Mercury emissions from South Africa's coal-fired power stations

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Abstract

Mercury is a persistent and toxic substance that can be bio-accumulated in the food chain. Natural and anthropogenic sources contribute to the mercury emitted in the atmosphere. Eskom's coal-fired power stations in South Africa contributed just under 93% of the total electricity produced in 2015 (Eskom 2016). Trace amounts of mercury can be found in coal, mostly combined with sulphur, and can be released into the atmosphere upon combustion. Coal-fired electricity generation plants are the highest contributors to mercury emissions in South Africa. A major factor affecting the amount of mercury emitted into the atmosphere is the type and efficiency of emission abatement equipment at a power station. Eskom employs particulate emission control technology at all its coal-fired power stations, and new power stations will also have sulphur dioxide abatement technology. A co-beneficial reduction of mercury emissions exists as a result of emission control technology. The amount of mercury emitted from each of Eskom's coal-fired power stations is calculated, based on the amount of coal burnt and the mercury content in the coal. Emission Reduction Factors (ERF's) from two sources are taken into consideration to reflect the co-benefit received from the emission control technologies at the stations. Between 17 and 23 tons of mercury is calculated to have been emitted from Eskom's coal-fired power stations in 2015. On completion of Eskom's emission reduction plan, which includes fabric filter plant retrofits at two and a half stations and a flue gas desulphurisation retrofit at one power station, total mercury emissions from the fleet will potentially be reduced by 6-13% by 2026 relative to the baseline. Mercury emission reduction is perhaps currently not the most pressing air quality problem in South Africa. While the focus should then be on reducing emissions of other pollutants which have a greater impact on human health, mercury emission reduction can be achieved as a co-benefit of installing other emission abatement technologies. At the very least, more accurate calculations of mercury emissions per power station should be obtained by measuring the mercury content of more recent coal samples, and developing power station-specific ERF's before mercury emission regulations are established or an investment into targeted mercury emission reduction technology is made.

Introduction

Mercury is a persistent and toxic substance that accumulates in the food chain, and even though mercury is present in trace amounts, exposure increases as it accumulates. Coal contains mostly ash, carbon and small amounts of sulphur, and the trace amounts of mercury that are mostly combined with the sulphur can be released into the atmosphere upon combustion (Miller 2007a). Coal is the primary and most widely used fuel in the electricity generation industry and constitutes 43% of the total fuel used globally (Pirrone et al. 2009), thus the importance of controlling or limiting the emissions in this industry is evident.

Due to the combustion of coal in coal-fired power stations, mercury is present in the immediate exhaust gas as vapour phase Hg^0 (elemental mercury) (Srivastava et al. 2006; EPA 2011a). As a result of oxidation reactions, oxidised mercury (Hg^{2+}) or particulate bound mercury (Hg^p) may be formed. Oxidised mercury, Hg^{2+}, can form in the presence of chlorine, Cl, (forming $HgCl_2$), and particulate-bound mercury, Hgp, can form in the presence of fly ash or unburnt carbon remnants. The formation of Hgp with fly ash and unburned carbon occurs as a result of chlorination before the conversion of elemental mercury to $HgCl_2$. The particulate-bound mercury can then be captured by downstream particulate abatement technology such as Fabric Filter Plants (FFP's) or Electrostatic Precipitators (ESP's).

Very limited information on the status of mercury emissions in African countries is available, although mercury emissions in Africa are increasing due to the rapid economic development in these countries. South Africa signed the Minamata Convention on Mercury on 10 October 2013; however, there is no legislation regarding mercury emissions at present. South Africa, being the most industrialised country in the continent of Africa, also has limited information on levels of mercury in resources, mercury

in products and mercury in emissions (Pirrone et al. 2009). It has previously been estimated that emissions of mercury as a result of power generation account for 77% of the total mercury emitted in South Africa (Pirrone et al. 2009). This figure, unless mitigated, is unlikely to decrease significantly, as coal is the main source of energy and the demand for base energy will increase with the increase in population.

Uncertainties in the mercury emission inventories can hamper the development of policies, but do not negate the benefits in establishing a baseline of control that can be further developed or improved. Calculations presented in this paper are intended to give an indication of the magnitude of mercury emissions from coal-fired power stations in South Africa. The mercury emission inventory needs to be refined by updating the measurements of mercury in coal, and determining South Africa-specific emission reduction factors based on mercury emission measurements at South African power stations.

This paper presents a baseline of the emitted mercury from 2011 to 2015, as a result of coal combustion in the electricity generation process, from the individual Eskom Holdings SOC Ltd ("Eskom") coal-fired power stations, utilising two sets of emission reduction factors. An estimate of expected mercury emission reduction in future is also presented taking into consideration Eskom's emission reduction plan. This paper did not include the three other non-Eskom owned smaller coal-fired power stations currently operating in South Africa: the Rooiwal Power Station and the Pretoria West Power Station in Pretoria, and the Kelvin Power Station in Johannesburg as well as the Sasol Secunda boilers. These three stations have a total generating capacity of 1 080 MW (compared to Eskom's installed 38 548 MW coal-fired power stations capacity – Eskom, 2016). The inclusion of these stations would not significantly change the values reflected in this paper. The results of these estimates can be used to compare co-benefits of emission control technologies implemented at Eskom's power stations at present or potentially in the future.

Methodology and Data

Eskom's coal-fired power stations

Eskom currently operates 14 coal-fired power stations located across South Africa. Medupi and Kusile Power Station are two new build power stations. Medupi's first unit came online in 2015, with all units expected to come online by 2021. Kusile Power Station is expected to commence with electricity production from 2017.

These power stations burn bituminous type coal, and employ particulate matter (PM) control technology – either Fabric Filter Plants (FFP's) or cold-sided Electrostatic Precipitators (ESP's) with SO3 flue gas conditioning (FGC). Kusile and Medupi Power Stations will also employ Flue Gas Desulphurisation (FGD), from commissioning at Kusile and six years after commissioning at Medupi.

Eskom's Emission Reduction Plan is focused on the reduction of SO_2 and PM through the retrofit of some ESP fitted stations with FFPs, as well as the addition of Flue Gas Desulphurisation (FGD) units at one or two stations. Eskom's current and future emission control technology is indicated in Table 1.

Table 1: Current and future emission control technology at Eskom's coal-fired power stations

Power Station	Emission control technology	
	Status Quo *	Emission reduction plan
Arnot	FFP's	No change
Camden	FFP's	No change
Duvha	FFP's & ESP's+FGC	HFTs onto ESP units
Grootvlei	FFP's & ESP's+FGC	All units with FFP
Hendrina	FFP's	No change
Kendal	ESP's + FGC	HFTs
Komati	ESP's + FGC	No change
Kriel	ESP's + FGC	FFP retrofit
Kusile*	FFP's & wet FGD	No change
Lethabo	ESP's + FGC	HFT upgrades
Majuba	FFP's	No change
Matimba	ESP's + FGC	HFT upgrades
Matla	ESP's + FGC	HFT upgrades
Medupi	FFP's	Wet FGD retrofit
Tutuka	ESP's	FFP retrofit

FFP's = Fabric Filter Plants, ESP's = Electrostatic Precipitators, HFT's = High frequency transformers, FGC = Flue Gas Conditioning
*Kusile is only expected to come into operation from 2017

Data sources

The data utilised to calculate the emitted mercury from the power stations includes the following:

- the amount of coal burnt per annum (tons) per power station (actuals from 2010 to 2015 and projections from 2016 on);
- the mercury content (ppm) of the coal used at each power station; and
- mercury emission reduction factors sourced from available literature.

Amount of coal burnt
The current and historic amount of coal burnt is provided by Eskom and is calculated by measuring the amount of coal coming into the power stations (to the coal stock yards, from the coal mines) and comparing this to the height, width, length as well as density dimensions of the coal stock yards. The amount of coal coming into the station is determined and weighed as it

arrives. Surveys of the coal stockpiles are conducted quarterly. The data used for historic coal burnt is presented in Table 2.

Table 2: Annual coal burnt at Eskom's coal power stations from 2011 to 2015 (Mt)

	2011	2012	2013	2014	2015
Arnot	6.98	6.82	5.97	6.03	5.45
Camden	4.23	4.90	5.25	5.23	4.53
Duvha	9.18	8.77	10.14	7.47	7.55
Grootvlei	3.58	3.48	4.15	4.28	3.25
Hendrina	6.96	6.02	5.13	6.52	5.36
Kendal	15.85	15.73	15.85	13.70	15.03
Komati	1.14	2.26	2.96	2.61	2.52
Kriel	9.21	8.30	8.43	8.13	8.19
Lethabo	17.52	16.32	16.17	16.22	15.37
Majuba	13.38	13.50	13.27	13.09	11.41
Matimba	14.93	14.63	13.95	13.70	13.44
Matla	11.31	11.70	10.75	11.41	11.66
Tutuka	10.74	11.18	10.61	11.15	10.78
Medupi	0.00	0.00	0.00	0.00	0.89
Total	125	124	123	120	115

The projected coal burnt data utilised for the estimates from the 2016 Eskom financial year onwards, are from Eskom's 10-year production plan of December 2015, which was the most recent available at the time of drafting this paper. This plan forecasts the amount of coal that will be burnt at each power station based on past trends of usage, expected maintenance, and prediction of total electricity demand. A financial year runs from the beginning of April to the end of March in the following year.

Mercury content of coal

The mercury content of coal data used is provided by Eskom (Delport, 2007) for six monthly samples collected from the end of 2004 until mid-2005, and from UNEP (2014) for monthly and annual coal samples collected between 2010 and 2012. The analysis of the coal samples by Delport (2007)was performed using a gold amalgamated spectroscopy technique. This sampling was conducted at the Consulting Research and Development Department (now known as the Research, Testing and Development Department, Group Sustainability Division). This data is reflected in Table 3. No recent samples have been measured by Eskom.

The average mercury in coal content for the coal used at Eskom's power stations ranges between 0.17 ppm (Arnot Power Station) and 0.38 ppm (Matimba Power Station; Table 3). At many power stations, the variability in mercury content is high from month to month. Kriel, Lethabo and Matimba Power Station have the highest variability in the mercury in coal content (Figure 1).

Table 3: Average mercury in coal content (ppm) of monthly and annual composite samples of coal used at Eskom's power stations. Annual samples are shown in bold.

Power Stations	2004 - 2005 samples (Delport, 2007)	2010-2012 samples (UNEP, 2014)	Average (ppm)
Arnot	0.17, 0.17, 0.13, 0.17, 0.15, 0.26	0.16, 0.12	0.17
Duvha	0.25, 0.26, 0.20, 0.19, 0.27, 0.23	0.21, 0.18, 0.19	0.22
Hendrina	0.21, 0.23, 0.17, 0.20, 0.20, 0.24	0.28, 0.23, 0.22	0.22
Kendal	0.25, 0.22, 0.29, 0.46, 0.31, 0.34	0.22, 0.21, 0.18, 0.21	0.27
Kriel	0.39, 0.35, 0.23, 0.23, 0.26, 0.55	0.12, 0.13, 0.14	0.27
Lethabo	0.25, 0.23, 0.29, 0.33, 0.46,0.64	0.40, 0.46, 0.15	0.35
Majuba	0.36, 0.33, 0.25, 0.29, 0.21, 0.28	0.29, 0.23, 0.28, 0.22	0.27
Matimba	0.61, 0.70, 0.33, 0.37, 0.22, 049	0.23, 0.25, 0.19	0.38
Matla	0.18, 0.20, 0.45, 0.22, 0.25, 0.49	0.28,0.23, 0.20	0.28
Tutuka	0.36, 0.34, 0.33, 0.23, 0.26, 0.24	0.18, 0.30, 0.22	0.27
Grootvlei		0.37, 0.28, 0.34, 0.32	0.33
Camden		0.20, 0.25, 0.22, 0.19	0.22
Komati		0.23, 0.20, 0.24	0.22
Medupi**			0.38
Kusile***			0.27

** Matimba's data was assumed for Medupi (due to proximity and source)

***Kendal's data is assumed for Kusile (due to proximity and source)
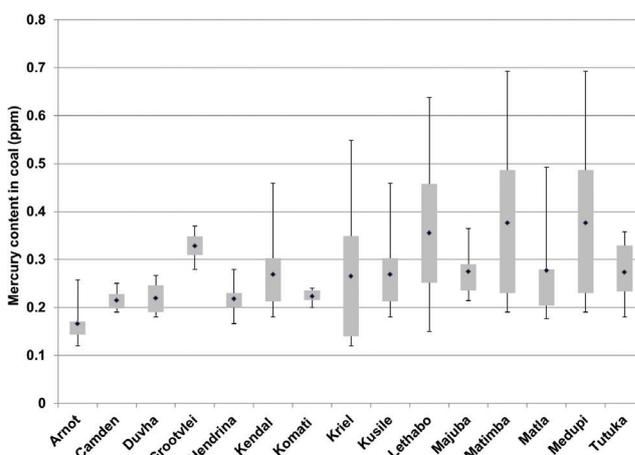
Figure 1: The mercury in coal content, based on the measurements presented in Table 3. Diamonds show average mercury content (ppm); the boxes show the range between the first quartile and the third quartile, and the whiskers show the minimum and maximum values

Although the mercury in coal measurements are extremely limited, it may be tentatively suggested that the mercury in coal content has declined at Kendal and Matimba between 2004/2005 and 2010-2012.

Emission Reduction Factors

The Emission Reduction Factors (ERF's) utilised to calculate the amount of mercury emitted from a coal-fired power station should take into consideration the type of emission control technology at a power station and the type of coal burnt as both of these can significantly affect the amount of mercury emitted. Two sets of emission factors are utilised in this paper, those from the EPA (2013) as well as those in the latest UNEP toolkit (2015), as represented in the Table 44. These factors are for bituminous coal.

Table 4: ERF's to calculate mercury emissions from bituminous coal

Emission control technology	ERF (%)	
	EPA 2013	UNEP 2015
FFP's	89	50
CS-ESP's	36	25
FFP's+CS-ESP's*	62.5	37.5
FFP+wet FGD	90	65
CS-ESP+wet FGD	66	65***

* This is determined by averaging the factors for FFPs & CS-ESPs
** The ESP factors consider general ESPs (not specifically CS-ESPs)
*** No factor available for an ESP & wet FGD combination in particular (only particulate matter filter & wet FGD)

The United Nations Environment Programme (UNEP) produced a toolkit with the intention to assist countries with developing mercury inventories. The first toolkit was developed in 2005, updated in 2011, and again in 2015. Default emission reduction factors are presented in the toolkit, those being 25% reduction of mercury from 'general ESPs' and a 50% mercury reduction from FFPs. The toolkit indicates that these default factors are based on "a limited database, and are expert judgments based on summarised data only with no considered systematic quantitative approach (i.e. consumption-weighted concentration and distribution factors derivation)".

In the United States, the Environmental Protection Agency (EPA) initiated an Information Collection Request (ICR) from 'Electric Utility Steam Generating Units', in 1998. One of the three main elements of the 1999 ICR was the acquisition of data by coal sampling and stack testing in order to determine mercury reductions from different 'representative unit configurations'. The data from the ICR 1999 indicated that bituminous coal-fired stations, with emission control technology, have higher levels of mercury capture than sub-bituminous or lignite coal-fired power stations with the same emission control technology. Currently the US EPA utilises emission factors based on the US ICR of 1999 and these are captured in their base case (v5.13). These factors are incorporated into the Integrated Planning

Model (IPM) of the US EPA which presents "forecasts of least cost capacity expansion, electricity dispatch, and emission control strategies" (EPA 2010, EPA 2013). The emission reduction factors from the UNEP 2015 toolkit as well as the EPA 2013 are used for the calculation of mercury emissions in this paper, and reflected in Table 44.

Data analysis method

The method used for the calculation of the amount of mercury emissions from each of the coal-fired power stations is a mass-balance formula, as also presented in the 'Toolkit for Identification and Quantification of Mercury Releases' (UNEP 2015).

Results and discussion

Mercury emissions from 2011 to 2015

The few studies that have estimated the amount of mercury emissions as a result of coal-fired power stations in South Africa reflect results that vary greatly. These results range from 9.8 tons of mercury emitted in 2004 (Dabrowski et al. 2008) to just over 83 tons in 2000 (Pacyna et al. 2006). According to our calculations, the amount of mercury emitted from the Eskom coal fleet in 2015 is between 16.8 tons (12.2-20.1 tons for the first-third quartile range) and 22.6 tons (16.9-26.6 tons for the first-third quartile range), depending on the selection of ERFs (EPA 2013 and UNEP 2015). The annual mercury emitted from each power station in 2015 is shown in Figure 2.
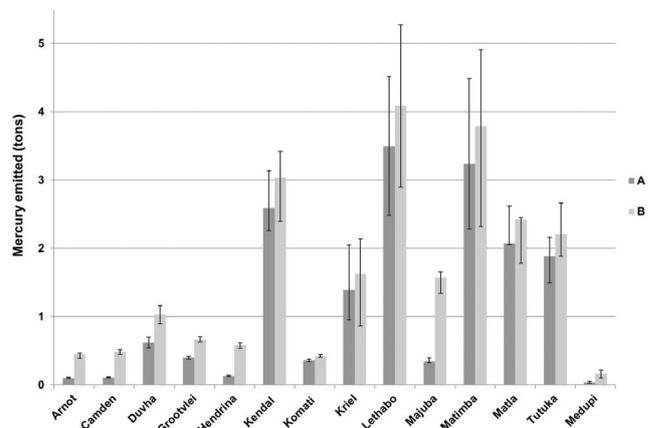
Figure 2: The mercury emitted per power station in 2015 using the two ERF's (A=EPA 2013 and B = UNEP 2015). The error bars reflect the first and third quartiles of mercury emissions per station, per ERF.

Matimba, Lethabo, Kendal, Matla, Kriel and Tutuka emitted the highest amount of mercury in 2015. These six stations produced on average just below 82% of the total mercury emitted by the fleet of coal power stations. Matimba and Lethabo alone contribute to just below 38% of the total mercury emitted by the fleet in 2015.

A slight decrease in mercury emissions is noticed from 2011 to 2015 (Figure 3). This is a direct link to the quantity of coal burnt since 2011 (Table 2), which has declined from an average of 17.9 tons in 2011 to an average of 16.8 tons in 2015, using the

EPA (2013) emission reduction factors, or from an average of 24.3 tons in 2011 to 22.6 tons in 2015 using the UNEP (2015) emission reduction factors. With the implementation of Eskom's emission reduction plan (Table 1), a further decrease in mercury emissions is expected due to the higher co-beneficial reduction of mercury emissions from the selected PM and SO_2 technology selected to be retrofitted (further discussed in section 3.2).

Mercury emission monitoring in power stations' stacks is required to validate mercury emission reduction factors and mercury emission estimates. The results in this paper show that estimates from previous reports could have been over estimates of the current mercury emissions from the power stations (Pacyna et al. 2006, Pirrone et al. 2009).
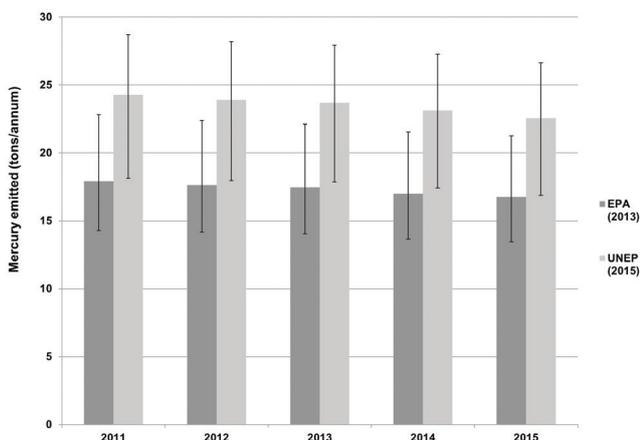
Figure 3: Mercury emissions from Eskom's coal-fired power stations from 2011-2015 using the two ERFs. The error bars reflect the first and third quartiles of mercury emissions.

Power stations with FFPs as emission control technology (Arnot, Camden, Hendrina, Majuba and Medupi) produce on average 0.01-0.07kg of mercury per GWh sent out (Figure 4 and Figure 5). This is significantly lower than the stations with ESPs (Kendal, Kriel, Lethabo, Matimba, Matla, Komati and Tutuka), emitting just under 0.11-0.13kg of mercury per GWh sent out. These differences are a direct reflection of the differing mercury emission factors from the EPA 2013 and UNEP 2015. The two stations, Grootvlei and Duvha, which had half ESPs and half FFPs implemented at the stations in 2015 emit just over 0.07-0.1kg mercury per GWh energy sent out.

The highest mercury-emitting coal power stations in 2015 are Lethabo (3.5 and 4.1 tons, with the EPA (2013) and UNEP (2015) emission reduction factors, respectively), Matimba (3.2 and 3.8 tons) and Kendal (2.6 and 3.0 tons). These figures are a function of the amount of coal burnt and the mercury content in coal. When comparing the amount of average mercury emitted per GWh of energy sent out, Matimba and Lethabo are the top two 'mercury per GWh' emitting stations, then followed by Kendal, Matla and Tutuka.

Currently in Eskom, five coal-fired power stations pre-wash coal prior to combustion (these are Arnot, Duvha, Hendrina, Lethabo and Matimba). Arnot and Hendrina have FFP's as an emission
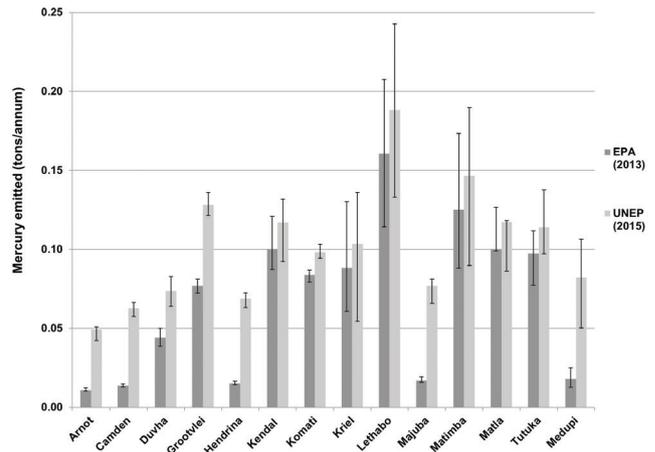
Figure 4: Mercury emitted per energy unit sent out per station using the two ERF's

control technology. Camden and Majuba, also have FFPs, and no coal washing. Arnot and Hendrina emit a lower amount of mercury per GWh sent out than Camden and Majuba (Figure 4). This can also be seen when comparing Duvha's mercury emitted per GWh sent out with Grootvlei which does not pre-wash coal, and which also has half ESPs and half FFPs.
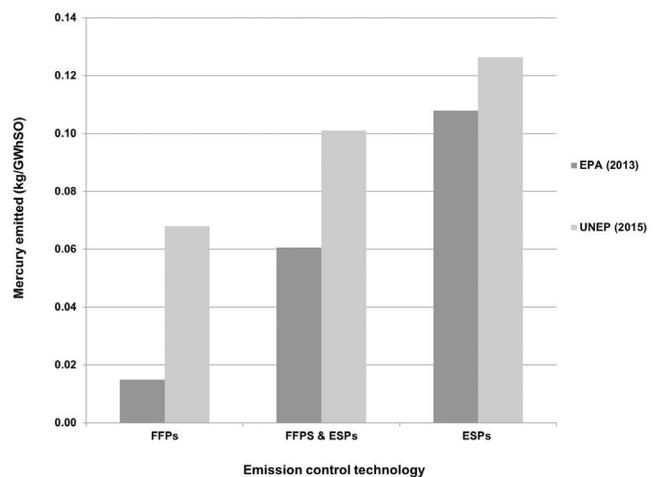
Figure 5: Relative mercury emitted per GWhSO per emission control technology in 2015

Projected mercury emissions from 2016 to 2026

In the absence of any emission abatement retrofits or upgrades, it is inconclusive whether total mercury emissions from Eskom's coal-fired power stations will increase or decrease over the next 10 years. Figure 6 and Figure 7 show future mercury emission trends with and without the implementation of Eskom's emissions reduction plan. Variations from year-to-year are mostly due to the projected total quantity of coal burnt per power station as well as the decommissioning of Arnot, Camden and Komati Power Stations within this time frame. The additions of the Medupi units as well as the commissioning of Kusile Power Station units are considered in the total mercury emissions per year.

The trends in mercury emissions over time in Figures 6 and 7 are influenced both by trends in coal burnt (which increases towards 2024/25), and also by the changing load factors of the different power stations over time. Since the different power stations have different particulate abatement technologies installed, the different emission reduction factors for the abatement technology installed result in the trends plotted.
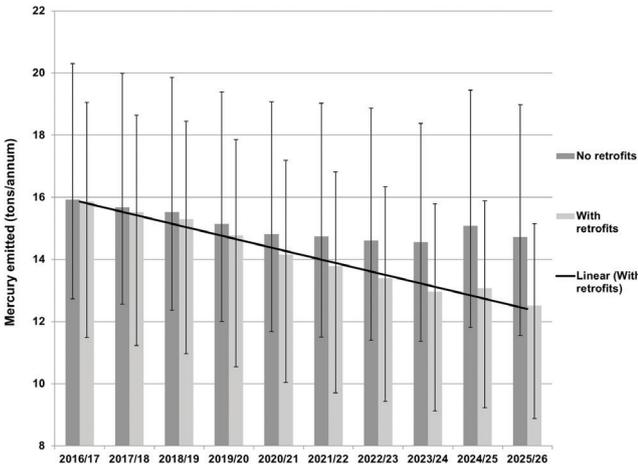
Figure 6: *Projected annual mercury emissions from 2016/17 to 2025/26 assuming no retrofits and the implementation of Eskom's emission reduction plan, using the EPA 2013 ERFs*
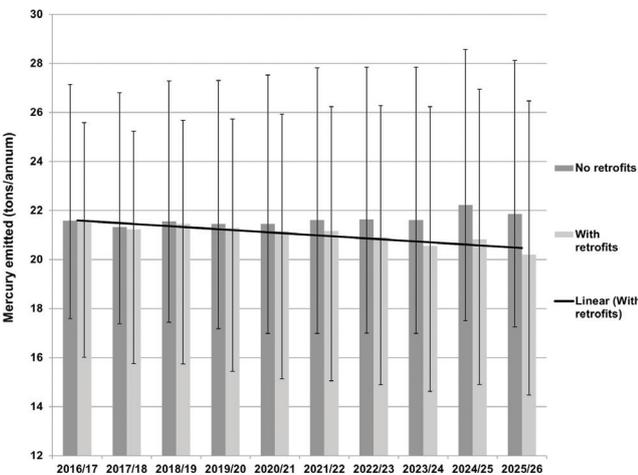
Figure 7: *Projected annual mercury emissions from 2016/17 to 2025/26 assuming no retrofits and the implementation of Eskom's emission reduction plan, using the UNEP 2015 ERFs*

Total mercury emissions are expected to be reduced by between 6% and 13% over the next 10 years as a result of the implementation of Eskom emission reduction/retrofit plan (Figure 6 and Figure 7). The retrofits in this time period (i.e. up to end of March 2026) include FFP retrofits on the ESP units at Grootvlei Power Station (affecting the emissions from 2016 onwards), FFP installations at Tutuka and Kriel Power Stations (affecting the emission from the power stations from 2019 and 2020, respectively), and lastly the installation of FGD at Medupi (affecting the emissions from 2022). The retrofits are assumed to occur at a pace of one unit per financial year, with the co-beneficial reduction of mercury emissions being realised the

year following retrofit. It is assumed that ESP upgrades and burner modifications (including the addition of high frequency transformers to an ESP) have no effect on mercury emissions, which is a conservative assumption.

Mercury emissions will be reduced even further with the further decommissioning of older coal units and the retrofitting of FGD outside of this 10 year window.

Conclusion

Factors that should be considered when selecting the most appropriate mechanism for mercury emission reduction from a power station include:

- the need to reduce or control specific pollutants. Focus should be on the need to control priority pollutants (those that have an effect on human health and are emitted in high quantities), meeting current emission limits and the subsequent co-beneficial reduction of mercury;
- the economic feasibility of the control technologies (for the power stations as well as the country). Additional to the cost of emission control technology, and the resultant impact on the economy, meeting the electricity demand in South Africa should be considered; and
- the life of the stations. This factor ties in with economic feasibility. Implementing costly technology on an old power station is not necessarily sustainable.

As most of South Africa's energy is derived from the combustion of coal, focus on energy saving initiatives, the introduction of renewables into the energy mix as well as improving the power stations' efficiency, would contribute to the reduction of mercury.

Setting and subsequent meeting of mercury control requirements at a power station and for a country begins with an assessment of baseline mercury removals achieved by emission control technologies already in place. This baseline assessment of the mercury emissions from the coal power stations in South Africa are a stepping stone to the drafting of regulations for the country.

The main driver for the establishment of mercury regulations in South Africa is the global concern of bio-accumulation in the food chain. Due to the goal of lowering the mercury emissions globally, the persistent nature of mercury, as well as the developing economic state of South Africa, a cap limit for the total mercury emissions from the generating coal-fired power station sector is recommended. This would allow for economic feasibility and flexibility in terms of retrofitting or implementing new technology in those power stations with a longer life, and thus a reduction could be established on the total mercury emissions from the fleet. A national cap limit on the mercury emission thus seems more appropriate than a specific limit for the individual coal stations.

Emission monitoring in power stations' stacks is required to develop power station-specific ERF's and validate mercury

emission reduction estimates before mercury emission regulations are established or an investment into targeted mercury emission reduction technology is made.

Acknowledgements

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