage will be artificially reduced. We are unaware of anyone else carrying out the exposure assessment in this way.

The sensitivity analysis shown in Figure 21 of the Eskom report demonstrates the errors arising from treating response functions as non-continuous, referring to a series of discrete intervals. Taking a 10 $\mu g.m^{-3}$ step in concentration, no effect of power station emissions is observed: in other words, the modelling does not show power stations generating more than 10 $\mu g.m^{-3}$ across the modelled domain and so there is no exposure above 10 $\mu g.m^{-3}$ to model for effect. Effects start to emerge when the interval is reduced to 5 $\mu g.m^{-3}$ and continue to increase as the increment in concentration is reduced. The smaller the interval, the bigger the estimate of damage. This variation is simply an artefact of the modelling approach. Response functions should be applied directly to modelled concentrations for each municipality: there is no need to define "*at what interval the ERFs would result in significant differences in health outcome incidences*".

The Eskom report uses an interval of 0.2 $\mu g.m^{-3}$, lower than the 0.75 $\mu g.m^{-3}$ interval that is the smallest shown in Figure 21. It follows then, that the estimated mortality that is fed through to the CBA is higher than shown in the figure, but the report provides no data. Halving the interval from 1.5 $\mu g.m^{-3}$ to 0.75 $\mu g.m^{-3}$ increases the impact of exposure to $PM_{2.5}$ by 48% (refer to the figures shown for diabetes, where impact increases from 135 deaths to 200 deaths). Without re-running the analysis, it is not possible to say by how much estimates should be increased with any certainty. Assuming that figures with no interval (i.e. moving from an interval of 0.75 $\mu g.m^{-3}$ to 0 $\mu g.m^{-3}$) should increase by a similar amount (48%) to that arising when moving from an interval of 1.5 $\mu g.m^{-3}$ to 0.75 $\mu g.m^{-3}$ would increase the estimate of the total number of deaths calculated in the previous section as attributable annually to the 13 power stations from 1,250 to 1,850. These combined changes, taking estimates from an original 534 cases per year to 1,850, lead to significant convergence with the estimate of 2,200 deaths calculated previously by Myllyvirta (2014).

Conclusion: The approach taken for linking pollutant concentrations with response functions is claimed by the authors to be conservative, leading to higher estimates of the number of deaths from various causes than might otherwise be calculated. It is concluded here, however, that this is not the case. The interval-based approach used in the Eskom report, however, has the effect of removing some part of exposure from the calculations, and hence is inherently non-conservative leading to underestimation of impacts. The degree of underestimation is unknown but could be up to 50%. This is additional to other biases to underestimation identified above.

3.7 Valuation

The discount rates used are very much higher than those adopted for socio-economic assessment for example in Europe, generally in the order of 4%. Further to this, no account is taken of future increases in earnings on willingness to pay: in Europe, the effective discount rate falls to around 2% once this is taken into account.

The effect of different discount rates on future valuations is shown in the following figure. The use of a rate of 8.5% reduces damages dramatically over time. After 20 years, present value of the damage is reduced to only 20% of the value without discounting. At the social discount rates typical of Europe, the figure declines more slowly, after 20 years corresponding to between 50% and 70% of the undiscounted estimated, significantly higher than the figures based on the 8.5% rate.

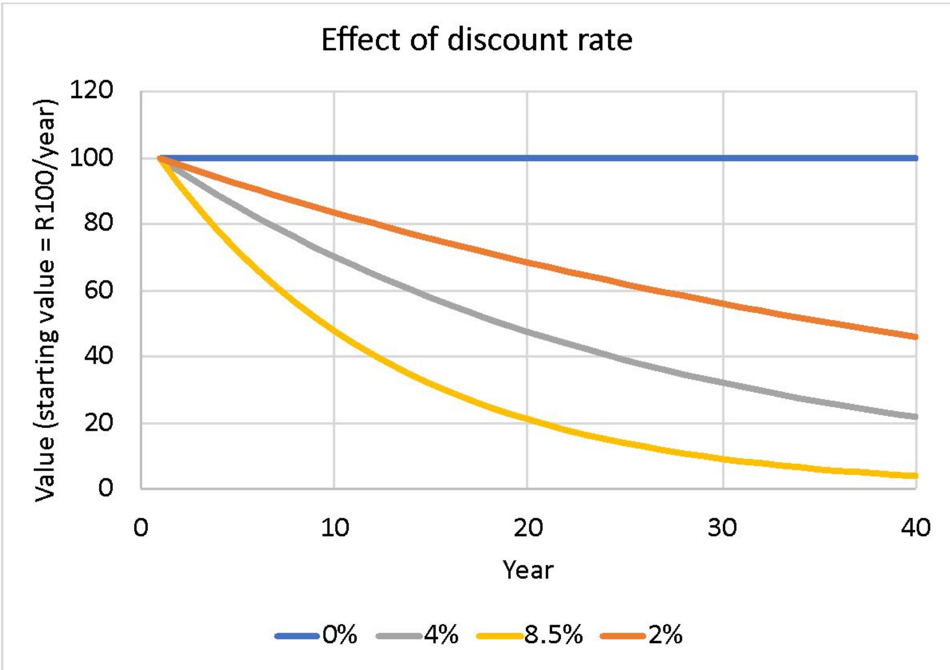

Figure 3. Effect of different discount rates on the value of damage in future years

This issue creates a significant distortion to the CBA because it affects costs and benefits to differing degrees. Much of the cost is borne upfront, for example during the installation of equipment. Benefits only start to accrue once installations are complete, but then continue for the lifetime of the installation. This delay in bringing in the benefits means that they will be discounted to a greater extent than costs.

Further information on the process for benefits transfer to convert the US value of statistical life adopted by the Eskom authors to a South African value would be useful. We would recommend that the OECD (2012) recommendations on mortality valuation were adopted: these would give a lower valuation per death than that adopted in the Eskom report. This is the only area of the analysis where we consider it likely that Eskom's assumptions may bias to exaggeration of benefit. The combination of a reduced discount rate and lower valuation would cancel each other to some extent.

Conclusion: The discount rate used, 8.5%, is significantly higher than that used in most socio-economic assessment and will bias to underestimation of economic damage, undermining the rights of future generations. This is likely to be offset to some degree by

the adoption of an estimate for the value of statistical life (VSL) that we consider too high (the only part of the Eskom analysis that provides any bias to overestimation)."

3.8 Presentation of results and data

The report does not provide detailed results and information on the scenarios assessed below the level of the final cost-benefit analysis. The following information, in particular, are lacking:

- Baseline emission levels
- Changes in emissions relative to baseline under each scenario
- Mortality impacts

For mortality, the only estimates provided are those shown in Figure 21 of the report (reproduced above). Even this does not show actual outputs from the Eskom CBA, but the results of a sensitivity analysis of the method used..

Conclusions: The lack of data availability makes it extremely hard to be able to draw conclusions on the validity of the Eskom analysis. Ideally, the following would be provided:

- **Change in emissions for each power plant over time**
- **Population weighted change in exposure for each scenario**
- **Attributable deaths by scenario**
- **Associated monetary values with and without discounting, over time.**

3.9 Uncertainty analysis

Uncertainty analysis appears to have been based on observed variation in the response functions recommended by the South African MRC, for cases where functions are provided separately for different pollutants for the same effect. This is not a valid basis for assessing uncertainty: the variation between these functions should primarily show variation in the strength of association of each endpoint with each pollutant.

It is stated that "The uncertainty inherent in the analysis remain constant across all scenarios." This may be true for the health analysis but it is not for the assessment of costs: scenarios that include early retirement of power stations will contain uncertainties that are not present when assessing the costs of retrofitting existing plant.

Conclusion: The uncertainty analysis does not provide a structured and full account of the uncertainties present in the CBA. The ranges provided have no firm basis and are hence not be relied upon.

3.10 Effects on overall results

Table 6 of the Eskom report is reproduced below. It is the only part of the report to provide results from the final analysis. The results given indicate that for the best estimates, the cost:benefit ratio ranges from 4.5 to 1.3 depending on scenario. A figure greater than 1 indicates that costs will exceed benefits, and suggests from an economic perspective that action should not be undertaken (acknowledging that additional factors may be brought into consideration that could change this conclusion where the C:B ratio does not deviate strongly from 1).

In this review we have identified a number of factors that bias strongly to underestimation in the results, especially:

- Restriction of the geographic range of assessment (a factor of at least 2)
- Artificial reduction of exposure by not treating response functions as continuous (50%)
- Selection of very conservative response functions from a flawed approach intended to avoid double counting (a factor 2 and possibly higher)
- Lack of account of non-mortality effects (around 10% in addition to all of the above).

Combining these factors generates an estimate of the likely degree of underestimation of benefits of action of at least a factor 5.

For valuation we have identified factors that bias both to over- and under-estimation, and consider these likely to cancel one another out.

Table 6 Costs and benefits NPV estimates (lower and upper ranges) for each scenario, and cost:benefit ratios

	FC (S1)		ERP (S2)		ERP+FGD (S3)		ERP+ED (S4)	
Million Rands	*lower*	*upper*	*lower*	*upper*	*lower*	*upper*	*lower*	*upper*
NPV of Costs	-43 369	-65 053	-16 923	-25 385	-21 205	-31 808	-16 923	-25 385
NPV of Benefits	2 403	21 625	1 962	17 661	2 252	20 264	3 374	30 367
NPV of Benefits minus Costs	-40 966	-43 428	-14 961	-7 724	-18 954	-11 544	-13 549	4 982
Cost: Benefit Ratio (*range*)	18.0	3.0	8.6	1.4	9.4	1.6	5.0	0.8
Cost: Benefit Ratio (*central*)	4.5		2.2		2.4		1.3	
Central estimate	**Cost=$54,210 Benefit = $12,010**		**Cost=$21,150 Benefit = $9,810**		**Cost=$26,510 Benefit = $11,260**		**Cost=$21,150 Benefit = $16,870**	

Table 2. Final results for the CBA provided by the Eskom report (figures for the central estimate in the yellow box have been added by the reviewers, based on the ranges given in the Eskom report).

The effect of a factor 5 would be sufficient to change the net cost for all scenarios under the central estimates to a net benefit (shown by the cost:benefit ratio falling below 1).

Table 3. Recalculation of the cost-benefit ratios from the Eskom report

	FC (S1)	ERP (S2)	ERP+FGD (S3)	ERP+ED (S4)
NPV cost	54,210	21,150	26,510	21,150
NPV benefits	60,050	49,050	56,300	84,350
Cost:benefit ratio	0.90	0.43	0.47	0.25

Conclusion: Accounting for the biases to underestimation of benefits identified in the Eskom report, we calculate that benefits would exceed costs by a significant margin. It is recommended that the analysis be repeated with stakeholder involvement in the characterisation of the methods used for analysis.

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5

6 Biographies of the review team

6.1 Dr Michael Holland

Dr Michael Holland (EMRC, Ecometrics Research and Consulting) provides consultancy on the development and implementation of environmental regulations, with expertise in health and environmental impact assessment, economic assessment and characterisation of uncertainty. He has worked in the areas of chemicals, air quality, climate change and waste management for over 25 years, starting with work as the technical coordinator of the ExternE (Externalities of Energy) study for the European Commission in 1991. He was core to the development of the impact pathway approach approach in the European Commission funded ExternE (Externalities of Energy) study, that underpins much current policy-related research on chemicals, air pollution, waste management and transport. Having worked for AEA Technology since 1991, Mike founded EMRC in 2002. EMRC's clients include the European Commission and its agencies, WHO, OECD, World Bank, national governments, local government, NGOs and private companies.

Holland has undertaken cost-benefit analysis of numerous policies including:

- European Union:
    - National Emission Ceilings Directive
    - Ambient Air Quality Directives
    - Thematic Strategy on Clean Air and its subsequent review
    - Sectoral analysis relating to the Industrial Emissions Directive
- UK government:
    - Clean Air Strategy and subsequent reviews

Holland has experience of applying research on the quantification of pollution effects in the UK, European Union, Romania (pre-accession to the EU), the USA and China. He has been an observer to the Socio-Economic Assessment Committee (SEAC) under REACH for the European Association of Environmental and Resource Economists since 2009. He was appointed to the UK's Chemicals Stakeholder Forum in 2011 as an independent expert in SEA and is a member of the Committee on the Medical Effects of Air Pollutants, reporting to the UK's Department for Health.

Holland has written or co-authored over 350 publications including books, papers, reports, articles and software tools, including the following:

- Burney, P.G.J., Ayres, J., Holland, M., Hurley, J.F., Lam, H., Strachan, D., Walton, H., Mills, I. and Gowers, A. (2016) Long-term Exposure to Air Pollution and Chronic Bronchitis, A report by the Committee on the Medical Effects of Air Pollutants. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/514203/COMEAP_long_term_exposure_to_air_pollution_and_chronic_bronchitis_report_2016.pdf
- Rabl, A., Spadaro, J. and Holland, M. (2014) How Much Is Clean Air Worth? Cambridge University Press.
- OECD (2016) The economic consequences of outdoor air pollution. http://www.oecd.org/environment/indicators-modelling-outlooks/the-economic-consequences-of-outdoor-air-pollution-9789264257474-en.htm (lead author for health impact assessment and valuation)
- Amann, M., Holland, M., Maas, R., Saveyn, B. and Vandyck, T. (2017) Costs, benefits and economic impacts of the EU Clean Air Strategy and their implications on innovation and competitiveness. For European Commission DG Environment.

6.2 Dr Joseph Spadaro

Joseph Spadaro is an Environmental Research Scientist, with a PhD from the École Nationale Supérieure des Mines de Paris, France (1999). Over the past three decades, he has worked in the United States (Princeton Univ, NJ, Argonne National Labs, Chicago, IL) and in Europe (École des Mines de Paris, International Atomic Energy Agency (IAEA), Austria, and Basque Center for Climate Change, Spain). Joseph was a principal investigator on the ExternE Project series of the European Commission (EC). Throughout his career, he has been an Expert Consultant on various projects funded by international organizations (World Bank, Joint Research Centre JRC of the EC, Climate and Development Knowledge Network, OECD, others).

Over the years, Spadaro has carried out basic and applied research on air/water/soil pollutant transport modelling, health risk assessment and uncertainty analysis, cost-benefit analysis, co-benefits of climate change mitigation interventions at the urban scale, and has developed integrated impact assessment models/software for research use and policy analysis. He has developed RiskPoll, a suite of integrated multimedia risk assessment methodologies for quantifying and valuing impacts on public health from routine exposure to classical pollutants, toxic metals, and organic species. At the IAEA, he was lead developer of Simpacts, a variant of the RiskPoll software, which is disseminated by the Agency to its Member States. In addition to his ongoing work on health hazards of air pollution, his research interests encompass the nexus between prioritization of long-term techno-economic options in support of urban climate mitigation/adaptation and clean air policies, health welfare, heat vulnerability, and reducing the food global carbon footprint.

Spadaro worked on the CIRCLE project (Costs of Inaction and Resource scarcity: Consequences for Long-term Economic growth) of the Environment Directorate at OECD to develop air pollution health impact indicators extending out to 2060. He has been contributing to the assessment of environmental and health implications of the European Commission's Action Plan on Circular economy, and is working on methodological enhancements to the AirQ+ model (health impacts of air quality) of the World Health Organization, European Centre for Environment & Health (WHO–ECEH), specifically working on epidemiological associations of ambient air pollution, a joint effort with the Global Burden of Disease community, lifetable and disability adjusted life year calculations (WHO software DALY Calculator). For WHO and EC−Joint Research Centre, he has developed methods and software tools to assess health co-benefits of carbon interventions (WHO software iSThAT for transportation, and CaRBonH for health benefits of the carbon reductions). Under WHO's Urban Health Initiative (transferring knowledge into action), he has contributed to the quantification of health benefits of carbon and air pollution reductions in Accra, Ghana and Kathmandu, Nepal.

Spadaro is co-author of several books and major technical works, including:

- How Much is Clean Air Worth? Calculating the benefits of Pollution Control, Cambridge University Press, 2014
- Burnett R et al. 2018. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. Proceedings of the National Academy of Sciences, 115(38):9592-9597
- Ostro B, Spadaro JV, et al. 2018. Assessing the recent estimates of the global burden of disease for ambient air pollution: Methodological changes and implications for low- and middle-income countries. Environmental Research 166:713-725), and conference contributions.