The Effectiveness of Ultra Low Emission (ULE) Technology in the Reduction of Nitrogen Dioxide Emissions from Power Plants

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Executive Summary

This project highlights the negative impacts on the environment and human health caused by Eskom's un regulated, high Nitrogen dioxide emissions from its coal fired power plants located in South Africa. The project proposes the installation of Ultra Low Emission (ULE) technologies in Eskom's coal fired power plants as a mitigative measure to reduce emissions to the neighbouring cities and the environment. Ultra-Low Emission technologies like low Nitrogen burners and Selective Catalytic Reduction (SCR) are introduced and explained.

The project aims at providing empirical evidence of the effectiveness of these ULE technologies in reducing Nitrogen dioxide emissions from coal fired power plants with the sole hope that stakeholders like Eskom can utilise these findings and be motivated to buy and install ULE technologies in their coal fired power plants.

Using both OMI satellite data and in situ CEMS data obtained before and after installation of Ultra Low Emission technology in Suizhong coal fired power plant in China, time series analysis of Nitrogen dioxide emissions and concentration between 2010 and 2018 is carried out. Ultra-Low Emission technologies were installed in Suizhong power plant in July 2014. The time series results show a sharp reduction of between 31% to 43% in Nitrogen dioxide emission following installation of ULE technology in 2014 at Suizhong coal power plant. This is evidence of the effectiveness of ULE technologies in reducing Nitrogen dioxide emissions in coal fired power plants.

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Background of the Problem

Eskom

The principal client and stakeholder in this project is Eskom. Eskom is South Africa's national electricity utility and is the biggest producer of electricity on the continent of Africa. The company was established in 1923 by the Electricity Supply Commission. The company has three divisions and roles namely; generation, transmission and distribution. Eskom generates 95% of all electricity used in South Africa and approximately 45% of electricity in Africa. (Wikipedia, 2022)

In South Africa, Eskom uses mainly coal fired power stations to generate electricity but also utilises gas turbine and nuclear technology at some plants. From **Figure 1** and **Figure 3**, Twelve of its coal fired power plants are clustered in the Mpumalanga province while the other two coal fired power plants are located in the Limpopo and Free state provinces.

Power plant	Province	Type	Date commissioned (planned)	Capacity (MW) (planned)	Status
Acacia Power Station	Western Cape	Gas turbine	1976	171	Operational
Ankerlig Power Station	Western Cape	Gas turbine	2007	1,338	Operational
Arnot Power Station	Mpumalanga	Coal-fired	1971-1975	2,352	Operational
Camden Power Station	Mpumalanga	Coal-fired	1967-1969; 2005-2008	1,561	Operational
Duvha Power Station	Mpumalanga	Coal-fired	1980-1984	3,600	Operational
Gourikwa Power Station	Western Cape	Gas turbine	2007	746	Operational
Grootvlei Power Station	Mpumalanga	Coal-fired	1969-1977; 2008-2011	1,180	Operational
Hendrina Power Station	Mpumalanga	Coal-fired	1970-1976	1,893	Operational
Kendal Power Station	Mpumalanga	Coal-fired	1988-1992	4,116	Operational
Komati Power Station	Mpumalanga	Coal-fired	1961-1966; 2009-2013	990	Operational
Kriel Power Station	Mpumalanga	Coal-fired	1976-1979	3,000	Operational
Kusile Power Station	Mpumalanga	Coal-fired	(2017–2025)	3,200 (4,800)	4/6 units operational
Lethabo Power Station	Free State	Coal-fired	1985-1990	3,708	Operational
Majuba Power Station	Mpumalanga	Coal-fired	1996–2001	4,110	Operational
Matimba Power Station	Limpopo	Coal-fired	1987-1991	3,990	Operational
Matla Power Station	Mpumalanga	Coal-fired	1979-1983	3,600	Operational
Medupi Power Station	Limpopo	Coal-fired	2015–2019	4,764	Operational
Port Rex Power Station	Eastern Cape	Gas turbine	1976	171	Operational
Tutuka Power Station	Mpumalanga	Coal-fired	1985-1990	3,654	Operational

Figure 1: Power stations or plants in South Africa that are operated and owned by Eskom. For each power plant, the province in which it is located, the type of generation technology used, date of commissioning, generation capacity in Megawatts (MW) and operational status are specified. (Source: Wikipedia 2022)

Location of Eskom's coal fired power plants and their Nitrogen dioxide emission levels

83% of South Africa's coal is mined in Mpumalanga and 90% of South Africa's electricity is generated from coal. This explains why Eskom has a cluster of twelve coal fired powerplants in Mpumalanga province. Proximity to coal mines and deposits in Mpumalanga province minimises transportation costs for Eskom that the company would have incurred if its coal fired power plants were distant from the coal mines. However, though this clustering and high density of coal fired power plants at Mpumalanga may be beneficial to Eskom, it poses a major environmental and health concern to the nearby settlements and cities such as Pretoria, Newcastle and Johannesburg because of the high levels and concentrations of Nitrogen dioxide emissions that emanate daily from this cluster of power plants. **Figure 2** shows the oldest coal fired power plant in South Africa.

Figure 2: Komati coal fired power plant located in Mpumalanga was commissioned in 1961 and is the oldest among those owned by Eskom. Old and aging power plants have inefficient power generation designs that emit large volumes of Nitrogen dioxide. (Source:Eskom,2022)

Formation process of Nitrogen Oxides during combustion in coal fired power plants

Nitric Oxides (NOx) generally refers to nitric oxide (NO) and nitrogen dioxide (NO_2). Coal contains Oxygen and Nitrogen and when this coal is heated to about 1600 degrees Celsius in the presence of Oxygen and Nitrogen from the air, Nitrogen and Oxygen combine to produce NO and NO_2 as shown by the equations below. (Romero and Wang, 2019)

$$N_2 + O \rightarrow NO + N$$

$$N + O_2 \rightarrow NO + O$$

$$2NO + O_2 \rightarrow 2NO_2$$

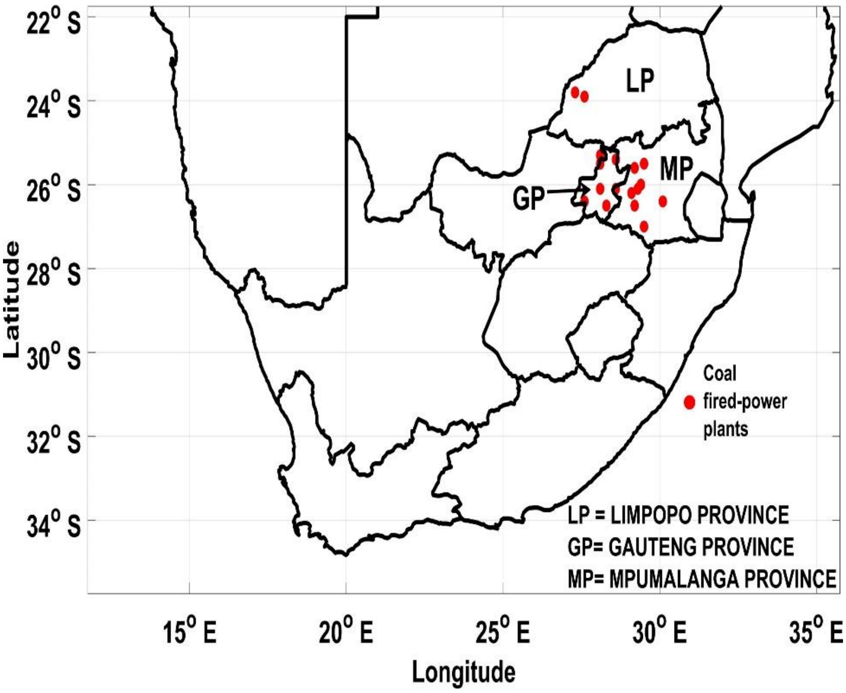

Figure 3: Map of South Africa showing the locations of coal fired power plants namely; Mpumalanga province, Gauteng province and Limpopo province. (Source: Shikwambana *et al*.,2020)

Green Peace Global Air Pollution Unit utilised the CALPUFF atmospheric modelling system (**Figure 4**) to carry out CALPUFF dispersion modelling to estimate the health impacts of the excess Nitrogen dioxide emissions with the modelling domain embracing the whole population of South Africa. The results indicated that the impact of excess Nitrogen dioxide emissions occur within 10 to 20km of each coal fired power plant (Myllyvirta,2019).

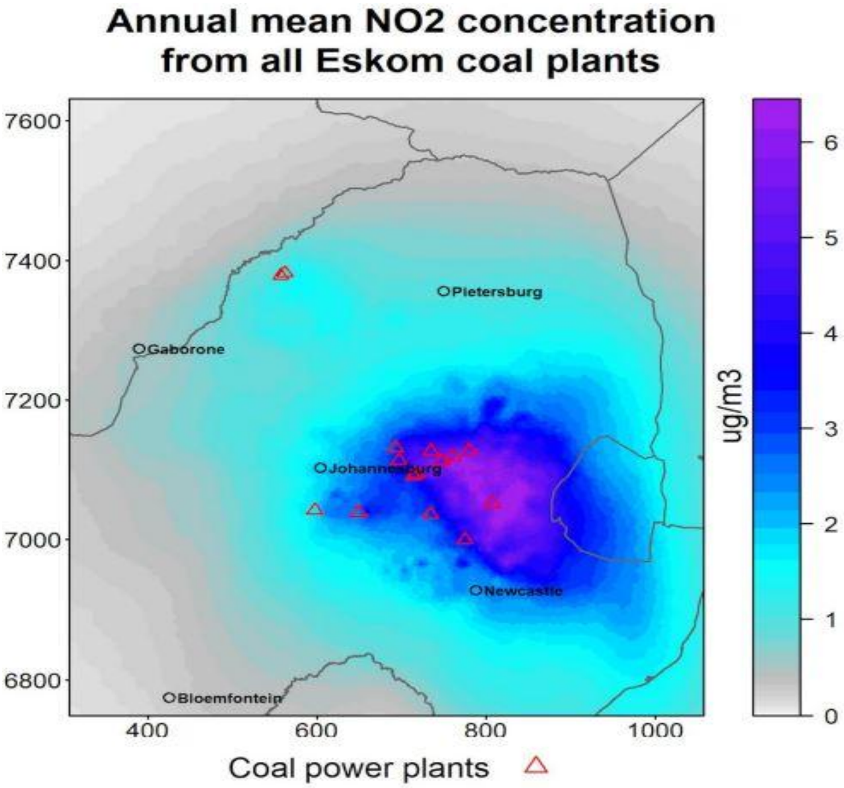

Figure 4: Map of average annual Nitrogen dioxide concentration measured in micrograms per cubic metre from all Eskom coal fired plants. The map provides evidence of Nitrogen dioxide plume pollution and emission into nearby cities like Johannesburg, Newcastle and Pietersburg at high concentrations between 2 and 5micrograms per cubic metre. (Source: Myllyvirta,2019)

Projected Impacts of Nitrogen emissions from Eskom's power plants on Human Health

For Health impact assessments, the CALPUFF modelling results indicated that emissions from Eskom power plants expose 280,000 people to at least one exceedance of South Africa's air quality standard for 1-hour NO_2 concentration (Myllyvirta,2019). According to Myllyvirta (2019), "Eskom is applying for wide-ranging postponements and suspensions from South Africa's Minimum Emission Standards (MES) that would allow it to operate its entire existing fleet of coal fired power plants without even rudimentary controls for three of the most dangerous pollutants emitted from coal-fired power plants: SO_2, NO_x, and mercury." The projected cumulative health impacts of excess emissions from Eskom's proposed non-compliance with South Africa's minimum emission standards was therefore also modelled. The results are summarised in **Figure 5** below. The projections show that, if Eskom's request to continue without adherence to minimum emission standards is granted, this will lead to an estimated 16,267 premature human deaths (95% confidence interval: 13,000 to 18,000 deaths) to occur. The pollutants responsible for these deaths will be the particulate matter (PM2.5) and Nitrogen dioxide from Eskom's coal fired power plants. These pollutants will cause lower respiratory infections, chronic obstructive pulmonary disease, diabetes, ischemic heart disease, lung cancer, stroke and other illnesses that will be fatal to humans residing in the polluted areas.

Pollutant	Cause of death	Premature deaths		
		Central	*Low*	*High*
PM2.5	Lower respiratory infections	5594	*5134*	*5934*
PM2.5	Chronic obstructive pulmonary disease	2346	*1894*	*2427*
PM2.5	Diabetes	1458	*487*	*1626*
PM2.5	Ischemic heart disease	2986	*2505*	*3131*
PM2.5	Lung cancer	1901	*1553*	*2168*
NO2	Stroke	1529	*897*	*1727*
All	All causes	453	*249*	*657*
	Total	16267	*12720*	*17671*

Figure 5: Projected cumulative health impacts of excess emission from Eskom's proposed non-compliance with minimum emission standards. The premature deaths values have a median(central) value together with lower bound (Low) and upper bound (High) values. (Source: Myllyvirta,2019)

The need to switch to Ultra Low Emissions (ULE) Technology interventions

To mitigate the above problems caused by high emission of Nitrogen dioxide by Eskom's coal fired power plants, this project proposes the fitting of Ultra Low Emission (ULE) technology in Eskom's coal fired power plants. The Ultra-Low Emission technology has been widely in use in China since 2014 when China's government enforced strict low emission standards for its coal fired power plants (Jiao *et al*, 2020). ULE has been suggested to reduce Nitrogen dioxide emissions by between 60% to 90%. (Romero and Wang, 2019) We shall show the effectiveness of this ULE technology by collecting and analysing satellite data and in situ data of Nitrogen dioxide emission for a coal fired power plant in China that was fitted with ULE technology in July 2014. It is important to collect Nitrogen dioxide data before the ULE was installed and Nitrogen dioxide data after the ULE was installed. This approach enables us to build a time series analysis of emissions involving all years before and after installation of ULE in order to show evidence of reductions in Nitrogen dioxide emissions after installation of ULE. If we can show, empirical evidence of significant reduction in emissions after ULE installation, then we shall have proved the effectiveness of ULE in reducing Nitrogen dioxide emissions(Tang *et al*,2019; Tian *et al*,2022). It is this empirical evidence that we seek to present to the management of Eskom in South Africa to convince them to install the ULE technology in their coal fired power plants. If Eskom, is convinced by the data analytics, we hope that they will buy and install the ULE and the death tolls of **Figure 5** will eventually be minimised. The proposed ULE technology combines use of low NO_x burners (LNBs) (**Figures 6 and 7**) and Selective Catalytic Reduction (SCR)(**Figures 7 and 8**) to reduce NO_x emissions.

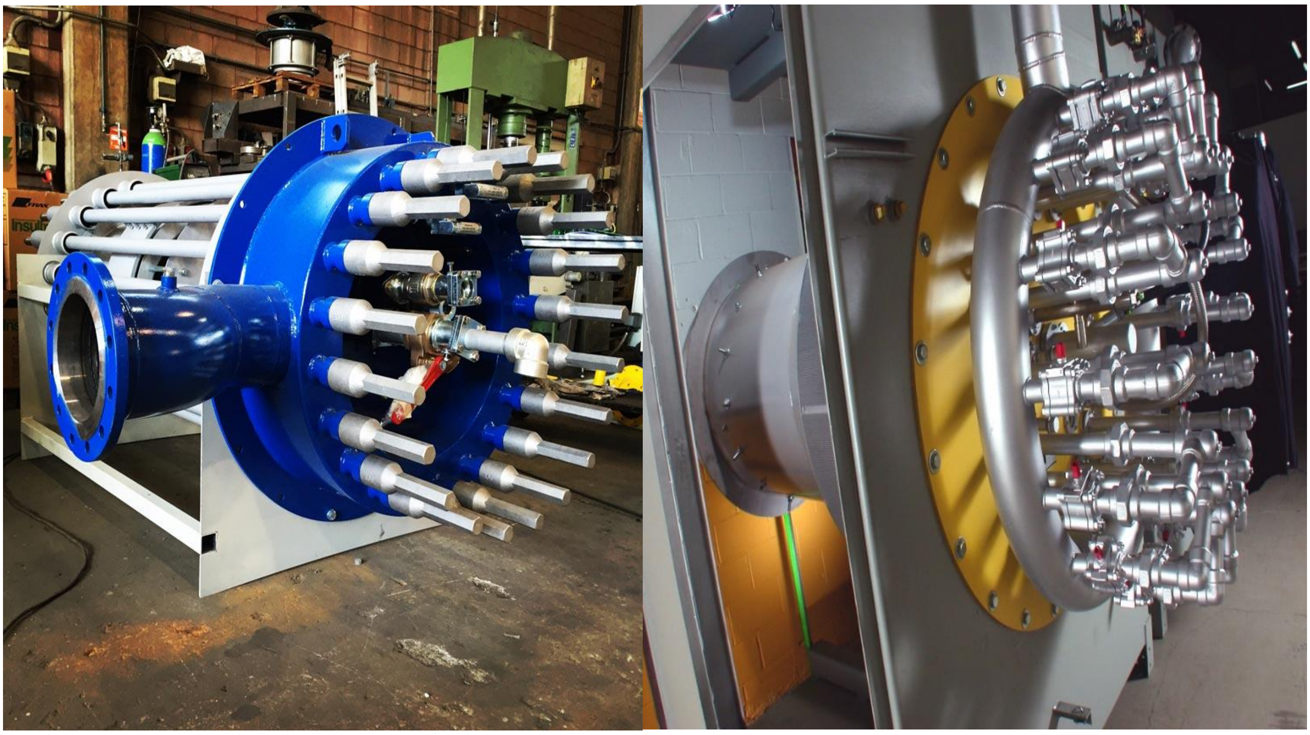

Figure 6: Two models of low NO_x burners (LNBs) (Source: Google,2022)

Ultra-Low Emission Technology (ULE)

Raw coal used in coal fired power plants contains Sulphur, Nitrogen, Carbon and other elements. During combustion in the power plant, these elements react at high temperature to produce Sulphur dioxide (SO_2), Nitrogen oxides (NO_x), Carbon dioxide (CO_2) and particulate matter ($PM_{2.5}$ or PM_{10}) or dust. These products of combustion are however harmful and detrimental to both the environment and human health when emitted to the atmosphere. In order to minimise these harmful emissions to the atmosphere, Ultra Low Emission (ULE) technologies have been developed and deployed in power plants. They include low NOx burners (LNBs), Selective Catalytic Reduction (SCR) for NOx control, Electrostatic Precipitator (ESP) or Fabric Filter (FF) for particulate matter ($PM_{2.5}$ or PM_{10}) control and Flue Gas Desulfurization (FGD) for SO_2 control (Romero and Wang, 2019). A standard coal fired power plant fitted with Ultra Low Emission technologies (**Figure 7**) should thus have all these ULEs to minimise emissions of Nitrogen oxides, Sulphur dioxides and Particulate Matter.

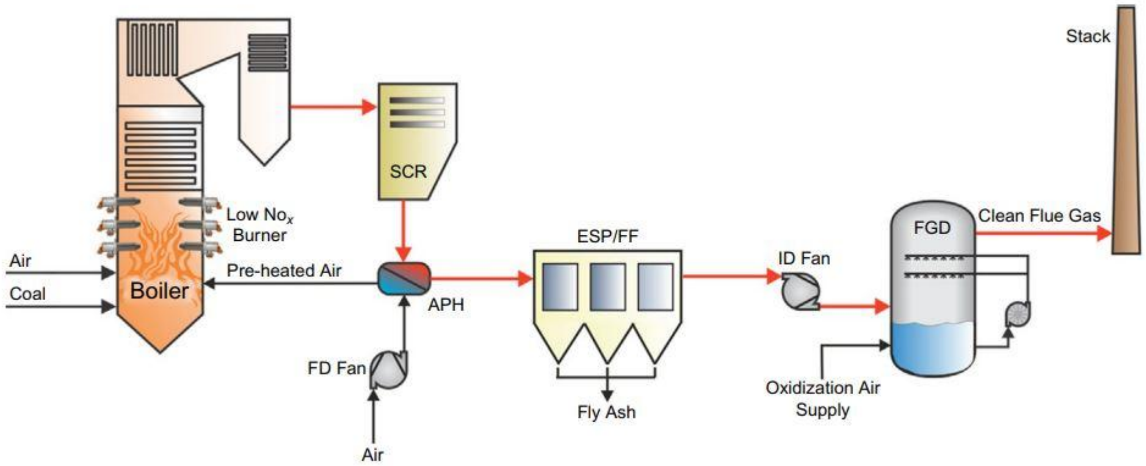

Figure 7: Typical design components of a coal fired power plant fitted with Ultra Low Emission technology. The key ULE technology components are low-NO_x burner, Selective Catalytic reduction (SCR) for NO_x control, Electrostatic Precipitator (ESP) or Fabric Filter (FF) for particulate matter control and Flue Gas Desulfurization (FGD) for SO_2 control. (Source: Romero and Wang, 2019)

<u>Denitrification systems and Low NOx burners</u>

Reduction of NOx emissions in coal fired power plants is attained by employing two approaches: combustion reduction and post combustion reduction. Combustion NOx reduction entails decreasing the temperature of the flame, reducing stay time in the combustion zone and nurturing a fuel rich environment(Romero and Wang, 2019). The ULE that achieves this is low NOx burners (LNBs). Low NOx burners (**Figure 6** and **Figure 7**) are the cheapest option and can reduce NOx emissions by 20 to 60%(Romero and Wang, 2019). They are also relatively easy to retrofit on most coal fired boilers. LNBs reduce combustion NOx by creating a fuel rich environment and lowering the combustion temperature through introduction of less air in the principal combustion zone thus restraining NOx production. (Romero and Wang, 2019).

Post combustion reduction of NOx relies on conversion of NOx to harmless Nitrogen and water via chemical reactions. A reagent is introduced that reacts with NOx in the presence or absence of a catalyst. The ULE that achieves this is Selective Catalytic Reduction (SCR) shown in **Figure 8**. This system can reduce NOx emissions to 90%. The commonest reagent used is ammonia (NH_3). The process involves NOx in the flue gas reacting with injected ammonia to yield harmless water and nitrogen after passing through a catalyst chamber. For optimal results, this process is best conducted at temperatures between 230 and 450 degrees Celsius. The reaction equations are shown below

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$
$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$$
$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

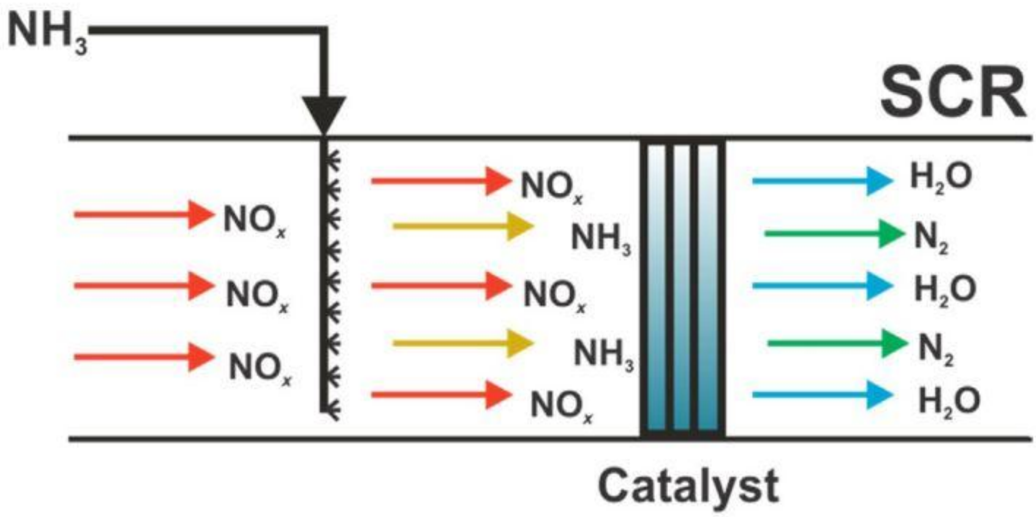

Figure 8: Post combustion NO_x reduction using Selective Catalytic Reduction (SCR) to produce the harmless products namely: water (H_2O) and nitrogen(N_2). Ammonia (NH_3) is used as the reagent. (Source: Romero and Wang, 2019)

This project therefore recommends the installation of Ultra low emission technologies such as Low NOx burners and Selective Catalytic Reduction to reduce the emission of NOx from Eskom's coal fired power plants. These technologies are now in wide use in China since 2014 and are relatively cheap and easy to install (Romero and Wang, 2019; Saw et al,2021; Prunet et al,2020). This project will be of interest to both owners of coal fired power plants globally and the companies that manufacture Ultra Low Emission technologies in general. Using both satellite and in situ data of NOx emissions from coal fired power plants, we provide empirical evidence in support of the effectiveness of Ultra Low Emission technologies in reducing Nitrogen dioxide emissions from coal fired power plants (Tang *et al*,2019; Tian *et al*,2022). It is hoped that the results of our data analysis will convince stakeholders like Eskom to install ULE technology in their coal fired power plants. It is also hoped that Governmental Environmental Management authorities will arise with proactive action to enforce the minimum emission standards to non-compliant companies like Eskom. The findings should also motivate ULE manufacturers to continue innovating newer, cheaper and more efficient ULE technologies that can guard the environment and human health against the dangers of exposure to nitrogen dioxides and other pollutant emissions from power plants.

Data

Our aim is to present convincing empirical evidence using both satellite and in situ data obtained for a coal fired plant that was retrofitted with ULE technology by showing evidence of reduction of emissions after installing ULE technology. This would convince Eskom and other power plant owners that the technology works and hopefully Eskom will buy and install the technology in its cluster of high emitting power plants found in South Africa.

This project therefore utilises both satellite and in situ Nitrogen dioxide emission data obtained for Suizhong Power Plant in China. This coal fired power plant was retrofitted with Ultra Low Emission technology in July 2014 following stricter new minimum emission standards introduced by the government of China in 2014(Jiao *et al*, 2020). Suizhong power plant is an isolated power plant having no neighbouring power plant within a 50km radius. The choice of an isolated power plant is so that we minimise the influence of other nitrogen dioxide sources other than Suizhong power plant. This will ensure that the in situ and satellite data obtained is of nitrogen dioxide emitted by the Suizhong Power plant. Other techniques such as wind rotation and over sampling (Potts *et al*,2021) were and can still be utilised to offset the impact of other local and external Nitrogen emission sources.

In situ NOx data for the Suizhong power plant was obtained from China's Continuous Emissions Monitoring System (CEMS) for the period from 1 January 2010 to 31December 2018(Jiao *et al*, 2020). The in-situ data was processed and reported as an annual average of the daily measurements. This approach will be useful in plotting time series trends of Nitrogen dioxide emissions for the nine years from 2010 to 2018.

Satellite data for tropospheric nitrogen dioxide emissions for Suizhong Power Plant was obtained from the Ozone Monitoring Instrument (OMI) spectrometer which is aboard the Aura satellite. Aura passes over China daily at 13:45 and has a spatial resolution of 24km by 13km. (Jiao *et al*, 2020). OMI data obtained was from 1 January 2010 to 31 December 2018.To ensure reliability of this satellite data, only data with cloud cover less than 30% was used. The satellite data was processed and reported as an annual average of the daily measurements. This approach will be useful in plotting time series trends of Nitrogen dioxide emissions for the nine years from 2010 to 2018.

YEAR	OMI MEASURED NO_2 CONCENTRATION(DU)	IN SITU CEMS NOx EMISSION AMOUNT(t)
2010	6.72	16.39
2011	7.73	18.08
2012	7.39	17.77
2013	7.68	14.92
2014	7.46	14.69
2015	5.46	15.24
2016	5.32	8.35
2017	5.19	8.68
2018	5.61	7.56

Method

Flow Chart

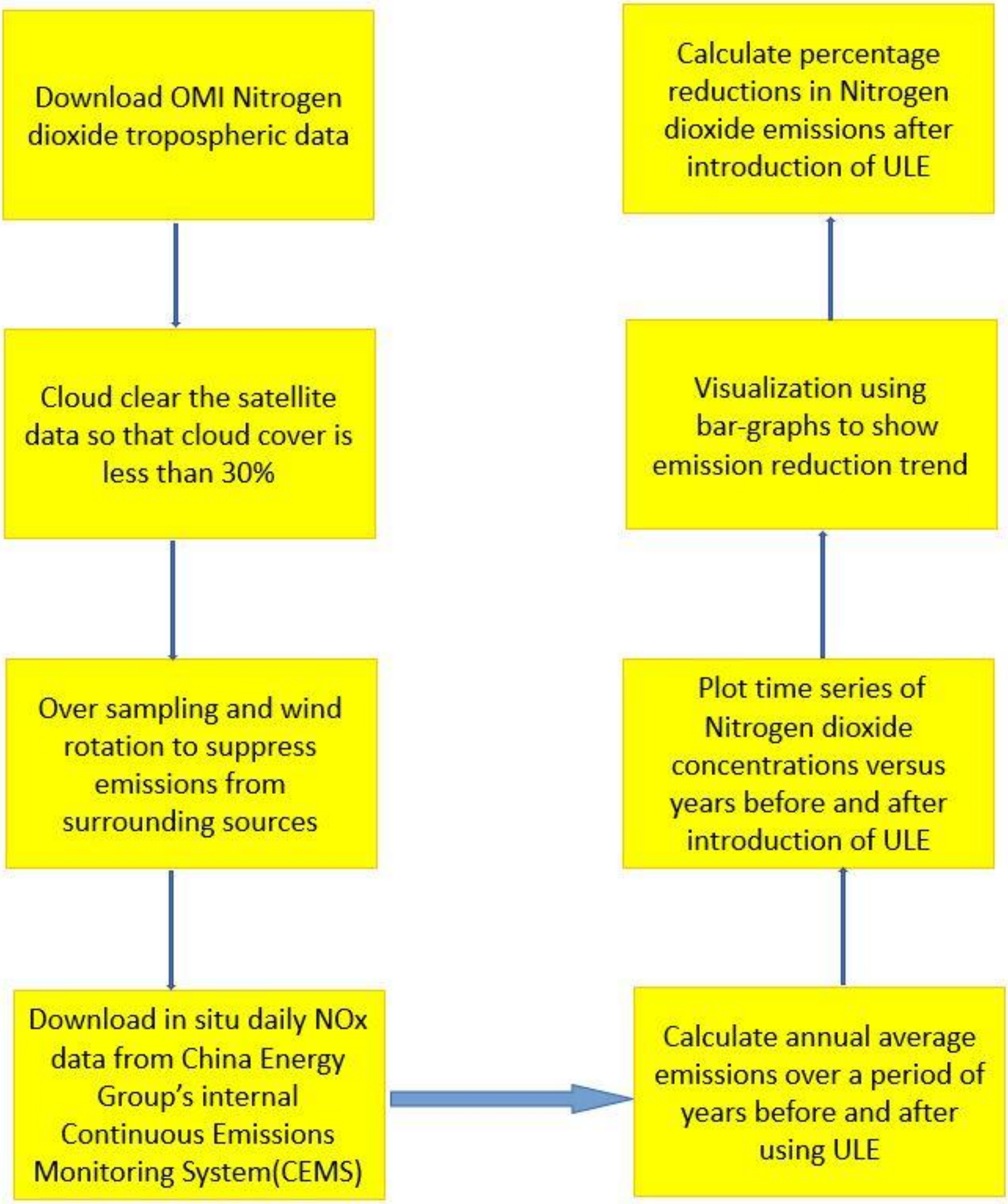

Figure 10: Flow chart showing the key project implementation steps and methods

The six procedures that will be followed in the project implementation are detailed below: First, OMI Nitrogen dioxide tropospheric column data is downloaded. This dataset is cloud cleared up to 30% cloud cover. This ensures the reliability of our dataset (Jiao *et al*, 2020). Over sampling and wind rotation (Potts *et al*,2021) are carried out to ensure that the satellite data being recorded for Nitrogen dioxide emissions does not consist of NOx emissions from other local and foreign emissions near and away from Suizhong power plant. This ensures that the plume data being captured by OMI is actually that from the point source of interest.

This is followed by the downloading of in situ daily NOx emission data from China's Continuous Emissions Monitoring System (CEMS). CEMS is a network of ground or site-based sensors that are installed by the government of China at coal fired power plants to track daily emissions (Jiao *et al*, 2020). Data from CEMS will be instrumental in validating remote sensed emission results from OMI data. The in-situ data acts as a set of checks and balances to our remote sensed satellite data. Next, from the daily records of emission data, we use R code to mutate the daily data into annual averages that are suitable for monitoring annual changes in emissions over the years using time series analysis. This we do for both in situ CEMS data and OMI satellite data.

The next step involves plotting time series plots for annual NOx emissions for both in situ CEMS data and the remote sensed OMI data. The time series plots should be able to display changes in emissions levels at Suizhong power plant after the installation of ULE technology. In order to visualize the changes in emission levels after the introduction of ULE technology at Suizhong power plant, our stake holders are presented with bar graphs. Lastly, we quantify the effectiveness of the ULE technology by calculating and quantifying the percentage reduction in nitrogen dioxide emissions.

Time Series Analysis of OMI and CEMS data

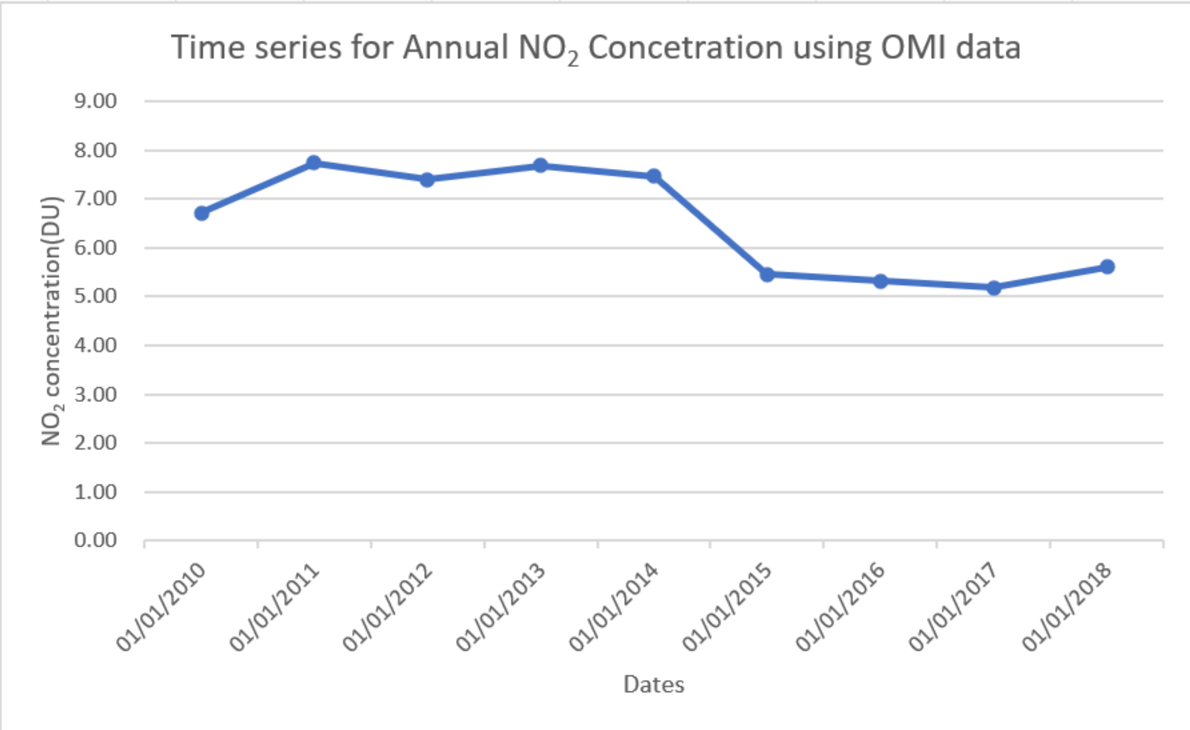

Figure 11: Time series plot of annual Nitrogen dioxide concentration in Dobson units using OMI data from 2010 to 2018. The graph shows a sharp decline in Nitrogen dioxide concentration from July 2014 when ULE technology was installed at Suizhong Power plant. There was drop from 7.5 DU in 2014 to about 5.2 DU in 2015 after ULE installation.

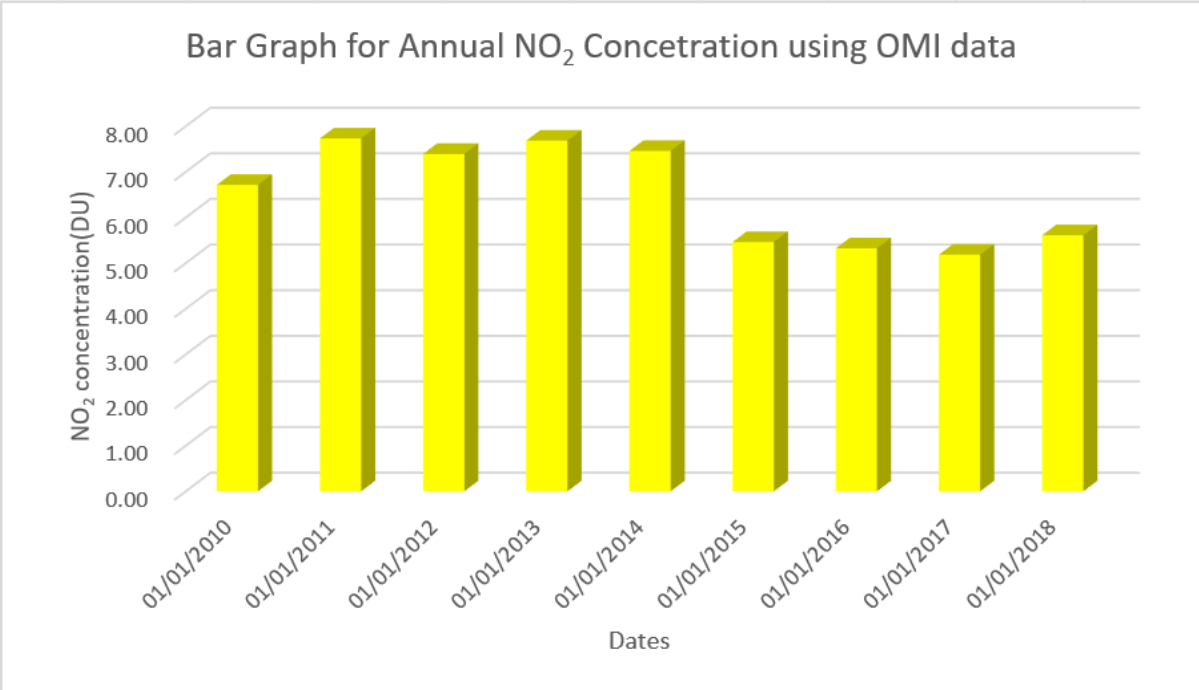

Figure 12: Bar graph showing annual Nitrogen dioxide concentration in Dobson units using OMI data from 2010 to 2018. The graph shows a sharp decline in Nitrogen dioxide concentration from July 2014 when ULE technology was installed at Suizhong Power plant. There was drop from about 7.3 DU in 2014 to about 5.1 DU in 2015 after ULE installation.

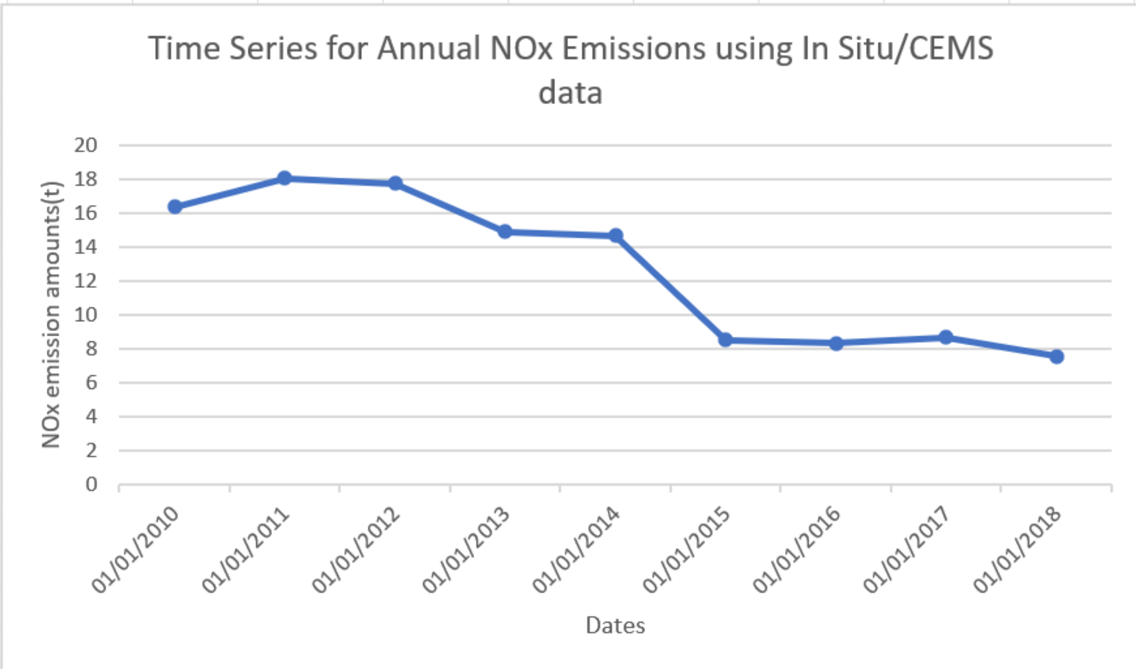

Figure 13: Time series plot of annual Nitrogen dioxide emissions in tonnes using in situ/CEMS data from 2010 to 2018. The graph shows a sharp decline in Nitrogen dioxide emissions from July 2014 when ULE technology was installed at Suizhong Power plant. There was drop from 14 tonnes in 2014 to about 8 tonnes in 2015 after ULE installation.

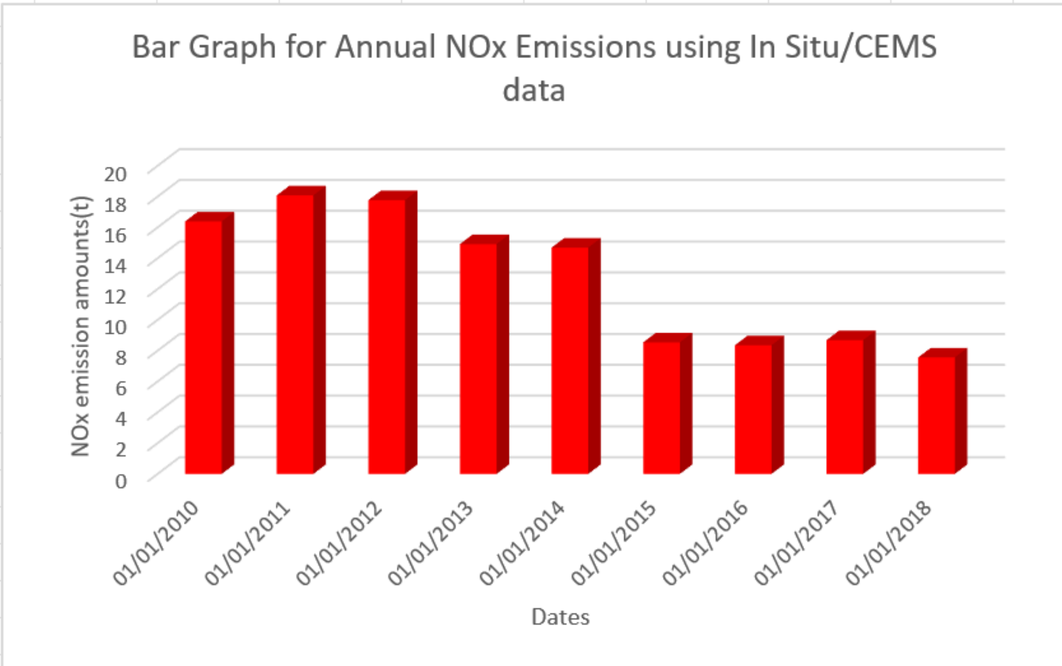

Figure 14: Bar graph showing annual Nitrogen dioxide emissions in tonnes using in situ/CEMS data from 2010 to 2018. The graph shows a sharp decline in Nitrogen dioxide emissions from July 2014 when ULE technology was installed at Suizhong Power plant. There was drop from about 14 tonnes in 2014 to about 8 tonnes in 2015 after ULE installation.

Discussion

Time series analysis (**Figure 11**) and bar graph (**Figure 12**) of OMI satellite data shows that there is a sharp decline in tropospheric Nitrogen dioxide concentration between 2014 and 2015. This reduction from 7.5 Dobson units in 2014 to 5.2 Dobson units in 2015 is attributed to the installation of Ultra low emission technology at Suizhong Power Plant in July of 2014.

From the satellite data, the percentage reduction in NO_2 concentration after ULE technology installation is calculated as

$$= (7.5-5.5)/7.5 \times 100\% = 30.6\%$$

Time series analysis (**Figure 13**) and bar graph (**Figure 14**) of in situ/CEMS data shows that there is also a sharp decline in tropospheric Nitrogen dioxide emission between 2014 and 2015. This reduction from 14 tonnes in 2014 to 8 tonnes in 2015 is attributed to the installation of Ultra low emission technology at Suizhong Power Plant in July of 2014.

From the in situ/ CEMS data, the percentage reduction in NO_2 emission after ULE technology installation is calculated as

$$= (14-8)/14 \times 100\% = 42.9\%$$

Clearly, from both analysis of satellite and in situ data sets, it's clear that there is a percentage reduction in nitrogen dioxide production. This is proof of the effectiveness of ULE technology in reducing nitrogen dioxide emissions at coal fired power plants.

Conclusions

In this project, we set out to use both OMI satellite data and in situ CEMS data of Nitrogen dioxide concentrations and emissions to provide evidence of the effectiveness of Ultra low emission technologies when installed in coal fired power plants. By use of time series analysis on data collected about Suizhong Power plant in China before and after ULE technology installation, we have quantified that ULE technology can bring down Nitrogen dioxide emissions by approximately 31% to 43%. This proves the effectiveness of ULE technology in reducing NOx emissions and concentrations in the atmosphere.

This evidence when presented to stake holders like Eskom in South Africa should convince them and motivate them to install the ULE technology. In addition, these findings should motivate companies involved in the design, production and sale of ULE technology to continue innovating so that higher emission reduction percentages are attained. Other stakeholders that may benefit from these findings are Environmental and Emissions Standards Enforcement agencies in governments. These agencies need to impose stricter low emission standards by insisting that all coal fired power plants must install Ultra low emission technologies in their power plants.

Limitations

All remote sensed satellite data is affected by cloud cover over a place. Removing pixels of cloud always leads to data loss (Potts *et al*,2021). This project was limited by cloud cover.

The presence of other nitrogen dioxide from other local and foreign sources apart from Suizhong power plant was a challenge. Wind will always play a role in transporting nitrogen dioxide from other emitters or sources to our study area. Over sampling and wind rotation are recommended for future research projects to mitigate these challenges (Potts *et al*,2021).

Accuracy of satellite data measurements can be improved by using higher resolution satellites like Sentinel 5P to access TROPOMI data (Potts *et al*, 2021; Saw *et al*,2021; Shikwambana *et al*,2020). However, because of limited time available for the project duration, the team was not able to fully process TROPOMI data sets to a usable format for time series analysis. In addition, because Sentinel 5P came into service in 2017 yet ULE technologies were installed at Suizhong Power plant in July 2014, the sentinel data was not available for years before 2017 and more especially for year 2014 and before. This meant that by using Sentinel 5P data only, it was impossible to acquire and plot data for the years before 2014 when ULE technology was not yet installed at Suizhong Power plant. Without this data, the reductions in concentration trends could not be quantified for the Suizhong power plant. Hence, in this situation, OMI data from Aura satellite was most feasible to use.

If Eskom management, goes ahead and installs ULE technology in its coal fired power plants say next year, after reading this report, then future research can utilise TROPOMI Sentinel 5P nitrogen dioxide emission data for the Eskom power plants and build a time series analysis that can be used to assess effectiveness of ULE technology at Eskom's power plants. The data before installation of ULE in 2023 will be available and that after installation.

References

Jiao, X., Liu, X., Gu, Y., Wu, X., Wang, S., and Zhou, Y. (2020). ‘Satellite verification of ultra-low emission reduction effect of coal-fired power plants’, *Atmospheric Pollution Research, 11*(7), pp.1179-1186, doi: 10.1016/j.apr.2020.04.005

Myllyvirta, L. (2019) ‘Air quality and health impacts of ESKOM’s planned non-compliance with South African Minimum Emission Standards’, *Greenpeace Global Air Pollution Unit,* Available at: https://www.greenpeace.org/static/planet4-africa-stateless/2019/03/8a84b69a-air-quality-and-health-impacts-of-eskoms-non-compliance.pdf

Potts, D. A., Ferranti, E. J., Timmis, R., Brown, A. S., and Vande Hey, J. D. (2021). ‘Satellite data applications for site-specific air quality regulation in the UK: Pilot study and prospects’, *Atmosphere, 12*(1659), pp.1-14, doi:10.3390/atmos12121659

Prunet, P., Lezeaux, O., Camy-Peyret, C., and Thevenon, H. (2020). ‘Analysis of the NO_2 tropospheric product from S5p Tropomi for monitoring pollution at City Scale.’, *City and Environment Interactions, 8*(100051), pp.doi:10.1016/j.cacint.2020.100051

Romero, C. E., and Wang, X. (2019). ‘Chapter 3 - Key Technologies for ultra-low emissions from coal-fired power plants.’, in Romero, C. E., and Yongsheng,Z. *et al.*(eds.) *Advances in Ultra-Low Emission Control Technologies for Coal-Fired Power Plants.* Bethlehem:Woodhead Publishing, pp.39–79, doi:10.1016/b978-0-08-102418-8.00003-6

Saw, G. K., Dey, S., Kaushal, H., and Lal, K. (2021). ‘Tracking NO_2 emission from thermal power plants in North India using Tropomi Data.’, *Atmospheric Environment, 259*(118514), pp.1-6, doi: 10.1016/j.atmosenv.2021.118514

Shikwambana, L., Mhangara, P., and Mbatha, N. (2020). ‘Trend analysis and first time observations of sulphur dioxide and nitrogen dioxide in South Africa using tropomi/sentinel-5 P Data.’ *International Journal of Applied Earth Observation and Geoinformation, 91*(102130),pp.1-13, doi:10.1016/j.jag.2020.102130

Tang, L., Qu, J., Mi, Z., Bo, X., Chang, X., Anadon, L. D., Wang, S., Xue, X., Li, S., Wang, X., and Zhao, X. (2019). ‘Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards’, *Nature Energy, 4*(11), pp.929–938, doi:10.1038/s41560-019-0468-1

Tian, X., An, C., Nik-Bakht, M., and Chen, Z. (2022). ‘Assessment of reductions in NO_2 emissions from thermal power plants in Canada based on the analysis of policy, inventory, and Satellite Data’, *Journal of Cleaner Production*, *341*(130859), pp.1-15, doi: 10.1016/j.jclepro.2022.130859

Wikipedia (2022) ‘Eskom’. Available at: https://en.wikipedia.org/w/index.php?title=Eskom&oldid=1126370119 (accessed 12 December 2022)